IMPACTITES AT THE UPHEAVAL DOME STRUCTURE, UTAH? Christian Koeberl[1], J. B. Plescia[2], Chris L. Hayward[3], and Wolf Uwe Reimold[3]. [1]Institute of Geochemistry, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria (christian.koeberl@univie.ac.at); [2]U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, U.S.A.; [3]Department of Geology, University of the Witwatersrand, Johannesburg 2050, South Africa.

Summary Upheaval Dome, in Canyonlands National Park, Utah, USA, is a unique structure on the Colorado Plateau. It has been interpreted as an impact structure [1-6] or as a pinched-off salt diapir [7]. A lag deposit of subrounded quartzose fragments was found [5] in a ring depression near the eastern margin of the structure and, based on vesicularity and apparent flow structure, the fragments were interpreted as impactites. Our petrographic studies (including cathodoluminescence microscopy) show no indication of a high-temperature history and are in agreement with a slow, low-temperature formation of the quartz nodules. Compositionally, the lag deposit samples are almost pure SiO_2, which show no chemical similarity to any of the possible target rocks (e.g., Navajo Sandstone), from which they should have formed by melting if they were impactites. Instead, the samples have relatively high contents of elements that indicate fluid interaction (e.g., hydrothermal growth), such as As, Sb, Ba, and U, and show positive Ce anomalies. Thus, we interpret the "lag deposit samples" as normal low-temperature (hydrothermally-grown?) quartz that show no indication of being impact-derived.

Introduction and Geological Background The about 5 km diameter Upheaval Dome structure is a spectacular landmark in the Canyonlands National Park in Utah and is located at 38° 26' N and 109° 54' W. Its origin has been the subject of controversy for considerable time. Recently, field work has been done on the structure, yet two distinctly different models for the formation of the structure are still discussed in the literature: impact origin (e.g., [1 - 5]) and salt diapirism [7]. We assume here that most of the arguments outlined in [1 - 5] substantiated the impact origin of the structure. The Dome consists of a deeply eroded sequence of complexely faulted and uplifted rocks that is surrounded by a structurally depressed ring syncline that also shows complex faulting. The rocks exposed at Upheaval Dome include the Triassic Moenkopi and Chinle Formations and the Wingate Sandstone, followed by the Kayenta Formation, and Triassic and Jurassic Navajo Sandstone [1, 2]. The strongly deformed center of the structure is bound by listric faults [1,2,5]. At the center of the structure, basement rocks are uplifted above their normal stratigraphic position.

The deformation and fault style at Upheaval Dome is incompatible with the stresses that occur in rocks above salt diapirs, and the structural features are similar to those observed at the Sierra Madera (Texas) or Gosses Bluff (Australia) impact structures. Kriens et al. [5] provided additional field geological and structural data to support the formation of the Upheaval Dome structure by impact. Huntoon and Shoemaker [3] suggested that the impact event may have caused the formation of the near-by Roberts Rift, and Alvarez et al. [6] speculated that impact-induced local seismicity may have been responsible for disturbances in near-by country rocks. Samples from the thin Moenkopi Formation siltstone beds are strongly shattered and contain shatter cones-like features [3, 5]. Shoemaker and Herkenhoff [2] noted a few grains with lamellar deformations, but it is not clear if those are impact-diagnostic planar deformation features (PDFs).

Lag Deposit Samples ("Impactites") Small quartzose nodules were reported by [5] and interpreted as impactites, supposedly providing further evidence for an impact origin of Upheaval Dome. The nodules were observed on the eastern side of the structure, within the ring syncline. The nodules occur within soil and windblown sand overlying the Navajo Sandstone and scattered across bare Navajo surfaces. The nodules are variable in size (typically 5 to 15 cm), have spherical to angular shapes, and generally are coated with thin desert varnish. Many of the samples contain numerous vugs considered to be vesicles. These samples were interpreted by [1, 2] to have once been molten ejecta that was ballistically emplaced, thus imparting an aerodynamic shape. The presence of crystalline quartz was interpreted to be the result of devitrification. However, the geologic context of the samples, the composition of crystalline low-temperature quartz, the orientation of vugs with respect to the margins, and the overall texture of some samples raised serious questions regarding their origin as impactites. In an effort to resolve the origin of these features, we performed petrological and geochemical analyses and a search for additional material, and potential sources for chert nodules in the geologic section were examined.

Additional nodules were found on the southeastern side of Upheaval Dome, in the same geologic context as those on the eastern side (within the ring syncline; in soil and windblown sand and on bare Navajo outcrop). In this second location the frequency of nodules is considerably greater than on the eastern side, and the morphology is more diverse (greater size range, variable varnishing, many angular fragments). This observation indicates that the material is more widespread around the Upheaval Dome structure than previously suspected. Additional material may occur elsewhere around the structure - a detailed search has not been conducted. Chert nodules occur in two stratigraphic positions above the Navajo Sandstone: directly above the Navajo in the Chert Pebble Unconformity [8] and in the Summerville Formation [9] (which is now considered part of the Morrison Formation). The Navajo Sandstone and the Summerville Formation, in the area around Upheaval Dome, were both examined. Chert in the Summerville Formation is of variable color, occurs in thin lenses, is unvarnished and angular with sizes much smaller than the dimensions of the nodules observed at Upheaval Dome. The material from the Summerville Formation is not considered to be a source. The Chert Pebble Unconformity at the top of the Navajo produces abundant chert pebbles of variable size, with and without desert varnish, of both angular and rounded shapes. Extensive deposits of chert pebbles were found in the areas surrounding Upheaval Dome both weathering out of the Chert Pebble Unconformity and as a lag across the upper Navajo surface. Chert derived from the Chert Pebble Unconformity is considered to be the source for the nodules observed at Upheaval Dome. The chert's origin has been suggested to be limestone pans or bed in the top part of the Navajo Sandstone, a section which was eroded leaving a lag of chert prior to the deposition of the overlying Entrada Sandstone [8].

Petrography The lag deposit samples are quartzose rocks with only minor amounts of other minerals. Two of three samples investigated in detail are crudely banded. The bands are defined by grain-size contrast of the quartz, between larger, original grains and finer-grained, newly-formed grains. The samples have suffered recrystallization in a dynamic environment with the development of strain domains within large, older grains, and breakdown of these grains into subgrains and discreet, less strained, small grains. Subgrain development and recrystallization usually occur around margins, but occasionally also in small areas within the large grains. Small inclusions, probably of chlorite, appear to define an earlier fabric, which may be kinked or folded foliation. A significant proportion of the phyllosilicate grains is crudely parallel to the banding of the samples and may represent growth during the stresses that led to the recrystallization of the quartz. Also present within the rock are needle-like inclusions, possibly of tourmaline. Rutile is not considered to be present because of the low Ti content of the samples. The rocks have been penetrated by veins and areas of intergranular carbonate, which forms anastomosing intergranular veins in a direction approximately parallel to the banding defined by the quartz. In no cases are these veins associated with brecciation of quartz grains. In two samples, there is a dark and extremely fine-grained material, also parallel to banding, within which quartz grain fragments are observed. This may represent hematite coating a joint or fracture surface. No planar deformation lamellae, flow-banding (in contrast to [5]), or evidence of melting were noted. The samples exhibit extremely dull blue cathodoluminescence (CL), which revealed no further details than visible by normal optical observation. This CL is typical of quartz that has undergone metamorphism at moderate temperature and pressure. One yellow-luminescent grain of approximately 30 mm length may represent a zircon grain. However, CL emissions are not diagnostic of mineral type, and this particular grain could not be observed in transmitted light. Petrographic evidence indicates that the samples have suffered normal metamorphic processes at moderate temperatures and pressures and do not show evidence of a high-temperature history.

Geochemistry The major and trace element composition (46 elements) of eight lag deposit samples and representative samples from the target stratigraphy (rock from the Cutler, Moenkopi, Chinle, Wingate, Kayenta, and Navajo Formations) were analyzed by neutron activation analysis (NAA) and X-ray fluorescence (XRF) spectrometry. The country rocks show a range in composition in agreement with the variety of rock types (mainly sandstones with different amounts of carbonate, cf. Table 1), but the lag deposit samples are almost pure silica, with very low contents of most lithophile elements. Siderophile element contents in these samples are very low with one exception - one sample has (compared to other nodules) somewhat elevated Cr and slightly elevated Co and Ni (but not Fe) contents; the sample has also elevated Zn and Sr contents, which argue for introduction by fluids. In comparison to the country rocks, and considering their general depletion in all elements, the lag deposit samples have fairly high As, Se, Br, Sb, Ba, and U contents. Chondrite-normalized rare earth element plots show distinct positive Ce anomalies, which are absent from the country rocks or dike rocks. We interpret these data to be the result of low-temperature fluid interaction and to be in agreement with a hydrothermal formation of these quartzose nodules.

Conclusions Based on our field work and the petrographic and geochemical analyses we conclude that there is no evidence to support the suggestion that the quartzose nodules found at the Upheaval Dome structure represent impactites. Rather, the nodules are simply a lag deposit from the Chert Pebble Unconformity at the top of the Navajo Sandstone.

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References: [1] Shoemaker, E. M., and Herkenhoff, K., 1983, EOS 44, 747. [2] Shoemaker, E. M., and Herkenhoff, K. E., 1984, LPS XV, 778-779. [3] Huntoon, P. W., and Shoemaker, E. M., 1994, GSA Rocky Mountain Section, Field Guide, 23 pp. [4] Louie, J. N., Chavez-Perez, S., and Plank, G., 1995, EOS 76, F337. [5] Kriens, B. J., Shoemaker, E. M., and Herkenhoff, K., 1997, GSA Field Trip Guide, BYU Geology Studies, 42, Part 2, 19-31. [6] Alvarez et al., 1998, Geology 26, 579-582. [7] Jackson, M.P.A., et al. 1998, GSA Bull. 110, 1547-1573. [8] Pipiringos, G. N., and O'Sullivan, R. B., 1975, Four Corners Geol. Soc. Guidebook 1975, 149-156. [9] McKnight, E. T., 1940, U. S. Geol. Survey Bulletin 908, 147 p.

Table 1. Comparison of Compositional Range of "Lag Deposit Samples" ("Impactites") and Country Rocks, Upheaval Dome.

	Lag Deposits		Country Rocks	
	Average	Range	Average	Range
SiO_2	98.92 ± 0.49	97.81 - 99.42	77.67 ± 13.93	57.51 - 94.72
TiO_2	0.01 ± 0.00	0.01 - 0.02	0.51 ± 0.29	0.24 - 1.15
Al_2O_3	0.01 ± 0.00	0.01 - 0.01	5.44 ± 1.89	2.01 - 7.25
Fe_2O_3	0.21 ± 0.40	0.044 - 1.26	1.26 ± 0.67	0.41 - 2.52
MnO	0.02 ± 0.01	0.005 - 0.05	0.06 ± 0.05	0.001 - 0.13
MgO	<0.01	<0.01	1.80 ± 2.12	0.01 - 5.98
CaO	0.32 ± 0.21	0.08 - 0.79	4.36 ± 4.21	0.03 - 11.41
K_2O	0.0092 ± 0.0056	0.0013 - 0.020	2.31 ± 0.84	0.85 - 3.55
P_2O_5	0.02 ± 0.00	0.01 - 0.02	0.10 ± 0.05	0.03 - 0.16
L.O.I.	0.36 ± 0.11	0.26 - 0.54	6.46 ± 5.43	0.74 - 14.73
Total	99.86		99.97	
Na	51 ± 17	34 - 83	1428 ± 1592	232 - 5100
Sc	0.079 ± 0.011	0.06 - 0.09	4.11 ± 2.04	1.28 - 6.51
Cr	5.63 ± 7.79	0.79 - 25.1	30.8 ± 20.6	9.06 - 75.8
Co	0.70 ± 0.16	0.48 - 0.97	4.07 ± 3.17	0.66 - 9.38
Zn	0.9 ± 0.4	0.5 - 1.9	26.6 ± 14.4	11 - 55
Rb	0.6 ± 0.3	0.28 - 1.40	58.3 ± 20.3	21.1 - 93.2
Zr	6 ± 2	3 - 9	509 ± 518	128 - 1740
Cs	0.037 ± 0.011	0.030 - 0.060	2.68 ± 1.44	0.53 - 5.17
Ba	124 ± 113	56 - 420	493 ± 237	226 - 980
La	0.40 ± 0.10	0.24 - 0.53	19.6 ± 13.2	5.03 - 46.2
Hf	0.041 ± 0.017	0.015 - 0.068	16.7 ± 18.6	3.98 - 61.3
Ta	0.0093 ± 0.0043	0.003 - 0.015	0.69 ± 0.59	0.16 - 2.05
Th	0.16 ± 0.03	0.11 - 0.21	6.59 ± 5.37	1.39 - 17.9

Major elements in wt %, trace elements in ppm.