

Geology of the Upheaval Dome impact structure, southeast Utah

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Abstract. Two vastly different phenomena, impact and salt diapirism, have been proposed for the origin of Upheaval Dome, a spectacular scenic feature in southeast Utah. Detailed geologic mapping and seismic refraction data indicate that the dome originated by collapse of a transient cavity formed by impact. Evidence is as follows: (1) sedimentary strata in the center of the structure are pervasively imbricated by top-toward-the-center thrust faulting and are complexly folded as well; (2) top-toward-the-center normal faults are found at the perimeter of the structure; (3) clastic dikes are widespread; (4) the top of the underlying salt horizon is at least 500 m below the surface at the center of the dome, and there are no exposures of salt or associated rocks of the Paradox Formation in the dome to support the possibility that a salt diapir has ascended through it; and (5) planar microstructures in quartz grains, fan-tailed fracture surfaces (shatter surfaces), and rare shatter cones are present near the center of the structure. We show that the dome formed mainly by centerward motion of rock units along listric faults. Outcrop-scale folding and upturning of beds, especially common in the center, are largely a consequence of this motion. We have also detected some centerward motion of fault-bounded wedges resulting from displacements on subhorizontal faults that conjoin and die out within horizontal bedding near the perimeter of the structure. The observed deformation corresponds to the central uplift and the encircling ring structural depression seen in complex impact craters.

1. Introduction

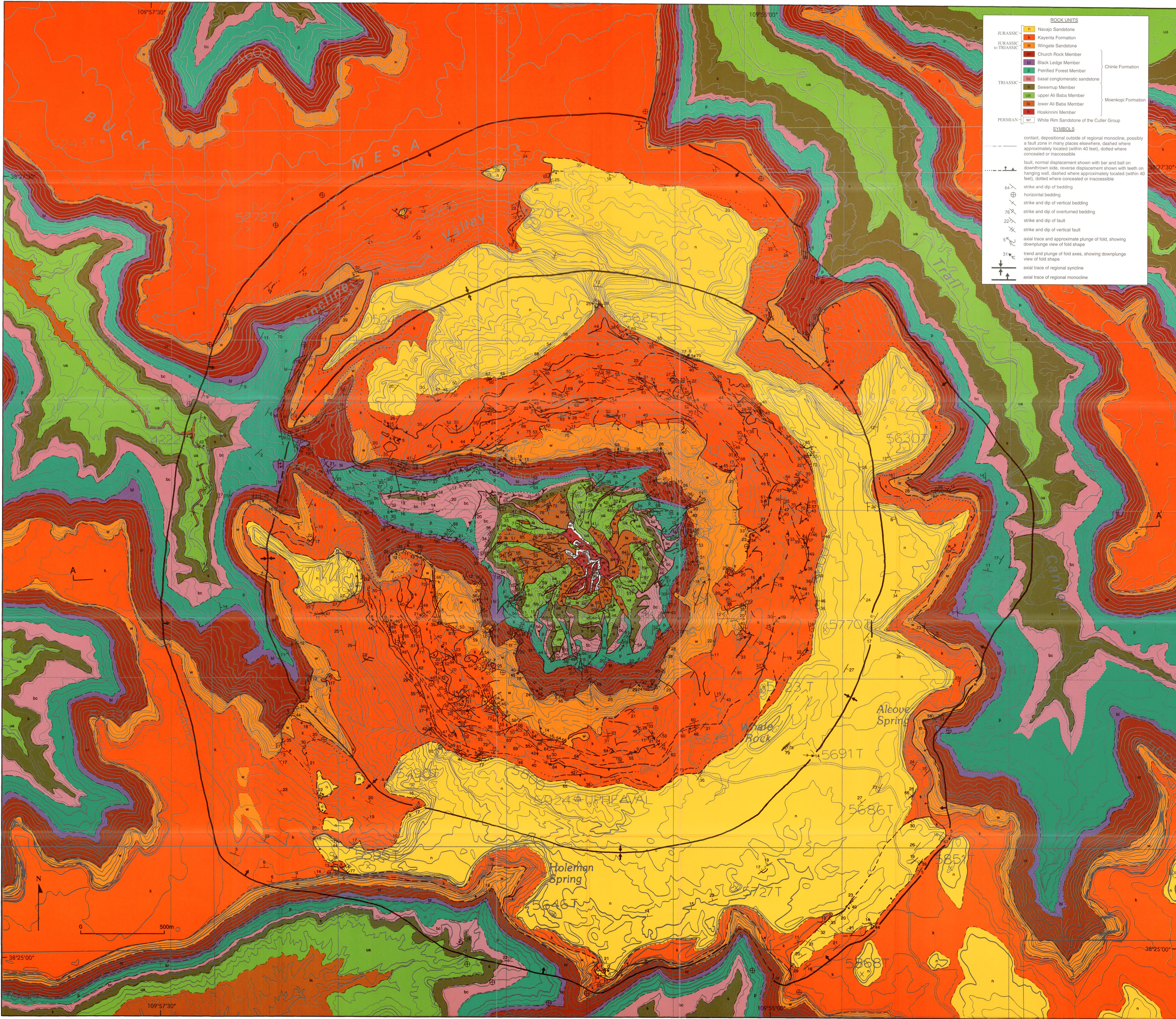
Impact of solid bodies is the most fundamental geologic process in the solar system, having formed the terrestrial planets and satellites and modified their surfaces until the present. The surface morphology of craters has been studied extensively in recent years on other planets and satellites including the Moon, but only a relative handful of impact craters on Earth have been closely scrutinized. This is largely due to the fact that many of the craters on Earth are buried or obscured by vegetation and/or erosion. The observations described in this paper indicate that Upheaval Dome, located in Canyonlands National Park, southeast Utah, is an eroded impact structure. We believe that it is one of the best-exposed impact structures in the world and thus one of the best places to study impact mechanics. Much of the three-dimensional

structure of Upheaval Dome is revealed in the deep canyons that have been eroded into it.

Existing field studies of impact structures on Earth and the morphology of craters on the other terrestrial planets and on the Moon have led to the recognition of a variety of structural classes of craters. Small impact craters typically have a simple bowl shape, and the rocks of their walls preserve much of the structure developed during passage of the shock wave and opening of an initial or transient cavity [Shoemaker, 1960]. Above a certain threshold size, the transient cavity collapses, and a complex crater is formed. Rocks of the walls and rim of the transient cavity subside and are transported inward, generally along listric faults [Melosh, 1989]. The convergent flow causes the rocks underlying the floor of the transient cavity to rise in a structurally complex central uplift. On Earth, the transition from simple to complex craters occurs at crater diameters of ~2 km in sedimentary rocks and ~4 km in strong crystalline rocks [Grieve, 1991]. In this paper, we show that Upheaval Dome is an example of a complex crater that is somewhat above the transition size. The dome and surrounding ring structural depression provide a particularly clear example of the deformation that accompanies transient cavity collapse.

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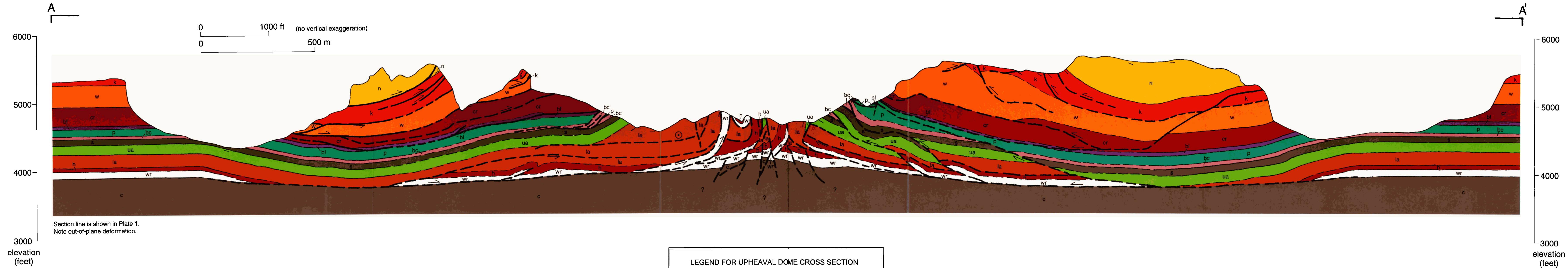


PLATE 2. GEOLOGIC CROSS SECTION OF UPHEAVAL DOME, CANYONLANDS NATIONAL PARK, UTAH

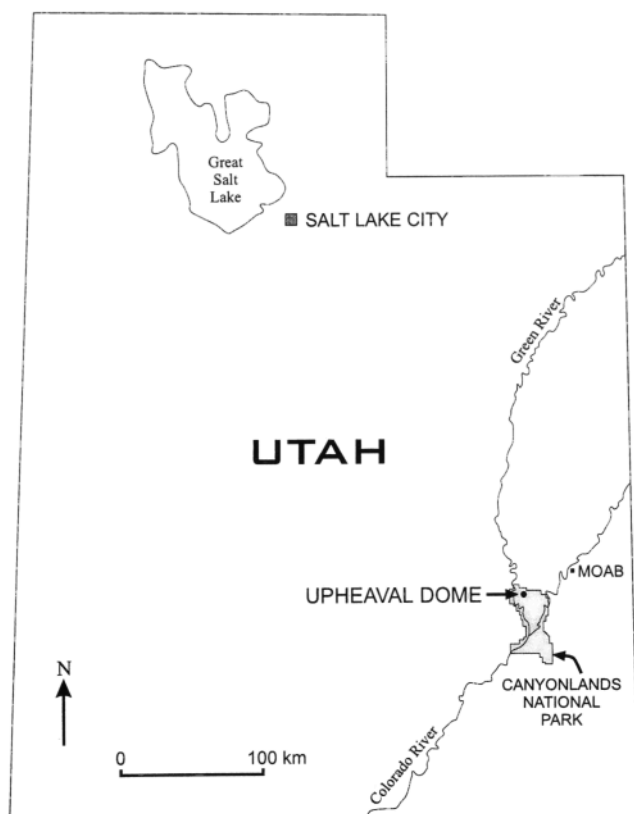


Figure 1. Map of Utah (latitude 37°–42°, longitude 109°–114°), showing location of Upheaval Dome.

2. History of Investigation

Upheaval Dome was first noted during a reconnaissance geologic study by B. H. Parker, who hypothesized that the structure was due to salt doming [Harrison, 1927]. Since then, the interpretation of this structure has been the subject of dozens of publications, and its origin continues to be debated. Bucher [1936] firmly advocated a cryptovolcanic origin for Upheaval Dome. Shortly thereafter, Boon and Albritton [1938] suggested that many of the Earth's cryptovolcanic structures were actually of impact origin, although they did not specifically mention Upheaval Dome. The first detailed description of Upheaval Dome was by McKnight [1940], who mapped the structure at 1:62,500 scale. While he considered that the structure might be of impact origin, he favored the hypothesis that the central uplift and surrounding structural depression were the result of salt flow in the underlying Paradox Formation. Shoemaker [1954, 1956] recognized clastic dikes of White Rim Sandstone at the center of the structure and initially supported the cryptovolcanic interpretation, also on the basis of the results of a geophysical survey that showed a pronounced magnetic anomaly over Upheaval Dome [Joesting and Plouff, 1958]. At that time, little was known about impact structures, but it later became evident that Boon and Albritton were correct.

As more impact structures were recognized throughout the world, it became possible to estimate the rate of impacts during the Phanerozoic within a factor of ~2 [Shoemaker, 1983]. This cratering rate and the total area and average age of rocks exposed on the Colorado Plateau implied that a crater of ~10

km in diameter should be present on the Plateau. This calculation prompted further field work at Upheaval Dome, and an impact origin was supported on the basis of the faulting and centerward motion of rocks that was observed [Shoemaker and Herkenhoff, 1984]. Recently, however, Jackson *et al.* [1998] have interpreted these faults to record motion of rocks into a cavity left behind by the upward passage of a salt diapir, now eroded away. The details of their hypothesis are outlined and discussed in section 4.

3. Geologic Setting

Upheaval Dome is located in the Canyonlands region of the Colorado Plateau in southeast Utah (Figure 1). Most of the region is underlain by nearly flat-lying to gently deformed sedimentary strata of Pennsylvanian to Cretaceous age (Figure 2). Northwest trending salt anticlines occur within the Paradox depositional basin of Pennsylvanian and Permian age [e.g., Cater, 1970; Doelling *et al.*, 1988]. Small salt diapirs (300–400 m across) and normal faults are found in the area of The Grabens at the south end of Canyonlands National Park [Huntoon *et al.*, 1982]. Upheaval Dome, a 2.5 km-diameter complex structural uplift surrounded by a 5 km-diameter annular structural depression, lies near the north end of the park (Figures 3 and 4). The dome is located near the western margin of the Paradox basin. The presence of known salt structures in the region influenced early interpretations that Upheaval Dome resulted from salt diapirism, but it is noteworthy that there are no other similar-size domal structures visible elsewhere in this part of the Colorado Plateau (Figure 2). This is contrary to what is observed in other areas of salt diapirism, where many such domes typically occur in close proximity to each other [e.g., Worrall and Snelson, 1989; Jackson *et al.*, 1990]. Upheaval Dome also lacks the normal faulting and stratal thinning typically seen in the center of salt domes. In addition to the above features, the region contains a pervasive northwest to north striking subvertical conjugate joint system. This joint system appears to postdate the deformation at Upheaval Dome, on the basis of the lack of folding or tilting of joints. Also present is a northeast striking, ~10 km-long fracture (the Roberts rift) located ~25–30 km northeast of Upheaval Dome, which Huntoon and Shoemaker [1995] suspected to be the result of impact at the dome.

Rock units exposed in the dome range from the White Rim Sandstone, the uppermost formation of the Permian age Cutler Group, to the middle of the Jurassic age Navajo Sandstone (Figures 4 and 5). Huntoon and Shoemaker [1995] proposed that upper Cutler Group rocks underlying the White Rim Sandstone (the Organ Rock Shale) are exposed in the dome center, but we interpreted and mapped these rocks as lower members of the Moenkopi Formation. Strata shown in Figure 5 older than the White Rim Sandstone have been penetrated by drilling. On the basis of subsurface strata encountered in a drill hole in the eastern part of the ring structural depression, the top of the highest salt lies >500 m below the lowest exposed surface outcrops (D. L. Baars, written communication, 1984; Buck Mesa 1 hole location shown in Figure 3). A recent seismic refraction experiment confirmed that no salt is present within 500 m of the surface in the central area of the dome [Louie *et al.*, 1995]. No trace of salt or associated rocks of the Paradox Formation has been found among the complexly faulted rocks in the center of the dome.



Figure 2. Landsat thematic mapper image of SE Utah (latitude 38°-38.75°, longitude 109.5°-110.25°), showing area in the vicinity of Moab and Canyonlands National Park (cf. Figure 1). North is up, resolution is 30 m/pixel. Most of the area is underlain by essentially flat-lying strata. Also clearly visible are NNE striking The Grabens area normal faults in bottom center of image. The salt diapirs found in the Colorado River channel at bottom center of image are too small to be seen here. Also shown are the locations of the Cane Creek anticline and Shafer dome (a broad, doubly plunging anticline), interpreted by Cater (1970) as salt structures, and the Roberts rift. Image is courtesy of Chris Lee (California State University, Dominguez Hills), annotated by Tim Parker (Jet Propulsion Laboratory).

4. Structural Geology of Upheaval Dome

With the exception of the talus slopes below the Wingate Sandstone, the quality of exposure at Upheaval Dome is very high, roughly 75-90% bedrock. Along canyon walls, the exposure of structural features is remarkably complete. Faults,

folds, and clastic dikes are conspicuous and were mapped at a scale of 1:6000 (Plate 1, folded in pocket).

Upheaval Dome is marked by a complexly faulted and folded central uplift, surrounded by a ring structural depression and a circular monocline that defines the perimeter of the structure (Figure 3). In the central uplift, the Moenkopi For-



Figure 3.

LEGEND

n	Jurassic Navajo Sandstone	c	Triassic Chinle Formation
k	Jurassic Kayenta Formation	m	Triassic Moenkopi Formation
w	Jurassic to Triassic Wingate Sandstone	wr	Permian White Rim Sandstone beds and clastic dikes



Figure 4. Oblique aerial photograph of Upheaval Dome, looking NW, for comparison with geology in Figure 3. Road at bottom of photograph and general topography can be used for matching with Figure 3. From center outward, major rock units are as follows: (1) White Rim Sandstone and Moenkopi Formation (light- to dark-colored central topographic high), (2) Chinle Formation (slopes below inner cliff), (3) Wingate Sandstone (inner cliff), (4) Kayenta Formation (circular moat between inner and outer cliffs), and (5) Navajo Sandstone (outer circular belt of light-colored cliff-forming rocks). Pronounced topographic high in center is associated with structural uplift of ~350 m. Ring structural depression (circumferential syncline) is visible in Navajo Sandstone at top right side of photo. Upheaval Canyon is visible at upper left and drains the center of the dome. Dark swath in uppermost left is the Green River. Location of closest undeformed section used in Figure 5 is below prominent cliff on south side of Upheaval Canyon, top left side of photo. Photograph is courtesy of Tom Till.

mation and White Rim Sandstone have been raised at least 350 m in elevation compared to outcrops in the undeformed perimeter of the dome. The White Rim Sandstone occurs primarily as clastic dikes and rarely as bedded strata. Proceeding outward from the central uplift to the vicinity of the syncline that encircles the uplift (the ring structural depression), there are circular outcrop bands of Chinle, Wingate, Kayenta, and Navajo units. The Chinle and Kayenta Formations are folded and thrust faulted, whereas the massive Wingate and Navajo Sandstones are mainly folded. Clastic dikes derived from Navajo to Wingate units are found in these out-

crops, and some of the Wingate Sandstone appears to have flowed as tongue-shaped masses into or overlapping the Chinle Formation. All rock units, for the most part, dip away from the central uplift until the axis of the encircling syncline is reached. Outward from the syncline axis, rock units of the Navajo Sandstone to the Moenkopi Formation are exposed and dip toward the central uplift. Normal faults in this area omit stratigraphic section. A few clastic dikes of sandstone are found in the Navajo, Kayenta, and Chinle units here. Further outward, the rock units flatten at the axis of an encircling monocline. This monocline is the outermost structure associ-

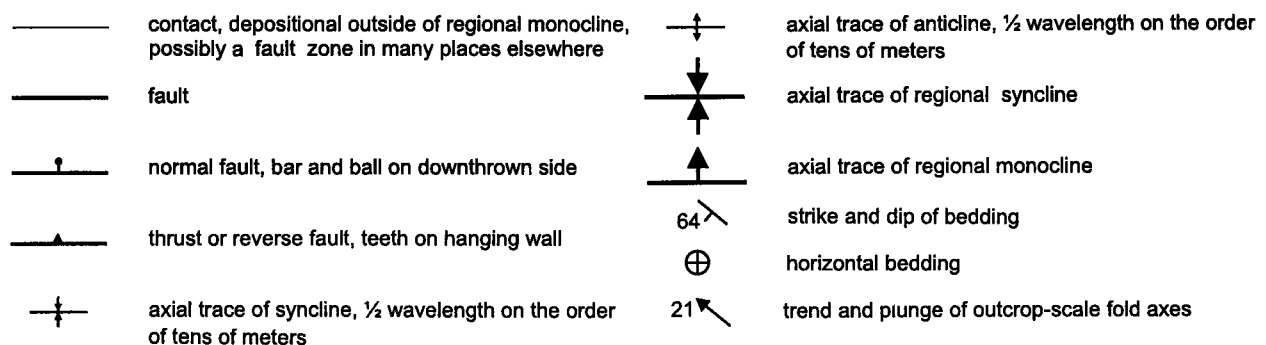


Figure 3. Simplified geologic map of Upheaval Dome, compiled from mapping at 1:6000 (Plate 1). Also shown is location of drill hole Buck Mesa 1, Husky Oil Company.

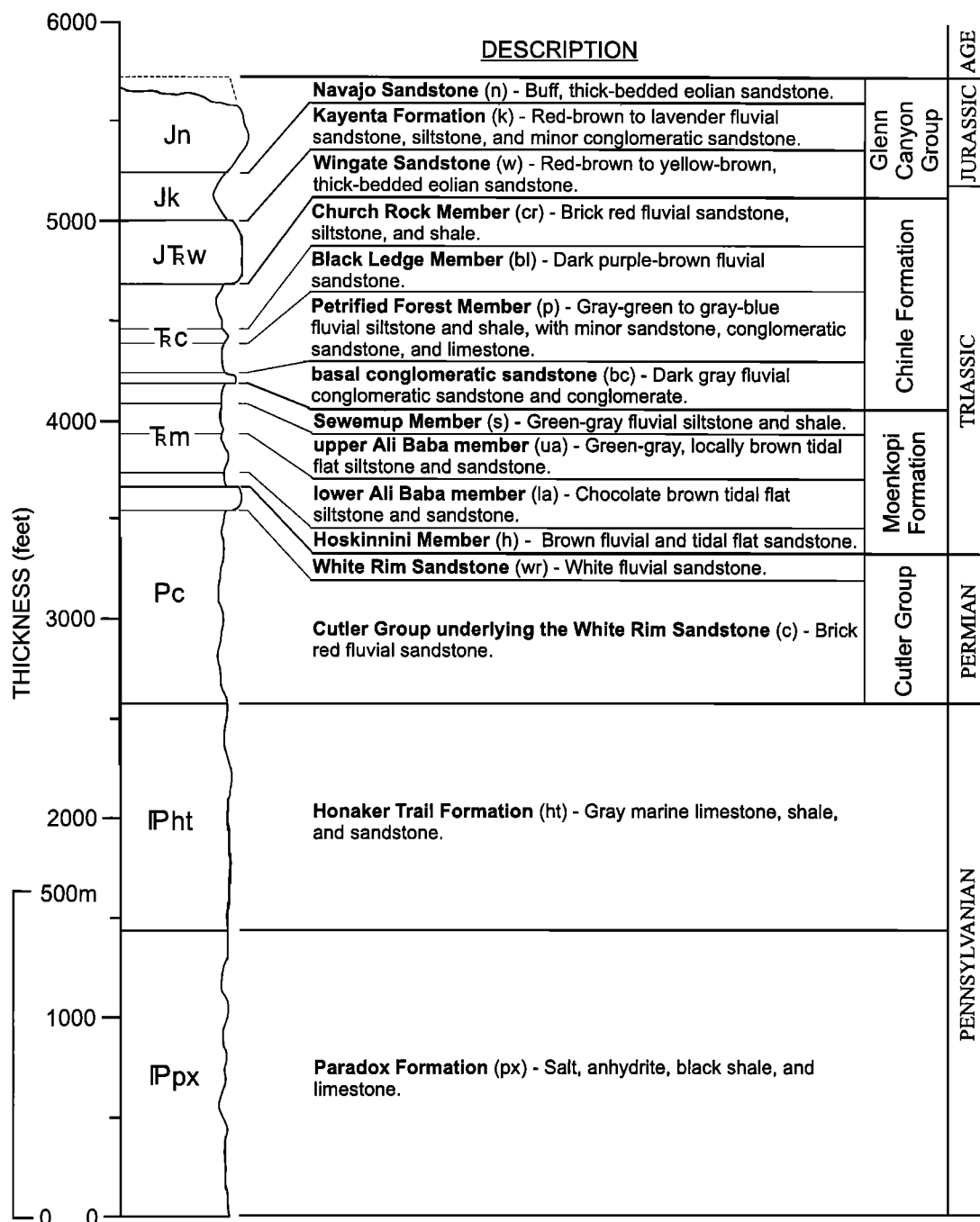


Figure 5. Composite stratigraphic column showing rock units and thicknesses in undeformed region around perimeter of Upheaval Dome. Map and cross-section rock unit labels are shown in parentheses. Column was constructed from three sources: (1) gamma log located near Willow Flat campground, ~5 km SE of Upheaval Dome (Murphy Range Unit 1, Pan American Petroleum Corp., reproduced by *McCleary and Romie* [1986], (2) stratigraphic observations of Moenkopi Formation at west end of Steer Mesa, ~4 km WSW of Upheaval Dome [*Stewart et al.*, 1972], and (3) stratigraphic field study of Chinle and Moenkopi Formations exposed on the south side of Upheaval Canyon, ~1 km WNW of deformed rocks at Upheaval Dome (mapped in 1997, see Figure 4). The age shown for the Wingate Sandstone corresponds to that described by *Peterson and Pipirinos* [1979], yet subsequent studies have suggested redefining the lower stratal boundary such that the unit is entirely Jurassic in age (F. Peterson, written communication, 1998). Older Paleozoic rocks and Precambrian crystalline basement lie below Paradox Formation but are not shown here. The top of the Navajo Sandstone is not exposed in or around Upheaval Dome, but estimated thickness (based on closest exposure) is shown with a dashed line.

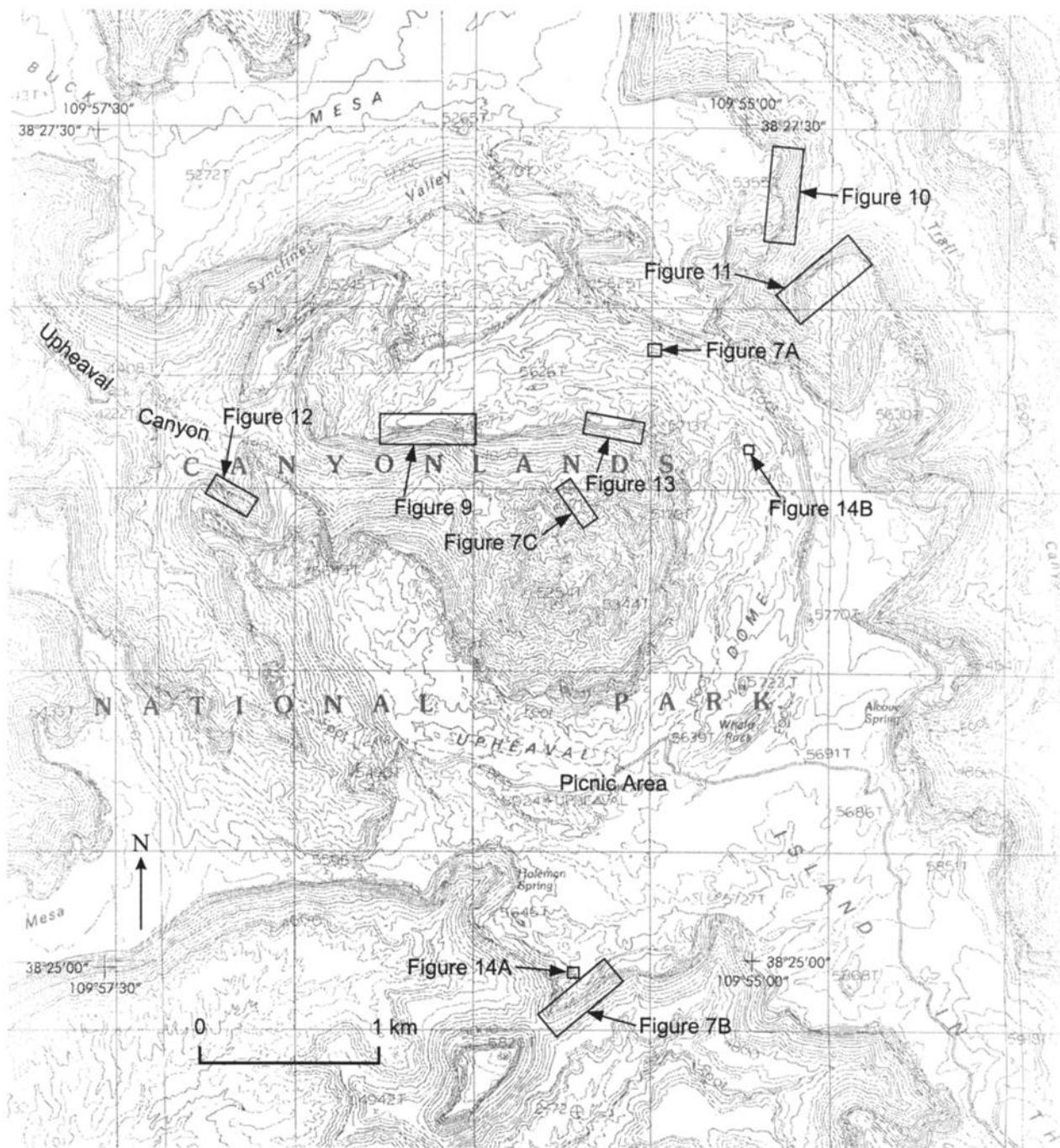


Figure 6. Locality map, showing place names and most photograph locations.

ated with Upheaval Dome. The region outward from the monocline is characterized by essentially flat-lying strata.

Our map data generally agree with mapping presented by *Schultz-Ela et al.* [1994] and *Jackson et al.* [1998], who interpreted the dome to record infilling of a cavity left behind by an ascending salt diapir which has since been eroded away. They infer that there are significant unconformities, growth faults, and a ring syncline caused by syndepositional rise of salt in the center. Their volume balance calculations show volume deficiency in the dome center, consistent with the passage of a diapir into a region above the present level of

erosion. They cite the presence of folded rocks as evidence for relatively slow (~ 20 Myr) development of the overall structure, much slower than the timescales of seconds to minutes thought to be associated with complex crater formation. We disagree with this pinched-off diapir interpretation and view the dome as an impact structure for the reasons outlined below.

There is an absence of salt and other rocks of the Paradox Formation in the dome. Although *Jackson et al.* [1998] account for the absence of salt by postulating complete dissolution of salt following dome formation, they do not explain the

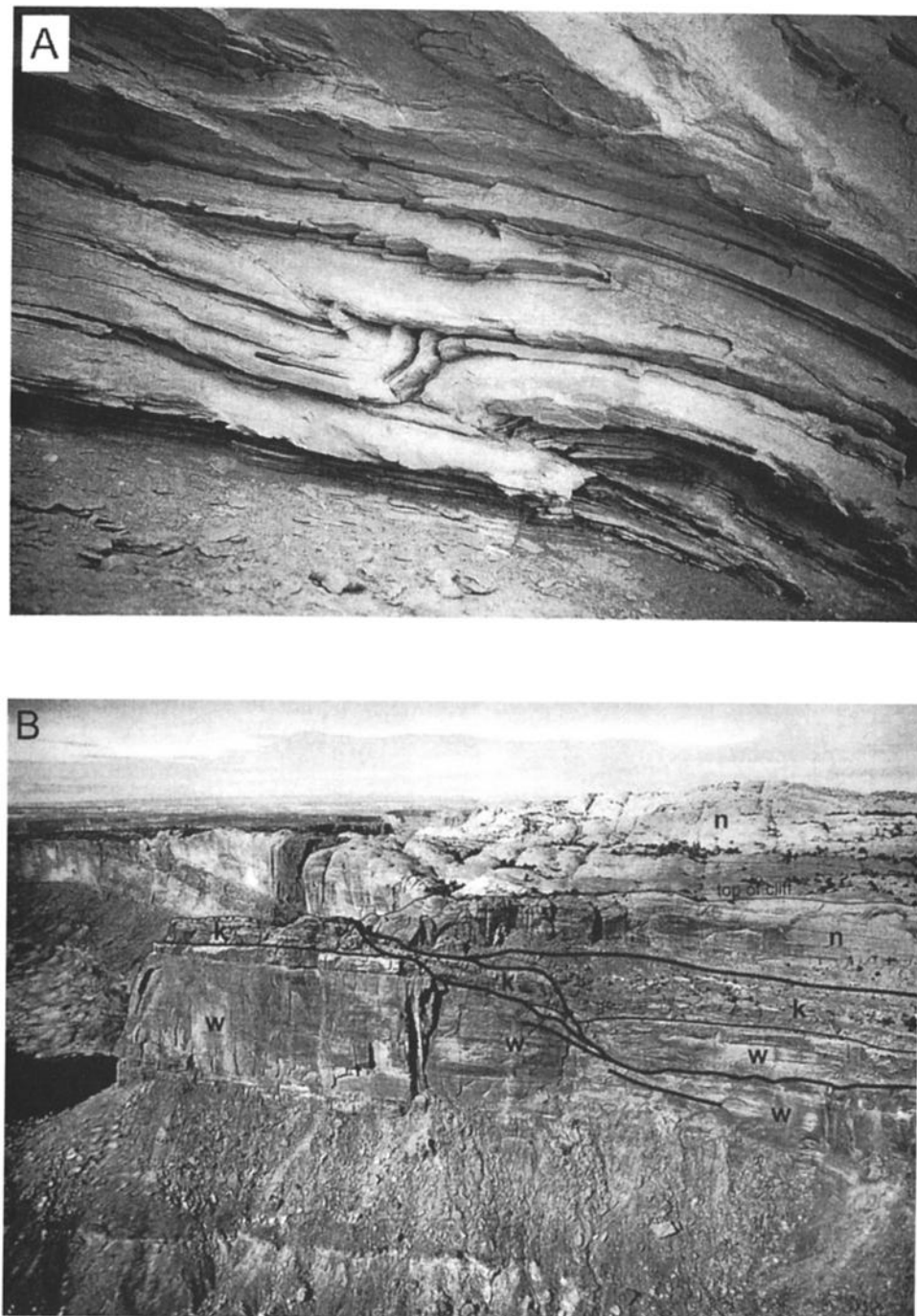


Figure 7. Photographs of faults. See Figure 6 for locations. (a) Thrust fault in Kayenta Formation. View is looking west at top-toward-the-center vergence. On a smaller scale, some top-away-from-center vergence is also visible above main fault. (b) Low-angle normal faults exposed in SW perimeter of dome. View is to NW, center of dome lies to right of photograph. One fault system can be seen dipping NE and cutting down through cliff of Wingate Sandstone (w). Note Kayenta (k)-Wingate contact (bedded Kayenta Formation in rubble-covered slope above Wingate cliff) offset by top-toward-the-center displacement. Navajo Sandstone (n), exposed in upper cliff and much of background, is also in fault contact with the Kayenta Formation. Note that Kayenta Formation has been significantly thinned by offset on both faults, and although difficult to see here, Navajo Sandstone displays reverse drag of bedding at southernmost end of upper cliff in foreground (cf. Plate 1). Note monocline visible in background. Scale of foreground in photograph is roughly 250 x 500 m. (c) View looking NE from center of dome at faulted and duplicated Moenkopi Formation of central topographic high. Clastic dike of White Rim Sandstone is visible at bottom right. Scale is ~80 m x 250 m.



Figure 7. (continued)

absence of limestones and black shales that are interbedded with the salt. If a salt diapir had ascended through the dome, some of these less soluble rock types of the Paradox Formation would have been entrained in the rising salt and would be exposed in the dome center. Such rock types would be easy to detect because of differences in color and composition from the White Rim Sandstone and younger units that are exposed in the center. Moreover, the structures seen in the dome are typical of those found in known complex impact craters [e.g., *Wilshire et al.*, 1972; *Offield and Pohn*, 1979; *Shoemaker and Shoemaker*, 1996]. In particular, these are as follows: (1) a central structural uplift formed by inward convergence of rocks via faulting and folding, (2) a circular outcrop pattern of rock units and a ring structural depression (an encircling syncline), and (3) clastic dikes. In light of the above evidence supporting impact, we interpret the significant unconformities cited by *Jackson et al.* [1998] as impact-related faults. We interpret the faulting and folding to represent brittle to plastic deformation as a result of rapid, gravity-driven sliding of heterogeneously lithified material; such deformation might in places resemble the rare growth faulting described by *Jackson et al.* [1998]. Using our data and the methods outlined by *Brewer and Kenyon* [1996], we found no volume loss associated with the deformation in the dome center, in contrast to *Jackson et al.* [1998]. Below, we describe the structural features of Upheaval Dome in more detail. Localities referred to in the text are shown in Figure 6.

4.1. Faults

Recognition of faults during mapping was relatively straightforward for the Chinle Formation and lower rock units, largely because of the tabular bedding geometry and numerous marker beds. Fault recognition was a more involved task in the Wingate Sandstone and higher units,

mainly because these units lack tabular bedding and marker beds. Instead, lenticular bedding and cross-bedding are widespread and cause some bed contacts to look superficially like faults. Gradational interfingering bedding relations exist at both Navajo-Kayenta and Kayenta-Wingate contacts, making bed-subparallel faults difficult to detect at these contacts. In cases where obvious bedding displacement could not be discerned in these units, criteria such as the presence of gouge, breccia, striae, drag folds, and high-angle (greater than $\sim 35^\circ$) bed cutoffs were used to map faults. Unfortunately, these features are not that common. Low-angle (less than $\sim 35^\circ$) bed cutoffs alone were not used as a criterion because they are common depositional features in undeformed sections of these units. As a result of the difficulties described above, a conservative approach to fault mapping was adopted for the Wingate to Navajo units, implying that there may be more faults in these units than shown in Plate 1.

Faults are found throughout Upheaval Dome with increasing frequency toward the center (Plate 1). Estimates of displacement along the faults shown in Plate 1 range from ~ 5 to 500 m, with the largest offsets occurring on the outer faults. In the center, faults with mappable displacement (> 5 –10 m offset) are spaced ~ 10 –50 m apart and are associated with chaotic structure and highly variable bedding attitudes. Throughout the structure, gouge, breccia, fault striae, and drag folds are developed only sporadically. Slickenfibers are notably absent. The scarcity of gouge, breccia, and striae is surprising and implies relatively low friction during displacement. Striae are particularly uncommon in the slope-forming, fine-grained units such as the Chinle and Moenkopi Formations. Thin- to medium-bedded Kayenta, Chinle, Moenkopi, and White Rim strata are generally much more faulted than the thick-bedded to massive Wingate and Navajo Sandstones.

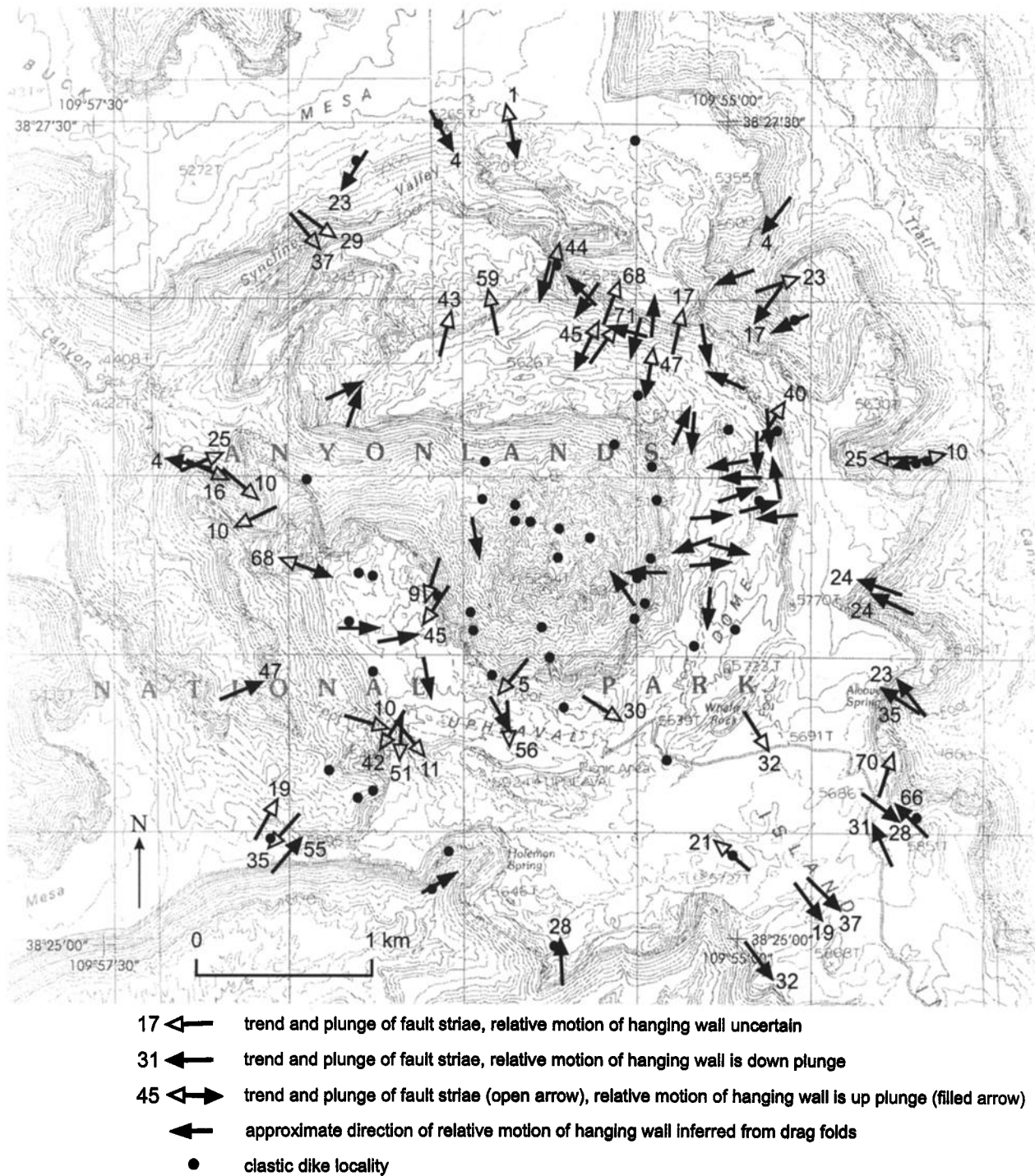


Figure 8. Map showing kinematic data and locations of clastic dikes. See Plate 1 for corresponding attitudes of faults.

Rock units in general are structurally thickened by repetition along thrust faults in the central area and structurally thinned by normal faults in the outer area (Figure 7, Plate 1). There are, however, some places in the central area where the Chinle Formation is structurally thinned. Kinematic data from offset bedding, drag folds, and fault striae indicate dominantly radial vergence on both normal and thrust faults, but some thrusts show approximately circumferential displacement (Figure 8). There is a notable absence of cross-

cutting relations between the variably verging thrusts. Along Upheaval Canyon (the breach west of the dome center), bed-parallel faults that omit strata can be traced into rising thrust faults on the flank of the central uplift (Figure 9, Plate 1). Near the perimeter, there are listric normal faults that locally show reverse drag (e.g., Figure 7) or trap-door structures (e.g., south-southeast perimeter, Plate 1). Some faults that have facilitated omission of strata die out along bedding planes rather than ramp up section as they are traced into undeformed rocks

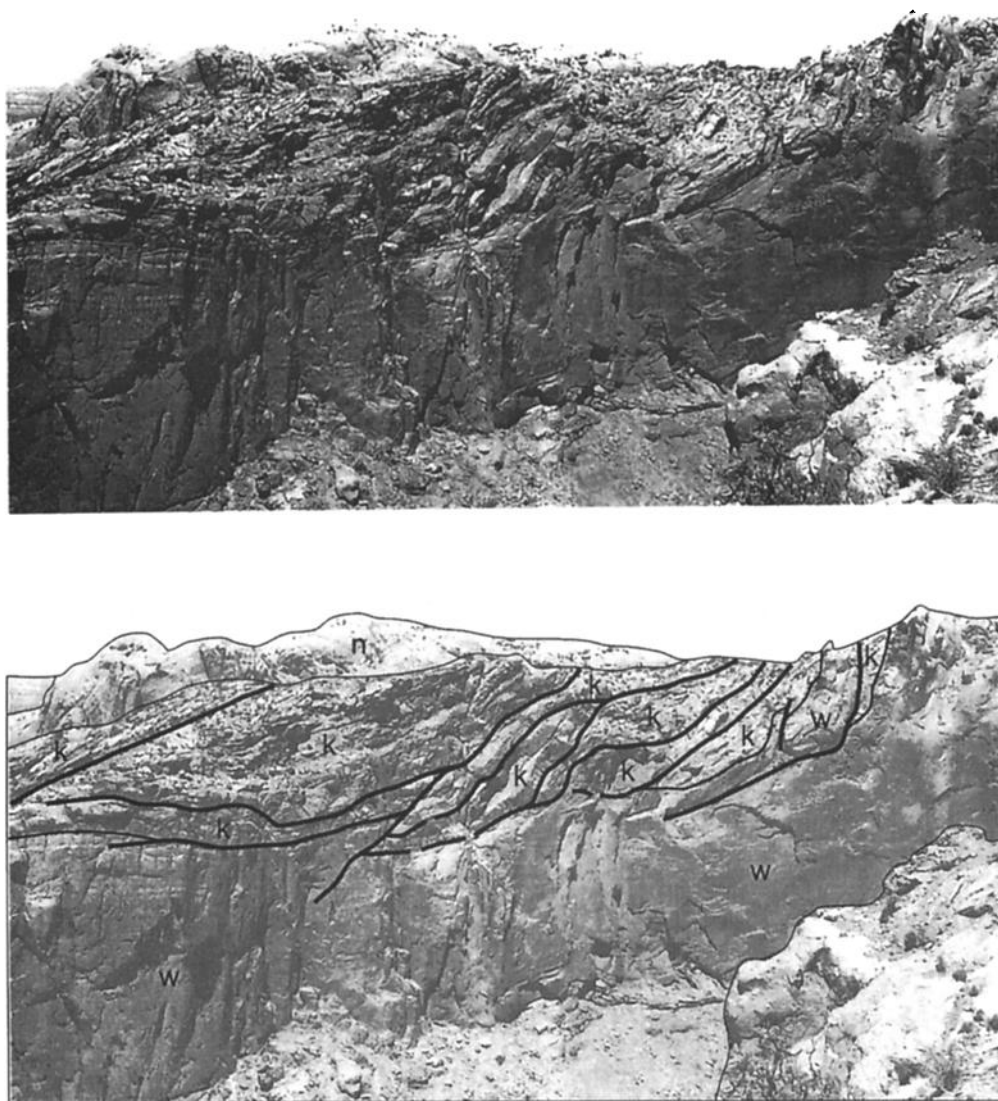


Figure 9. Looking north at cliff showing thrust faults in Kayenta Formation (k) and Wingate Sandstone (w) from south side of Upheaval Canyon. Motion is inferred to be top-toward-center. Navajo Sandstone (n) in background lies concordantly on Kayenta Formation, but contact is not visible here. There is a foreground outcrop at lower right. Scale of photograph is ~250 m x 550 m.

(Figure 10). In places, these faults seem to have facilitated centerward motion of a fault-bounded wedge of rock (Figure 11). Alternatively, there is the possibility that two episodes of faulting may have occurred, the first of which involved radially outward motion of the hanging wall (such as might be expected during the excavation stage of crater formation). For example, such outward motion might be inferred for the hanging wall of the structurally highest fault shown in Figure 11. However, in areas where there is physical continuity of exposure between these types of fault zones and the undeformed perimeter (e.g., at the north-northeast, northwest, and southeast perimeters), there is no thickening or folding of strata in the hanging wall where the fault dies out. This implies that there was little, if any, outward motion of the hanging wall. Furthermore, we were unable to find any cross-cutting relations that support two episodes of faulting. For these reasons, we suggest that the fault system shown in Fig-

ure 11 is coeval and has facilitated centerward motion of a fault-bounded wedge of Wingate Sandstone. It appears that in addition to structural thinning by listric normal faulting, there is a component of thinning by wedge faulting. Some of the listric normal faults are connected to the wedge fault systems (Figure 12). Generally, the listric normal faults are structurally above the wedge faults.

4.2. Folds

Folds of many scales and orientations occur throughout Upheaval Dome (Plate 1). Half wavelengths vary from 0.5 cm to 1 km, and fold axis orientations are mostly circumferential (parallel to circumferential segments drawn around the center) or radial (parallel to radii drawn outward from the center). The largest folds have circumferential axial traces and are as follows: (1) a monocline that delimits the boundary



Figure 10. View looking WNW at fault in Chinle Formation. See Figure 6 for location and Figure 8 for additional kinematic data from the area. Fault is shown as dying out at right side of photo as it becomes bed-parallel. Attempts to trace this fault NW into undeformed perimeter reveal that it never ramps up section but rather dies out in Chinle either here or farther to the NW. Note also that monocline is only developed in hanging wall. Monocline appears to have formed in response to faulting, which may have facilitated centerward motion of a wedge-shaped block of Chinle Formation from the fault zone (compare with Figure 11, located 330 m SE of here). Additional faults (shown as dashed lines) may be present to left of this fault (and connected to it) but are obscured by cover. Unit labels are as follows: cr, Church Rock Member; bl, Black Ledge Member; and p, Petrified Forest Member (all units within Chinle Formation). Scale of photograph is ~250 m x 550 m.

between Upheaval Dome and the surrounding nearly flat-lying undeformed strata, and (2) a syncline lying in the region of transition between normal and thrust-faulted areas. Curiously, the monocline is not found everywhere around the structure. In a reentrant at the north-northeast perimeter, the monocline is seen only in the Kayenta Formation, where it is associated with small normal faults (Plate 1). In canyons at the northeast and south-southeast perimeters, it is found only in the hanging wall of wedge faults that cut the Church Rock Member of the Chinle Formation and die out in bedding planes at the perimeter (e.g., Figure 10). This suggests that the monocline in these areas was formed by bending of hanging wall strata in response to removal of strata along these wedge faults. There is the possibility that similar faults exist at the base of the monocline elsewhere in the map area but lie below the present level of exposure and also die out along bedding planes rather than ramp upward in the perimeter. Stratal thinning by such faulting is also evident in the trough of the large-scale circumferential syncline where exposed in cliff walls below the Navajo Sandstone, but listric normal faults are also associated with this fold.

Smaller folds with half wavelengths of the order of tens of meters are well exposed in the Wingate Sandstone cliff and are dominantly closed, upright folds of radial orientation (Figure 13). Similar-scale radial open folding of faults in the nearby Kayenta Formation suggests that this folding postdates the faulting, but in places, these folds appear to be truncated

by faults. Even smaller, outcrop-scale folds are common in the Kayenta Formation and are present to a lesser extent in the Chinle and Moenkopi Formations. These folds are open to isoclinal, upright to inclined, and are approximately circumferential or radial in orientation. A few of these are found in the cross-bedding of otherwise undeformed outcrops and are thus probably due to local soft-sediment deformation. Radial folds of all scales generally plunge away from the center. Circumferential folds in the Kayenta Formation are in places asymmetric or show drag where related to faults. Where discernible, centerward vergence is usually indicated, but a few folds record outward vergence. No cross-cutting relations were found between these two types of verging folds. The presence of drag folds and absence of folded faults in the outcrop-scale folds suggest that these folds formed contemporaneously with or prior to the faults.

4.3. Clastic dikes

Clastic sand dikes are found throughout Upheaval Dome in all rock units and compose roughly 2-15% of the outcrops. High percentages of clastic dikes are found in the center of the structure, and their number decreases radially outward (Figure 8). Cross-cutting relations show that at least some of the clastic dike injection preceded faulting (Figure 14), but the occurrence of dikes along fault planes indicates synkinematic to postkinematic injection. No systematic orientation of

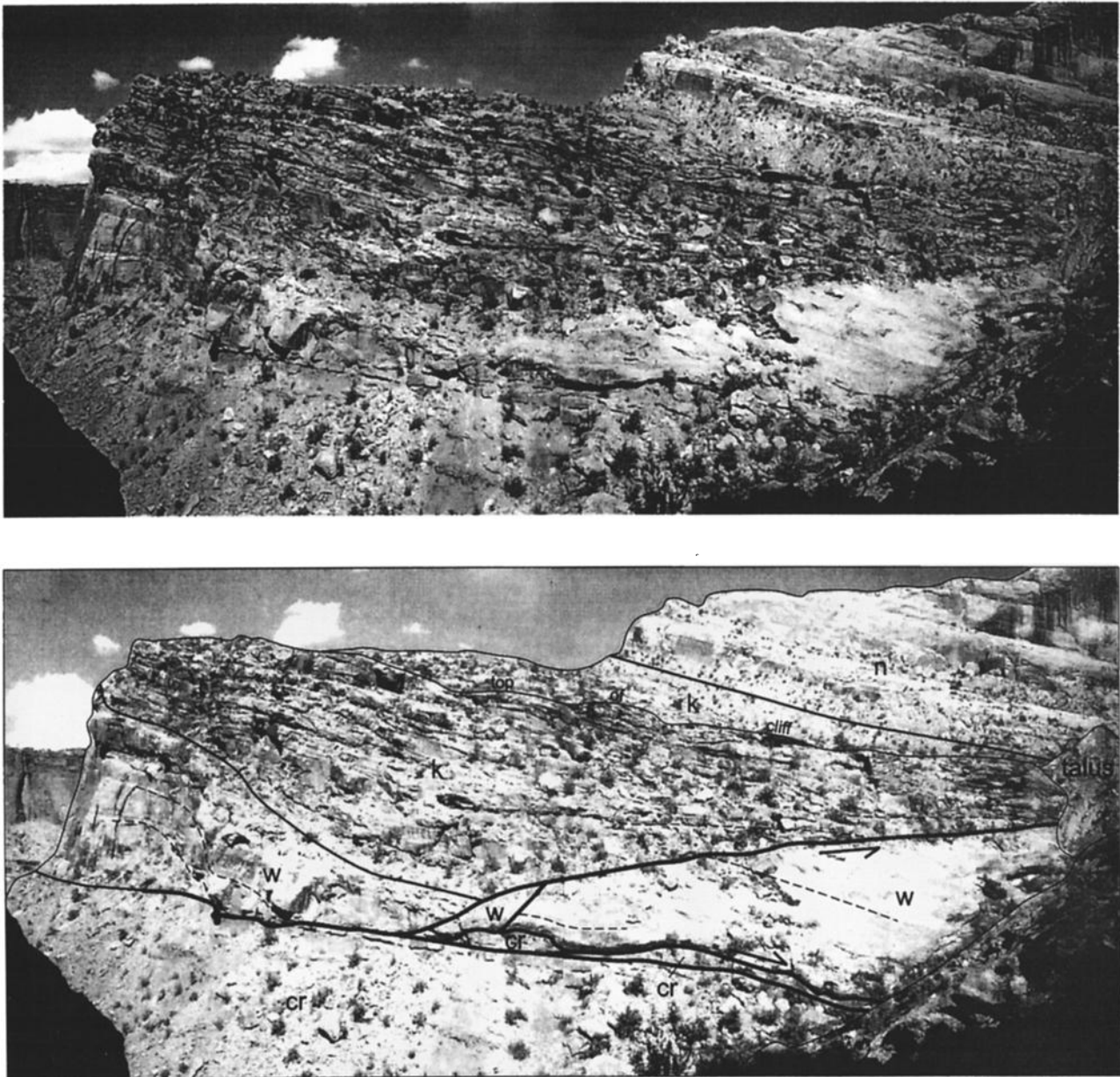


Figure 11. Looking ESE at cliff showing apparent motion of fault-bounded wedge of rock toward center of Upheaval Dome. See Figure 6 for location and Figure 8 for additional kinematic data. Bedding traces within rock units are shown with dashed lines. Unit labels are as follows: n, Navajo Sandstone; k, Kayenta Formation; w, Wingate Sandstone; and cr, Church Rock Member of the Chinle Formation. Basal fault is shown as dying out along bedding but may continue around corner at left side of photograph. Scale of photograph is ~250 m x 600 m.

clastic dikes is apparent. In most cases, the dikes have been injected along faults and fractures and range in thickness from less than a centimeter to several meters. A few appear to have flowed into the host rock without the aid of a fracture. These clastic dikes have contorted flow structure and contacts that are lobate or resemble flame structures, indicating local plastic or fluid behavior of the host rock during emplacement (Figure 14). At the base of the Wingate Sandstone cliff near the center, beds of the Church Rock Member of the Chinle Formation are locally shoved upward into fluidized Wingate Sandstone, which has, in turn, flowed downward as clastic dikes into the Church Rock Member. In some places at the

base of the cliff, lobate masses of Wingate Sandstone apparently flowed centerward and overlap the Church Rock Member.

The clastic dikes are composed of orange, red, or white quartzose sandstone. White dikes are found mainly in the center of the dome, and the orange and red dikes occur near the center to the perimeter of the dome. Orange-colored dikes in the Chinle Formation have in some cases been physically traced to sources at the base of the Wingate Sandstone, but in general, protoliths for the clastic dikes are inferred on the basis of color, mineralogy, and the assumption that they are not far traveled. Thus white dikes in the center were derived from

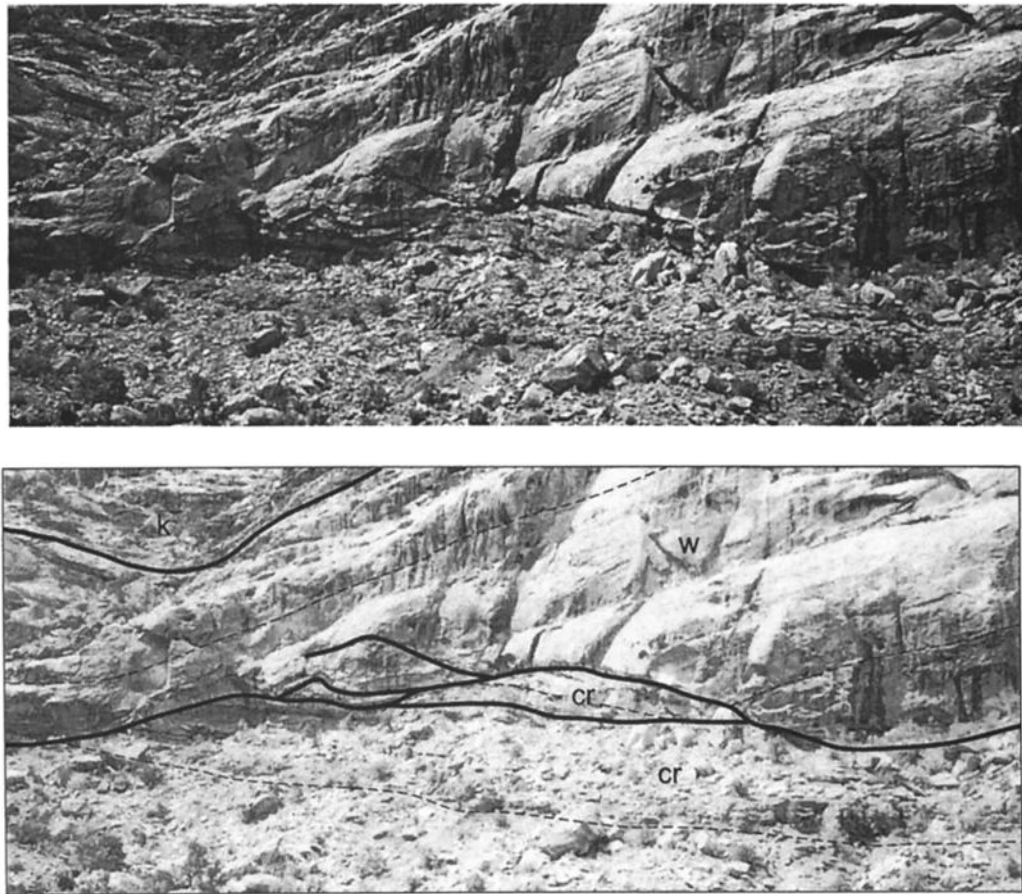


Figure 12. Looking south at bedding cutoffs in Wingate Sandstone (w) and Church Rock Member of the Chinle Formation (cr) consistent with motion of a wedge of rock toward center (located left of photograph). Bed-parallel fault zone at base of Kayenta Formation (k) is also shown. See Figure 6 for location and Figure 8 for additional kinematic data. Fault zone at Wingate-Church Rock contact can apparently be traced southward along this contact for 1 km before it ramps up section in the direction of the undeformed perimeter (see Plate 1). About 500 m south, a fault-bounded wedge of Wingate Sandstone is linked to both fault zones shown here (see Plate 1). Scale of photograph is ~80 m x 200 m.



Figure 13. Looking NNE at radial folds in basal Wingate Sandstone. Width of view is ~300 m.



the White Rim Sandstone; orange dikes in the Kayenta Formation are from the Wingate Sandstone or Navajo Sandstone, and the orange dikes in the Navajo Sandstone and red dikes in the Kayenta Formation are derived from the formations in which they occur.

In thin section, clastic dike samples show a broad range of grain fracturing. The most highly fractured grains are seen in samples from the center of the dome (Figure 15). Possible planar deformation features are present in some of the White Rim dike samples that we examined (discussed in section 5).

4.4. Interpretation of Structural Features

Displacement along normal faults and structural thinning of strata in the perimeter and occurrence of thrust faults, radial folds, and structurally thickened strata in the center demonstrate motion of rock from the perimeter toward the center of the structure (Figure 16). The subsidiary outward verging contractional structures may be back thrusts and back folds formed during this centerward motion, although an earlier and largely overprinted stage of minor outward verging deformation (expected during the crater excavation stage) cannot be ruled out. As shown by continuous exposure in Upheaval Canyon, the normal and thrust faults are coeval and connected components of a listric fault system that facilitated gravitational sliding of rocks toward the center (Plates 1 and 2). This style of deformation is interpreted to have extended only to the base of the White Rim Sandstone, on the basis of the lack of exposures of older rocks in the central uplift. Some centerward motion of fault-bounded wedges also occurred on subhorizontal faults that conjoin and die out within subhorizontal bedding near the perimeter of the structure. Removal of strata by such wedge faulting, and to a lesser extent, listric normal faulting, accounts for the creation of the large-scale



Figure 14. Examples of clastic dikes. (a) Outcrop from perimeter of Upheaval Dome, looking east. West dipping normal fault at top truncates near-vertical sandstone dike. (b) Looking NW at clastic dike in Kayenta Formation. Hammer rests on country rock, dike is toward right. Note contorted flow structure and lobate contact with country rock.

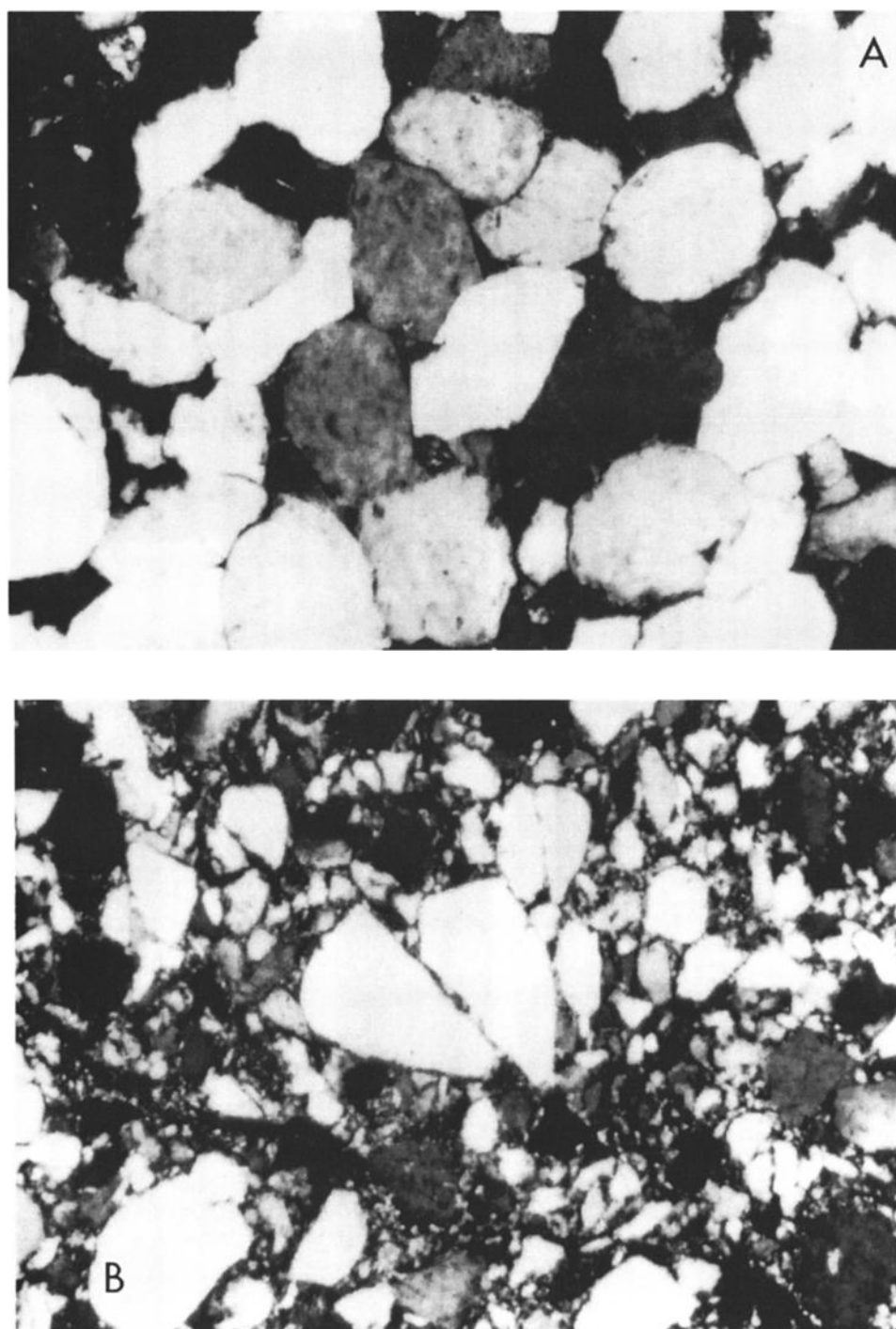


Figure 15. Photomicrographs of White Rim Sandstone (quartz arenite), crossed polars. Scale of both photos is 2 mm x 3 mm. (a) Sample from undeformed section exposed on Shafer Trail, 10 km ENE of Upheaval Dome. Note well-sorted, rounded, and compacted texture. (b) Sample of White Rim Sandstone dike from center of Upheaval Dome. Note pervasive fracturing of grains and resultant increase in angularity and fine-grained matrix.

circumferential syncline and monocline. All the above deformation is interpreted to represent the collapse stage of complex crater development, during which a central peak and ring structural depression were formed. The central uplift was volumetrically accommodated by removal of material from the margin, which in turn formed the ring structural depression and monocline. While elastic rebound [Melosh, 1989] may have contributed to central peak formation, it is

not required to produce the observed uplift. In our view, the central uplift at Upheaval Dome corresponds to an eroded central peak, and the large-scale syncline and monocline represent an eroded ring structural depression.

The prevalence of faults in the dome illustrates that the rocks largely behaved brittly during impact and subsequent gravitational sliding, but the occurrence of folds and clastic dikes indicates some fluid to plastic behavior. Massive to

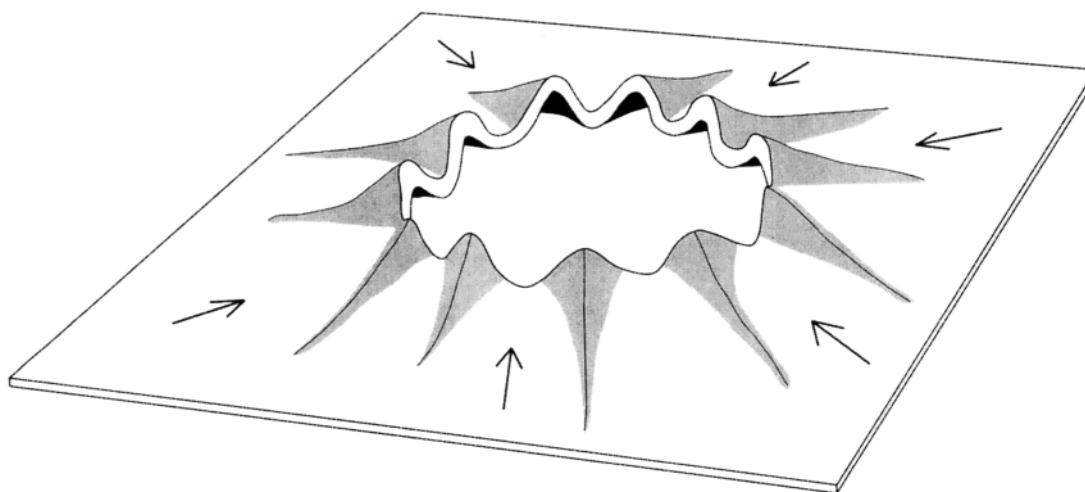


Figure 16. Diagram showing how convergent flow from perimeter to center causes radial folding and concomitant plastic thickening in Wingate Sandstone. Prior to erosion, Navajo Sandstone may have looked similar to this. In other exposed rock units, similar strain has been accommodated mainly by faulting with some folding. Original drawing is by Lottie Soll (California Institute of Technology).

thick-bedded, relatively homogeneous formations such as the Wingate Sandstone and Navajo Sandstone appear to be relatively free of mappable faults, whereas thinner-bedded, lithologically heterogeneous formations are cut by numerous faults. In places, the Wingate and Navajo units show pervasive microfaulting. Local plastic to fluid behavior of the Wingate and, to a lesser extent, other units may be due to the presence of fluids and/or a low degree of lithification, since the deformation in many places resembles that seen in soft-sediment landslides. The presence of pressurized fluids could have mobilized the material in the clastic dikes [Huntoon and Shoemaker, 1995].

In summary, the development of Upheaval Dome began with fracture and local fluidization (clastic diking) of rocks during impact compression. The distribution of clastic dikes (frequency decreasing radially outward) is consistent with that expected to result from impact. Some outward motion of rock may have occurred during this stage, but evidence is sparse. Following excavation of the transient cavity, there was convergent flow of brittle to plastic material toward the center and some continued emplacement of clastic dikes. This convergent flow formed the central uplift and ring structural depression.

5. Planar Microstructures

Thin sections from samples of clastic dikes of the White Rim Sandstone near the center of Upheaval Dome show planar microstructures in quartz grains (Figure 17). Planar fractures are the most commonly occurring microstructures, some of which are decorated. Although planar fractures are not alone diagnostic of shock deformation [French, 1998], some Upheaval Dome grains have multiple sets of microstructures, perhaps planar deformation features. The lack of obvious planar deformation features indicates that these samples were only weakly shocked [Grieve *et al.*, 1996]. The samples show little porosity and appear similar to those of Kieffer's [1971] class 1b Coconino Sandstone samples, indicative of shock pressures up to 5.5 GPa. The sample shown in Figure 17 is currently being analyzed to distinguish shock from tectonic

deformation using the technique described by Gratz *et al.* [1996].

6. Shatter Surfaces and Shatter Cones

Shatter cones are conical fracture surfaces decorated with "fan-tailed" patterns of ridges and grooves that diverge away from the apices of the cones. They were first recognized at Steinheim Basin, Germany [Branco and Fraas, 1905], and have been found at many other, but not all, impact structures [Dietz, 1963, 1968]. They also have been produced by high-speed impact experiments and by detonation of chemical and nuclear explosives [Shoemaker *et al.*, 1961; Bunch and Quaide, 1968; Schneider and Wagner, 1976; Roddy and Davis, 1977]. Rock types in which they are best developed tend to be well-lithified carbonate and crystalline igneous intrusive. Milton [1977] estimated that shatter cones form over a range of shock pressures from ~2.5 to 25 GPa.

Shatter cones were reported by Shoemaker *et al.* [1993] in thin sandstone beds of the Moenkopi Formation near the center of Upheaval Dome. These cones are rare and not as finely decorated and grooved as shatter cones found at many other impact structures (Figure 18). This may be due to the fact that the rocks at Upheaval Dome were poorly lithified and/or porous clastic strata during impact. In places on the central uplift, however, thin beds of siltstone and very fine sandstone of the Moenkopi are pervasively cut by roughly planar fractures decorated with fan-tailed patterns of grooves and ridges. We refer to these fractures as "shatter surfaces." Generally, the shatter surfaces are inclined at angles of ~45°–60° to the bedding. Multiple sets of shatter surfaces are present in individual beds. Locally, shatter surfaces can be traced with varying strike over arcs with radii of curvature of tens of centimeters. The shatter surfaces along these arcs appear to be segments of large cones whose apices point stratigraphically upward. We suggest that the shatter surfaces observed at Upheaval Dome have been formed in response to shock pressures within the lower part of the range over which typical shatter cones are formed.

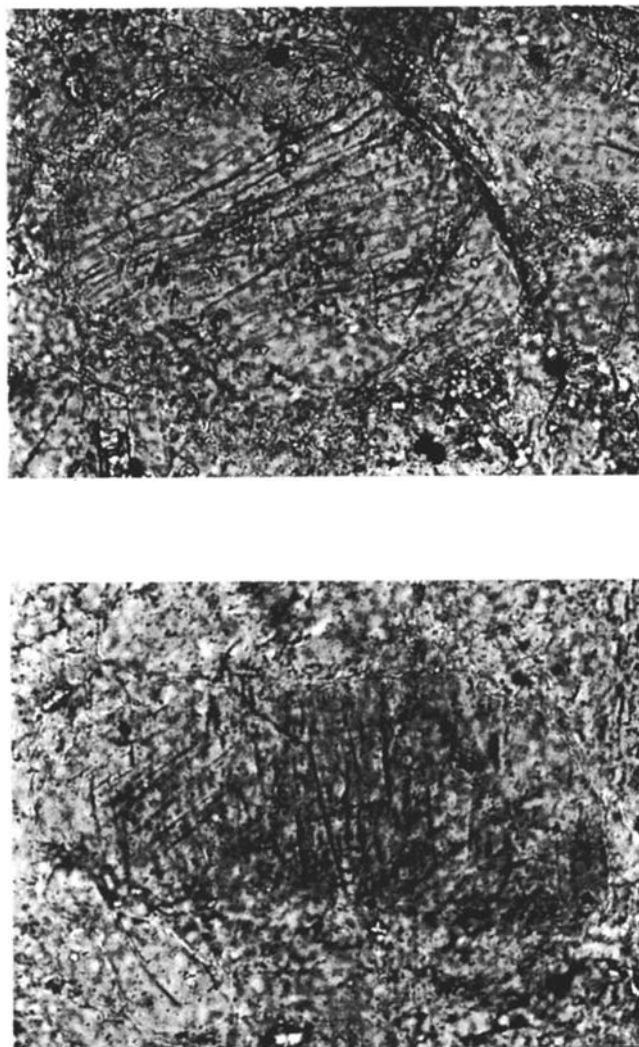


Figure 17. Planar microstructures in quartz grains from one sample of White Rim Sandstone dike near center of structure. Grains are ~0.3 mm across, with plane-polarized light, same scale in both photomicrographs. At least two sets of planar microstructures are visible in each grain.

7. Discussion and Conclusion

Detailed geologic mapping at Upheaval Dome has yielded several lines of evidence for an impact origin. The structure of Upheaval Dome corresponds to that expected for a complex crater. The pattern of faulting, folding, and clastic dike injection at Upheaval Dome resembles that seen in other known impact structures and is particularly similar to that of the Sierra Madera structure, southwest Texas [Wilshire *et al.*, 1972]. Shock effects include fractured quartz grains, weakly developed shatter cones and shatter surfaces, and planar microstructures in some quartz grains.

A lag deposit of resistant quartzose cobbles occurs in patches and as individual fragments within the ring structural depression. The cobbles rest on the Navajo Sandstone and on alluvium and wind-blown sand derived from the Navajo Sandstone. The areal extent of the deposit is ~300 × 400 m. We previously suggested that these cobbles may be “impactites” formed by cooling and solidification of impact melt

[Kriens *et al.*, 1997]. More recent field work suggests that they may be concretions or diagenetic nodules unrelated to the impact. Chert pebbles and cobbles up to 13 cm across are ubiquitous at the top surface of the Navajo Sandstone in southeastern Utah [Pipiringos and O’Sullivan, 1975]. They were apparently derived from erosion and weathering of authigenic chert in limestone pans or beds within the upper part of the Navajo Sandstone [Wright and Dickey, 1957; Peterson and Pipiringos, 1979] and have become concentrated at the unconformity at the top of the Navajo Sandstone. The chert cobbles are generally not as dark or rounded as the possible impactites found at Upheaval Dome. Recent geochemical analyses by Koeberl *et al.* [1999] show that the Upheaval Dome samples are nearly pure silica, unlike the composition of the other rocks exposed in the structure. It is therefore unlikely that these samples were formed during the impact event.

The maximum extent of the listric faults that bound the structure defines a final crater diameter of at least 5 km. The amplitude of the structural uplift (in kilometers), U , is given approximately by

$$U = 0.086D^{1.03} \quad (1)$$

where D is the final crater diameter in kilometers [Grieve *et al.*, 1981; Grieve and Pilkington, 1996]. For a crater of 5 km diameter, the expected uplift is ~450 m. Taking into account erosion of the central part of the structure, the observed structural uplift at Upheaval Dome is consistent with the scaling relationship derived from other terrestrial impact craters.

Dence *et al.* [1977] found that for terrestrial craters >2.4 km in diameter in crystalline rocks, the rim diameter D is related to the impact energy E by

$$D = 1.96 \times 10^{-5} E^{1/3.4} \quad (2)$$

where D is in kilometers and E is in joules. Assuming that the energy for sedimentary rocks is 20% less than the energy for crystalline rocks [Dence *et al.*, 1977], the kinetic energy of the impactor that formed Upheaval Dome was at least 2.4×10^{18} J. For an impact velocity of 20 km/s, this corresponds to an impactor mass of 9.7×10^9 kg. Asteroid densities vary between 2200 and 8000 kg/m³ [Wetherill, 1977], implying that an asteroidal impactor would have been between 100 and 170 m in radius. Comets have much lower densities, but generally impact Earth at higher velocities, so the size of a cometary impactor would be similar. If there has been substantial erosion of the impact structure since it formed, somewhat larger impactors would be indicated.

Shoemaker and Herkenhoff [1984] suggested that since the time of impact, 1–2 km of strata might have been removed from the vicinity of Upheaval Dome and that the crater likely was formed in late Cretaceous or Paleogene time. Their suggestion implied that the crater-like head of Upheaval Canyon, located in the center of Upheaval Dome, is strictly the result of differential erosion that occurred long after the impact structure was formed. Our reexamination of unusual lobes of Wingate Sandstone along the walls of Upheaval Canyon now leads us to speculate that the depth of erosion of the impact structure may be less.

Lobate or tongue-like structurally coherent masses of Wingate Sandstone and adjacent beds of the upper Chinle Formation occur low on the wall of the crater-like topographic fea-



Figure 18. Shatter cone in sandstone of Moenkopi Formation found near the center of Upheaval Dome. Scale is in centimeters.

ture at the head of Upheaval Canyon. At least one of these masses is displaced down the wall across lower beds of the Chinle along a contact that is roughly parallel with the wall. Elsewhere, one of the Wingate lobes penetrates into the underlying Chinle. We suggest that these lobes may represent partly fluidized sandstone that slumped along the walls of the initial transient cavity. If so, the walls of the present topographic crater would have been close to the final position of the transient cavity walls after their inward migration during crater collapse. This inner, constricted crater has been breached on the west side, and all strongly shocked rocks evidently have been removed from the center by erosion. The total erosion of the center, however, might be no more than a few hundred meters, sufficient to remove any deposits filling the initial crater and any strongly shocked material and to produce the highly dissected central topography we see today.

The deep canyons in the landscape surrounding Upheaval Dome and incised into the impact structure have been cut subsequent to impact. This episode of canyon cutting is no older than integration of the upper with the lower Colorado River drainage at ~5 Ma and the cutting of the lower Grand Canyon [Lucchitta, 1972]. Recent work suggests that deep canyon cutting in the center of the Colorado Plateau, upstream from the Grand Canyon, has occurred chiefly in the last half million years [Lucchitta *et al.*, 1994]. Upheaval Dome may have been formed late in the history of denudation of the central Colorado Plateau, possibly as late as a few mil-

lion years ago. It is also possible that the impact occurred in the Jurassic not long after deposition of the Navajo Sandstone. This earlier timing estimate is compatible with that proposed by Alvarez *et al.* [1998] on the basis of soft-sediment deformation seen in Jurassic rocks directly overlying the Navajo Sandstone 30–40 km north-northeast of Upheaval Dome. Chapman [1987] reported clusters of vertical, cylindrical sandstone structures that occur in the Middle Jurassic Upper Member of the Carmel Formation on the Paria Plateau in southern Utah (T 43 S, R 1 E, sec. 32) and interpreted them as having formed by sand liquefaction resulting from rapid overloading of sediments or seismic shock [Reineck and Singh, 1980; Bolt and Darragh, 1983]. The lack of impact deformation of the regional north to northwest striking joint system is also consistent with a Mesozoic impact event. Fission-track investigations at the University of Pennsylvania of shocked apatite from the center of the dome are currently underway to further constrain the age of Upheaval Dome.

Our field study of Upheaval Dome has permitted us to examine the mechanical behavior of rocks and the kinematics of structures associated with collision and subsequent formation of the central uplift and ring structural depression in sedimentary target bodies. It appears that even at relatively shallow depth below the transient crater and zone of impact melting, planar deformation features are not well developed in sedimentary rocks. Shatter cones are only weakly developed in the particular rock types present at Upheaval Dome. Brittle

fracture and injection of clastic dikes are the most easily recognized response to the stresses induced by impact. Similar clastic dikes at the Roberts rift may also be due to impact [Huntoon and Shoemaker, 1995], but this hypothesis does not explain the apparent absence of dikes in the area between the dome and the rift. The clastic dikes at Upheaval Dome may be related in origin to pseudotachylite dikes seen in other complex craters. Following impact, centerward flow along listric faults, accompanied by fault wedging, plastic folding, and additional clastic dikeing, has produced the central uplift and ring structural depression. Early fracture upon impact may have facilitated introduction of fluids into the faults and thus reduced frictional resistance to gravitational sliding. The listric normal faults at the perimeter of the dome are of lower dip angle than those inferred to bound slumped terraces on the walls of lunar complex craters, but have a similar sense of shear and are considered to be coeval with terrace development.

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