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Upheaval Dome, Canyonlands, Utah: Strain Indicators that Reveal an Impact Origin

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ABSTRACT

Upheaval Dome in the northern part of Canyonlands National Park is the best exposed impact crater on the earth. The 5.5 km (3.4 mi) diameter crater is deeply eroded by Upheaval Canyon, thus offering excellent views of its structural features in both plan and profile.

Structures produced during the three stages of cratering are preserved. The conclusion of the contact and compression stage and earliest part of the crater excavation stage are represented by pseudo-shattercones and clastic dikes. Mechanical thickening of the stratigraphic section by conjugate thrust faults and ductile crowding structures adjacent to the opening transient crater remain from the crater excavation stage. A record of the gravity-driven modification stage is preserved as: (1) listric normal faults that carried material back into the transient crater, (2) imbricated thrust sheets piled against the central peak representing the material that slid back into the transient crater, (3) a ring syncline produced by mechanical thinning associated with the listric normal faulting, (4) outwardly plunging anticlines which reveal shortening of the circumferences of the ring-shaped hanging wall blocks as they contracted toward the center, and (5) a prominent central peak caused by rebound. The destruction of the transient crater by the inflow of material during its collapse coupled with rebound of the central peak produced a ring structure, thus classifying Upheaval crater as a small complex crater.

No fragments of the impactor, no highly shocked target rocks, and no melt rocks produced by the impact have been identified. These appear to have eroded completely from the site.

The age of the Upheaval impact has not been determined. The problem is that datable strata deposited immediately after the impact have eroded. Other workers have speculated that the impact was responsible for regionally extensive soft-sediment deformation observed in the Carmel Formation. If so, the impact dates from Jurassic time and its original size was little bigger than the outer limits of the present deformed zone.

PURPOSE

The purpose of this article is to describe the structural geology of the Upheaval impact crater. Impact cratering progresses through three stages: (1) contact and compression, (2) excavation, and (3) modification. Care is taken to identify the different types of structures observed in the crater and to relate them to the stage during which they formed. Unraveling how and when particular structures formed is accomplished by deducing the causative stresses from the observed strains and observing the cross-cutting relationships between the various structures.

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UPHEAVAL DOME

Upheaval Dome is a small complex impact crater, meaning that it is a multiple ring crater (figure 1). It is the finest exposed complex crater on the earth, a distinction attributed to the fact that the crater is deeply eroded. As shown on figure 2, it occupies an elevated position in the Island in the Sky district of northern Canyonlands National Park between the deeply entrenched Green and Colorado rivers. The desert setting carries the quality of exposure to the sublime.

The deformed zone which defines the Upheaval impact structure is about 5.5 km (3.4 mi) in diameter. A prominent central peak dominates the structure and is ringed by a syncline. The rocks exposed in the crater range from the Permian Organ Rock Shale in the eroded core to

Figure 1. Upheaval Dome, Canyonlands National Park, Utah, viewed toward the northwest. The light colored, rounded rocks beyond the outermost ring are the Navajo Sandstone which is preserved in the ring syncline. The width across the center of the photograph is 2.6 km (1.6 mi).

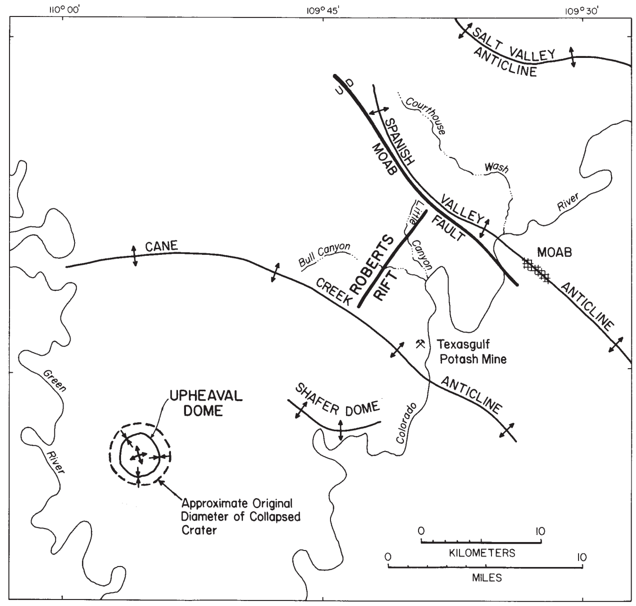

Figure 2. Location of Upheaval Dome between the Green and Colorado rivers, Canyonlands area, Utah. Upheaval Canyon trends westward from the center of the dome to the Green River. Trail Canyon trends northwestward along the northeast side of the dome. Holeman basin opens to the south toward the Green River along the south side of the dome.

the Jurassic Navajo Sandstone preserved in the ring syncline (figure 3). West-draining Upheaval Canyon heads in the crater, and provides an impressive radial profile through its west side that is 360 m (1,200 ft) in height. Tributaries to Upheaval Canyon have etched into the flanks of the central peak and others have dissected the ring syncline producing excellent profiles through the ring structures. One small gulch, eroded through the core of the central peak, exposes the Organ Rock Shale directly under the hypocenter. The south-facing wall of Holeman basin along the Green River Canyon beautifully exposes the outermost ring fault, yielding one of the most definitive structural outcrops present. Trail Canyon along the northeastern margin also profiles the outer ring but not with such clarity.

Upheaval Dome is readily accessible by paved road by taking Utah State Highway 313 south to the Island in the Sky district of Canyonlands National Park and following the signs to the crater rim. Hiking trails provide excellent access to overlooks and to the crater interior.

ORIGIN

The origin of Upheaval Dome has been the subject of speculation in a long, highly conflicting series of academic and popular articles. Only the most substantive or exotic are cited below. The field seems to have narrowed lately to salt diapirism (doming caused by flowage of buried salt) and impact; but this is not simply a debate about different processes, rather it reflects deeper philosophical divisions.

The diapirists favor mechanisms that are rooted in process gradualism, a manifestation of Darwinian evolution that was merged into the geologic paradigm during the 19th century as uniformitarianism. This was our forebearers means of rejecting the capriciousness of creationism which was prevalent at the time, and which embraced catastrophic events. A consequence is that there is a reticence on the part of many classically trained geoscientists to acknowledge that impactors from space are of supreme but periodic importance as geologic agents (French, 1990). Impactors are often viewed uncomfortably because they seem to be reviving the heretical notions of catastrophic processes which appear ad hoc much like the biblical flood (Hartmann and Miller, 1991, p. 49-50). Unfortunately the pejorative label “ad hoc” is commonly misused in place of “stochastic” when actual catastrophic geologic processes are discounted by uniformitarianists.

There is a rich literature favoring variations on a salt diapir origin for Upheaval Dome (McKnight, 1940; Fiero, 1958; Mattox, 1968). The latest and most substantive of these appears in Jackson and others (1998). The salt theories pivot on the presence of approximately 500 m (1,600 ft) of Pennsylvanian Paradox salts under the site prior to the impact (Woodward-Clyde Consultants, 1983, figure 5-12). There is, however, no salt in the exposed core of Upheaval Dome or any mineralogical evidence that any salt passed upward through the feature.

As part of a multiple hypothesis screening exercise, McKnight (1940, p. 127) raised the alternate possibility that the dome could be caused by intrusion of an igneous plug which remains buried. Using elements of both salt flowage and igneous intrusion, Joesting and Plouff (1958) proposed a model whereby igneous rocks were fortuitously intruded into the core of an existing salt dome. This

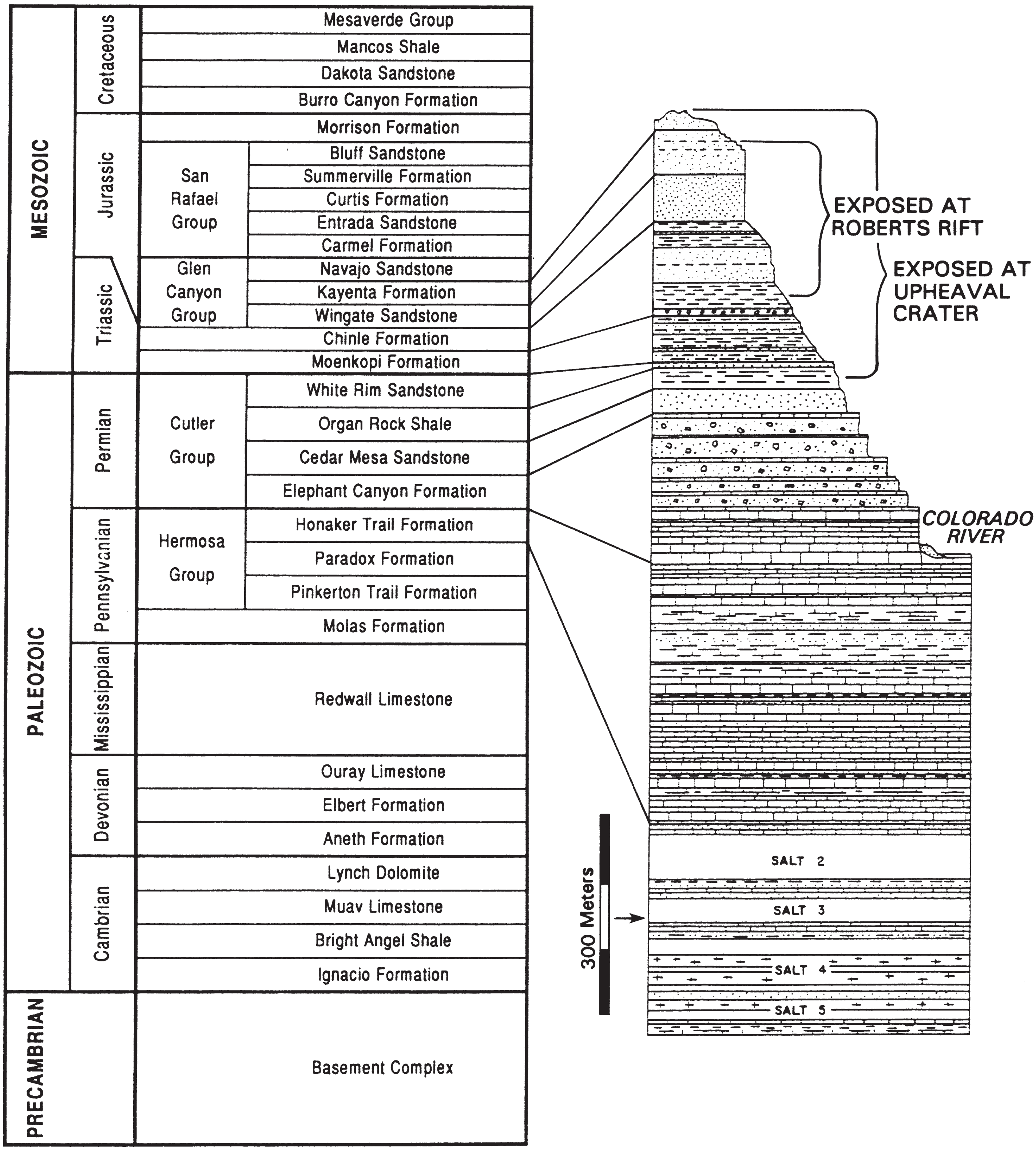

Figure 3. Stratigraphy in the vicinity of Upheaval Dome and Roberts rift, Canyonlands area, Utah. It is now thought that the land surface at the time of impact was near the top of the Carmel Formation. Only the upper part of the Paradox Formation is shown in the right column. Bar scale goes with the right column; left column is not to scale.

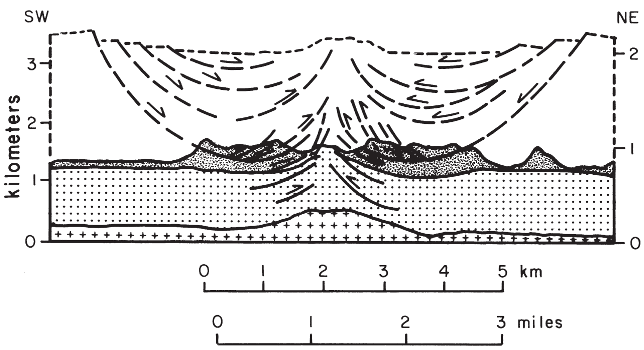

Figure 4. Historic structural cross-sectional sketch through Upheaval Dome, Canyonlands, Utah, redrawn from Shoemaker and Herkenhoff (1984). At the time this cross-section was made, it was assumed that the impact was a Cretaceous-Tertiary event so 2 km (1.2 mi) of eroded Mesozoic strata was inferred to cover the site. It now appears that the impact occurred during Jurassic time when only the thin Carmel Formation mantled the site. To actually fit observations, the structures shown must be scaled down by a factor of 0.6 and dropped down so that the top of the inferred structural profile coincides with the land surface.

conveniently explained a gravity high detected by them over the dome without having to consider the radical alternative of a central peak in an impact structure.

Kopf (1982) proposed an entirely different concept by which the dome was caused by an hydraulic ram mechanism involving overpressured fluids driven and localized by unspecified tectonic forces.

Significantly, Upheaval Dome won a place on Bucher's (1936) cryptovolcanic explosion crater list. The idea here was that the crater was caused by a gaseous explosion of probable volcanic origin but without subsequent intrusion or eruption of igneous rock. Boon and Albritton (1936) had the prescience to argue that many of Bucher's cryptovolcanic structures were in fact impact structures. Bucher's list subsequently proved to be a reliable catalog of impact sites.

Shoemaker and Herkenhoff (1984) revealed that Upheaval Dome is a deeply-eroded impact structure. Their cross section, redrawn here as figure 4, shows the essential character of the crater. A definitive treatment of the impact followed in Kriens and others (1999). Huntoon and Shoemaker (1995) used the energy from the Upheaval impact to explain hydraulic fracturing and clastic dike emplacement found both within the crater and at the curious Roberts rift located 22 to 32 km (14 to 20 mi) along a northeast radii. Similarly, Alvarez and others (1998) used the seismic energy from the impact to explain soft-sediment deformation within the Jurassic Carmel Formation in the vicinity, thus tentatively proposing a timing for the impact.

IMPACT CRATERING

A bullet hitting a wall serves as a poor analog for an impact because the velocity of the bullet is far too small relative to its mass, thus not enough energy is transferred to the target to simulate the damage of an impact. Typical impactors arrive at 10 to 20 km/sec ($2.2x10^4$ to $4.4x10^4$ mi/hr). Melosh (1989, p. 53) reveals that impactors having velocities of more than a few km/sec impart to the target energies exceeding those in an equivalent volume of chemical explosives. Impactors moving at velocities in excess of 100 km/sec ($2.2x10^5$ mi/hr) impart energies that exceed nuclear explosives. Consequently, an impact is best viewed as the instantaneous deposition of an enormous amount of energy on the surface of the target body.

Cratering results from the rapid radial propagation of energy into the target. Thus impactors with all but the most oblique incident angles, those from vertical down to about 10 degrees, leave circular craters. It is evident then that the theory of impacts is identical to the theory for explosions on surfaces. An excellent analog for the development of a complex crater is that of a liquid drop falling into a still pool of water.

An analysis of Arizona's Meteor crater by Shoemaker (1963) provides a useful scaling perspective. The crater is 1.1 km (0.7 mi) in diameter and was produced by a massive, but relatively small, nickel-iron meteorite. The energy required to blow out the crater was equal to what could be delivered by 10^5 ton object arriving at 20 km/sec ($4.4x10^4$ mi/hr). Such an object, only 30 m (100 ft) in diameter, could produce a crater 37 times its diameter.

Melosh (1989) has delineated three stages in the cratering process: (1) contact and compression, (2) excavation, and (3) modification. Evidence for all three is present in an uneroded crater, with the structures resulting from the later stages superimposed on the earlier. The job of sorting particular classes of structures out and assigning them to a stage relies on an analysis of cross cutting relationships between the various classes of structures present in order to sequence them coupled with an analysis of stress indicators to assign them to the correct stage. The latter is facilitated by knowing approximately when specific classes of structures formed based on observations from explosions.

The contact and compression stage involves the transfer of kinetic energy from the projectile to the target. This stage is very brief and lasts only as long as it takes for the shock wave leaving the point of contact to travel through the impactor, reflect off its trailing surface and arrive back at the point of contact. At this moment, the projectile is unloaded and its remains simply go along for the ride as the crater opens around it. For a silicate projectile 10 m (33 ft) in diameter traveling at 10 km/sec ($2.2x10^4$ mi/hr), the contact and compression stage is over in 10^{-3} sec; for a projectile 1 km (0.6 mi) in diameter the elapsed time is 10^{-1} sec (Melosh, 1989, p. 46). Contact pressures are extreme, in the range of 102-103 GPa (10^{10}-10^{11} lbs/in^2) for geologically significant impacts.

A hemispheric shock wave propagates into the target during the excavation stage, so it and a trailing rarification wave set the target material into motion initiating a subsonic excavation flow that opens a transient crater. The

Figure 5. Sandstone dike exposed on the east flank of the central peak of Upheaval Dome, Canyonlands, Utah, that was injected downsection from the White Rim Sandstone into the Organ Rock Shale during the earliest part of the excavation stage. The slightly overturned Organ Rock beds dip steeply to the left and their tops face toward the right. The White Rim Sandstone, folded to the vertical, lies just off the photo to the right. View is toward the north.

target material under the point of impact is accelerated to a large fraction of the impactors velocity. Streamlines of the flowing rock radiate from the impact site and curve upward to the free surface of the target. By the time the excavation flow is underway, the shock wave has long since left the site of the impact. The excavation stage ends when the opening of a bowl-shaped transient crater ceases. The excavation stage is over in seconds to minutes even for large impacts. The material strength and gravity of the target become important only as this stage draws to a close. Arizona's small Meteor crater is a transient crater that was too small to undergo significant modification after the excavation stage was over.

The modification stage is gravity-driven. Intermediate-size craters collapse through large scale slumping and a central peak rises as the compressed rocks below the crater rebound. The slumping and rebounding rocks fill and destroy the transient crater. The resulting ring structures are called complex craters and Upheaval Dome is a small example of this type.

STRAIN FEATURES

The primary evidence that Upheaval Dome is an impact structure includes: (1) a morphology that is consistent with proven impacts, and (2) the presence of subsidiary structures having sequencing, forms and stress indicators expected in an impact. Melosh's three stages for crater development provide a useful framework that can be used to classify the various structures present.

Earliest Excavation Structures

The rapid movement of the shock wave into the earth produces unambiguous diagnostic indicators in the form of highly shocked target rocks exhibiting shattercones, high pressure phases of quartz (coesite, stishovite), crystal planar deformation features, melts, etc. Unfortunately these near surface indicators eroded from Upheaval Dome long ago. However, Shoemaker and others (1993) found samples of thin siltstone beds from the Moenkopi Formation inside the crater that are pervasively shattered and which yield pseudo-shattercones.

As the shock wave radiates into the earth, it expands and deteriorates into strong stress waves. Aquifers and petroleum reservoirs in the vicinity undergo a brief series of strong compressions and dilations as the stress waves pass. The fluids become acutely overpressured during the compressions resulting in hydraulic fracturing which propagates into surrounding strata. As the fractures open, mobilized rock fragments plucked from both the reservoir and fracture walls become entrained in the escaping fluids and move into the fractures. These natural proppants hold the fractures open, and are preserved as clastic dikes.

Huntoon and Shoemaker (1995) found two classes of clastic dikes that they associate with the Upheaval impact. The sharply domed Organ Rock, Moenkopi and Chinle strata in the central peak are riven with clastic dikes comprised of cataclastically broken sand grains derived from the White Rim Sandstone. The dikes range up to 0.6 m (2 ft) thick and extend both up- and down-section from the White Rim Sandstone (figure 5). The sands were mobilized as fluids flowed out of the compressed sandstone aquifer into opening hydraulic fractures. The shattering of the grains attests to the extreme pressures that developed as the strongest stress waves passed through the aquifer. It is possible that the fluids were locally volatilized.

Roberts rift is the second example of hydraulic fracturing attributed to the impact, but in this case not conclusively proven to be caused by it. The rift crops out northeast of the crater at a radial distance of between 22 and 32 km (14 and 20 mi). The fissure contains clasts derived from the Pennsylvanian Paradox Formation and younger rocks which have been injected as much as 1,000 m (3,300 ft) upward into the Mesozoic section (Hite, 1975). The ori-

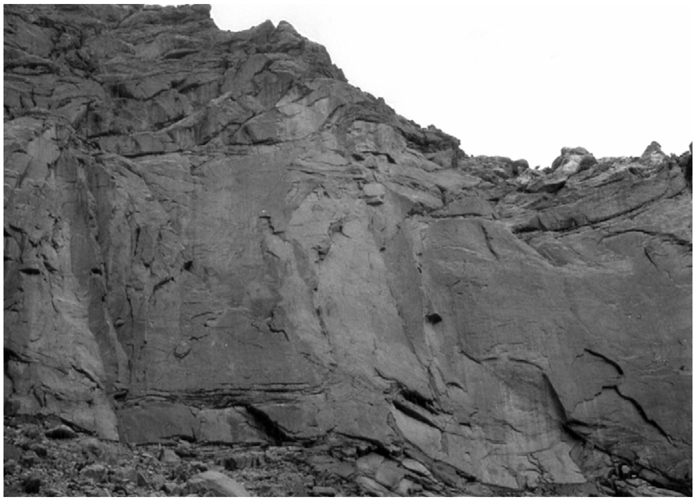

Figure 6. Ductile thickening of the lower Wingate Sandstone by thrust faulting and folding near the bottom of the cliff attributed to rapid movement of material out of the crater during the excavation stage, and imbricated thrust sheets comprised of beds of the Kayenta Formation at the top of the cliff attributed to the piling up of inward moving rocks against the rising central peak during the modification stage, Upheaval Dome, Canyonlands . View is of the north wall of Upheaval Canyon, on the west flank of the central peak which lies to the right.

Figure 7. Listric normal fault that carried Navajo and Kayenta strata toward the right into the transient crater as it collapsed during the modification stage, Upheaval Dome, Canyonlands, Utah. The center of the crater is to the right. Notice how the faulting cuts out the upper half of the Wingate section just to the right of center. The same fault passes under the Wingate Sandstone outcrop in the right foreground. This type of mechanical thinning produced the ring syncline around the crater. View is toward the northwest from Holeman basin.

gin proposed for the fissure is passage of strong stress waves through an highly localized, already overpressured fluid compartment in the Paradox Formation which triggered hydraulic fracturing. Petroleum fluids and hydrogen sulfide brines moving into the fissure entrained rock fragments torn from the reservoir and fissure walls. The clasts served as natural proppants which rendered the fissure permeable, allowing for upward circulation of the reducing fluids which caused bleaching that extends into the wall rocks as much as 15 m (50 ft).

Excavation Structures

There is rapid flow of rock from the point of impact as a transient crater opens. The maximum principal stresses are oriented radially away from the hypocenter. They are near horizontal in the near-surface rocks, and produce outward thrusting there. Thrust plates having the form of flattened donuts with the impact at their centers expand outward and grow in circumference at near-surface levels as the crater opens. The rocks directly under the impact flow downward thus greatly depressing the floor of the opening transient crater.

Ductile and mechanical thickening structures are preserved in the Wingate Sandstone that are attributed to this stage. Included are outward verging thrust faults, low-angle conjugate shears and ductile thickening of beds, all of which caused the rim of the transient crater to rise. Conjugate shears and shortening folds of all scales in which the maximum principal stress orientations parallel the flow lines of the outwardly moving rock are common in the older rocks exposed in the core.

Modification Structures

Gravity forces dominate during the modification stage when the transient crater collapses and the depressed rocks below the impact flow upward into the transient crater. Projectile fragments and crater material are expelled from the closing transient crater and fall to earth leaving diagnostic, widely distributed residues.

The ejecta from the Upheaval impact eroded long ago (Koeberl and others, 1999) along with the highly shocked, near-surface rocks. In contrast, the structures produced when the crater collapsed and its floor rebounded are the best preserved of the structures because they were the last to be superimposed on the rocks.

Figure 4 is a snapshot of conditions at the end of the modification stage. The most revealing features on this section are the numerous listric normal faults which allowed the rocks along the perimeter of the transient crater to glide inward and upward on the rebounding central peak. As the rocks impinged on the rapidly rising central peak, the early arrivals were overrun by later arrivals, producing a stack of outwardly dipping imbricated thrust sheets on the flanks of the peak (figures 4 and 6).

The outer limit of deformation is delimited by the most prominent listric normal faults found at Upheaval Dome. As shown on figure 7, these dip inward and displace younger rocks downward and inward toward the central peak. The stratigraphic section was mechanically thinned around the perimeter of the structure as the hanging wall rocks moved inward. This thinning produced the ring syncline (figure 8). The Navajo Sandstone, the youngest unit now remaining in the crater, is pre-

Figure 8. Profile through the syncline that rings Upheaval Dome as exposed in a tributary on the south side of Upheaval Canyon, Canyonlands, Utah. The center of crater is to the right. The upper cliff is the Navajo Sandstone; the lower cliff the Wingate Sandstone. The right-dipping surfaces in the Wingate cliff to the left of photo center are faults; surfaces in the Kayenta and Navajo strata in the foreground are bedding. The syncline developed as the hanging wall blocks moved toward the right as the transient crater collapsed during the modification stage.

Figure 9. Outward-plunging radial synclines at the base of the Wingate cliff which are underlain by a listric normal fault that separates the Wingate Sandstone and some Chinle shales caught in the core of the fold from the almost flat-lying Chinle Formation below, Upheaval Dome, Canyonlands, Utah. The folds developed as the circumference of the hanging wall block - a donut-shaped ring - contracted as the rocks moved radially into the crater during the modification stage. View looking outward from the center of the crater toward the northwest.

served in the syncline.

The outward dips of the strata in the central peak increase toward the hypocenter, and stand vertical or even slightly overturned under it. The erosionally resistant White Rim Sandstone near the center of the crater juts almost vertically above its surroundings forming a discontinuous crown which surrounds the eroded core comprised of Organ Rock Shale.

The circular profile provided by the inward-facing Wingate cliff is deformed by a series of radiating, outwardly plunging anticlines (figure 9). The boundary between the folded Wingate Sandstone and the less deformed underlying Chinle shales is a listric normal fault along which the Wingate Sandstone moved toward the center. The radial anticlines in the Wingate Sandstone formed as space problems developed in the shrinking ring-shaped hanging wall block as it glided toward and contracted around the central peak. Shortening of its circumference was largely accommodated by the radial folds in the Wingate Sandstone. Additional shortening occurred along sets of minor conjugate thrust faults whose intersections also radiate from the center. The orientation of the maximum principal stress in the contracting donut, as deduced from the radial anticlines and accompanying minor conjugate thrusts, was horizontal and parallel to the circumference of the crater.

Some of the listric normal faults on figure 4 first functioned during the excavation stage as thrust faults that allowed the hanging wall rocks to move out of the transient crater. They were reactivated in an opposite sense during the modification stage when the crater collapsed (figure 10).

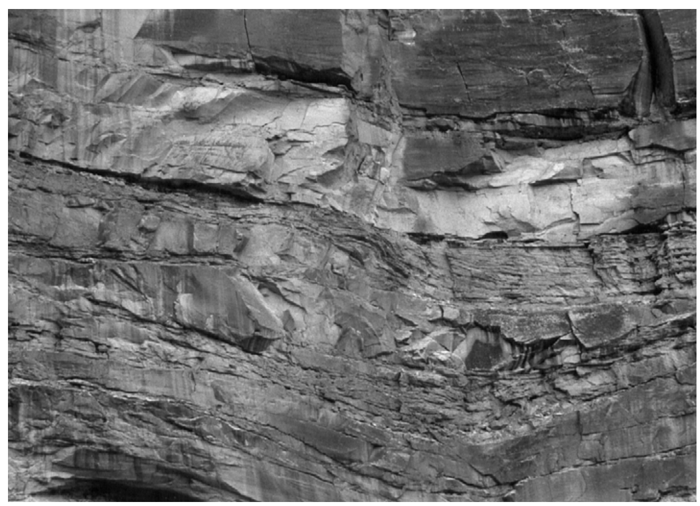

Figure 10. View toward the center of the crater of numerous listric normal faults (modification stage) and possibly some thrust faults (excavation stage) in the upper part of the Wingate cliff in the east wall of Syncline valley, Upheaval Dome, Canyonlands, Utah. Layering is bedding; numerous discontinuities are fault surfaces. The relative motion of the hanging wall rocks was either away from or toward the viewer depending on whether the fault was active during the modification or excavation stage.

AGE

The age of Upheaval crater has not been determined. The problem is that the crater is deeply eroded so crucial melt rocks and post-impact crater-filling sediments are missing. One certainty is that the crater is younger than the Jurassic Navajo Sandstone which was deformed by the impact and is the youngest unit exposed in the vicinity.

Alvarez and others (1998) propose a cause and effect linkage between the impact and soft sediment deformation in the Carmel Formation. The Carmel Formation exhibits strange region-wide wavy beds, internal shear discontinuities, sand-filled pipe-like liquefaction structures and other odd features leading to the conclusion that the unit experienced large-magnitude shaking before it became indurated. The Upheaval impact is viewed as a likely source for the required extreme seismicity implying a Jurassic age for the event. The nearest outcrops of the Carmel Formation lie 15.2 km (9.5 mi) west and 26.5 km (16.5 mi) north-northeast of the crater. However, the sand-filled pipe-like liquefaction structures and related features occur at great distances from Upheaval crater. For example, exceptionally well developed examples lie 260 km (165 mi) to the southeast near Laguna Pueblo, New Mexico (Megrue and Kerr, 1965; Moench and Hilpert, 1968). Those distances are so great, it is difficult to attribute the liquefaction features to the impact. Consequently their association with the impact remains suspect until additional evidence is forthcoming.

Accurate dating of the impact will help constrain the original size of the crater. If the impact occurred near the end of Carmel deposition, the 5.5 km (3.4 mi) diameter observed today is but slightly smaller than the original diameter. However, the deformed zone could be substantially larger if the impact occurred later when a considerable thickness of Mesozoic strata covered the site.

WHAT ABOUT SALT DIAPIRISM?

The greatest problem with salt diapirism at Upheaval Dome turns on the fact that there isn't another diapiric structure like it anywhere within the 40,000 km^2 (15,000 mi^2) part of the Paradox basin that is underlain by the Pennsylvanian Paradox salt section. To have a structure that is so totally unique defies plausibility because the causative environment is so widespread. There are salt diapirs in the Paradox basin, some rather close to the Upheaval impact, but their morphologies are radically different than that of Upheaval Dome, and their structures are consistent with salt domes found elsewhere in the world.

Eighty-five percent of the Paradox Formation in the Canyonlands area is comprised of thick beds of almost pure halite and potash separated by interbeds of gypsum, limestone, dolomite and shale which account for the remaining 15 percent. The unit reaches 16,000 ft (5,000 m) thick. The salts have been flowing at variable rates since shortly after they were deposited over 300 million years ago, and they are actively flowing today (Huntoon, 1988). The largest structures associated with the flowage are the grand salt anticlines which are the characteristic structure of the Paradox basin (Cater, 1970).

The largest population of salt diapirs in the Paradox basin are those that have risen off the salt bulges which core the salt anticlines. They cause refolding of the axes of the anticlines into strings of domes and basins. The biggest of these is the approximately 3 by 8 km (2 by 5 mi) elliptical Onion Creek diapir along the Cache Valley salt anticline 30 km (19 mi) northeast of Moab where the salt is actively extruding to the land surface (Coleman, 1983; Hudec, 1995). Smaller diapirs are exposed along the Cache Valley anticline north of the Colorado River, and along other salt anticlines such as the Spanish Valley collapsed anticline which trends through Moab.

An odd, second class of salt diapirs consisting of four examples is found where the Paradox salts have pierced the Honaker Trail Formation along the floor of Cataract Canyon. These are small, about 0.5 km (0.3 mi) in diameter or less. They breach the structurally thinned strata under the floor of the canyon where it has been arched up and eroded by the Colorado River during emplacement of the modern gravity tectonic Meander anticline-Needles fault zone complex (Huntoon, 1982).

Diapirs are otherwise uniformly missing in other settings within the Paradox basin; specifically, in the large expanses of rather flat-lying strata between the salt anticlines. Upheaval Dome occurs in one of these otherwise barren areas.

Both classes of proven diapirs exhibit commonalities. (1) Salt is present in the structures. (2) Caprock consisting of the Honaker Trail Formation and the Paradox gypsum, carbonates and clastics remain where the diapirs have breached the surface and been subjected to dissolution. Where dissolved, each cubic meter of caprock represents approximately 6 m^3 of intruded rock. (3) Remnants of the Paradox and Honaker Trail formations are commonly smeared along the diapir-wall rock contacts. (4) All stress indicators exhibit maximum principal stress orientations that are vertical including conjugate shears and kink folds in the domes above the diapirs, in the wall rocks adjacent to the diapirs, and in the salt cores. The stress indicators are most important because they reveal that the causative maximum principal stresses were vertical above and immediately surrounding the diapirs consistent with their gravity tectonic origin. Vertical maximum principal stresses in the diapirs contrast starkly to the sub-horizontal maximum principal stresses associated with the near-surface excavation and modification structures at Upheaval Dome.

Invoking a pinched-off diapir (one in which the salt totally evacuated the structure once it formed) to explain Upheaval Dome is particularly difficult because there is no evidence that salt moved through the core of the structure. Missing is an identifiable throat through which the salt passed even though the exposures of the entire core are exceptional. There are no allochthonous Paradox or Honaker Trail residuals anywhere in the core which would reveal that those rocks passed through. Lastly, there is no bleaching of the reddish-brown Organ Rock Shale in the core despite the fact that such bleaching is prevalent around the known salt diapirs. The bleaching agents are hydrogen-sulfide salt brines and petroleum fluids which are present in the salt section.

MODIFICATION BY SALT FLOWAGE

Has Upheaval Dome been modified by post-impact flowage of Paradox salts into the buried core of the structure? Specifically, has salt flowage caused additional doming within the structure? After all, there is a considerable thickness of Paradox salts in the region.

I have searched for evidence for deformation that could be attribute to post-impact salt flowage but have been unable to identify any. For example, there is no discernable refolding of impact-produced fault surfaces. More importantly, no high-angle conjugate faults have been imprinted on the rocks anywhere within or near the crater. High-angle conjugate faults, particularly ring faults, would reveal even minor amounts of subsequent diapirism.

DISCUSSION

The origin of Upheaval Dome has captured the imagination of every geoscientist who has observed it. Almost everyone who has worked in the area has felt obligated to comment in the literature on at least some aspect of its peculiar form and to speculate on its origin. Disagreement about its origin still prevails, but the list of plausible causative scenarios has converged over the years to two ideas now led by a wave of impactors and a dwindling but vocal core of salt diapirists.

I have come to embrace an impact origin based on the following objective criteria. (1) There isn't a salt diapir anyplace in the vast Paradox basin with a structure remotely similar to Upheaval Dome, although many classical diapirs are present. (2) The structural character of Upheaval Dome is identical to that of proven impact structures, whereas there is no known diapir with its structure. (3) The temporal relationship between different classes of strain features and the strain orientations that can be deduced from them at Upheaval Dome are consistent with the different stages of crater growth, whereas they are inconsistent with those of diapirs. (4) There are no remnants of Paradox or Hermosa strata, some of which are insoluble, either in the core or around Upheaval Dome to reveal that salt moved through the structure. (5) The energies required to produce many of the classes of structures observed in Upheaval Dome, to cause the shattering of sand gains in the clastic dikes in the core of the crater, and to possibly cause the hydraulic fracturing at Roberts rift and the soft-sediment deformation of the Carmel Formation far exceed those available in diapirism.

At this writing Upheaval Dome has not been conclusively proven to be an impact crater to the satisfaction of the last skeptic because the "smoking gun" in the form of an impactor fragment, true shattercone, impactite, melt rock, planar deformation feature, coesite, stishovite, or some such definitive feature remains to be discovered. Ironically, once it is, Upheaval Dome will become the archetype morphological example of a small complex impact crater both here on earth and on nearby solar bodies because it is so well exposed in the three dimensions.

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