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Seismic reflection study of Upheaval Dome, Canyonlands National Park, Utah

Z. Kanbur,[1] J. N. Louie,[2] S. Chávez-Pérez,[3] G. Plank,[4] and D. Morey[5,6]

Abstract. The origin of Upheaval Dome, in Canyonlands National Park of southeastern Utah, has been a topic of controversy among geologists and planetary scientists. The structure has long been thought to have been created by salt diapirism from the underlying Paradox Formation. Recent studies have suggested that impact could have formed the dome. To test the various hypotheses, we acquired, processed, and interpreted seismic reflection data within and adjacent to the structure. Both conventionally stacked and prestack-migrated images show <100 m relief in the Paradox Formation, contrary to salt diapirism hypotheses. Further, we have identified features within the images typical of impact structures, such as listric normal faults having displacements toward the center of the dome. Deformation occurs in two depth ranges, with the faulting that created the central uplift appearing only above the Hermosa Formation, in the upper 800 m of the structure. The images also suggest limited fracturing of the Hermosa and salt flow in the Paradox Formation, perhaps due to gravitational relaxation of the crater form. Our image of a nearly flat top of the Paradox salt strongly favors an impact origin for Upheaval Dome.

1. Introduction

Upheaval Dome, in Canyonlands National Park of southeastern Utah, is an unusual structural feature on the Colorado Plateau (Figure 1). Despite repeated discussions in previous studies [e.g., *Jackson et al.*, 1998], its origin remains controversial. This region is underlain by a vast deposit of salt in the Pennsylvanian age (323-290 Ma) Paradox Formation. Thus Upheaval Dome has been thought to be a salt dome due to diapirism of the Paradox [*McKnight*, 1940; *Nettleton*, 1934; *Mattox*, 1975; *Huntoon et al.*, 1982; *Jackson et al.*, 1998]. However, researchers such as *Kriens et al.* [1999] have found detailed geologic evidence suggesting that it may be the largest exposed impact structure on the Colorado Plateau. The impact was estimated to have occurred between Cretaceous and Paleogene time (140-24 Ma), based upon the inferred depth of subsequent erosion [*Shoemaker and Herkenhoff*, 1984]. Recent discovery of regional synsedimentary deformation, possibly due to impact shaking [*Alvarez et al.*, 1998], suggests an earlier, post-Navajo, Jurassic age (200-140 Ma).

Figure 1

In order to test the impact hypothesis, researchers from the Jet Propulsion Laboratory, Pasadena, the University of Nevada, Reno, California State University at Dominguez Hills, and the University of Utah carried out NASA-funded geophysical surveys across Upheaval Dome in January 1995, including seismic refraction and reflection surveys and a gravity survey [*Louie at al.*,

1995]. We processed the collected seismic reflection data to obtain common-midpoint stacked and prestack-migrated sections with a view to probing ~1 km deep into the Upheaval Dome structure.

This study aims to find primarily the geometry of the top of the Paradox Formation and, secondarily, the nature of displacement above it. We believe that combination of the results of the seismic reflection study with those obtained from other geophysical and geologic studies will detail how Upheaval Dome was formed.

Seismic reflection techniques have successfully defined the character of known impact structures, including the Siljan impact structure, Sweden [*Juhlin and Pedersen*, 1987], and the Haughton impact crater, Canada [*Scott and Hajnal*, 1988; *Hajnal et al.*, 1988]. In the area of the Siljan impact structure, estimated to be 52 km in diameter, deep seismic reflection data identified several important geometrical parameters related to features of impact mechanics, including the former transient cavity, the diameter of the transient crater, structural uplift, and maximum excavation depth [*Juhlin and Pedersen*, 1987]. At the Haughton impact a 10.25 km long reflection profile imaged a section between the central peak and the rim of the crater. The upper 1.5 s of reflection data revealed that the impact disturbed the entire 1900 m section of highly competent Paleozoic (548-243 Ma) strata and suggested a structural diameter of 24 km. These studies demonstrated that the seismic reflection method can play a major role in establishing characteristics of complex terrestrial impact craters. For a structure like Upheaval Dome, where an underlying salt layer adds to the complexity, seismic reflection is the technique of choice.

2. Background

In the Paradox Basin, southeastern Utah, salt anticlines are prevalent, and these features have been subjected to intensive study and exploration. There is no doubt that salt plays a major role in the formation of these features [*Mattox*, 1975]. Upheaval Dome is different from these features in that it is almost circular in plan view and consists of a central dome encircled by a distinct rim syncline [*McKnight*, 1940; *Mattox*, 1975]. The maximum diameter of the disturbed area is 4800 m; the area lying within the axis of the rim syncline has an average diameter of 3700 m [*Mattox*, 1975; *Huntoon et al.*, 1982]. *Kriens et al.* [1999] interpret logs from wells drilled near the Green and Colorado Rivers (San Juan County) as consistent with their interpretations of rocks of Pennsylvanian to Upper Cretaceous age (323-65 Ma) encountered in closer Canyonlands well logs. Table 1 describes stratigraphic columns of the Upheaval Dome area [*McKnight*, 1940; *Baars and Seager*, 1970; *Baars*,

Table 1

1971].

The Phanerozoic (post-635 Ma) stratigraphic section has a maximum thickness of ~3600 m in the Upheaval Dome area [*McKnight*, 1940]. The section contains sedimentary rocks ranging in age from Cambrian to Jurassic (635-144 Ma) that lie above a Precambrian (pre-635 Ma) basement complex. Important features of the stratigraphic section of Upheaval Dome are the more than 900 m of Pennsylvanian (323-290 Ma) salt overlain by approximately 300 m of limestone and that these units lie beneath as much as 1000 m of shales and sandstones.

Several different hypotheses have been put forward with a view to explaining the above geologic observations in terms of the origin of Upheaval Dome. These include salt dome, cryptovolcanic, and meteor impact hypotheses. Figure 2 shows schematic cross sections for salt dome and impact origins of the dome. *Harrison* [1927] attributes the complexly faulted central uplift surrounded by an annular depression to differential loading and salt flowage. *McKnight* [1940] mapped Upheaval Dome and interpreted it to have been formed by salt diapirism in the underlying Pennsylvanian age (323-290 Ma) Paradox Formation over a prolonged period. *Nettleton* [1934], *Mattox* [1975], and *Huntoon et al.* [1982] also suggested a salt diapirism origin of the dome.

Figure 2

Huntoon et al. [1982] showed in a geologic map of Upheaval Dome that the rocks exposed include the Cutler, Moenkopi, and Chinle Formations, the Wingate Sandstone and the Kayenta Formation of Triassic (248-206 Ma) age, and the Navajo Sandstone of Triassic and Jurassic (248-144 Ma) age. The section at the top of Figure 2 reflects their interpretation of the structure as a salt dome. The outcropping formations in the dome have been described in more detail by further mapping [*McKnight*, 1940; E. G. Sable, whose work is discussed by *Mattox*, 1975; *Jackson et al.*, 1998; *Kriens et al.*, 1999].

Bucher [1936] proposed a cryptovolcanic origin for Upheaval Dome based on the regional presence of numerous igneous intrusive bodies within and adjacent to the Paradox Formation. Originally, *Shoemaker* [1954, 1956] supported Bucher's claim after identifying the clastic dikes of White Rim sandstone at the center of the dome and considering the magnetic anomaly found there by *Joesting and Plouff* [1958]. *Joesting and Plouff* [1958] reported a slight positive gravity anomaly as well, which is inconsistent with the hypothesis that Upheaval Dome is underlain by a salt diapir.

Upheaval Dome differs from the many salt dome anticlines in the region by its circular shape, while the anticlines are more or less elongated [*Kriens et al.*, 1999]. *Dachille* [1962] assigned a high probability to an im-

pact origin. *Shoemaker and Herkenhoff* [1984] and *Shoemaker et al.* [1993] asserted that it was formed by impact and subsequently eroded, exposing the lower section of the structure (bottom section of Figure 2). They based their claims on the occurrence of radially convergent displacement accompanied by intense deformation of the rocks at the center of the dome, folding of strata on the flanks of the central uplift as observed at other impact structures [*Wilshire et al.*, 1972; *Milton et al.*, 1972], and pseudo shatter cones in the Moenkopi Formation indicative of moderate shock pressures.

Kriens et al. [1999] identify Upheaval Dome as an eroded impact crater, originally at least 5 km in diameter. On Earth an impact crater larger than 2-4 km transitions from a simple shock cavity to a complex structure modified by the inward collapse of an initial or transient cavity, probably within seconds to days of impact. *Melosh* [1989] described the development of a complex crater as subsidence and radially inward transport of the walls of the transient cavity along listric faults, with the convergent flow raising the bottom of the transient cavity into a complex central uplift. *McKnight* [1940], *Joesting and Plouff* [1958], and *Schultz-Ela et al.* [1994] all observed the characteristic thinning of the Wingate sandstone, which is primarily due to such listric faults on the margins of Upheaval Dome, and the reversal of dip direction toward the dome center, creating thrust faulting. At Upheaval Dome we presume that collapse of the transient cavity would have been completed in a far shorter time than the millions of years required for significant salt diapirism.

In the area of the central uplift the thickness of Kayenta sandstone is almost doubled, with *Schultz-Ela et al.* [1994] and *Jackson et al.* [1998] describing Upheaval Dome as a spectacularly exposed example of radial contraction accompanied by circumferential shortening (middle of Figure 2). Detailed structural mapping by *Kriens et al.* [1999] showed that fault wedging, plastic folding, and clastic diking accompanied the listric faulting to create the central uplift, with volume equal to that of the ring syncline (or structural depression).

A 1995 seismic refraction study by *Louie at al.* [1995] showed no evidence of any salt diapir within 500 m of the surface below the center of Upheaval Dome. Seismic sources positioned in and outside the structure provided first-arrival data to arrays of sensors deployed across the entire structure on a southeast to northwest reversed profile. Excellent first-arrival records from the central depression and Buck Mesa (Figure 1; bottom of Figure 2) did not show the advancement of first-arrival time that any extant salt plug would have. Instead, travel paths outside the ring syncline showed early arrivals, suggesting a shattered and low-velocity core to the structure.

Our seismic reflection survey, also carried out in 1995, was designed to reveal structural and stratigraphic details from the top of the Paradox salt upward, and at radial distances between 1 and 3 km from the center of Upheaval Dome. Our profiles show the depth of the Paradox salt and the trend of vertical fault displacements with depth and suggest areas of structural thinning and thickening and fault geometries. These results support the volume calculations of *Kriens et al.* [1999] and are more consistent with their impact hypothesis than with the pinched-off salt diapir hypothesis of *Jackson et al.* [1998].

3. Field Procedure

A 48-channel seismic reflection survey collected data at 10 m station and 40 m source intervals along a 5 km profile using a 317 kg hammer, with recording by a Bison instantaneous floating-point instrument. Table 2 shows the field parameters. Both the extreme topographic relief in the area around Upheaval Dome and the special requirements for mitigating the environmental impacts of a survey in a National Park limited the placement of seismic sources to the main access road (Figure 1). These limits allowed collection of vertical incidence reflection data only as close as 1 km from the center of the Dome. The 5 km survey along the road does span the entire width of the ring syncline and crosses to outside the rim monocline.

Table 2

4. Data Processing

We first applied the common midpoint (CMP) stacking technique to map the reflectors underlying Upheaval Dome. The processing flow was similar to that used for ordinary shallow seismic exploration. The main distinction was the extra care exercised in prestack dip filtering. The data collected are obviously affected by ground roll, air waves, and other coherent noise that makes it difficult to see shallower reflection signals clearly in many records. Also, sideswipe off the nearby steep canyon walls makes the raw data more complex, but reflections with up to 1 s two-way travel time are clear in most of the records.

A frequency analysis using 20 Hz bands showed that most reflection energy was in the range of 15-100 Hz. We applied band-pass frequency filtering with 20% taper in that range (tapering up from 12-15 Hz, then down from 100-120 Hz). Even though the band-pass filtering removed air waves successfully, ground roll was still present, due to the overlapping of signal and noise frequencies. That makes it necessary to use velocity filtering to remove the ground roll and other coherent noise from the shot records (a process called dip fil-

tering when applied to stacked sections). We used the (x,t)-domain technique of *Hale and Claerbout* [1983] for this purpose. The average highest apparent velocity of ground roll and other coherent noise seen in the records was 0.840 km/s.

We used a low-velocity-cut (high-dip-cut) filter to remove coherent noise having apparent velocities of 0.840 km/s in absolute value and lower. Figures 3a and 3b show 17 raw shot gathers before and after application of the frequency band-pass filter and the low-velocity-cut filter. The velocity filter obviously improved the signal-to-noise ratio but could not remove all of the noise from the data. We also applied a hand-picked mute to all data records to remove first-arrival direct and refracted waves, enhancing the earlier reflections. The basic processing sequence was trace equalization gain, band-pass filtering, velocity filtering, muting, normal move-out (NMO) velocity analysis, and common midpoint (CMP) gather and stack.

Figures 3a and 3b

4.1. Stacked Sections

For an effective CMP stack result we divided the curved survey line into two sections in order to avoid stacking midpoints that are too scattered. Thus the first section stacks data involving ray paths oriented in the W-E direction, partly transverse to the dome, and the second section stacks those in the NNW-SSE direction radial to the dome (Figure 1). To obtain the CMP-stacked section, we had to identify the best stacking velocity model by performing NMO velocity analysis. Velocities picked from constant velocity test stacks (not shown) made at 200 m/s increments ranged from 2000 to 5400 m/s. After choosing the best stacking velocities as functions of time at several different shot locations, we obtained the CMP-stacked sections (Figure 4).

Figure 4

As these stacks do not represent the reflections seen so easily on the field records (Figure 3), we only make a few observations from them. Section 4.2, on prestack migration, gives our main results. All seismic sections here are scaled for the best representation of reflections, leading to horizontal exaggerations of 1.2 to 1.9 times. Our filtering and velocity analysis, and Figure 3, suggested that there is little significant reflection energy after 1 s two-way travel time. Therefore we cut the processing time length to half of the original record length.

The apparent dominant frequency of the seismic data is 45 Hz at ~0.2 s two-way travel time, giving a maximum vertical resolution of 20 m and maximum horizontal resolution of 80 m, using the average stacking velocity of 3700 m/s. The depth conversion accuracy is about ±20 m, corresponding to a 200 m/s stacking velocity error. Table 3 shows the computed interval velocities that we used to check the picked velocities. Section 1 shows higher velocities overall than section 2 from con-

Table 3

ventional NMO analysis, due to more steeply dipping structure, nonplanar reflectors, the cross-dip geometry of the section, and our lack of static corrections. The depths obtained for section 1 could thus be ~10% too large. *Louie et al.* [1995], on the other hand, showed from the coincident refraction survey that velocities are higher below the ring syncline than they are farther from the dome's center. Section 1 samples mainly the ring syncline.

A strong, flat-lying reflection appears on section 1 (Figure 4) approximately at 0.6 s, corresponding to a depth of 1100 m. This reflection is much weaker on section 2. A strong reflection appears on the stacked sections approximately at 0.2 s two-way travel time (~370 m depth after conversion with the 3700 m/s average stacking velocity). Although this reflection appears discontinuously on section 1, it is strong and straight on section 2 (Figure 4). This is consistent with vertical deformation decreasing radially away from the center of the dome. On section 2 at both ends of this 0.2 s flat reflection, diffraction hyperbolas and disrupted stratigraphy suggest the locations of two normal faults. The fault nearer the dome was also mapped in the 300 m high canyon walls by *Kriens et al.* [1999], as forming the rim monocline of Upheaval Dome. A possible fault surface reflection dips from 0.25 to 0.35 s two-way time (~460 to 650 m depth), toward the central uplift on section 1 (labeled A on Figure 4).

4.2. Prestack Migration

In some cases a stacked section, processed under a number of assumptions, may not be fully interpretable when the assumptions are violated. For example, NMO correction and the CMP stack ideally require laterally homogeneous and horizontally layered media. Small dips and mild lateral variations of velocities can be, to some extent, handled without significant extra effort. However, as the degree of lateral heterogeneity and the dips of layers increase, the two processes perform poorly [*Jain and Wren*, 1980]. Upheaval Dome is characterized by both strong lateral heterogeneity and steeply dipping layers and as such renders the task of interpretation difficult. The sinuousity of the survey line adds more difficulties. Reflection points at depth deviate significantly from the midpoint locations and are not necessarily in the same vertical plane. These complexities caused reflections on the field records to have nonhyperbolic and, for a few records, negative move-outs. No stacking velocity can correct for negative move-outs without first considering the geometric irregularities causing them [*Louie et al.*, 1988]. Prestack migration is a process that can efficiently handle the geometric irregularities and lateral heterogeneities.

The prestack migration algorithm used in this paper

is a Kirchhoff summation method. Based mainly on three assumptions, the method simplifies the task of inverting an elastic wave field for an image of the earth through which it has propagated [*Le Bras and Clayton*, 1988]. These assumptions reduce the inversion of reflection data to a process similar to the Kirchhoff sum migration of *Jain and Wren* [1980]. The method requires travel time curves computed from a velocity model. We used interval velocities obtained from the stacking velocity picks (Table 3) as the velocity model to calculate travel times using *Vidale*'s [1988] finite difference solution of the Eikonal equation.

The Kirchhoff prestack imaging is done through mapping unsorted seismogram traces into a depth section by computing the travel time from the source to the depth point and back to the receiver, through the velocity model. The velocity model has 200 m/s velocity error and a corresponding depth error of 10% in the depth section. The travel time calculation includes turning rays, which allows for imaging reflections off the down-facing sides of structures. Within the travel times down to and up from every point in the data volume, the value of the seismogram is summed into the section at the depth point. Coherent and continuous events will indicate structure in the depth section. Figures 5 and 6, followed by Figures 7 and 8, show the results of Kirchhoff prestack migration on sections 1 and 2, respectively.

Figures 5 and 6

Figures 7 and 8

5. Interpretation of the Seismic Data

For Figures 6 and 8 we have overlain our stratigraphic interpretations on the migrated sections 1 and 2, respectively, with ties to well logs. Solid white lines give our interpretation of structure related to the Paradox salt, the results we will emphasize here. Dashed white lines show our interpretatons of structure above the Paradox, which we consider less certain.

A first view of Figures 4, 5, and 7, showing stacked and prestack migration sections, shows primarily the geometry of the top of the Paradox Formation. The Paradox depth here has a relative depth precision of better than 20 m and an absolute depth accuracy better then 50 m. These sections also indicate some complicating factors in the interpretation of the seismic data from Upheaval Dome. (All sections have horizontal exaggerations of 1.2-1.9 times.) These complications include diffractions, probable reflections from out of the planes of the profiles, migration artifacts, and the complicated structure of section 1. These problems can be minimized by including constraints from the stratigraphic section and available well log data, a proper understanding of faulting mechanisms based on surface geology [*Jackson et al.*, 1998; *Kriens et al.*, 1999], and recognizing the diagnostic features of such faulting in

the sections.

The seismic line intersects the ring syncline indicated by geologic mapping [*Huntoon et al.*, 1982; *Jackson et al.*, 1998; *Kriens et al.*, 1999] within the eastern part of section 1 and off the north end of section 2 (Figures 1 and 2). The ring syncline has a radius of ~1750 m. An acoustic well log (Buck Mesa 1, Husky Oil Company) is located in the same ring syncline 600 m north of the bending point of the seismic line (Figure 1). We convolved a 15-100 Hz band-limited wavelet against the acoustic velocity profiles defined by the well log, to produce synthetic seismograms on a depth axis (Figures 5 and 7). The three synthetic traces were generated from the separate velocity logs of the two different transducer separations in the logging tool, with a trace from an averaged profile in between. These synthetics allow correlation of reflections in both the sections with the interpreted log.

Note the strong reflections from thin but very low velocity (large transit time) shaly layers within the Paradox salt. Surrounding these shaly intervals are thin layers of anhydrite showing velocities above 6 km/s. The nearly constant sonic transit times of the massive salt intervals are all delayed by hole enlargement by dissolution during drilling, which is why the traces of the two transducer distances separate only over those intervals. The massive salt should have high velocities close to those of the anhydrite layers. The effect of this bias on the synthetics is that the salt-top reflection looks weaker in the synthetics than the reflections from the shaly intervals, when they should be more equal in strength.

A gamma ray log, Murphy Range Unit 1, acquired by the Pan American Petroleum Corporation (PAPC) and reproduced by *McCleary and Romie* [1986], is located 3700 m SSE of the end of section 2. This allows correlation of reflections toward the south end of section 2 with the log. The gamma ray log has been interpreted by PAPC. Lithologic formations were identified by correlating to a reference gamma ray log. We identified the major picks on the sonic log as formation boundaries by correlating with the interpreted gamma ray log. *Kriens et al.* [1999] made an independent interpretation of the sonic log that is identical below 500 m depth. The log interpretations allowed proper identification of formations on the seismic sections. Figures 5 and 7 show the correlations between the logs, the synthetic, and our migrated sections right through the Paradox, to 2.5 km depth. Figures 6 and 8 are limited to the upper 1.5 km of depth, to concentrate on our interpretations of structure in the upper Paradox and above.

5.1. Depth to the Paradox Salt

The acoustic well log locates a salt layer (the Paradox Formation) that extends from 1160 to 2200 m depth. The primary result of our study is a strong reflection shown on Figures 5 and 6 approximately at 1160 m depth throughout section 1 and on Figures 7 and 8 toward the north end of section 2 (solid white lines on interpretations). The same reflection is much weaker on the CMP-stacked sections (at ~0.6 s in Figure 4) without prestack migration. The stacked section of section 2 does feature a shallower reflection at 0.2 s two-way travel time, which is not obvious at 370 m depth on the migrated section 2 (Figures 7 and 8). Migration artifacts created by a boundary in the velocity model used in the prestack migration obscure reflections at that depth in section 2.

We present only 0.8 s two-way travel time on the stacked sections (Figure 4) and a maximum depth of 2.5 km on the prestack-migrated sections, corresponding to approximately 0.9 s (Figures 5 and 7). The upper reflections are better defined in the stacked section, and the lower ones are better defined in the prestack-migrated section. This may be due to the laterally homogeneous velocity model used and the lack of static corrections. Note as well that we show uninterpreted migrated sections to 2.5 km depth (Figures 2, 5, and 7) but interpreted sections to only 1.5 km depth (Figures 6 and 8).

The Paradox Formation reflection appears to be almost entirely flat-lying, showing no more than 100 m depth variation (solid white lines on Figures 6 and 8). It shows a bulging just inside the ring syncline (just above and right of the arrow on Figure 5 pointing to the Paradox top) that could be attributed to upward movement of salt involved in minor diapirism or perhaps to deformation during the passage of the impact shock wave. Following the strong reflection that is at the depth of the Paradox top in the well log synthetic, the displacement of a slice of the Paradox top almost 400 m wide appears upward instead of downward (Figure 6). The section shows that any upward movement would be 100 m at maximum. The strong reflection from the shaly interval, just below the Paradox top, shows much less, if any, vertical displacement (Figures 5 and 6). The 100 m of upward movement can be thought to have caused the thrust faults shown at the center of Figure 6 at 1.1 km depth, breaking the continuity of the reflection corresponding to the top of the bulge.

The absence of interpreted thrust breaks above the Hermosa Formation suggests a mode of deformation not related to salt diapirism. The deformation caused by the Paradox Formation ends within the Hermosa Formation, the top of which seems relatively less deformed

on the section (Figure 6 at 0.8 km depth). The deformation is at its 100 m maximum at 1.2 km depth and may decrease to a minimum resolvable 50 m toward 0.75-0.8 km depth. Deformation at the same depth range in section 2 may decrease radially outward (Figures 7 and 8).

This bulging in the Paradox Formation may have been caused by a limited episode of salt diapirism. *Jackson* [1995] gives an example from Colorado Canyon, Utah, where erosionally induced differential loading created a complex pattern of limited upwelling of Pennsylvanian Paradox evaporites. *Harrison* [1927] attributed differential loading to erosional removal of overburden.

Our results (solid white lines on Figures 6 and 8) show an up to 100 m salt uplift at the top of Paradox Formation, at 1150 m depth. *Huntoon et al.* [1982] suggest 300 m maximum stratigraphic uplift at the center of Upheaval Dome. The 100 m salt uplift we observe is limited to one area 400 m wide below the ring syncline, however, and does not appear to be part of an uplift ramp toward the center of a diapir (Figure 2). Instead it may be related to the ring of high velocities seen below the ring syncline by the refraction surveys of *Louie et al.* [1995]. Both our seismic refraction and reflection results do not indicate the presence of Paradox salt at depths of <1100 m. Therefore we have evidence for no more than 100 m of Paradox salt diapirism during the formation of Upheaval Dome.

Section 2 (Figures 7 and 8) shows <100 m deflection of the Hermosa or Paradox Formation tops but suggests substantial northward dips of the Cutler, Moenkopi, and Chinle Formation tops into the ring syncline from the rim monocline. The ring syncline is thus confined to the section above the Hermosa and is not expressed in any ring depression or moat in the Paradox salt top. A moat in the salt top equal in volume to that of uplifted salt would be required for substantial diapirism (top and middle of Figure 2).

Development of such a moat would also be the only mechanism for development of the ring syncline under any salt diapirism hypothesis. The amount of vertical deformation should also increase downward through the section to the moat. Figures 7 and 8 show that neither the top of the salt nor the prominent shaly reflectors within the upper Paradox have deformed vertically more than 100 m across the rim monocline. Thus no salt could have been mobilized from below the ring syncline to form any substantial diapir. Given the 300 m of stratigraphic uplift within the center of Upheaval Dome (Figure 2, bottom), we favor an alternative origin, such as impact, that would develop the radially convergent features mapped by *Jackson et al.* [1998] and by *Kriens et al.* [1999].

A salt diapir hypothesis that would generate the

observed convergence features would be the development of Upheaval Dome as a vertically pinched-off diapir. This type of salt structure was first recognized elsewhere by *Stille* [1925], lately supported by *Coward and Steward* [1995], and advocated for Upheaval Dome by *Schultz-Ela et al.* [1994] and *Jackson et al.* [1998]. However, within the central depression of Upheaval Dome, no one has found any Paradox Formation outcrop or diapiric lag fragment. *Jackson et al.* [1998] propose a substantial volume of "erupted" salt and a resultant 250 m lowering of the top of the Paradox Formation below the ring syncline (middle of Figure 2). Our finding of 100 m maximum salt uplift under the ring syncline (solid white lines on Figure 6) and no depletion or depression of the salt top across the rim monocline (solid white lines on Figure 8) thus specifically rejects their hypothesis of a pinched-off salt diapir.

5.2. Other Impact-Related Structure

We can glean a few secondary details about this impact structure from our sections. The dashed white lines on Figures 6 and 8 show our less certain interpretations of structures above the Paradox. The main features of a complex impact structure are the convergent central uplift and the megablock zone of listric normal faulting, both directed radially inward [*Croft*, 1985]. When evaluating these features at Upheaval Dome, one must take into account the effect of erosion. *Kriens et al.* [1999] estimate that at least a few hundred meters of erosion, to the top of the Wingate sandstone, may have taken place at Upheaval Dome (Figure 2, bottom).

The central uplift is generated by an inward and upward movement mainly of the deepest affected horizons [*Grieve et al.*, 1981; *Dence et al.*, 1977]. During the brief modification stage this structure develops as the transient cavity collapses. The upward movement of rocks in the central uplift generates a domal form. The border between the transient cavity and the megablock zone is called the structural rim uplift [*Juhlin and Pedersen*, 1987]. The expected displacement in the megablock zone is downward faulting toward the center. One additional complexity to the structure of Upheaval Dome is the effect of the salt, which may flow long after the impact and central uplift processes have completed. Even a small amount of salt uplift could superimpose additional deformation on the structure.

Above the Paradox Formation reflection a suite of reflections dip northwestward and may reverse toward the central uplift. These layers match with the well log observations of formation boundaries, as can be seen on Figures 6 and 8 (dashed white lines). The reflections almost converge toward the ring syncline. The original suite of reflections are destroyed within the original limit of the transient cavity by faulting, as seen on sec-

tion 1 (Figure 6). We found thrust faults toward the central uplift on the west side of prestack section 1 (Figures 5 and 6) and several normal faults along shallower reflectors under the ring syncline on prestack section 2 (Figures 7 and 8). The west dipping reflections at the center of Figures 5 and 6 may represent listric faults in the oblique cross section of section 1, dipping toward the central uplift from below the ring syncline. A listric fault also appears on the stacked section of Figure 4, marked A. In section 2 (Figures 7 and 8) above the Hermosa are several normal faults, both within and outside of the ring syncline. The Figure 8 interpretation marks these faults. Layers dip gently downward from the south toward the north and dip much more abruptly in the northernmost part of section 2 (Figures 7 and 8) as expected inside a ring syncline (Figure 2, bottom).

5.3. Effects of the Underlying Salt on Crater Modification

We observe that the degree of deformation generally decreases downward and increases toward the central part of the dome. On the other hand, the deformation increases somewhat both upward and downward from the top of Hermosa Formation. This shows that there may be two factors involved in the deformation observed beneath Upheaval Dome. The first factor is the impact. The upper parts of our cross sections suggest that the type of deformation we describe in sections 5.1 and 5.2 must be due to a force that comes from above. An impact shock wave and the collapse of a transient cavity are two examples of such a force. The faults found, thrust in cross section 1 (Figure 6) and normal in section 2 (Figure 8), are located in the migrated sections as expected from an impact model (Figure 2, bottom).

The second factor is the salt of the Paradox Formation, which through flow may have further modified the complex impact structure. Our interpretations of sections 1 and 2 (Figures 6 and 8) suggest that listric normal faults of the central uplift process may have broken through the top of the Hermosa Formation below the ring syncline. We cannot tell from our work on section 1 (Figure 6) whether that faulting may have simply lifted some of the Hermosa, thinned it, or thickened it tectonically. Our interpretation suggests thinning of the Hermosa where listric faults have sliced along its top. Removal of material from the Hermosa by listric faulting, at intermediate depths, might have caused the drooping of overlying rocks, forming the ring syncline.

The 100 m of salt uplift shown at the top of the Paradox on section 1 (Figure 6) is also below the ring syncline in this oblique section. We suggest that uplift to be the result of limited salt flow into the broken or thinned area of the Hermosa, forming an antiformal or

reverse-faulted rise in the top of the Paradox Formation (Figure 2, bottom). This uplift may have subsequently restored the top of the thinned Hermosa to near its original depth. The original topographic form of the complex crater, which would have been deepest around the ring syncline, may have provided some gravitational drive to this salt uplift below. The high-standing central uplift, as well, may have driven ~100 m depression of the salt below the center of the structure. The prestack sections show that the resultant effect of salt flow is absent in the upper 750 m of the sections.

6. Conclusion

The principal finding of this work is that the upper part of the Paradox Formation does not show the more than 100 m of relief expected for any salt diapirism origin of Upheaval Dome. No salt diapirism model for Upheaval Dome can produce a Paradox salt top as flat as our sections show, below both the structural rim and the ring syncline (Figure 2). Stratigraphic deformation due to salt diapirism would also have increasing amplitude with depth, but we observe the opposite. The amplitude of deformation decreases with depth in the upper 750 m. A source of deformation acting from above downward, such as impact, can explain the pattern of faulting and folding better than one from below, like a salt diapir. We have identified several ancillary features in the seismic sections as being representative of parts of a complex impact structure such as the central uplift, listric faults, and megablock zone.

The 100 m maximum salt uplift we do observe is not a shallowing toward the center of the structure, as would be expected for a salt dome or salt diapir model. Instead, any salt uplift is confined to below the ring syncline and is limited to <100 m as well. Such displacement is inconsistent with all salt diapir models. Our observations of a relatively flat topography for the top of the Paradox Formation, with no moat in the salt top below the ring syncline (Figure 2, middle), specifically disproves the pinched-off salt diapir hypothesis of *Jackson et al.* [1998]. Our surveys do not show any of the geometric features in this interface that would be required volumetrically for any salt diapirism model. Thus our results are most consistent with the impact model for the formation of Upheaval Dome.

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helped us to mitigate any environmental impacts of the geophysical surveys. Jerry Schuster of the University of Utah provided the 300 kg hammer source as well as the 48-channel reflection recording system. The Incorporated Research Institutions for Seismology provided PASSCAL recorders for the refraction experiment and allowed crucial participation in the field by Marcos Alvarez of the Stanford Instrument Center. Z. Kanbur's thesis research at UNR was supported by Suleiman Demirel University of Turkey, and S. Chávez-Pérez was supported by the CONACyT program, Mexico. Comments from K. Herkenhoff, J. Plescia, R. A. Schultz, and two anonymous referees extensively improved the manuscript.

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Table 1. Generalized Stratigraphic Section, Upheaval Dome, Utah

System	Formation*	Thickness,* m	Formation†	Thickness,† m	Rock Type
Jurassic	Navajo	49-103	Navajo	76-167	ss
Jurassic	Kayenta	49-76	Kayenta	61-91	s+sh, ss
Jurassic	Wingate	64-104	Wingate	49-137	ss
Triassic	Chinle	143	Chinle	60-274	sh, s+sh, ss
Triassic	Moenkopi	160	Moenkopi	0-396	sh, s+sh, ss
Permian	Cutler	305	Cutler	0-457	ss, sh, s+sh
Permian	Rico	176			lim, ss, sh
Pennsylvanian	Hermosa	555	Honaker Tr.	100+	lim, sh, ss
Pennsylvanian	Paradox	610	Paradox	152+	salt, anh, sh
Mississippian, Devonian, & Cambrian	undiff.	610			lim, sh, ss

Rock type abbreviations as follows: ss, sandstone; s, sandy; sh, shales; lim, limestone; anh, anhydrite.

*After *McKnight* [1940].

†After *Baars and Seager* [1970] and *Baars* [1971].

Table 2. Field Acquisition Parameters

	Acquisition Parameter
Date	January 1995
Spread type	off-end
Number of channels	48
Group spacing	10 m
Group type	40 m linear
Geophones per group	14
Geophone type	6 Hz
Source spacing	40 m
Source type	317 kg weight drop
Source stacks	10-20 impacts
Minimum offset	20 m
Maximum offset	480 m
Nominal fold	6
Sampling rate	2 ms
Record length	2 s
Low-cut filter	16 Hz
High-cut filter	250 Hz

Table 3. Interval Velocities

Two-Way Time, s	Velocity, m/s
Section 1	
0.201	2600
0.307	4100
0.473	4700
0.592	5500
0.863	5900
Section 2	
0.094	2000
0.201	2350
0.343	3490
0.473	4060
0.757	5470

Figure 1. Map showing the locations of the seismic reflection line and two wells at Upheaval Dome, Canyonlands National Park, southeast Utah. Well locations, shown as diamonds, are approximate. Seismic sections 1 and 2 are located between geophone group stations 101 and 250, and 250 and 420, respectively. The stations were spaced at 10 m intervals along the access road. Shaded relief is from the U.S. Geol. Surv. 1:62,500 Canyonlands National Park map, courtesy of the Perry-Castañeda Library map collection of the University of Texas at Austin. The ring syncline was mapped by *Huntoon et al.* [1982] and by *Kriens et al.* [1999].

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Figure 2. Schematic cross sections for salt dome, pinched-off salt diapir, and impact hypotheses for the origin of Upheaval Dome. These sections follow a NW-SE line passing through the seismic reflection sections and the refraction experiment. Formation boundaries do not distinguish between depositional and fault contacts. Above the Cutler Formation, depths are taken from the W-E section of *Kriens et al.* [1999]. Below, depths are taken from our interpretations of the Buck Mesa 1 and Murphy Range 1 wells. Small circles show where a hypothesis fits formation depths in the well; small crosses show where it does not. In the impact section the thick dashed line suggests the surface crater form at the minimum depth of erosion; the thin dashed lines at the Paradox and Hermosa tops show their maximum vertical deflection interpreted from the reflection sections.

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Figure 3. Examples of 48-channel field records. Each of the records, all plotted side by side, covers an offset range of ∼20-480 m. The 17 shot points represented are at intervals of ∼200 m along the reflection line. (a) Raw records; notice the strong influence of coherent noise with low apparent velocities (steep slopes), such as ground roll and air waves. (b) The records after application of band-pass frequency and dip filters; ground roll and air waves have been greatly reduced.

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Figure 4. CMP-stacked sections. Normal move-out (NMO) stacking velocities were determined at several locations by analysis of constant velocity stacks. Section 1 shows the stack along a west-east straight-line projection of the original profile between geophone group stations 101 and 250 (Figure 1). Station 101 and the left side of section 1 are 200 m from the edge of the central depression and 800 m from the center of Upheaval Dome. Section 2 shows the stack along a NNW-SSE straight-line projection of the original profile between stations 250 and 422. Approximate vertical exaggeration with the 3.7 km/s average NMO velocity is 0.57 times. Dome features are labeled, including a possible listric fault at A.

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Figure 5. Prestack migration to 2.5 km depth along section 1 (Figure 1). The dual-tool sonic log and synthetic from the Buck Mesa 1 well located close to the east end of the section is shown to the right, for correlation. The top of the Paradox Formation on the sonic log correlates well in depth with the most coherent reflection on the migrated image. Vertical exaggeration is 0.54 times.

Figure 5. Prestack migration to 2.5 km depth along section 1 (Figure 1). The dual-tool sonic log and synthetic from the Buck Mesa 1 well located close to the east end of the section is shown to the right, for correlation. The top of the Paradox Formation on the sonic log correlates well in depth with the most coherent reflection on the migrated image. Vertical exaggeration is 0.54 times.

Figure 6. Section 1 prestack migration to 1.5 km depth, with the interpreted correlations (black dashed lines) between formation tops in the Buck Mesa 1 log and synthetic (arrows), and the section. The location of the ring syncline is indicated; the derrick symbol shows the well location, projected parallel to the syncline axis. A solid white line shows the Paradox salt top, along with a strong reflection from within the upper Paradox. Other reflections and faults with less certain interpretations are marked with dashed white lines, including faults bounding a possible 100 m uplift of the Paradox Formation top at the lower center. Vertical exaggeration is 0.85 times.

Figure 6. Section 1 prestack migration to 1.5 km depth, with the interpreted correlations (black dashed lines) between formation tops in the Buck Mesa 1 log and synthetic (arrows), and the section. The location of the ring syncline is indicated; the derrick symbol shows the well location, projected parallel to the syncline axis. A solid white line shows the Paradox salt top, along with a strong reflection from within the upper Paradox. Other reflections and faults with less certain interpretations are marked with dashed white lines, including faults bounding a possible 100 m uplift of the Paradox Formation top at the lower center. Vertical exaggeration is 0.85 times.

Figure 7. Prestack migration to 2.5 km depth along section 2 (Figure 1). The sonic log and synthetic from the Buck Mesa 1 well located close to the north end of the section are shown on the left, and a gamma ray log from the Murphy Range 1 well 2.5 km from the south end of the section is shown on the right for correlation. Elevation differences between the depth scales of the wells and section are shown. There is a close correlation between the top of Paradox Formation seen from both the logs and a strong and coherent reflection on the seismic section. Arrows point out additional features. Vertical exaggeration is 0.61 times.

Figure 7. Prestack migration to 2.5 km depth along section 2 (Figure 1). The sonic log and synthetic from the Buck Mesa 1 well located close to the north end of the section are shown on the left, and a gamma ray log from the Murphy Range 1 well 2.5 km from the south end of the section is shown on the right for correlation. Elevation differences between the depth scales of the wells and section are shown. There is a close correlation between the top of Paradox Formation seen from both the logs and a strong and coherent reflection on the seismic section. Arrows point out additional features. Vertical exaggeration is 0.61 times.

Figure 8. Section 2 prestack migration to 1.5 km depth, with the interpreted correlations (black dashed lines) between formation tops in the Buck Mesa 1 and Murphy Range 1 well logs and synthetic (arrows) and the section. A solid white line shows the Paradox salt top, along with a strong reflection from within the upper Paradox. Other reflections and faults with less certain interpretations are marked with dashed white lines. The well logs and section show <100 m deflection of the Hermosa or Paradox Formation tops; and suggest northward dips of the Cutler, Moenkopi, and Chinle Formation tops into the ring syncline from the rim monocline. The ring syncline is thus confined to the section above the Hermosa and is not expressed in any moat in the Paradox salt top, which would be required for substantial diapirism. Vertical exaggeration is 0.84 times.

Figure 8. Section 2 prestack migration to 1.5 km depth, with the interpreted correlations (black dashed lines) between formation tops in the Buck Mesa 1 and Murphy Range 1 well logs and synthetic (arrows) and the section. A solid white line shows the Paradox salt top, along with a strong reflection from within the upper Paradox. Other reflections and faults with less certain interpretations are marked with dashed white lines. The well logs and section show <100 m deflection of the Hermosa or Paradox Formation tops; and suggest northward dips of the Cutler, Moenkopi, and Chinle Formation tops into the ring syncline from the rim monocline. The ring syncline is thus confined to the section above the Hermosa and is not expressed in any moat in the Paradox salt top, which would be required for substantial diapirism. Vertical exaggeration is 0.84 times.

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