PS Evolution and Origin of Two Large Mud Diapirs within the Wilkins Peak Member of the Green River Formation*

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Abstract

The Greune and Verde mud diapirs, with surface exposures ranging in size from 70 to 90 meters in diameter, are exposed within the Wilkins Peak Member of the Eocene Green River Formation near Flaming Gorge Reservoir, southwest Wyoming. These diapirs are sourced from the lower unit of the Wilkins Peak Member (lower, middle and upper units can be defined based on dominant lithology), and were emplaced into the upper unit of the Wilkins Peak Formation. The structures contain brecciated dolomicritic mudstones with minor amounts of siliciclastic clays, and pervasive quartz veining is present throughout both diapirs. Though heavily disturbed, original bedding can be seen in both localities; either dipping radially towards the margins of the diapir as is dominant at the Greune diapir to the southwest, or titled but near horizontal as is the dominant expression at the smaller Verde diapir in the northeast. At its current surface exposure, the Greune diapir can be seen in contact with several fluvial sand channel bodies within the upper Wilkins Peak strata, and these fluvial sandstones transition from regional, near horizontal dips to steeply dipping beds and bed sets within 50 meters of the diapir. These sands show no signs of brittle deformation, and dip ranges from 20-50° radially away from the center of the diapir to the north, west, and east where sands are observed. These are interpreted here to have been deformed pre-lithication, at or near the surface, by the rising mud diapir, offering an important bound on the timing of diapirism near the end of the early Eocene. Deformation structures such as clastic dikes, brecciation and convoluted bedding have been documented by others at or near this stratigraphic interval in Utah, Wyoming, and Colorado, and these smaller structures have been interpreted as seismites. We suggest that these mud diapirs are a larger-scale expression of this same seismic activity.

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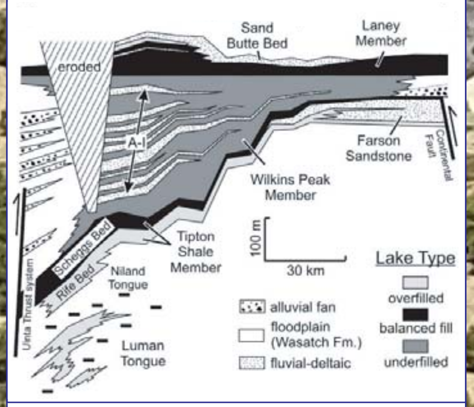
ABSTRACT

The Greune and Verde mud diapirs, with surface exposures ranging in size from 70 to 90 meters in diameter, are exposed within the Wilkins Peak Member of the Eocene Green River Formation near Flaming Gorge Reservoir, southwest Wyoming. These diapirs are sourced from the lower unit of the Wilkins Peak Member (lower, middle and upper units can be defined based on dominant lithology), and were emplaced into the upper unit of the Wilkins Peak Formation. The structures contain brecciated dolomicritic mudstones with minor amounts of siliciclastic clays, and pervasive quartz veining is present throughout both diapirs. Though heavily disturbed, original bedding can be seen in both localities; either dipping radially towards the margins of the diapir as is dominant at the Greune diapir to the southwest, or titled but near horizontal as is the dominant expression at the smaller Verde diapir in the northeast. At its current surface exposure, the Greune diapir can be seen in contact with several fluvial sand channel bodies within the upper Wilkins Peak strata, and these fluvial sandstones transition from regional, near horizontal dips to steeply-dipping beds and bedsets within 50 meters of the diapir. These sands show no signs of brittle deformation, and dip ranges from 20-50° radially away from the center of the diapir to the north, west, and east where sands are observed. These are interpreted here to have been deformed pre-lithification, at or near the surface, by the rising mud diapir, offering an important bound on the timing of diapirism near the end of the early Eocene. Deformation structures such as clastic dikes, brecciation and convoluted bedding have been documented by others at or near this stratigraphic interval in Utah, Wyoming, and Colorado, and these smaller structures have been interpreted as seismites. We suggest that these mud diapirs are a larger-scale expression of this same seismic activity.

Stratigraphy

The Eocene Green River Formation in the area of study is composed of three distinct members: The Tipton Shale, the Wilkins Peak Member, and the Laney Member (Figure 2, Bradley, 1929; Bradley, 1931, Bradley, 1948; Bradley, 1964; Picard and High, 1968; Bradley and Eugster, 1969; Eugster and Hardie, 1975; Desborough, 1978; Dickinson et al, 1988; Carroll and Bohacs, 1999). Lithofacies dominantly represent lacustrine depositional conditions, and this is perhaps one of the most studied ancient lacustrine systems in the world. An abundance of preserved tuff and ash deposits have led to excellent age control within the Green River Formation (Smith et al., 2010), adding confidence to regional correlations and mapping efforts. The Tipton Shale is composed of oil shales and marlstone, the Wilkins Peak is characterized by carbonate and evaporitic facies, and the Laney Member contains carbonates, oil shales and volcaniclastics (Surdam and Stanley, 1979; Sullivan, 1985; Pietras and Carroll, 2006; Carroll and Bohacs, 1999).



North to south cross section of the Green River Basin (modified fron Pietras and Carrol, 2006).

Quadcopter drone used for high resolution, multiple perspective aerial photography of the field areas.

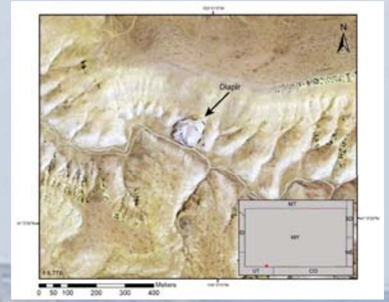
Methods

Several large diapiric structures are presently exposed at the surface in Sweetwater county, Wyoming hear the eastern shore of Flaming Gorge Reservoir. The Greune diapir described here (Figure 3a) was first identified in the field, and subsequent investigation of aerial photos led to the discovery of the smaller Verde diapir to the east. Detailed observations made at the Greune diapir include description of the geometry and internal characteristics of the diapir as well as the surrounding strata and the relationship between the diapir and the host rock. Samples of the diapir were collected for analysis along two cross-sections (Figure 3b), and a scintillometer was used to measure a discrete outcrop gamma ray profile along cross section 1 from east to west (Figure 3b).

High-resolution aerial photography was executed utilizing a DJI Phantom 3 drone. 186 photos were collected at the Greune diapir. XXX aerial photos were collected at the Verde diapir. Aerial images collected at the diapirs were then processed utilizing Agisoft Photoscan software to create high-resolution three-dimensional photogrammetric, and digital elevation models.

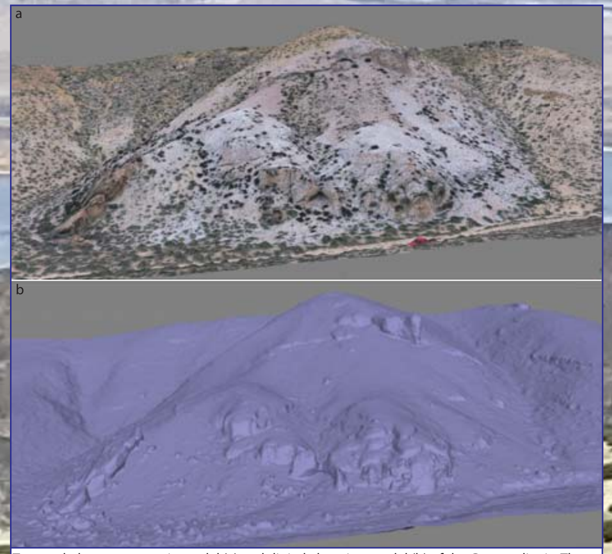
Eleven samples from the Verde diapir (Figure 3b) were analyzed for chemical composition using XRD analysis at Brigham Young University in Provo, Utah. Samples were prepared utilizing an Al2O3 standard, and analysis was performed using the Rigaku MiniFlex 600 benchtop XRD system. XRD data was then evaluated using Rigaku PDXL software.

Additionally, the same sample was analyzed using whole rock pyrolysis + total organic carbon (TOC)/carbonate carbon techniques at Brigham Young University on the Wildcat Technologies HAWK Workstation. A standard Pyrolysis+TOC method was used, where the sample was heated from 300^0 C to 850^0 C at a rate of 25^0 C/minute during the pyrolysis stage, and from 300^0 C to 850^0 C at a rate of 25 ^{0}C/minute during the oxidation stage.



Greune Diapir

- 90x98 meters in diameter.
- Exhibits remnant bedding.
- Contains large carbonate clasts near base.
- Large siliceous diagnetic veins.
- XRD analysis indicates dolomicrite composition.

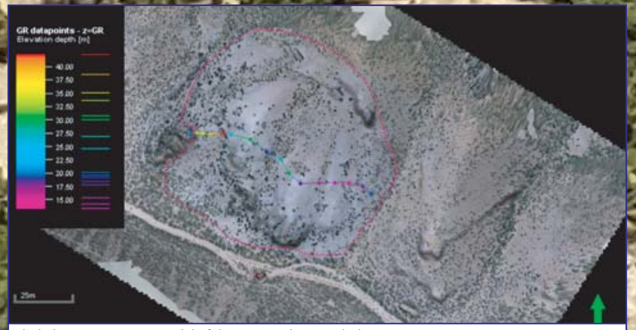


Textured photogrammetric model (a) and digital elevation model (b) of the Greune diapir. The diapir is exposed on the north side of a deep ravine. The dolomitic composition of the diapir creates low cliff outcrops.

Silicious diagenetic veins within the Greune diapir. Diagentic veins are largely concentrated near the eastern edge and trend north to south (top). Thickness of the veins ranges from 2-5 cm.

Preserved bedding in the Greune diapir.

Field photgraph and textured photogrammetric model of deformed strata at the Greune diapir. Fluvial sandstones exposed to the west of the diapir are 2.5 m thick and exhibit plastic, grainflow deformation. The interaction of the Greune diapir with the sandstones of the Wilkins Peak Member offers insight into the timing of emplacement.

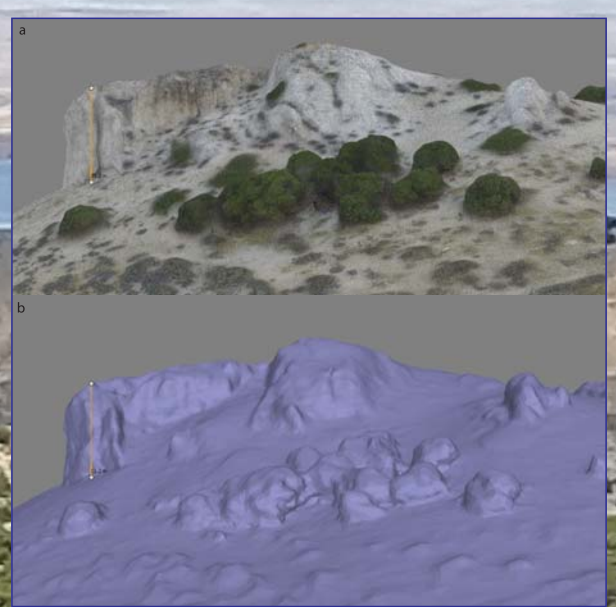


Tiled photogrammetric model of the Greune diapir with discrete outcrop gamma ray measurement line.

Proximal to the Greune diapir in particular, strata of the upper Wilkins Peak Member show evidence of deformation associated with the emplacement of these mud diapirs. Fluvial sandstones are seen in contact with the western, northern, and eastern margins of the Greune diapir, and range from carbonate-cemented, medium-grained sandstones to pebble conglomerates containing rip-up clasts. At each margin, these fluvial packages show an abrupt change in dip within tens of meters of the diapir (Figure 9). Regional dip of the Wilkins Peak Member is near horizontal, but near the diapir these sands dip radially away from the diapir at steep angles, upwards of 50o (Figure 10). Despite the rapid change in dip proximal to the diapir, there is very little brittle deformation – the sands are interpreted to have been deformed plastically, suggesting that they were deformed post-deposition but pre-lithification.

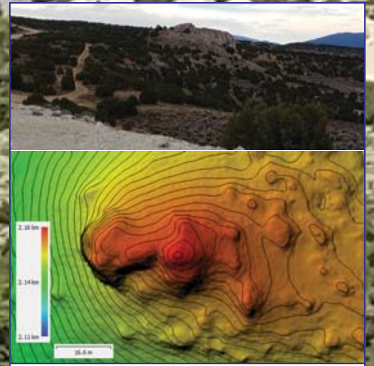
Verde Diapir

- 2.4 miles east of 1st diapir.
- 30x60 meters.
- Prominent remnant bedding.
- Fine siliceous diagentic veins.



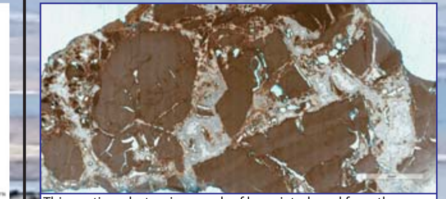
Textured photogrammetric model (a) and digital elevation model (b) of the Verde diapir. The diapir creates a low peak and visible local landmark. Measurement mark is 11.2 meters.

Preserved bedding in the Verde diapir. Bedding within the diapir is more prominent and dips to the north. Diagentic veins within the Verde diapir are also more fine than within the Greune diapir.

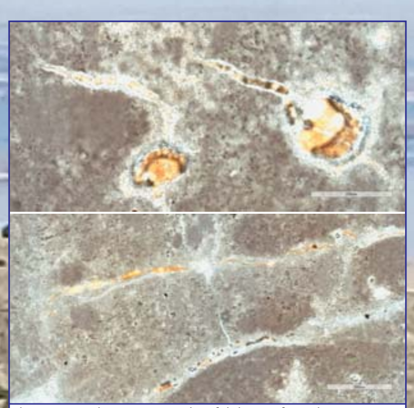


Wide angle photo and contoured digital elevation model of the Verde diapir. The dolomitic composition of the diapir is highly resistant to weathering. Countour interval is 3 meters.

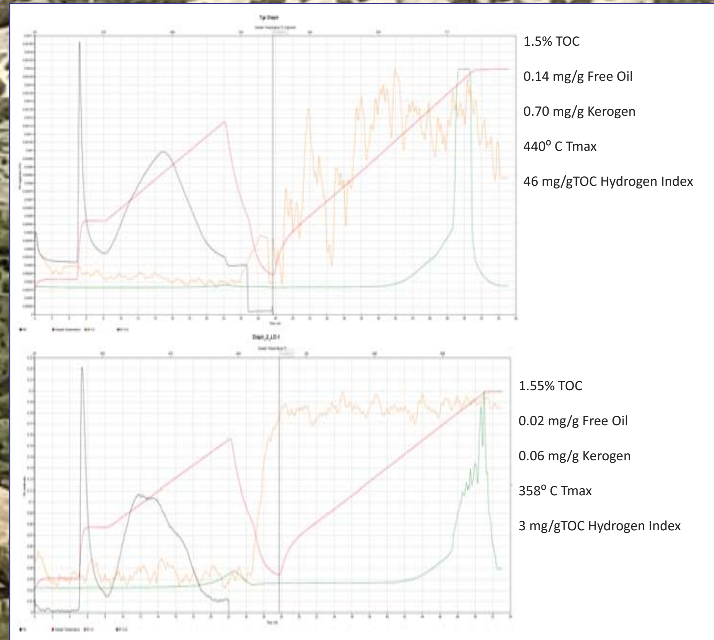
While the timing of the emplacement of the Greune and Verde mud diapirs matches well with the examples given by Toro and Pratt (2015), and Gulliver (2006), the style and scale of deformation is somewhat different. Toro and Pratt identified several examples of brittle deformation within the Bridger Basin nearby, but at a much smaller scale. In the depocenter of the basin, the lower Wilkins Peak reaches a thickness of 400 feet, the middle unit is as thick as 500 feet, and the upper Wilkins Peak is ~300 feet thick (Sullivan, 1985). There are important differences compared to the longer clastic dikes documented by Gulliver as well. Though not at the depocenter, and we likely do not include the full thickness of all three members between the mobilized lower Wilkins Peak and their emplacement within the upper Wilkins Peak strata, the length of the sediment mobilization here is almost certainly much longer than even what is seen in the 100 meter clastic dikes of the Piceance Basin. The long length of mobilization and the brittle, pervasively brecciated nature of these mud diapirs suggests that these soft sediment deformation structures were mobilized from greater depths than the other features discussed here, and that there was a higher relative degree of lithification pre-mobilization in comparison. Part of the higher degree of lithification is attributed to a greater burial depth before mobilization, and part is likely due to the high carbonate concentration within these micro-dolomitic muds. The Greune and Verde diapirs, though attributed to the same seismic activity as the seismites of Toro and Pratt and Gulliver, represent a different style of soft sediment deformation than has been previously documented in this basin.



Thin section photomicrograph of brecciated mud from the Greune diapir.



Thin section photomicrographs of dolomite from the Greune diapir exhibiting kerogen filled fractures and vessicles. Scale bar for upper photo is 200 μm. Scale bare for lower photo is 300 μm.



Whole rock pyrolysis results from samples collected at the Greune (top) and Verde (bottom) diyapirs.

Whole Rock Pyrolysis

Though dominantly composed of dolomicritic mud with varying minor amounts of siliciclastic material, the preserved strata of the diapirs contain varying amounts of organic carbon. Pyrolysis analysis of 27 samples from within the diapirs shows an average Total Organic Carbon (TOC) content of 1.8%, with a maximum of 3.12% within the Greune diapir. These kerogens are Type IV, gas-prone kerogens, which are typical of either terrestrial organic matter or very thermally mature kerogens. T_{max} data, derived from pyrolysis analysis, suggest that these samples are within the mid to late oil zone, suggesting that there has been some thermal maturation of the samples due to burial. This elevated level of preserved organic material correlates well with elevated gamma ray values as acquired with a hand-held scintillometer.

Aknowlegements

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Conclusion

Based on the work of many others (Gulliver, 2007; Smith et al., 2010, Toro and Pratt, 2015, others), seismites are being increasingly recognized within the Greater Green River Basin. These soft sediment deformation features are attributed to late-stage Laramide tectonism near the end of the Wasatchian, a particularly active tectonic period within the early Eocene in this region (Pietras el al., 2003; Pietras and Carroll, 2006). Both brittle and ductile deformation structures have been observed in multiple localities, with small (5 meters and less) brittle and ductile structures within the Bridger Basin and larger (100 meter) fluidized clastic dikes within the Piceance Basin to the south. This deformation is attributed to seismic activity based on the tectonic setting in which they were formed, as well as the fact that they formed in a dominantly lacustrine environment, where quiescent conditions minimize the likelihood of many other external triggers.

The dolomicritic muds within these diapirs have undergone non-fluidized, brittle deformation, and display a larger scale of adjacent deformation than has been previously documented. The amount of sediment displaced in conjunction with each of these diapirs is much larger than the vertically restricted structures of Toro and Pratt (2015), and has a diameter several magnitudes of order greater than what is seen in the narrow, elongate clastic dikes of Gulliver (2007). These are by far the largest single seismic indicators within the basin based on sheer volume of sediment displaced, with a diameter of nearly 100 meters across at the Greune diapir. In both the modern and within the rock record we see evidence of seismicity triggering large mud diapirs, with large seismic events in the modern leading to structures of similar size (Delisle, 2004). The presence of the Greune and Verde diapirs within the Wilkins Peak Member in the southwest Bridger Basin of Wyoming adds further evidence that this area was seismically very active during the later Wasatchian, and suggests that some of these seismic events could have been quite large.

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