ABSTRACT

Upheaval Dome (Canyonlands National Park, Utah) is an enigmatic structure previously attributed to underlying salt doming, cryptovolcanic explosion, fluid escape, or meteoritic impact. We propose that an overhanging diapir of partly extrusive salt was pinched off from its stem and subsequently eroded. Many features support this inference, especially synsedimentary structures that indicate Jurassic growth of the dome over at least 20 m.y. Conversely, evidence favoring other hypotheses seems sparse and equivocal.

In the rim syncline, strata were thinned by circumferentially striking, low-angle extensional faults verging both inward (toward the center of the dome) and outward. Near the dome’s core, radial shortening produced constrictional bulk strain, forming an inward-verging thrust duplex and tight to isoclinal, circumferentially trending folds. Farther inward, circumferential shortening predominated: Radially trending growth folds and imbricate thrusts pass inward into steep clastic dikes in the dome’s core.

We infer that abortive salt glaciers spread from a passive salt stock during Late Triassic and Early Jurassic time. During Middle Jurassic time, the allochthonous salt spread into a pancake-shaped glacier inferred to be 3 km in diameter. Diapiric pinch-off may have involved inward gravitational collapse of the country rocks, which intensely constricted the center of the dome. Sediments in the axial shear zone beneath the glacier steepened to near vertical. The central uplift is inferred to be the toe of the convergent gravity spreading system.

INTRODUCTION

Upheaval Dome is located in Canyonlands National Park (Island in the Sky district), in the western part of the Colorado Plateau, southeastern Utah (Fig. 1). The dome is one of the most enigmatic and controversial geologic structures in North America. Hypotheses for its origin include cryptovolcanic explosion, meteoritic impact, fluid escape, and subsurface salt diapirism. We document here a new explanation for the origin of Upheaval Dome—the pinched-off salt diapir hypothesis.

Upheaval Dome forms a mound that has strongly deformed uplifted beds in the center of the dome. Strata have been elevated 120–250 m above their regional levels. Beds near the center of the dome are tightly folded and cut by faults having generally radial strikes. The central uplift passes outward into a prominent rim syncline, then into a rim monocline, outside of which strata show merely gentle regional tilting (Fig. 2). The center of the dome is a topographic depression eroded 350 m below the surrounding escarpment, which is breached by a canyon cut through its west wall.
The dramatic canyon relief and generally superb exposures make Upheaval Dome a leading attraction for tourists and geologists.

Tectonic Setting

In Middle Pennsylvanian time, the Paradox basin formed as a northwest-trending foreland basin to the basement-cored Uncompahgre uplift (Ohlen and McIntyre, 1965), which was thrust over the northeast edge of the basin along the Uncompahgre fault (Fig. 1; Frahme and Vaughn, 1983; Ge et al., 1994b; Huffman and Taylor, 1994). The deepest part of the trough adjoined the Uncompahgre uplift, and the basin thinned toward gentle crustal upwarps that bounded the basin to the south and west. Folding and faulting accommodated downward bending of the crust into the axis of the Paradox trough.

Salt accumulated in the deepest part of the Paradox basin shortly after the Uncompahgre thrust fault became active. Prograding sediments shed from the Uncompahgre uplift expelled the salt southwestward, forming a series of northwest-trending salt walls and anticlines (Baars, 1966; Ge et al., 1994a, 1997). Salt structures decrease in amplitude and age of initiation away from the Uncompahgre uplift. Truncations and lateral thickness changes indicate that diapirs grew mostly during Permian time, but salt continued to flow until at least 100 m.y. ago (Doelling, 1988). Near Upheaval Dome, roughly 75 km southwest of the Uncompahgre fault, most salt structures are gentle anticlines (Fig. 1), but small diapiric stocks are locally exposed.

The Paradox basin has been affected by at least three more tectonic episodes since Late Cretaceous time. (1) Crustal shortening related to the Laramide orogeny (Late Cretaceous–early Tertiary) reactivated the Uncompahgre fault and may also have reactivated some of the smaller basement faults within the basin. (2) Oligocene laccoliths built the La Sal, Abajo, and Henry Mountains. (3) The basin may have been slightly stretched in Cenozoic time (Ge and Jackson, 1994; Hudec, 1995; Ge et al., 1996). These events had negligible effects on the flat-lying strata around Upheaval Dome. Finally, the Colorado Plateau was greatly uplifted after mid-Miocene time (e.g., Thompson and Zoback,
Permian time as the Uncompahgre highlands stone, dolomite, gypsum, anhydrite, black shale, (1983). The evaporitic facies consist of 70%–90% evaporites were deposited in the vicinity of Up- heaval Dome (Woodward-Clyde Consultants, 1981), and thin toward the basin margins.

Borehole data suggest that roughly 720 m of Paradox Formation evaporites collected here of the White Rim Sandstone. Only the upper two units may be exposed in the center of Upheaval Dome (extreme deformation there hinders stratigraphic correlation). The Organ Rock Member comprises fluvial dark-reddish-brown siltstones and mudstones. The overlying White Rim Sandstone is a clean white sandstone de- posited in coastal eolian environments (Steele, 1987). Sandwiched between finer-grained units, the resistant White Rim Sandstone weathers into prominent ledges and benches. A major hiatus (TR-1 from 264 to 247 Ma) followed deposition of the White Rim Sandstone.

The Moenkopi Formation (Fig. 4) records a ma- rine transgression from the west that created a va- riety of fluvial to shallow-marine environments dominated by fine-grained sediments (O’Sullivan and MacLachlan, 1975; Molenaar, 1981). To map the center of Upheaval Dome, we divided the Moenkopi Formation into three informal units, which are strata-parallel and continue at least 10 km from the dome margins in basins to the south and west. The lower Moenkopi siltstone weathers brownish-red to grayish-red. The lithologic varia- tion and weathering character define structures well. The middle Moenkopi Formation comprises reddish shale containing layers of fine-grained, yellow, flaggy, calccreous sandstone. This member separates the lower reddish Moenkopi member from the upper Moenkopi siltstones that weather to buff-gray or olive-gray featureless masses.

After another major hiatus (TR-3 from 240 to 227 Ma) in Late Triassic time, the continental Chine Formation (Fig. 4) spread across the top of the Uncompahgre uplift, eliminating the Paradox basin as a physiographic feature. We divided the Chine Formation into four map units, from bot- tom to top, (1) basal Moss Back Member sand- stone and conglomerate, which generally crop out as prominent gray ledges or dip slopes; (2) Petri- fied Forest and Church Rock Member shales (la- beled “Lower Chine” in subsequent figures), which weather gray, blue-gray, or lavender, as dis- tinct from the yellowish-gray upper Moenkopi shales; (3) another prominent sandstone about one-third up from the Chine Formation base; this finer-matrix pebble conglomerate is probably the Black Ledge sandstone of the Church Rock Mem- ber (Stewart et al., 1959); (4) shale and siltstone weathering brick, brown, or orange-red are inter- preted to be the upper part of the Church Rock Member (combined with the Black Ledge mem- ber as “Upper Chine” in subsequent figures).

After a brief hiatus (J-0, from 210 to 206 Ma), sedimentation remained continental, with deposi- tion of the Jurassic Wingate Sandstone, a wet erg (the lower Wingate strata representing central erg facies, and the upper Wingate strata representing distal, less arid, back erg facies containing silty interbeds). The mainly fluvial Kayenta Formation and the dry erg Navajo Sandstone then accumu- lated. The Jurassic Navajo Sandstone is the high- est stratigraphic level exposed in Upheaval Dome. Using regional thicknesses of higher units derived from the Book Cliffs area to the north (Molenaar, 1981), we estimate that an additional 1600 to 2200 m of section were deposited above the dome. That upper limit corresponds with the thickness of missing strata required to encase the currently unroofed La Sal laccoliths intruded in middle Cenozoic time some 55 km east of Up- heaval Dome. These Cretaceous and Tertiary units were eroded during Miocene–Holocene up- lift of the Colorado Plateau.

**Hypotheses for Origin of Upheaval Dome**

Upheaval Dome was first described by Harrison (1927) as “Christmas Canyon Dome.” He suggested that salt flowed into the dome be-

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**Stratigraphic Setting**

The oldest known sedimentary rocks beneath Upheaval Dome are Cambrian-Mississippian clastic and carbonate rocks (Fig. 4). Passive-mar- gin sedimentation in the area ceased with the on- set of Ancestral Rockies deformation and led to restricted-marine conditions in Middle and Late Pennsylvanian time. A carbonate shelf rimmed the basin’s southern and western margins as saline facies accumulated in the axis of the basin near the Uncompahgre uplift. As much as 2 km of Paradox Formation evaporites collected here (Hite, 1960) and thin toward the basin margins. Borehole data suggest that roughly 720 m of evaporites were deposited in the vicinity of Up- heaval Dome (Woodward-Clyde Consultants, 1983). The evaporitic facies consist of 70%–90% halite in most places and minor amounts of lime- stone, dolomite, gypsum, anhydrite, black shale, and siltstone.

Restricted marine conditions ended in Early Permian time as the Uncompahgre highlands shed a wedge of marginal marine and continental clastic sediments (Cutler Group, Fig. 4) south- westward across the basin. In the area of Up- heaval Dome, the Cutler Group comprises three formations; from bottom to top, these are the Cedar Mesa Sandstone Member, the Organ Rock Member, and the White Rim Sandstone. Only the upper two units may be exposed in the center of Upheaval Dome (extreme deformation there hinders stratigraphic correlation). The Organ Rock Member comprises fluvial dark-reddish-brown siltstones and mudstones. The overlying White Rim Sandstone is a clean white sandstone de- posited in coastal eolian environments (Steele, 1987). Sandwiched between finer-grained units, the resistant White Rim Sandstone weathers into prominent ledges and benches. A major hiatus (TR-1 from 264 to 247 Ma) followed deposition of the White Rim Sandstone.
cause of unloading produced by canyon erosion in a former meander in the Green River. We know of no such evidence for such a meander. McKnight (1940), Fiero (1958), and Mattox (1968) also postulated an underlying salt dome. Given the strong evidence for lateral constriction rather than lateral extension in the dome center (presented in the following), we reject the notion of a buried salt dome below Upheaval Dome. Moreover, a preliminary report by Louie et al. (1995) concluded from a seismic refraction line across the dome that there is no large salt plug near the surface. Similarly, collapse due to salt dissolution, as envisaged by Stokes (1948), is equally implausible because strata in the center of the dome rise more than 100 m above their regional elevation (Fig. 2).

Bucher (1936) noted similarities between the structures at Upheaval Dome and the Steinheim Basin, Germany, and proposed that Upheaval Dome was cryptovolcanic. Structures in the central depression were interpreted to be a result of explosive release of gases trapped near a shallow igneous intrusion. No igneous rocks have been found within 55 km of the dome center, although geophysical anomalies (described in the following) around Upheaval Dome suggest that igneous rocks may underlie the Paradox salt. Kopf (1982) also interpreted deformation in the dome center to result from sudden upward release of a fluid slurry tectonically overpressured by a deep fault system.

Boone and Albritton (1938) were the first to suggest that Upheaval Dome might have been produced by meteoritic impact. They noted that Upheaval Dome contained many features typical of impact, including circular shape, central dome, peripheral folds, radial faults, and intense deformation. Shoemaker and Herkenhoff (1983, 1984) and Shoemaker et al. (1993) argued, for similar reasons, that there was an impact in Late Cretaceous or Paleogene time (Fig. 5A). They interpreted the thinning of Mesozoic strata observed by McKnight (1940) and Fiero (1958) to be due to normal faulting rather than depositional onlap. They explained the lack of primary physical evidence for impact by suggesting that the crater and much of its floor had been deeply eroded. Kriens et al. (1997) interpreted a lag deposit of eroded cobbles as impactite ejecta indicating that Upheaval Dome formed possibly as late as a few million years ago. Huntoon and Shoemaker (1995) proposed impact as the cause of Roberts rift, a breccia-filled fissure 10 km long located more than 20 km from the dome.

We present a new alternative to the impact hypotheses. We propose that the structural and stratigraphic relations at Upheaval Dome—especially those indicating protracted growth of the structure—can best be explained as the result of stem pinch-off below an overhanging diapiric salt extrusion (Fig. 5B; Schultz-Ela et al., 1994a, 1994b). The central part of the structure contains overburden strata pinched in around what we infer to be the necked-off stem of a broadly overhanging, partly extrusive pancake of salt that was subsequently removed by erosion. Pinched-off diapirs are common below the sea floor in the Gulf of Mexico and in other salt basins (e.g., Jackson et al., 1995), but their stems are difficult to image with seismic data because of the steep stratal dips, large lateral variations in seismic velocity, and structural complexity. To our knowledge, no stems of entirely pinched-off diapirs are exposed at the surface, except where greatly squeezed by orogenic contraction. If our hypothesis is correct, the superb three-dimensional exposure and accessibility of Upheaval Dome make it a prime candidate to examine the response of country rock to the necking and pinching off of a diapir in an area relatively unaffected by orogeny.

**Figure 4.** Stratigraphic section through formations at or below the surface of Upheaval Dome and younger eroded units. Data from the Buck Mesa #1 well log, Fiero (1958), Mattox (1968), and Woodward-Clyde Consultants (1983).
CIRCUMFERENTIAL FOLD SYSTEM

The geology of Upheaval Dome is shown in maps (Figs. 6, 7, and 8) and two cross sections. A conventional linear section trends roughly west-northwest across the entire dome and its surroundings (Fig. 15), and a circular section encircles the dome core to illustrate the roughly radial structures there (Fig. 16).

The largest and most continuous structures in Upheaval Dome are three circular folds having axial traces concentric about the core of the dome (Figs. 6 and 8). From the surrounding undeformed strata toward the core of the dome, this circumferential fold system comprises an outer rim monocline, a rim syncline, and an inner dome. In the structural descriptions that follow, “inward-outward” and “inside-outside” are relative to the center of Upheaval Dome. “Circumferential” is a synonym for the concentric or tangential direction.

The rim monocline defines the perimeter of Upheaval Dome, separating the regional homocline from the rim syncline (Fig. 2). The rim monocline trace is mostly outside the mesa containing the dome center (Fig. 6). The monoclinal bend is broad and gentle where it involves massive Wingate Sandstone (northwest of the dome). Conversely, the monocline is a sharp kink where it is defined by thinly interbedded Chinle clastic rocks (east of the dome).

Inward from the rim monocline, stratal dips measured increase to a mean of 15°–20° and a maximum of 73° then decrease to zero as strata flatten in the floor of the rim syncline. Most of the Navajo Sandstone—the youngest unit present—is preserved within this syncline (Fig. 6). Navajo Sandstone dips slopes define most of the rim syncline, but several erosional alcoves expose cross sections through the fold (Figs. 3 and 6).

Successively older units crop out toward the core of Upheaval Dome (Fig. 6). Stratal dips become subvertical to overturned in the central uplift; there, Moenkopi strata have been elevated perhaps as much as 250 m above their regional datum outside the rim monocline, and surrounding Wingate strata have been lifted 120 m. The inward increase in dip is disrupted in two concentric zones of steep dip, separated by zones of gentle dip. A discontinuously preserved, inner steep zone 0.7–0.8 km from the dome center affects the upper Wingate Sandstone and lower...

Figure 5. Schematic illustrations of hypotheses for meteoritic impact and salt dome pinch-off for the evolution of Upheaval Dome. (A) Impact hypothesis modified from Shoemaker and Herkenhoff (1984) by adding a specific present topographic profile, transient crater profile (dotted), typical lower limit of pervasive fracturing (shaded), and other features typical of impact craters. (B) Maps and cross sections illustrating the diapiric pinch-off inferred in the text.
Figure 6. Geologic map of Upheaval Dome. The Chinle Formation is undifferentiated except for the Black Ledge member, and the middle and upper Moenkopi intervals are combined. Geologic details in the central depression appear in Figure 7; corners are marked by L brackets. Locations and view directions of panoramas in Figures 11, 13, and 14 are marked with large numbers and pairs of arrows; intersection point marks the observer’s position.
Figure 7. Geologic maps of the central depression, showing (A) stratigraphic units and faults, and the linear and circular lines of sections in Figures 15 and 16.
Figure 7. (Continued).
Kayenta Formation (described in Inner Contractional Systems section). A virtually continuous outer steep zone 1.2–1.6 km from the dome center affects the inner margin of the lower Navajo Sandstone. There, dips steepen markedly from 20°–30° to 40° and commonly higher (Fig. 8). Bounding surfaces of dune-scale Navajo Sandstone cross beds become vertical to overturned locally (e.g., near the Syncline Loop Trail in the southwest). Southeast of the dome, at Whale Rock, the innermost Navajo strata dip steepens to a subvertical attitude within ~100 m of the inner Navajo contact (Fig. 9). Inward from the vertical Navajo strata, however, dips in the basal Navajo and underlying Kayenta strata flatten (around 40°).

The circumferential fold system of Upheaval Dome perturbs a regional homocline dipping 1.2° to the north-northwest. This homocline forms the southern limb of the gentle Grays Pasture syncline (Hunter, 1988). In the rim syncline is a crescentic low (Fig. 2), which is a typical fold interference pattern where a rim syncline is superposed on a regional homocline (Ritz, 1936). Two structural highs (stippled) are present: one is the inner circular dome described above; the other is a low, elongated periclinal dome adjoining the western flank of Upheaval Dome, also noted by Fiero (1958).

SYNSEDIMENTARY STRUCTURES

A wide variety of synsedimentary features are present in Upheaval Dome but have not been observed elsewhere in the region. These features provide evidence for deformation of Upheaval Dome over at least 20 m.y., during deposition of the Chinle, Wingate, and Kayenta Formations (Fig. 4). Deeper stratigraphic units (Moenkopi and Cutler Formations) are exposed only in the core of the dome, where they are too deformed to reveal lateral stratigraphic variations. The upper contact of the highest unit in the dome (Navajo Sandstone) is not exposed and is generally too massive and coated with desert varnish to expose large-scale internal geometries. Thus, although we describe evidence of synsedimentary deformation for only three units, we do not exclude the possibility of similar features in other formations.

Deformation During Deposition of the Chinle Formation

The upper Chinle Formation contains angular discordances of as much as 27° in alcoves B, C, and D on the east of the dome (Fig. 6), in the extreme south, and in Syncline Valley in the north-

Figure 8. Summary map of Upheaval Dome outer structures. Circumferential fold traces are dotted. Transport directions (large black arrows) of hanging walls of extensional faults are dominantly inward in the south and outward in the north.
west. If the truncating surfaces are restored to horizontal, truncated strata dip consistently outward from the dome. This apparent radial symmetry eliminates regional tilting as the cause. Because of poor exposure, we cannot determine the origin of all the observed truncations. If they are primary, the truncated strata may have been foresets deposited by rivers draining outward from a gentle dome. Alternatively, erosion may have cut across gently domed strata. Either way, the truncations suggest doming late in the time of Chinle Formation deposition. These truncations are below the commonly discordant, faulted base of the Wingate Sandstone.

Deformation During Deposition of the Wingate Sandstone

Wingate Internal Diastems. Panorama 9 (Fig. 15, A and B), west of the Holeman Springs alcove, extends from outside the rim monocline to the rim syncline. Here, the Wingate Sandstone thickens from ∼50 m on the west edge of the profile to more than 75 m to the east. No faults offset continuously traceable bedding in the top and bottom of the Wingate Sandstone. Instead, the thickness changes by a combination of onlap against the base of the Wingate strata and truncation beneath a correlatable mid-Wingate surface. From a uniform thickness outside the rim monocline in the west, the Wingate Sandstone gradually thins inward toward the center of the profile. The abrupt deepening of the stratigraphic section beneath the mid-Wingate erosional truncation surface. From the other end of the section, the Wingate Sandstone also thins westward because ∼40 m of lowermost Wingate strata onlap against the top of the Chinle Formation (the J-O unconformity of Pipiringos and O’Sullivan, 1978).

Figure 11C is a schematic reconstruction of the inferred deformation. Stage 1 shows the lower Wingate strata thickening inward (rightward) from point A, which we interpret as the margin of the shifting peripheral sink around the dome. Stage 2 shows a bulge forming in the lower Wingate strata over the flexed margin of the sink. The uplifted crest of the bulge between points C and D is then eroded. Truncations on the eastern (inward) limb of the eroded bulge are not visible in this panorama, but are exposed farther east in the Holeman Springs alcove. Stage 3 shows deposition of the upper Wingate Sandstone across the erosional surface.

Wingate Sandstone Growth Folds. Wingate Sandstone cliffs ring the depression eroded into the center of Upheaval Dome. In these cliffs, the basal Wingate Sandstone contact is deformed into a train of prominent, mostly upright folds (Fig. 12), as noted by others (Shoemaker, 1954; Fiero, 1958; Mattox, 1968; Shoemaker and Herkenhoff, 1983, 1984). They are best exposed on the northeast and southwest walls of the interior depression (Figs. 6 and 8). Fiero (1958) asserted that the fold axes parallel the dominant joint system, and that slip on closely spaced joint planes caused the folding, whereas other workers reported radial axes (Shoemaker, 1954; Shoemaker and Herkenhoff, 1983, 1984) and a lack of shattering in the folded sandstones (Mattox, 1968, Plate 4, Fig. 2). From the limited exposure in the third dimension and their distribution around most of the inner cliffs except for Upheaval Canyon, we conclude that these folds trend radially and probably plunge outward.

The folds seem to have formed by circumferential shortening of the basal Wingate Sandstone (see section on Inner Contractional Systems). Spacing between the antiforms generally ranges from 150 to 190 m. Given a typical Wingate Sandstone undeformed thickness of about 100 m, the wavelength to thickness ratio of these folds is far smaller than values observed elsewhere in nature, theory, or experiment for a vast variety of layer and matrix properties (reviewed by Price and Cosgrove, 1990). Accordingly, it is improbable that the Wingate Sandstone buckled as a single layer of massive, lithified sandstone.

Further evidence corroborates the unusual folding behavior of the Wingate Sandstone. The top contact of the Wingate Sandstone is also folded, but not in harmony with the bottom contact. The folds visible within the formation are also disharmonic with regard to the top and bottom contacts.

In the northeast wall of the interior depression are the two best-exposed radial folds deforming the base of the Wingate Sandstone. There, lower Wingate strata thin upward over the antiforms and thicken above the adjacent synforms, indicative of growth folds (Fig. 12).

These data suggest that folding began during Wingate Sandstone deposition, when the sands were unlithified. Kriens et al. (1997, p. 23) concluded that local deformation of the Wingate Sandstone may have been due to “the presence of fluids and/or a low degree of lithification,” resembling “soft-sediment slides.”

Deformation During Deposition of the Kayenta Formation

Basal Kayenta Channels. Detachment faults (described in the section on Outer Extensional Systems) transect or follow much of the Wingate-Kayenta formation contact, which creates an irregular, wavy surface. However, this contact is also wavy because Kayenta formation fluvial sand channels to 5–6 m deep were eroded into the top of the Wingate back erg dunes and interdunes. Away from each channel, the sand packages thin, pinch out, and grade into shale drapes above adjoining paleohighs. These large channels and paleohighs are well exposed in panoramas 9 (Fig. 11) and 12 (Fig. 14). In panorama 9, the upper Wingate contact is fairly smooth outside the rim monocline of Upheaval Dome but deeply channelized inside the monocline, indicating that channeling was enhanced by increased fluvial gradients related to deepening of the rim syncline at the start of deposition of the Kayenta Formation.

Kayenta Formation Internal Diastems and Inferred Shifting Rim Synclines. Repeated and variable tilting is indicated by bounding surfaces at the base of and within the Kayenta Formation in spurs south of Upheaval Canyon near the present axis of the rim syncline (panoramas 12–14; Figs. 13 and 14). These surfaces divide the Kayenta Formation into lower, middle, and upper packages.

The lowest truncation surface, EB0, is the erosional base of the Kayenta Formation referred to in the preceding section. The truncation surface indicates that upper Wingate strata were tilted inward before they were obliquely planed off as
lower Kayenta strata began to accumulate (panorama 14 and Fig. 16, early Kayenta). The next-higher diastem, the intra-Kayenta EB1 (panorama 13), also cuts downsection outward. The EB1 truncation surface is the base of an erosional channel complex and is marked by a channel sandstone. This sense of truncation for both the EB0 and EB1 surfaces suggests that subsidence was localized inboard (eastward) of the end of panorama 13 during deposition of the lower Kayenta Formation (Fig. 10, mid–early Kayenta).

The upper truncation surface (EB2, panorama 14 and Fig. 10, mid-Kayenta) cuts downsection inward, opposite to the truncation sense of EB0 and EB1. The EB2 surface is exposed in several ridges on both sides of Upheaval Canyon and is marked by a pale, upward-finining sandy bar that toplaps meter-scale foresets. The EB2 surface is the preserved erosional base of an upper Kayenta Formation channel-fill complex overlain by a channel sandstone. This sense of truncation for both the EB0 and EB1 surfaces suggests that subsidence was localized inboard (eastward) of the end of panorama 13 during deposition of the lower Kayenta Formation (Fig. 10, mid–early Kayenta).

The simplest explanation for these shifting locations is that the rim syncline migrated as Upheaval Dome evolved over a lengthy period (Fig. 10). These shifting depocenters are typical of salt tectonics, where lateral salt flow and sedimentary accommodation space are intimately linked.

**Kayenta Growth Faults.** Incomplete evidence suggests that many of the normal faults offsetting Wingate and Kayenta strata (described in the next section) may be the age of the Kayenta Formation. Several faults die out upward into the Kayenta Formation, and faults offsetting the Navajo Sandstone base are rare (we saw only one, at the west end of Syncline Butte). This scarcity is partly because many Kayenta faults are cut by the present-day erosional surface before reaching the Navajo Sandstone. However, in the few places that Navajo Sandstone erosional remnants still rest across faulted strata (e.g., north side of alcove B), the well-bedded Navajo basal strata are unfaulted. Another explanation for the upward termination of faults within the Kayenta Formation is that the faults could dissipate upward among many small slip surfaces within the Kayenta strata. However, in widespread areas where the Kayenta Formation is well exposed, we see no evidence for such upward splaying of faults. Instead, the Kayenta faults die out upward with an abruptness typical of growth faults. For example, stratigraphic separations in faults at the base of the Kayenta Formation are as follows: 30 m of separation dying out 20 m above (panorama 14); 25 m of separation dying out 20 m above (panorama 12). This upward decrease of throw is accommodated by 25–30 m of stratigraphic thickening of the lower Kayenta Formation in the hanging wall of the fault. We have not correlated meter-scale individual packages across faults to confirm thickening by growth faulting, but the impression of syndepositional faulting on several panoramas is striking.

**OUTER EXTENSIONAL SYSTEMS**

McKnight (1940) and Fiero (1958) both described major thickness variations in the Wingate Sandstone and Kayenta Formation within the rim syncline of Upheaval Dome. Some variations are produced by the stratigraphic variations described here. However, as noted by Shoemaker and Herkenhoff (1984), most thinning is due to slip on ramp-flat extensional faults surrounding the dome. All these circumferential faults are exposed only inside the trace of the rim monocline, and so are inferred to be related to the formation of Upheaval Dome. Figures 14, 17, and 19 illustrate the structural style of these faults (panoramas 4 and 5 in Fig. 17).

Three-dimensional exposures reveal the following characteristics. The faults are either simple listric faults or a series of ramps and flats. Even the ramps are low-angle faults, cutting bedding at a mean apparent angle of ~13° and ranging from 9° to 25° (standard deviation). Very locally, however, ramp dips are near vertical over short segments. The flats form detachments mostly at the base of the Kayenta Formation or Wingate Sandstone. Extensional ramps between these two levels are responsible for thinning the Wingate Sandstone (panoramas 2, 4, 5, 6, 11, and 14 in Figs. 14 and 17). Less commonly, ramps thin the Kayenta Formation as well (panorama 3.
Figure 11. (A) Panorama 9 traced from photographs of Holeman Spring alcove and adjoining exposures farther west on the south side of Upheaval Dome. Panorama location and view direction are shown in Figure 6. (C) Schematic reconstruction of synsedimentary deformation of the Wingate Sandstone in panorama 9, exaggerated vertically by 2x.

Fig. 17). In addition, local flats are common within the Kayenta Formation and rare in the middle Wingate Sandstone. Measurements from photographs of oblique sections through exposed faults offsetting the base of the Kayenta Formation provide rough separations for the largest fault in each panorama. For the outward-verging faults, the mean stratigraphic separation is 35 ± 15 m, and the mean apparent slip is 120 ± 55 m (standard deviation). For the inward-verging faults, the mean stratigraphic separation is 25 ± 11 m, and the mean apparent slip is 98 ± 24 m.

What was the effect of these faults on tectonic transport? Shoemaker and Herkenhoff’s (1984) schematic section portrays inward-dipping listric faults linking with outward-dipping thrust systems in the core of the dome (Fig. 5A). That linkage would transport rock inward to the core of the dome.

Our mapping confirms the existence of the inward-dipping extensional fault systems but reveals that they are only half of the extensional picture. As summarized in Figure 8, an equal number of extensional faults dip outward. As a group, their abundance, lengths, and stratigraphic separations are similar to the inward-dipping faults. The outward-dipping faults cannot be linked with the inner thrust faults in the manner advocated by Shoemaker and Herkenhoff (1983, 1984). Most normal faults in the northern half of...
Figure 11. (B) Photograph of a similar view to that in A; on the far right is the eastern portal of the alcove.

Figure 12. Northward view of radial growth folds in the lower Wingate Sandstone in the northeast cliffs of the inner depression. The lowermost Wingate strata are isopachous and are interpreted to be prekinematic. Above here, strata thin over the antiform and thicken in the synform, indicating growth of the fold early during deposition of the Wingate Sandstone. The growth-wedge taper is extreme (~15°) on the right limb of the antiform but much less on the left limb; we interpret this as an initially asymmetric fold verging to the right. After a period of stability, indicated by overlying isopachous units, the fold was tightened further into a symmetric fold late in Wingate Sandstone deposition.

Figure 13. Photograph southwest across Upheaval Canyon showing truncation surfaces of variable dip within the Kayenta Formation. The view superimposes one spur (panorama 14) on another (panorama 12) immediately to the southwest. Compare with Figures 14 and 17. Navajo Sandstone on Syncline Butte forms the foremost skyline, behind which are flat-lying strata outside the rim monocline and, just visible, the snow-capped peaks of the Henry Mountains laccoliths.
Figure 14. Panoramas (Pan) traced from photographs of outward-verging extensional fault systems encircling Upheaval Dome. Panorama locations and view directions are shown in Figure 6. The view directions of panoramas 2 and 13 have been reversed ("mirrored") from the actual view so that the outward direction from the dome center is consistent throughout the figure. EB—erosional base of fluvial channel complex; PH—paleohigh draped by Kayenta shale that grades laterally into channel sandstones filling an erosional scour in the top of the Wingate Sandstone. C1 through C5 are channels. Scales are approximate because of perspective.
the dome transported rock outward, whereas most normal faults in the southern half transported rock inward. This is true whether the faults are exposed inside or outside the trace of the present rim syncline.

INNER CONTRACTIONAL SYSTEMS

Contractional structures dominate the center of Upheaval Dome (Fig. 7). Shoemaker and Herkenhoff (1984) inferred “convergent displacement” of rocks. We agree and recognize both radial and circumferential shortening, which was volumetrically balanced by vertical extension. This bulk constriction is expressed by a different structural style in each formation, described in the following in order of increasing proximity to the dome’s center.

Kayenta Fold-and-Thrust Belt

As noted by Shoemaker and Herkenhoff (1984), stratigraphic repetition due to thrusting accounts for the anomalously thick outcrop belt of the Kayenta Formation (Figs. 6, 15, and 19). The Kayenta Formation appears to be folded and faulted everywhere in its outcrop belt between the inner Navajo Sandstone and Wingate Sandstone cliffs. As in the outer extensional systems, lithologic variations in the fluvially deposited Kayenta Formation caused faults to form ramps and flats. The typically lenticular depositional units resemble the anastomosing fault-bounded bodies, making faults difficult to recognize. However, the details of these structures are spectacularly exposed where Upheaval Canyon cuts a radial section (Fig. 19). From photogeology we infer that this exposed section typifies deformation elsewhere in the contracted Kayenta Formation.

In Upheaval Canyon, ramp-flat thrust faults in the Kayenta Formation form a thrust duplex. The floor thrust of the duplex detached along the lower Kayenta Formation contact; the roof thrust (poorly exposed and conjectural) is near the top of the formation (Figs. 15 and 19). Fault spacing decreases and folding associated with the faulting increases inward. Some thrust faults show normal separation over parts of their trajectories, particularly those that continue downward into the Wingate Sandstone near the rim syncline (Fig. 19B, center), suggesting that the lower parts of the faults had multiple displacement histories.

The thrust duplex in the Kayenta Formation appears to accommodate much more shortening than in the underlying Wingate and overlying...
Navajo Sandstones. That anomaly is explicable if the duplex formed mainly by shear due to flexural slip between the adjoining massive sandstones as they folded. Tanner (1992) described smaller versions of such duplexes, which formed on the limbs of larger chevron folds (Fig. 19B, inset); his duplexes have smooth roofs, no hanging-wall anticlines above each link thrust, and relatively small fault offsets. The roof and floor thrusts may both continue beyond the flexural-slip duplex. This type of duplex evolves where thrust propagation was resisted by facies or thickness changes, or by transfer zones between faults propagating on different movement horizons (Cruikshank et al., 1991). Thus, the Kayenta thrust duplex may be caused as much by upward flexure of the layered succession as by inward contraction.

Wingate Structures

Both radially and circumferentially trending folds have been mapped in the Wingate Sandstone cliffs facing the central depression. The radially trending antiforms distort the basal Wingate Sandstone contact (Figs. 12 and 20) and indicate circumferential shortening. Most intervening radial synforms have been eroded back to the same encircling cliff as the radial antiforms and are partly hidden by talus (Figs. 8 and 20B). A few radial synforms are less eroded and retain a complex three-dimensional curvature. For brevity, we informally refer to these doubly curved synformal radial lobes as “dog tongues” (name suggested by Rudy Kopf, 1992, personal commun.).

The dog tongues preserve the lowest and most inward exposures of the Wingate Sandstone (Figs. 8 and 15). The most complete dog tongue is in the northeast corner of the Wingate Sandstone cliffs. Synformal Wingate strata there dip inward to levels far below the contact with the Chinle Formation on either side of the lobe. The radial axis of the dog tongue forms a trough bordered by radial antiforms. Farther inward, the same Wingate strata reverse steeply upward along a circumferential fold axis, like the upward-curled tip of a tongue (Fig. 20C).

Wingate strata in the tip of the best-exposed dog tongue appear to onlap the basal Wingate Sandstone contact (Fig. 20C). The basal Wingate Sandstone contact in the dog tongues is also discordant to Chinle Formation bedding (Fig. 20C) and to a bedding-parallel cleavage in folded Chinle Formation siltstone and shale. The contact is typically marked by rubble. We interpret this doubly disor-
dant contact as a salt weld (see reconstruction section following). Just below the folds, the Chinle Formation appears to be relatively undeformed, but exposures are poor in quality.

At the upper, outer end of the dog tongues, exposed upper Wingate strata are deformed into upright, nearly isoclinal folds that trend circumferentially (Fig. 20C) and are cut by steep reverse faults. Such folds are well exposed on the eastern side of the central depression near the inner edge of Wingate Sandstone exposures (Figs. 20B and 21). These folds do not appear to affect the sporadically exposed basal Wingate Sandstone contact. Dips in much of the lower Wingate Sandstone and upper Chinle Formation are typically
much less than the subvertical orientations observed in the upper Wingate Sandstone. As with the radial antiforms and synforms described here, it is difficult to envision a well-lithified Wingate Sandstone folding internally in this extreme, strongly discordant manner.

Compared with the intensely faulted Kayenta Formation, few visible faults cut the underlying Wingate Sandstone. The Wingate faults strike radially and dip steeply (Fig. 8). They tend to cut through the radial antiforms and along the boundaries of the dog tongues. The radial faults can be traced outward into the Kayenta Formation, where they commonly curve into oblique or circumferential orientations.

Deformation along the inner Wingate Sandstone cliffs thus indicates both radial and circumferential shortening induced by radially inward movement. Farther inward, the circumferential shortening in the older exposed units dominates the strain, as described in the following.

Chinle Deformation in Central Depression

Most of the Chinle Formation in the inner deformation crops out on inward-facing slopes below the Wingate Sandstone cliffs (Fig. 6). The slopes are largely covered with talus exposing only small windows of the Chinle Formation. The resistant Moss Back Member (basal Chinle) and Black Ledge (mid-Chinle) sandy conglomerates crop out as ledges typically segmented by thrusts and reverse faults. Because most of the Chinle Formation shales are weathered or covered, their internal structure is poorly known. However, structural variation increases toward the center of the interior depression from the relatively uniform outward dips below the Wingate Sandstone cliffs (Fig. 7). The innermost outcrops of the Chinle Formation are folded and faulted similarly to the underlying Moenkopi Formation.

Central Moenkopi Formation Constriction

The Moenkopi Formation occupies most of the dome’s core. Structures are expressed well in bare, rugged terrane by variations in color and lithology (Fig. 7). The Moenkopi Formation in the central uplift was radially and circumferentially shortened. A linear cross section (Fig. 15) captures structures with circumferential strikes, whereas a subcircular section (Fig. 16) crosses subradial strikes. Attitudes vary greatly over short distances, and structures tend to be irregular and discontinuous. The Moenkopi Formation outcrops can be divided into two sectors having different structural styles: converging radial thrusts in the southwest half, and more circumferentially oriented folds and thrusts in the northeast half.

The southwestern zone of steep radial thrusts has the most regular structure of the interior depression. The hanging walls moved in a counterclockwise direction and imbricated the clockwise-dipping Moenkopi strata (Figs. 7 and 16). We liken that movement to the closing of the leaves of a camera diaphragm, where circumferential shortening increases inward. No marker lines are available to determine the strike component of slip on these thrusts. The left-lateral separation may have been derived all or in part from dip slip. Two of these thrusts continue outward as steep faults cutting upward through the Wingate Sandstone. Toward the center, the thrusts merge, die out, lose definition where parallel lower Moenkopi strata are on both sides, or continue as clastic dikes.

The regular radial thrusts in the southwest grade into highly variable structures in the northeastern half of the interior depression. Structures show more local variation, including small folds, short faults, and abrupt attitude changes that result in complex, extremely detailed outcrop patterns rather than the radial stripes exposed to the southeast (Fig. 22). Thrusts vary in strike and vergence. Folds are common and rarely cylindrical, varying from conical to irregular, and generally persist less than 100 m.

Although the structural pattern in the northeast defies simple characterization, the overall strain remains constrictional, as shown by subhorizontal radial and circumferential shortening and subvertical extension indicated by the presence of the central uplift. Crowding from inward movement of the rocks caused the constriction. The complexity and intensity of the central deformation, which has obscured large-scale synsedimentary structures, preclude detailed reconstruction of the inner deformation history.

Dome Center and Clastic Dikes

Clastic dikes are abundant in the center of Upheaval Dome. The dikes are composed of clean white sandstone, presumably derived from the underlying White Rim Sandstone of the Cutler Group. Other authors have described the White Rim outcrops as coherently emplaced blocks (McKnight, 1940; Mattox, 1968). However, the main lenticular dikes anastomose, branch into veins, and are discordant with country rock. All these features indicate that the dikes are intrusive, as inferred by Fiero (1958), Shoemaker and Herkenhoff (1984), and Kriens et al. (1997). In places, the sandstone is laminated but is generally massive. The dike thickness is generally less than 15 m but as much as 30 m. Lengths are typically less than 70 m, but the long dike complex in the center extends more than 400 m. In addition, more-isolated clastic quartzose dikes of unknown source are exposed as far out as the outer part of the thrust duplex in the southern wall of Upheaval Canyon. Some clastic dikes are sourced by the Moss Back Member conglomerate (D. Bice, 1997, personal commun.).

We infer that some of these steep dikes were emplaced along faults. In some places, faults visibly connect with the ends of the dikes. Elsewhere, the same rock type is on either side of the dike such that an aligned fault would be obscure (Fig. 7). Most dikes intrude the lower Moenkopi Formation, but extend upward into the middle and upper Moenkopi Formation in their northern outcrops. Quartz cementation makes the dikes much more resistant than the surrounding rocks, and they form towering spires and irregular walls in the center of Upheaval Dome.

The microstructure of the clastic dikes is described and discussed in Part 3 (Data Repository item 9891) but can be summarized as follows. Our nine thin sections contained abundant mi-

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![Figure 17. (Continued).](image-url)
Sandstone in exposures of the Cutler Group else-
where. That possibility cannot be excluded be-
cause of the similar appearance of the Organ
Rock and lower Moenkopi shales. However, if
the Organ Rock Member shale were present, we
would expect to see much of the overlying
White Rim Sandstone—an exceptionally promi-
nent and resistant marker—in place rather than
as discordant dikes.

**SUMMARY OF EVIDENCE FOR IMPACT VERSUS PINCH-OFF**

Shoemaker and Herkenhoff (1984) proposed
that a meteorite impact near the end of Cretaceous
or in Paleogene time excavated a transient crater
1.3 to 1.4 km deep. That became instantly modi-
fied by gravity to a final diameter of 8 to 9 km,
forming Upheaval Dome. Evidence they cited to
support that hypothesis included the circular dim-
pled shape, inward-verging listric normal faults
near the periphery, inward-verging thrust faults
near the center, folds plunging radially outward
from the center, crushed quartz grains in clastic
dikes, and geophysical anomalies. They thought
that erosion removed 1–2 km thickness of the up-
per part of the crater. Kriens et al. (1997) revised
these estimates by proposing impact within the
last few million years and a smaller modified
crater. Kriens et al. (1997, p. 20 and 26) used a
crater diameter of 5 km to calculate the rise of
the central uplift, and advocated a modified transient
crater diameter “close to . . . the walls of the pres-
ent topographic crater,” which is only 2 km wide.
The current central depression of Upheaval Dome
was thought to be entirely erosional in origin by

Table 1 summarizes the evidence for or against
meteoritic impact and diapiric pinch-off at Up-
heaval Dome. A full discussion of each criterion
to explain our evaluation of the evidence can be
found in Part 3 (see footnote 1). Despite the fact
that Upheaval Dome is far better exposed than
any terrestrial impact crater, we consider that
the evidence for impact there is sparse and equivocal.
Part 3 contests the evidence for shatter cones,
planar deformation structures in clastic dikes, and
ejecta breccia. Kriens et al. (1997, p. 28) con-
cluded that the most diagnostic evidence for im-
 pact (planar deformation features and shatter
cones) were “not well developed.” The scarcity
of features diagnostic of impact in Upheaval
Dome might be ascribed to too much or too little
erosion. However, the many apparently missing
features would cover the complete range of shock
zonation and depths. Thus, it seems implausible
that only a few contestable features have been
found in a superbly exposed, high-relief structure
containing abundant thick sandstones.

In contrast, a wide range of structures (Table 1)
attests to the gradual growth of Upheaval Dome
as a salt structure. The strongest argument for di-
apirism is the stratigraphic evidence indicating
protracted growth of Upheaval Dome over at
least 20 m.y., which is incompatible with hyper-
velocity impact.

**VOLUME IMBALANCE INDICATES SALT LOSS AND PRIMARY THICKNESS CHANGES**

The pinch-off and impact hypotheses can be
tested in two ways by comparing selected rock
volumes in Upheaval Dome. This section sum-
marizes the data presented, together with the
methodology and assumptions, in Part 2 (see
footnote 1).

First, we examined the variation in elevation of
the base Wingate Sandstone horizon relative to its
regional elevation. That variation includes the de-
pressed rim syncline and the elevated central
mound (the center of which is eroded). The vol-
ume of rock depressed below the base Wingate
Sandstone regional datum is 0.74 km³, compared
with only 0.29 km³ to 0.33 km³ above the regional
datum. This volumetric mismatch of 220% to
260% can only be plausibly explained by the loss
of 0.45 km³ to 0.41 km³ salt from Upheaval

<table>
<thead>
<tr>
<th>TABLE 1. EVIDENCE FOR PINCH-OFF AND IMPACT HYPOTHESES</th>
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<tr>
<td>Observation</td>
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<tr>
<td>Circularly</td>
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<td>Central uplift</td>
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<td>Clastic dikes</td>
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<td>Crushed quartz grains</td>
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<td>Inner constrictional zone</td>
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<tr>
<td>Outer extensional zone</td>
</tr>
<tr>
<td>Radial flaps (dog tongues)</td>
</tr>
<tr>
<td>Presence of underlying salt</td>
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<tr>
<td>Gravity and magnetic anomalies</td>
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<tr>
<td>Contiguous anticline</td>
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<td>Nearby salt structures</td>
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<tr>
<td>Rim syncline</td>
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<tr>
<td>Rim monocline</td>
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<tr>
<td>Growth folds</td>
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<td>Growth faults</td>
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<tr>
<td>Shifting rim syndilines</td>
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<tr>
<td>Truncations and channeling</td>
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<tr>
<td>Onlap</td>
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<tr>
<td>Multiple fracturing and cementation</td>
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<td>Steep zones</td>
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<td>Outward-verging extension</td>
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<td>Volume imbalance</td>
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<tr>
<td>Shatter cones</td>
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<tr>
<td>Planar microstructures in quartz</td>
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<tr>
<td>Ejecta breccia</td>
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<tr>
<td>Salt below rim syncline</td>
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<tr>
<td>Lack of salt at the surface</td>
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<tr>
<td>Lack of nearby piercement diapirs</td>
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<tr>
<td>Lack of meteoric material</td>
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<td>Lack of melt</td>
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<td>Lack of in-situ breccia</td>
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<tr>
<td>Lack of shock-metamorphic minerals</td>
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<tr>
<td>Lack of outer fault terracing</td>
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<td>Lack of overturned peripheral flap</td>
</tr>
</tbody>
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Dome since the Chinle Formation was deposited. Impact would allow lateral flow of Paradox salt but would entail no loss of salt volume because the salt was not exposed to dissolution. Conversely, the pinch-off hypothesis requires a considerable loss of salt as the emergent diapir and glaciers dissolved. The gross volumetric imbalance therefore supports diapirism and is incompatible with impact.

**SALT-TECTONIC HYPOTHESIS: A RECONSTRUCTION**

We now attempt to reconstruct the evolution of Upheaval Dome by diapiric pinch-off. Figure 18 shows a seismic example with some similarities to the diapiric structure that we envisage. The pinched-off stem is marked by a vertical secondary salt weld. An erosional section through the necked stem would expose strata steepening inward to form a central uplift, above which the subhorizontal tertiary salt weld represents a salt glacier largely evacuated of salt by the overburden load. The former salt glacier here is strongly asymmetric because the Gulf of Mexico has an extensive slope. In contrast, we envisage a symmetric salt diapir and glacier above Upheaval Dome, now eroded off.

**Initiation of Diapirism**

Published subsurface data are lacking, except for one well, so the deep structure and early evolution are highly speculative. The sparse and ambiguous evidence for what initiated the inferred diapirism can be accommodated in two hypotheses for the structural evolution: (1) salt tectonics alone, or (2) initiation by impact followed by salt tectonics.

Our hypothesis is illustrated in Figure 23. Geophysical anomalies indicate basement uplift or dense rocks below the Paradox salt (see footnote 1). One possibility is that emplacement of an igneous intrusion into the salt initiated salt upwelling by arching the overburden and softening the salt by adding heat and water. Alternatively, an irregular configuration of basement fault scarps generated by Pennsylvanian to Permian extension might have obstructed southwestward flow of salt, squeezed ahead of prograding sediments. Any such obstruction would favor local upwelling of salt (Ge et al., 1997). Upwelling and local stretching of overburden draped above the tilted corner of a basement fault block might initiate a diapir that evolved into a passive stock during continued sedimentation.

The following history (Fig. 23) combines the most internally consistent interpretation of available data with mechanically reasonable processes. The restoration cannot be area balanced because the circular dome did not undergo plane strain: inward-moving rocks increased the cross-sectional area, whereas outward-moving rocks decreased the area. Thus, the restoration had to be schematic and was carried out as follows. (1) To emphasize the strains, we ignored compaction. (2) Individual faults were omitted, but progressive thickening and thinning by strain is schematically portrayed. (3) Strata were unfolded by vertical shear. (4) The cross section was pinned at both ends, so that the overall length remained constant. (5) The diapir diameter approximates the value estimated for the time of Chinle Formation deposition in Part 2 (see footnote 1).

**Stage 1: End of Pennsylvanian Time**

By the end of Honaker Trail Formation deposition (stage 1), we envisage an emergent, passive stock surrounded by a gentle rim syncline. In general, crests of passive stocks are periodically buried but continually break through their veneer of overburden to remain close to the depositional surface.

**Stage 2: End of Chinle Formation Deposition**

At this stage, we envision that the stock was still emergent. The gradually thickening overburden would have increased the pressure on the salt source layer, causing the salt to flow at increasing rates up the emergent stock. The climate was relatively wet, so much of the salt probably dissolved as fast as it emerged. However, enough salt survived that the stock began to extrude as a salt glacier, forming a flange that overhung surrounding strata (for detailed discussions of this type of salt tectonics, see Fletcher et al., 1995; Talbot, 1995;
Figure 19. (A) Photograph and (B) broader interpreted panorama 15 (Pan—traced from photographs) of the Kayenta Formation thrust duplex and the abrupt transition into the adjoining extensional system farther west (left). Both views are northward across Upheaval Canyon; the dome center is to the right. Note the steepened deformation front of the duplex (extreme right). See Figures 14 or 15 for stratigraphic explanation; one (or more) of the Kayenta Formation EB units is stippled. Scale varies greatly because of perspective, but the Wingate Sandstone (black) is about 80–100 m thick. Inset shows a similar but smaller duplex produced by folding in southwest England (after Tanner, 1992).

Figure 20. Views of dog tongues. Wingate strata in the lobes are ~60 m below the adjoining elevation of their basal contact. (A) Photograph looking radially outward at the northeast cliffs of the inner depression.

Figure 21. Northward view of several circumferential, upright, tight to isoclinal folds in upper Wingate and lower Kayenta strata. Note the abrupt transition between the Wingate-Kayenta steep zone in the twin spires (center) and open-folded Kayenta Formation on the right. At the extreme left are the northern cliffs of the inner depression.
Figure 19. (Continued).

Figure 20. (Continued). (B) to (E) idealized diagrams showing (B) radial fold traces on a Wingate horizon, where the central trace defines the dog tongue flanked by two higher antiforms (cf. Fig. 12); (C) radial cross section, and (D–E) schematic restoration of the dog tongue, showing its inferred origin as a flap overlying a flange of glacial salt that was subsequently removed to form a salt weld.
Talbot and Alavi, 1996). Chinle Formation strata currently truncated against the basal Wingate Sandstone contact in the dog tongues may have originally terminated against the overhanging salt face (Figs. 20E and 23).

If primary, the angular truncations sporadically exposed in the upper Chinle Formation suggest that local tilting took place (e.g., alcoves B, C, and D). The apparently radial tilts of these truncations suggest that they were related to growth of a rim syncline around a dome. The degree of faulting during deposition of the Chinle Formation is unknown; some of the faults exposed today in the core of the dome may have formed during the growth phase of the inferred diapir and were reactivated during pinch-off.

Stages 3 and 4: End of Wingate Sandstone to End of Kayenta Formation Deposition

Onlap, truncation, and channeling in Wingate and Kayenta strata indicate shifting axes of subsidence and deposition. We deduce shifts in the sites of active salt withdrawal, an erratic pattern typical of growing salt domes (e.g., Seni and Jackson, 1983). Many of the inward-dipping and outward-dipping Kayenta growth faults may have initiated near the hinge lines of these localized depotrughes. The dog tongues are thought to represent upper Wingate strata onlapping emergent salt, the presence of which prevented lower Wingate strata from accumulating locally (Figs. 20 and 23). This emergent salt would have been an early aborted phase of glacial extrusion before the main extrusion during Navajo Sandstone deposition. Growth folds in the lower Wingate Sandstone suggest that the central part of the dome had begun to fold radially, indicating that the flanks of the dome were beginning to slide inward. This process accelerated during final pinch-off later.

Stage 5: End of Navajo Sandstone Deposition

Salt Extrusion. We infer that glacial salt spread fastest during deposition of the Navajo Sandstone. The inferred glacier reached a width of at least 3 km. Collision between the outward-spreading glacier and inward-gliding strata is recorded by the zone of abrupt steepening in the Navajo Sandstone (Figs. 8 and 23). The steep zone suggests that the outer edge of the extruding salt extended well outside the present limits of the central depression during Navajo Sandstone deposition (Figs. 6 and 23).

Diapir Pinch-Off. Two lines of evidence suggest—but do not prove—that the most plausible time of pinch-off was during the extrusion of salt that occurred during Navajo Sandstone deposition. (1) Most of the constrictional deformation in the Wingate Sandstone appears to have occurred before it was lithified, indicating that pinch-off could not have occurred too late in the geologic history. The radial growth folds indicate that wall rocks may have begun to move radially inward during early deposition of the Wingate Sandstone. (2) Physical models (Jackson et al., 1997; B. C. Vendeville, 1996, personal commun.) indicate that where salt is forced rapidly up and out of a feeder stock closing by lateral compression, salt extrudes vigorously during stem pinch-off.

The outward migration of steep zones (Fig. 8) suggests that the dome originally widened upward. Pinch-off of the feeder produced different results at different structural levels. For example, in the narrowest part of the diapir (Moenkopi Formation and Cutler Group), pinch-off continued...
Stage 6: Post-Navajo
Base salt – geometry unknown

Stage 5: End Navajo
Base salt omitted

Stage 4: End Kayenta
Regional tilt
Outward-verging extension
Contraction
Inward-verging extension

Stage 3: End Wingate
Salt flange
Future dog tongue
Eroded bulge

Stage 2: End Chinle
Salt flange

Stage 1: End Pennsylvanian
Passive diapir
Rim syncline

Figure 23. Schematic reconstruction of the salt-tectonic evolution of Upheaval Dome.
until rocks from opposite sides met at the center, completely closing the feeder during deposition of the Navajo Sandstone. That resulted in the highly evolved constrictional features preserved in the Moenkopi Formation in the central depression.

The White Rim Sandstone clastic dikes, which could have been emplaced along Moenkopi Formation faults during the earlier growth phase of the dome, would have been rotated, distorted, and possibly reactivated during pinch-off.

The soft-sediment response of the Wingate Sandstone in the dog tongues also suggests that the weight of Wingate strata overburden expelled salt from the early, abortive Chinle Formation salt flanges at that time. Expulsion produced a salt weld, juxtaposing suprasalt Wingate strata against subsalt Chinle strata (Figs. 20 and 23). The unlithified dog tongues were then strongly folded during constrictional pinch-off.

Closing of the diapir stem at Cutler Group and Moenkopi Formation levels would have ended diapiric pinch-off. Higher stratigraphic units originally adjoined wider parts of the overhanging diapir, so they did not completely close off before inward gliding stopped (Fig. 23). Thus, higher stratigraphic units never developed structures such as in the Moenkopi Formation because they never moved close enough to the center to produce the requisite amount of strain. Pinch-off ended late during, or after, deposition of the Navajo Sandstone. The base of the Navajo Sandstone is strongly folded by the rim syncline, which is unlikely to have continued deepening after pinch-off ended. The upper contact of the Navajo Sandstone is no longer preserved.

Examples of allochthonous salt sheets overlying pinched-off stems are common in the Gulf of Mexico (Wyatt et al., 1993; Diegel et al., 1995; Fletcher et al., 1995; Rowan, 1995) and Red Sea (Heaton et al., 1995) and have also been observed by us on proprietary seismic data from the North Sea, northwest Germany, and west Africa. However, the mechanism for diapiric pinch-off is unknown. Pinch-off is the core of our hypothesis for Upheaval Dome, yet we are unsure how it occurs (Fig. 5B).

We do not regard this gap in knowledge as evidence against the pinch-off hypothesis for the following reasons. (1) The lack of detailed mechanical knowledge reflects a gap in salt tectonics theory generally rather than an anomaly specific to Upheaval Dome. (2) Three-dimensional seismic data indicate that the process occurs whether or not we understand it. (3) The limited physical modeling of dome pinch-off in brittle country rock (Lemon, 1985) reproduces several of the main features observed at Upheaval Dome: a rim syncline that deepened markedly when pinch-off began, a central uplift with subvertical strata below the pinched-off diapir, peripheral normal faults, and numerous unconformities. However, because gravity gliding was not permitted in Lemon’s (1985) physical models, no central zone of contraction formed in them.

How do inward-moving strata overcome the outward pressure exerted by the salt stem? The most likely mechanism for pinch-off is gravity gliding of the country rocks down an inward-dipping top salt surface into the weaker rock composing the salt diapir (Fig. 5B). The process would be enhanced by salt dissolution. The diapir pinches off as a result of the partially buttressing toe of a radially inward-dipping spreading system. Gravity spreading is driven by the loss of gravity potential, which results in an excess volume of rock depressed below regional elevation compared with the volume of rock raised above regional elevation. Part 2 (see footnote 1) examines the implication of volume imbalances for understanding the process of pinch-off, for explaining primary thickening, and for estimating the diameter of the vanished diapir.

Stage 6: Present Day

Pinch-off would have ended salt rise, which allowed Cretaceous strata to bury the allochthonous salt sheet. During Tertiary time, Upheaval Dome was uplifted and eroded. Because soluble salt was more easily removed than the surrounding rocks, the present topographic surface may partly reflect the original shape of the overhanging lower contact of the allochthonous salt. However, outside the mesa surrounding Upheaval Dome, erosion was greater and all strata were deeply dissected.

CONCLUSIONS

1. We propose that pinch-off of a salt diapir best explains the sedimentary and deformational structures at Upheaval Dome. Evidence summarized here suggests that inward constriction of overburden strata accompanied necking of the stem of a broadly overhanging salt extrusion, subsequently removed by erosion.

2. In the rim syncline, the Wingate Sandstone and overlying Kayenta Formation are greatly thinned by circumferential extensional faults. These low-angle normal faults are either simple listric faults or series of ramps and flats. Most exposed faults slipped during or after deposition of the Kayenta Formation. Normal fault vergence shows a strong dichotomy: in the north, most faults transported rock outward from the dome, whereas in the south, most faults transported rock inward.

3. In the core of the dome, the bulk strain is constrictional, and includes both radial and circumferential shortening. Radial shortening dominates the periphery of the dome core, but circumferential shortening predominates farther inward. In the western sector of the dome’s core, the hanging walls of radial thrusts moved counterclockwise and imbricated the persistently clockwise-dipping Moenkopi Formation, like the closing of a camera’s leaf diaphragm. Elsewhere in the dome core, strain is highly variable, but is constrictional overall.

4. In the core of the dome, many steeply dipping clastic dikes link with the radial fault systems. The lenticular sandstone dikes form a continuous network more than 400 m long, presumably derived from the underlying White Rim Sandstone. Their intrinsic origin is indicated by branching, anastomosing veins and discordance with country rock.

5. Arguments have been advanced for the formation of Upheaval Dome by either meteoritic impact or salt tectonic processes. We think that evidence favoring meteoritic impact is sparse, being restricted to a lag deposit of cobbles, part of two weakly developed shatter cones, and undocumented planar structures in quartz. The paucity of typical impact features in Upheaval Dome might be ascribed to too much or too little erosion. However, these missing features cover the full range of shock zonation and depths. It seems implausible that so few have been found in a structure that is better exposed in three dimensions than any terrestrial impact structure.

6. We think that the weight of the evidence strongly favors salt tectonics. Evidence favoring diapiric pinch-off includes a lack of the following features associated with hypervelocity impact: meteoritic material, melt, in situ breccia, shock-metamorphic minerals, outer fault terracing, and overturned peripheral flap. Conversely, the presence of the following features at Upheaval Dome all favor diapirism: rim syncline, rim monoclone, steep zones in inner limb of rim syncline, outward-verging extension, radial synformal flaps (dog tongues), underlying mother salt and nearby salt structures, multiple episodes of microfracturing and sealing, and postemplacement microfracturing in the clastic dikes. Volume imbalance between uplifted and depressed regions of the dome indicates massive salt loss of at least 0.4 km³ after deposition of the Chinle Formation.

The most compelling evidence for diapirism in Upheaval Dome is the wide range of synsedimentary structures spatially restricted to this circular structure. They include angular truncations, onlap surfaces, channeling, growth faults, growth folds, shale diapirs, and shifting rim synclines. These signs of synsedimentary deformation localized around the dome indicate gradual growth over at least 20 m.y. and exclude the possibility of geologically instantaneous deformation required by hypervelocity impact.
7. Many details of the structural evolution are speculative because subsurface data are sparse. We envisage that a passive stock less than 1 km in diameter and surrounded by a gentle rim syncline emerged in Pennsylvania time. The salt remained at or near the surface throughout Permain, Triassic, and Early Jurassic time. Increasing sedimentary load on the Paradox source layer below increased the flow rate of salt up the diapir, eventually resulting in extrusion of salt glaciers near the end of Chine Formation deposition and during Navajo Sandstone deposition, when a salt glacier spread to an estimated diameter of 3 km. 8. Growth folds in the lower Wingate Sandstone indicate that the walls of the diapir began to move inward during Early Jurassic time. We think that this inward movement was produced by gravity spreading along an inward-dipping top salt surface. Spreading culminated in complete pinch-off of the diapir during deposition of the Navajo Sandstone. pinch-off produced constrictional strain and structural thickening in the center of the dome, with concurrent extension around the dome periphery.

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