HYPOTHETICAL TECTONIC EVOLUTION OF THE LA SAL MOUNTAINS AND THE UNCOMPAHGRE PLATEAU BASED ON UPPER MANTLE TOMOGRAPHY

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Introduction and Purpose of the Project

The La Sal Mountains (Fig. 1) in east-central Utah, contain hypabyssal-cored laccolithic domes that were developed from the magmatic intrusions during the Mid-Tertiary time (Cass et al., 1963, and Ross, 1997). The igneous rocks in the La Sal laccolith are well exposed and identified as Oligocene nosean trachyte (Ross, 1997). Mutschler et al. (1997) describes this intrusion and others in the Colorado Plateau region as "passive hot spots" from upflow upper mantle plumes. East of the La Sal Mountains is the NW-SE trending Uncompahgre Plateau (Fig.2) where WNW- ESE striking left-lateral oblique-slip are the most common faults (Fig. 3), possibly a result of extension along the anticlinal hinge of the Uncompahgre Plateau developed from the Laramide compressional stresses (Fig.6) of the Colorado Plateau (Livaccari, 2007, Livaccari, et al., 2016, and Trumbo, et al., 2016). In both areas, the mineralized fault zones (Fig. 5) identified contain silicified sandstone breccias with veins of fluorite, quartz, amethyst, calcite, alunite/jarosite, pyrite, chalcopyrite, hematite, malachite, azurite, and barite of epithermal origin (Fig. 7). Geochemical analysis of these mineral samples from the faults suggest the hydrothermal fluids were heated by former magmatic bodies in the subsurface (Fig. 8). Magnetic (Fig. 9) and gravity (Fig. 10) anomalies indicate possible mafic to ultramafic intrusive bodies are likely to be located in the upper crust under the Uncompahgre Plateau as shown in Figure 11 (Ross, 1997 and Casillas, 2004). The tectonic developments of these areas are debatable, but we believe the formation processes for both areas are likely to be derived from the rising low shear velocity plume in the upper mantle (Figs. 12 - 14). Evidences can be seen from the upper mantle tomographic data in 2D views (Fig. 13). Therefore, the model shows the existence of low shear velocity plume at 60-720 KM depth (Fig. 14). This indicates the upwelling plume may be responsible for the tectonic and structural development of the LaSal Mountains and Uncompahgre Plateau (Fig. 15).

Figure 1. The La Sal Mountains, near Gateway, Colorado (Photo by the authors).

Figure. 2. Northern Uncompahgre Plateau, Colorado. Unaweep Canyon at left and Ryan Park at right (Photos by the authors).

General Structures and Cross Section of the Grand Mesa Through the La Sal Mountains

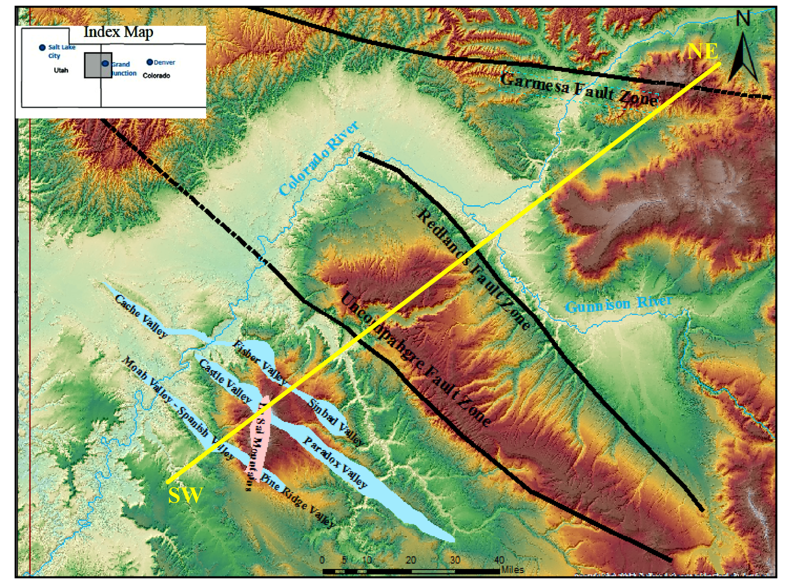

Figure 3. General structure map of the study area. NW-SE trending collapse salt valleys are shown in blue. Cross-section along yellow line is shown in Figure 4 below.

- Folding and faulting plus magmatic intrusions (~1.4 BYA) in Proterozoic sedimentary, igneous, and metamorphic rocks (Hedge, 1968, Case, 1991)
- During Pennsylvanian to Permian Periods, uplift of the Ancestral Uncompahgre from formation of the Ancestral Rocky Mountain Orogeny. Erosion of older rocks on top of the Ancestral Uncompahgre and deposition of sediment into Paradox Basin at southwest and Eagle Basin at northeast. (Condon, 1997, Blakey and Ranney, 2008, Fillmore, 2011)
- Uplift of modern Uncompahgre Plateau in Laramide Orogeny ~70 to 40 Mya (Stone, 1977, Baars 1981, Blankey and Ranney, 2008, Fillmore, 2011, Livaccari, et al., 2016)
- Emplacement of La Sal Mountains intrusives and eruption of San Juan extrusives ~32 to 26 Mya (Ross, 1997, and Fillmore, 2011)
- Continued uplift and increased erosion of sedimentary strata ~10 to 6 Mya (Karlstrom et al., 2015)
- Further exhumation and incision of Unaweep Canyon ~6 to 0.8 Mya (Sinnock, 1981, Aslan et al., 2008, Trumbo, et al., 2016)

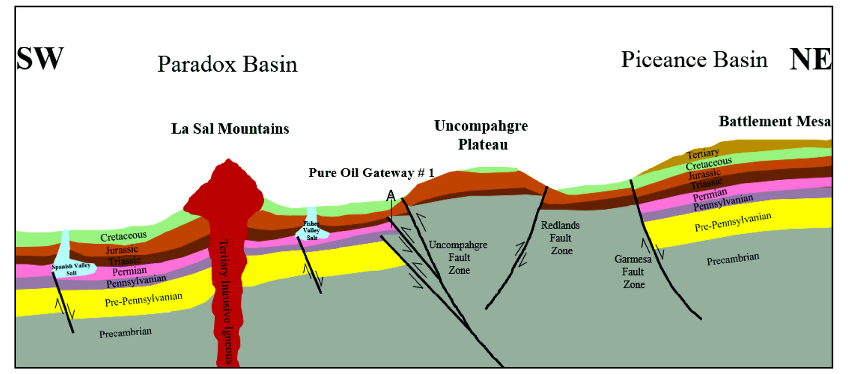

Figure 4. General Cross Section of the area. See yellow line in Figure 3 for location of cross-section.

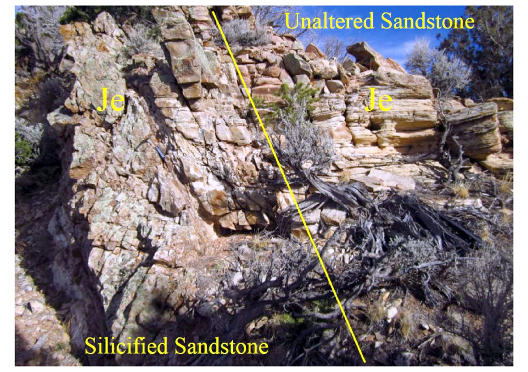

Figure 5. A fault zone in the northwestern Uncompahgre Plateau showing silicified and unsilicified Jurassic Entrada Sandstone. Silicified Entrada Sandstone is related to the result of hydrothermal activity (Photo by the authors).

Structure Map of the Northern Uncompahgre Plateau

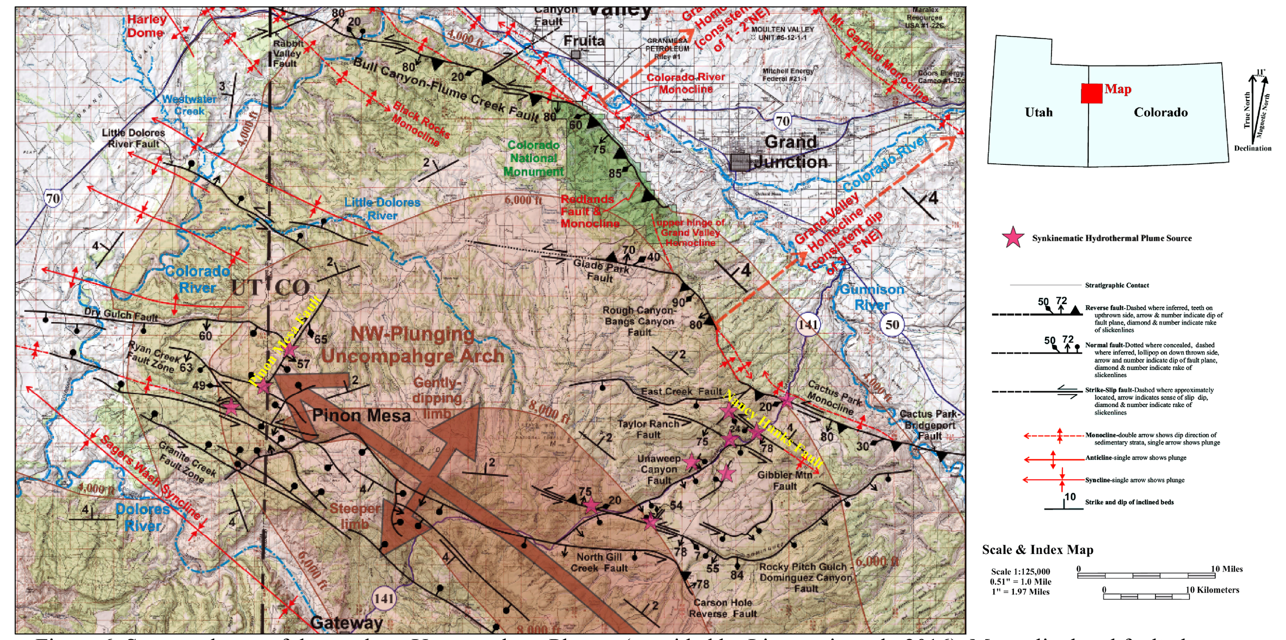

Figure 6. Structural map of the northern Uncompahgre Plateau (provided by Livaccari, et al., 2016). Monoclinal and faulted structures were developed from compressional stress during the Laramide Orogeny.

Mineral and Geochemical Summary

Figure 7. Common minerals found in the fault zones in the Uncompahgre Plateau. From left to right: A) hematite, B) empithermal barite and quartz, C) malachite, D) flourite and amythest (Photos by the authors).

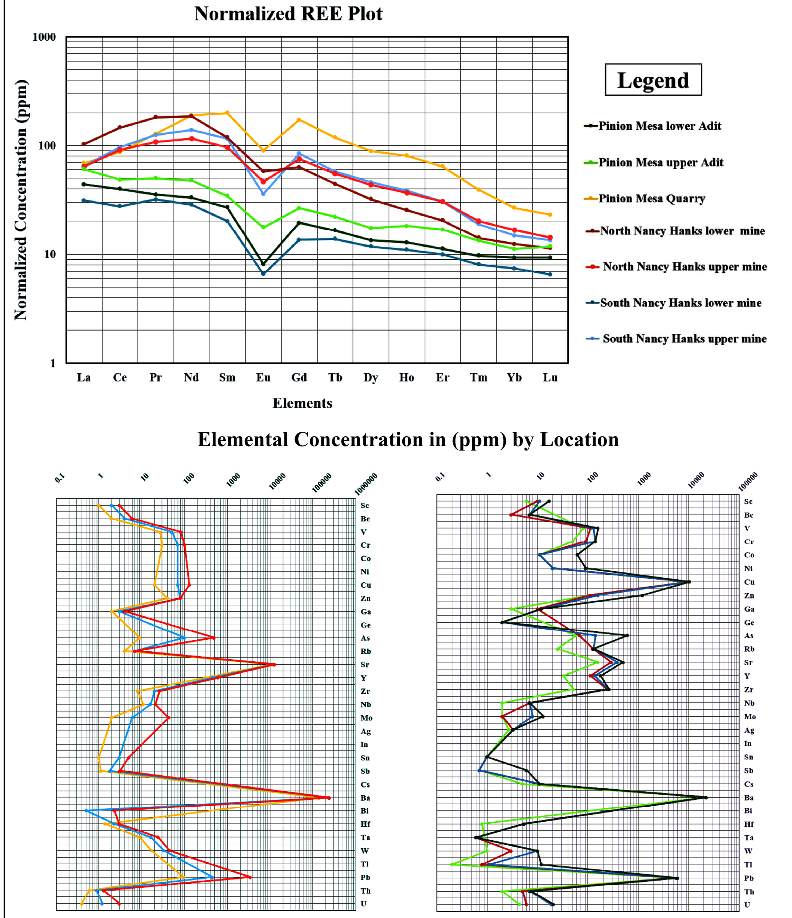

Figure 8. Geochemical analysis of the samples collected from the mineralized zones Pinon Mesa Fault and Nancy Hank Fault (pink stars in Figure 6). Geochemical data and analysis provided by Trumbo, et al., (2016).

Preliminary Geochemical Summary

Multiple samples were gathered from seven mineralized zones along fractures in Unaweep Canyon and Pinon Mesa (Fig. 6). The samples were crushed and micro-milled. A whole rock lithogeochemistry analysis was performed using ICP-OES and ICP-MS at ACTLabs, Canada. REE data returned was then chondrite normalized and plotted (McDonough, 1995). The graphed data points indicate the minerals were derived from an intermediate source rock (Fig. 8). Because samples were taken from vein material they reflect the chemical constituents of the source rock and not that of igneous intrusive heat source. What is of interest is the high concentration of both Cu and Sr in the elemental analysis from Pinon Mesa (Fig 8 bottom). Cu-carbonates are locally sourced from the epithermal systems of the La Sal mountain group. Sr concentrations in the Pinon Mesa area are on the order of ppt, but anomalously low in all other areas. In further analysis, the Sr could be subjected to an isotopic analysis to compare to La Sal group data to determine if the porphyry copper source is related to late mineralization.

Residual Intensity Magnetic Anomaly Map

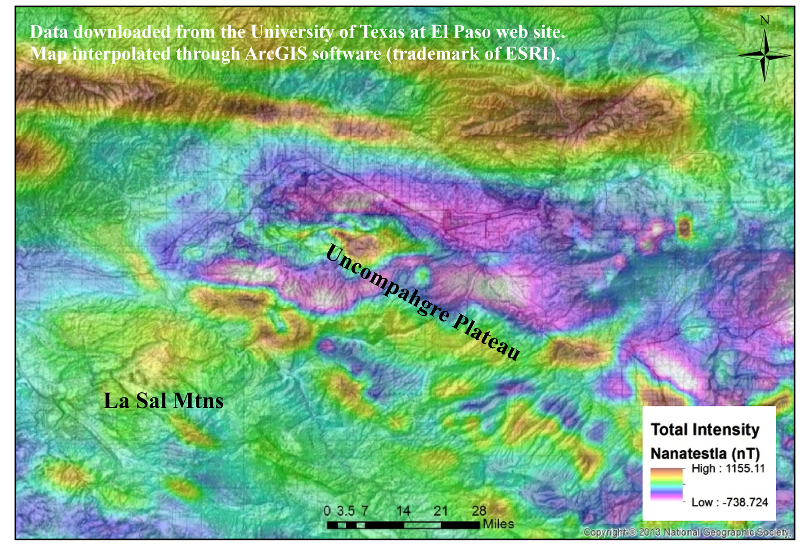

Figure 9. The aerial residual magnetic map shows strong anomalies in the La Sal Mountains and central part of the northwestern Uncompahgre Plateau. These magnetic anomalies indicate magnetic sources in the crust.

Bouguer Gravity Anomaly Map

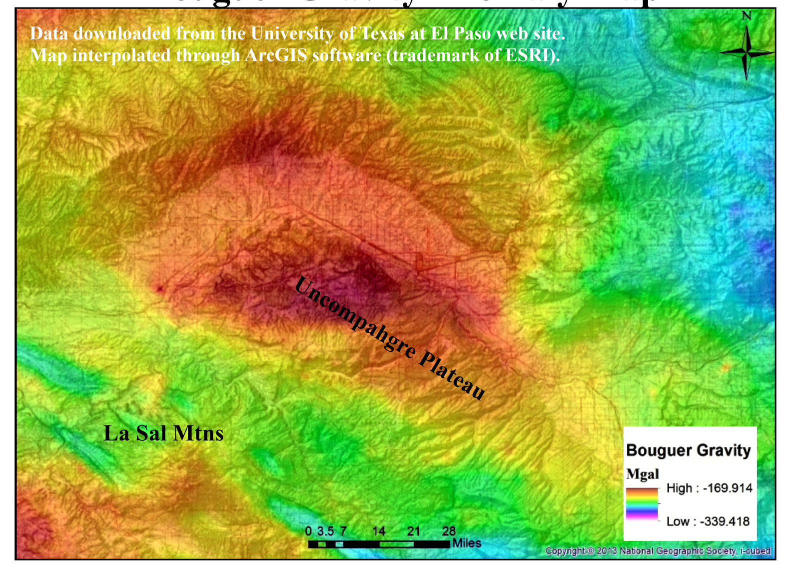

Figure 10. Bouguer Gravity map of the La Sal Mountains and part of the northwestern Uncompahgre Plateau shows areas of gravity highs (>-150 Mgal). These anomalies are likely to be related to high density rocks at depth, possibly mafic types, in the crust (see Fig. 11 below).

Gravity Modeling Profile

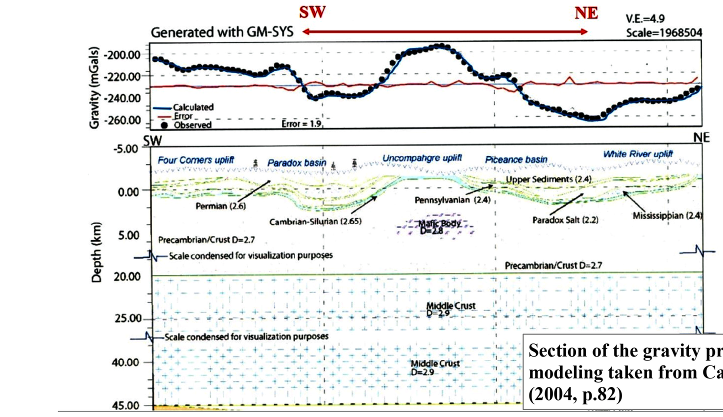

Figure 11. Casillas (2004) creates the geometry of the possible existence of the mafic body in the Uncompahgre Plateau. His result shows the calculated and observered gravity anomalies are nearly compatable for the mafic body with the assummed density of 2.83 gm/cm³ at ~5 KM depth.

Magnetic and Gravity Summary

- Magnetic anomalies indicate possible near surface sources, possibly small to large mafic intrusive plugs at various shapes and depths. They may be peripheral intrusive bodies from larger batholithic magmatism body in central and southwestern Colorado according to Mutschler et al, (1997) and Blankey and Ranney (2008).
- Bouguer gravity anomalies indicate mass addition under the Uncompahgre Plateau, possibly intrusive mafic body.

Upper Mantle Tomography Summary

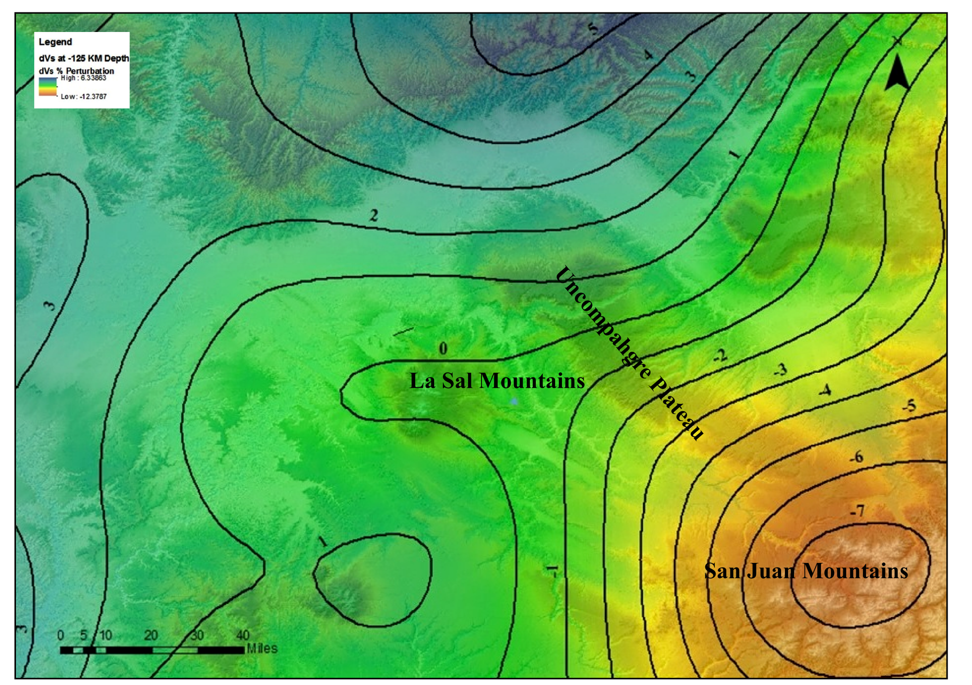

Figure12. dVs % Perturbation at -125 Km depth. Note the extending shear velocity perturbation from the San Juan Mountains.Dr. Brandon Schmandt of University of New Mexico provided Upper Mantle Tomographic data. Spline interpolation and contour lines made through ArcGIS 10.4.)

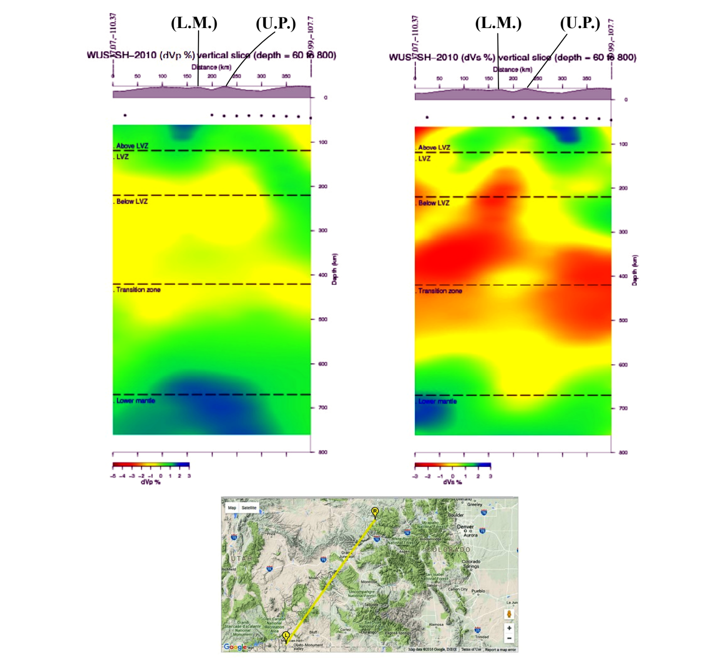

Figure 13. Upper mantle tomography. Note the bulges underneath the La Sal Mountains (L.S) and Uncompahgre Plateau (U.P.), an indication of upwelling low compressional and shear velocity plumes. (Cross-sections from http://ds.iris.edu/ds/products/emc/)

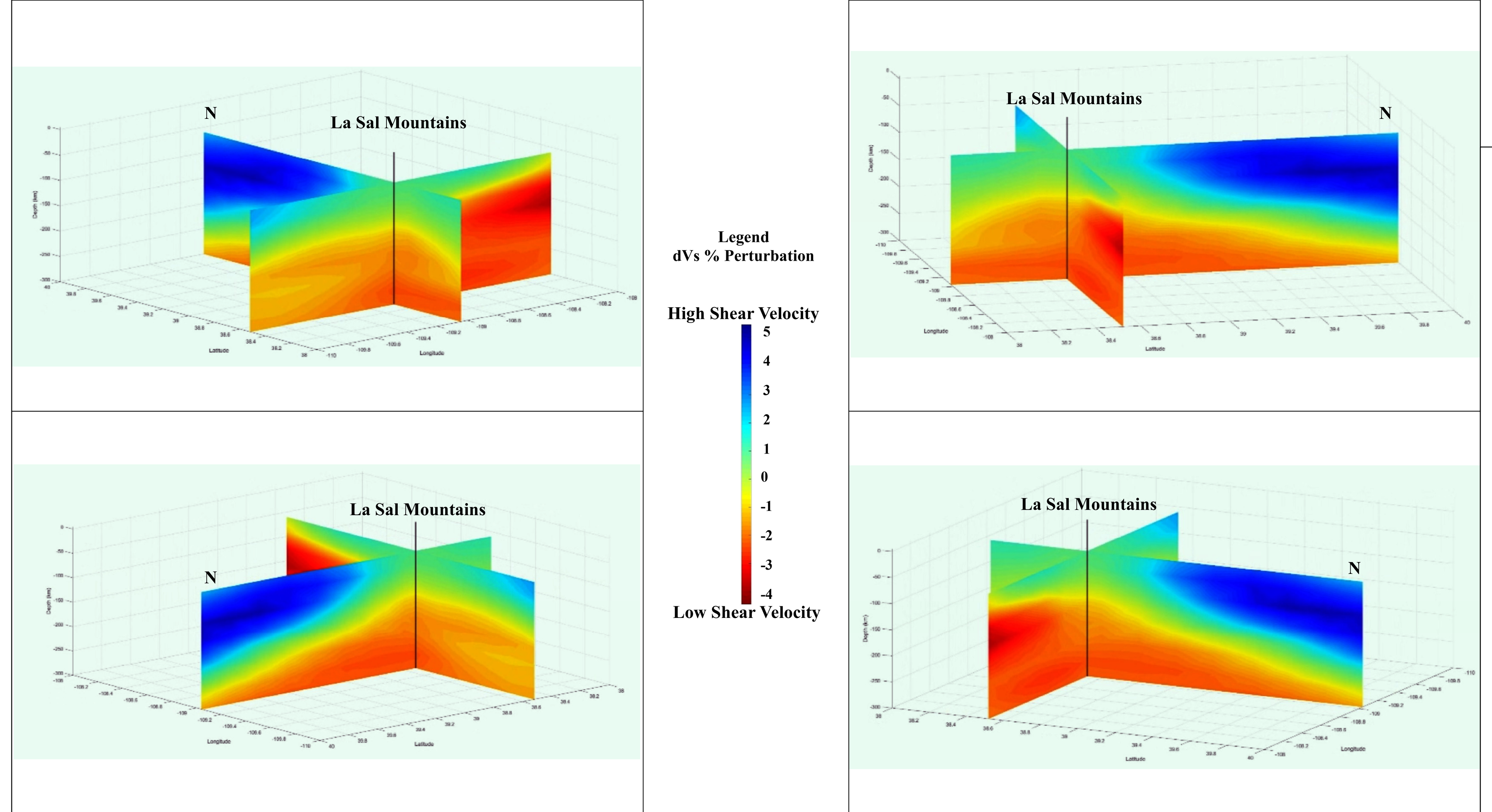

Figure 14. 3D modeling from Matlab rotating at 360°. La Sal Mountains at intersection of E-W and N-S line (109.233° W, 38.483° N). Dr. Brandon Schmandt of University of New Mexico provided Upper Mantle Tomographic data.

- Tomographic maps and 3D model indicate rising shear velocity plume in the mantle under the La Sal Mountains and the Uncompahgre Plateau, likely to be peripheral extension from the San Juan Mountains.
- Timeline is still uncertain for the rising upper mantle plume (Oligocene vs. Late Cenozoic-need more information on the direction of flows of the mantle plumes).

Summary and Timeline

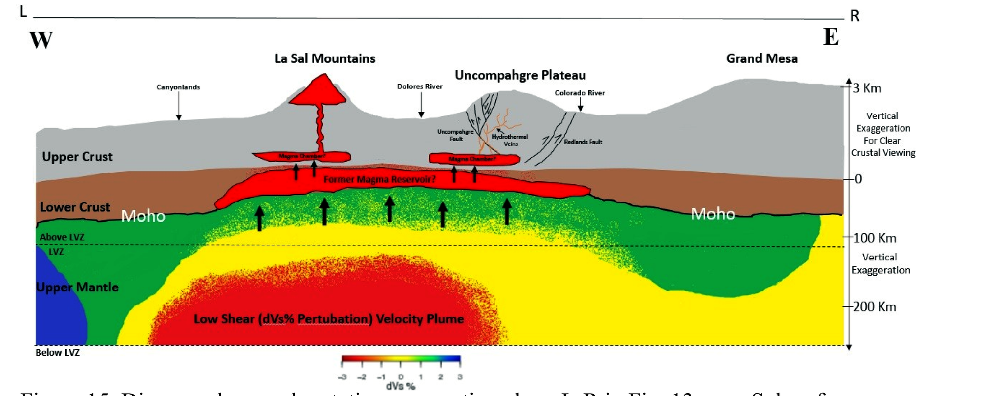

Figure 15. Diagram shows schemtatic cross-section along L-R in Fig. 13 map. Subsurface geology is based on magnetic, gravity, geochemistry, and upper mantle tomography. Salt deposits and sedimentary layers removed for clear viewing. Uncertainties remain due to lack of exposure in surface geology and lack of subsurface data.

- Uplift of modern Uncompahgre Plateau in Laramide Orogeny ~70 to 40 Mya generated by compressional forces related to the collision of the Farralon Plate and North American Plate (Stone, 1977, Baars 1981, Fillmore, 2011, Livaccari, et al., 2016)
- Late Laramide extensional forces due to upwelling of the mantle through the break up of the Farralon Plate in the Aesthenosphere. Major faults reactivated and mineralized (metasomatism) in the uplifted Uncompahgre Plateau forming cataclastic zones of silicified sedimentary beds
- Emplacement of La Sal Mountains intrusives and eruption of San Juan extrusives and the begining of hydrothermal mineralized veins ~32 to 26 Mya (Ross, 1997, Fillmore, 2011)
- Continued uplift and increased erosion of sedimentary strata ~10 to 6 Mya (Karlstrom et al., 2015)
- Late Cenozoic uplift of the Uncompahgre Plateau (Shoemaker, 1956, Cater, 1970, Heyman, 1981, Sinnock, 1983, and Ross, 1997)

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