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2D & 3D Interpretation of Magnetic Survey Data in the Presence of Reversely Magnetized Rocks

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ABSTRACT

Magnetic survey data is often used as part of a geothermal exploration program to better understand geologic structure, hydrothermal alteration, and depth-to-bedrock. However, geologic interpretation of magnetic survey data can be complicated by the presence of reversely magnetized rocks. Tertiary volcanic rocks (which are generally magnetic) are abundant in Nevada and the rest of the Great Basin where geothermal exploration takes place. In addition, many magnetic reversals have occurred during the Tertiary which means that reversely magnetized volcanic rocks are not rare and their presence likely obscures the geologic interpretation of magnetic survey data at many geothermal prospects, possibly leading to erroneous interpretation. Paleomagnetic analysis is the best tool to determine if a rock outcrop is reversely magnetized or not; however, paleomagnetic data is not commonly available because it requires specialized expertise to acquire. Several other tools and techniques are presented here to help discern whether reversely magnetized rocks may be present in a study area to aid geologic interpretation of magnetic survey data. These include: comparison of magnetic survey data with geologic maps, magnetic susceptibility measurements, radiometric age dating, and analytic signal mapping. Examples of 3D geophysical inversion modelling of magnetic survey data are also presented to outline the challenges and opportunities of modelling reversely magnetized rock bodies in 3D to better characterize their geometry and structure in the subsurface. Specifically, a 3D magnetic inversion modelling technique called Magnetic Vector Inversion is shown to successfully model reversely magnetized rock units at the Argenta Rise study area which is part of the U.S. Department of Energy funded INGENIOUS project.

1. INTRODUCTION

Magnetic survey data is commonly available and is used often in conjunction with other geoscience tools for geothermal exploration. Some advantages of magnetic survey data are that it is one of the lowest cost geophysical datasets to acquire and it is already available in the public domain at a regional-scale (or better) for many areas of interest in the Great Basin. Magnetic survey data is commonly interpreted in map view to infer geologic structures (e.g. faults), demagnetized areas potentially caused by geologically-recent geothermal activity, and to generate depth-to-basement maps in sediment-filled basins.

However, there is a persistent problem related to the geologic interpretation of magnetic survey data that is often ignored: magnetic reversals. Throughout geologic history, changes in the dynamo in the Earth's core have caused the planet's magnetic field to switch polarity (i.e. the north magnetic pole becomes the south magnetic pole, and vice-versa). Rocks that form during a period of reverse magnetic polarity, get magnetized in a direction that is opposite to the present-day "normal" magnetic field. As a specific example, mafic volcanic rocks (that are magnetic because they contain the magnetic mineral magnetite) that are erupted when the Earth's magnetic field is reversed, cool and solidify and become reversely magnetized. This is problematic because if reversely magnetized rocks are present (and the geologic interpreter doesn't know it) then the geologic interpretation of the magnetic survey data is likely to be erroneous.

It turns out that large volumes of magnetic, mafic volcanic rocks have been erupted in Nevada and elsewhere in the Great Basin during the Tertiary. These geologically young volcanic rocks are either at or near the land surface and, therefore, have a strong effect on the magnetic response that is measured in a magnetic survey used in geothermal exploration. Since many magnetic reversals have occurred during the Tertiary, the mafic volcanic rocks that were erupted in the Great Basin during these periods of reverse polarity have likely been emplaced as reversely magnetized rock. Thus, these bodies of reversely magnetized rock could obscure and make ambiguous a geologic interpretation of magnetic survey data that could lead to incorrect structural interpretations at a geothermal exploration project. Accordingly, a robust and low-cost method to determine the location and geometry of reversely magnetized rocks within a magnetic survey study area would be useful.

This paper describes both map-based and 3D methods to make more accurate geologic interpretations of magnetic survey data when reversely magnetized rocks are present. First, 2D map-based methods are presented to identify where reversely magnetized rocks may be lurking. Second, 3D magnetic inversion modelling methods are also presented that help infer the location, shape, and orientation of reversely magnetized geologic bodies in the subsurface. Third, an example of 2D and 3D interpretation of magnetic survey data is presented from the Argenta Rise study area in northern Nevada, an area that is part of the U.S. Department of Energy funded INGENIOUS project.

2. BACKGROUND

The State of Nevada is awash in Tertiary volcanic rocks (Figure 1). The generalized geology map of Nevada (Tingley, 1999) reveals abundant volcanic rocks from the Tertiary (2½ - 66 Ma) exposed at the land surface. Certainly, additional volumes of Tertiary volcanic rocks are buried beneath young alluvial deposits as well. Most all of these volcanic rocks in Nevada are magnetic to some degree with the mafic volcanic rocks being the most strongly magnetic.

The geomagnetic polarity timescale shows that many magnetic reversals have occurred during the Tertiary with long stretches of time where the Earth's magnetic field was reversed (i.e. the opposite of what it is today). In fact, Figure 2 shows that during the Cenozoic Era, the Earth spent about the same amount of time under reverse polarity conditions as it did under normal polarity. During these periods of reverse polarity, magnetic volcanic rocks erupted in Nevada would have retained a reverse magnetization when they cooled. Thus, reversely magnetized rocks are likely quite common in Nevada.

Taken together, these two pieces of information suggest that geologic interpretation of magnetic survey data at geothermal prospects in the Great Basin is likely complicated because of the possible presence of reversely magnetized volcanic rocks.

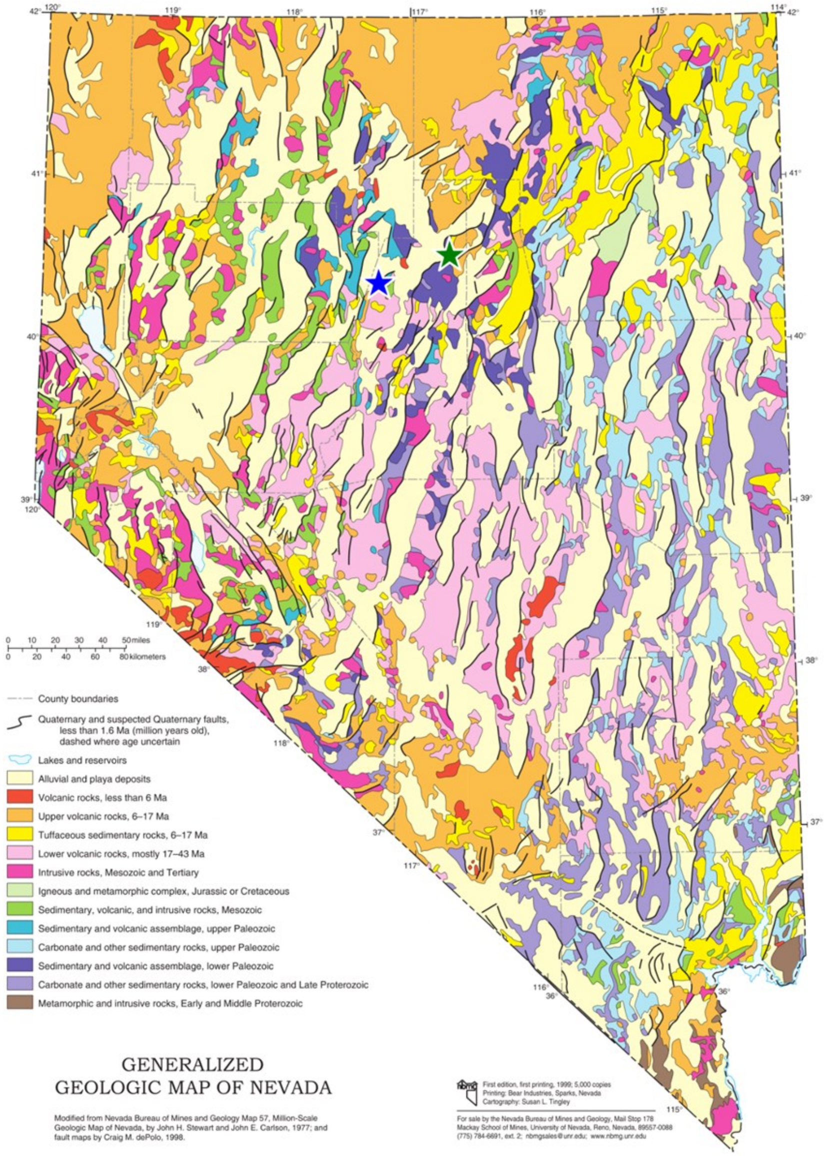


Figure 1: Generalized geologic map of Nevada (Tingley, 1999) showing an abundance of Tertiary volcanic rocks that could potentially be reversely magnetized. Tertiary volcanic rocks are shown in light pink (Lower volcanic rocks, mostly 17-43 Ma), orange (Upper volcanic rocks, 6 – 17 Ma), and red (Volcanic rocks, less than 6 Ma). The Tertiary period lasted from ~66 Ma to ~2½ Ma. The Blue star shows the location of the Buffalo Valley volcanic field (Figure 3). The green star shows the location of the Mule Canyon quad geologic cross-section B-B' (Figure 4).

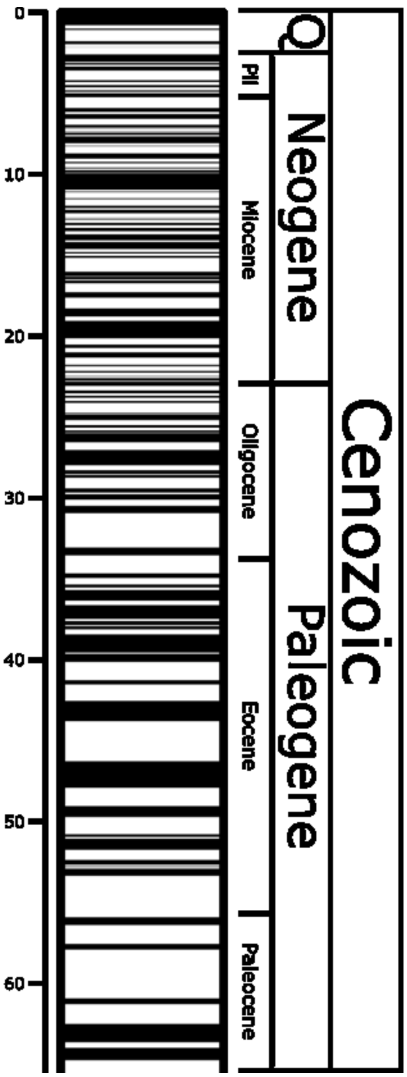


Figure 2: Magnetic polarity timescale for the Cenozoic (~66 Ma to present) from Cande and Kent (1995). Black bars represent periods of normal polarity while the white bars are periods of reverse polarity. The abundance of reverse polarity time intervals suggests that many of the volcanic rocks erupted during the Tertiary are reversely magnetized. The Tertiary period is the informal term for the combined Neogene and Paleogene periods.

The reason why reversely magnetized rocks make interpretation of magnetic survey data more complicated is as follows. Usually, strongly magnetic rocks cause magnetic "high" anomalies on magnetic survey maps. However, areas with strongly magnetic, but reversely magnetized rocks often appear as a magnetic "low" in a magnetic survey map. This is because the magnetization in the reversely magnetized rock body is oriented in opposition to the ambient magnetic field of the Earth. When the magnetic survey sensor passes over the reversely magnetized rocks, a portion of the ambient magnetic field has been "cancelled out" by the rocks that are magnetized in the opposite direction and a lower magnetic field response is measured. However, a magnetic "low" on a magnetic survey map can also represent other geologic features such as: a) non-magnetic or weakly magnetic rock material such as quartz sandstone, clean limestone, fine-grained mudstone, or igneous rocks lacking magnetic minerals, or b) formerly magnetic rock units in which the magnetic minerals suffered chemical decomposition to non-magnetic minerals via hydrothermal alteration. It can be challenging to know which of the options is the correct geologic explanation for a magnetic "low" particularly if magnetic survey data is interpreted in isolation without accompanying insight from a geologic map and rock property measurements from the study area.

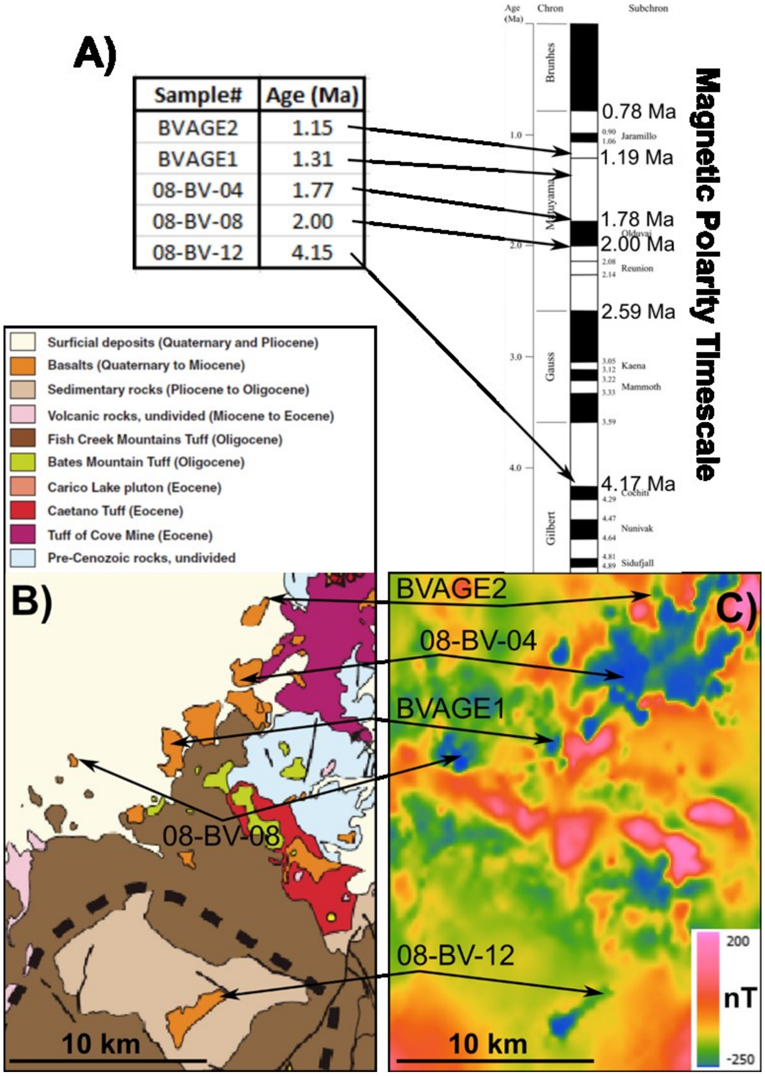
In the field, reversely magnetized volcanic rocks are visually indistinguishable from normally magnetized volcanic rocks. The common way to determine whether or not an outcrop of rocks is reversely magnetized is to drill a small core sample from the outcrop and send it to a lab for paleomagnetic analysis. Paleomagnetic analysis requires specialized expertise and is most commonly done in academic circles; it is not usually done in industry as part of a geothermal exploration program. As a result, paleomagnetic data, which would tell you whether or not a rock unit is reversely magnetized is, quite often, not available.

3. GEOLOGY AND ROCK PROPERTY ANALYSIS

In the absence of paleomagnetic data, how can we assess which areas may contain reversely magnetized rocks and which areas do not? The first step is to compare a geologic map with a magnetic survey map. Are mafic volcanic rocks (that are likely to be strongly magnetic) on the geology map co-located with "low" features on the magnetic survey map? If they are, then the mafic magnetic rocks may be reversely magnetized and may be the cause of the magnetic "low" anomalies (Figure 3).

To provide further corroboration, a bit of geological field work is required. In the field, hand-held magnetic susceptibility measurements on the outcrops in question can measure how strongly magnetic the rocks are at the land surface. If the handheld magnetic susceptibility measurements show that the rocks actually are strongly magnetic, but they are co-located with a magnetic "low" on a magnetic survey map, this provides additional evidence that the rocks are likely reversely magnetized. Alternatively, a trip to the field may show that the magnetic "low" on the magnetic survey map is co-located with non-magnetic to weakly magnetic rock types or an area of extensive hydrothermal alteration (that returns low magnetic susceptibility measurements with the hand-held meter). In this case, the magnetic "low" anomaly is not due to reversely magnetized rocks, but rather, the rocks are not magnetic.

Lastly, if high-resolution age dates are available for the volcanic rocks under study, a comparison of the age of the rock with the magnetic polarity timescale can be instructive (Figure 3). If the rock is magnetic and the age of the rock falls within a period of reverse magnetic polarity, the rocks in the outcrop are likely reversely magnetized.



Sample#	Age (Ma)
BVAGE2	1.15
BVAGE1	1.31
08-BV-04	1.77
08-BV-08	2.00
08-BV-12	4.15

Figure 3: Geologic, magnetic, and radiometric age data for (likely) reversely magnetized, Quaternary basalts from the Buffalo Valley volcanic field, Nevada. A) ^{40}Ar-^{39}Ar radiometric age data from 5 samples of basalt collected in the Buffalo Valley volcanic field (Cousens et al., 2013) which were all erupted during periods of reverse magnetic polarity (white areas on the Magnetic Polarity Timescale), B) Geologic map of the Buffalo Valley volcanic field (John et al., 2008) showing the rock sample locations from (A), C) TMI-RTP magnetic data from the USGS GeoDAWN project covering the same area shown in (B) with rock sample names and locations indicated. Notice that the rock samples are located in magnetic "low" anomalies even though basalt is a strongly magnetic rock. This is because these basalt samples are likely reversely magnetized. Paleomagnetic measurements would be useful to confirm this conclusion.

4. ANALYTIC SIGNAL MAPPING

One approach to improve map-based interpretation, in the presence of reversely magnetized rocks, is to use the analytic signal of the magnetic field (Roest et al., 1992). An analytic signal map can be calculated from magnetic survey data and it assists in the determination of the geometry of magnetic rock bodies regardless of whether or not they are reversely magnetized (Figure 4). Specifically, rock bodies with normal or reverse polarity will both appear as "high" features on an analytic signal map (because both rock bodies are magnetic). This is in contrast to reversely magnetized rock bodies that are commonly co-located with a "low" feature on a TMI-RTP magnetic survey map. In summary, areas where you find an analytic signal "high" in the same location as a TMI-RTP "low" may have reversely magnetized rocks in that location. Comparison of TMI-RTP and analytic signal maps is particularly useful in areas where there are no outcrops of the bedrock to map geologically and/or test with magnetic susceptibility measurements.

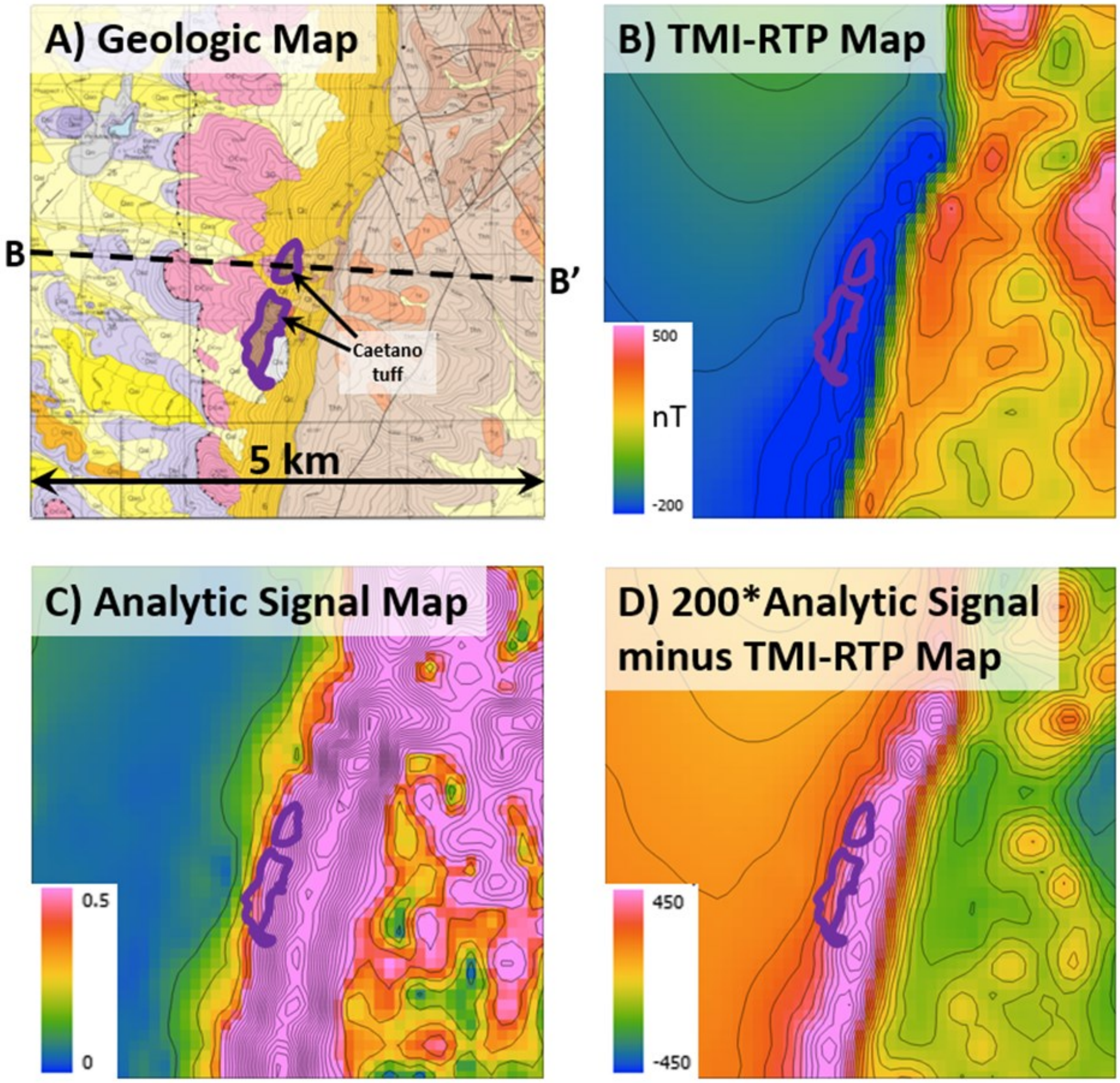


Figure 4: Comparison of geology and magnetic maps in the Argenta Rise area, northern Nevada. A) Portion of the geologic map from the Mule Canyon quadrangle (from John and Wrucke, 2003) with the reversely magnetized Caetano tuff outlined (thick purple line). The orange unit north and south of the Caetano tuff outcrop is Holocene colluvium which likely covers more Caetano tuff. B) USGS GeoDAWN magnetic survey data (TMI-RTP) showing the correlation between the reversely magnetized Caetano tuff and a magnetic "low" anomaly. C) the analytic signal calculated from the magnetic survey data shows that the Caetano tuff is co-located with high analytic signal values. D) the TMI-RTP map subtracted from the analytic signal map shows a high ridge that is likely associated with the reversely magnetized Caetano tuff rocks that extend under the Holocene colluvium. Geologic cross-section B-B' is shown in Figure 5. TMI-RTP = Total Magnetic Intensity – Reduction to Pole.

5. 3D MAGNETIC INVERSION MODELLING

5.1 Background

Three-dimensional inversion modelling of magnetic survey data has been used as a geoscience exploration tool for the past few decades (Li and Oldenburg, 1996). The purpose of the method is to enable better understanding of the 3D distribution of magnetic and non-magnetic rocks in the subsurface in an effort to clarify geologic structure and rock unit geometry.

Early versions of 3D magnetic inversion modelling codes, called scalar magnetic inversion, assumed all rocks were normally magnetized (i.e. reversely magnetized rocks were not present). The consequence of this assumption is that when you performed a 3D magnetic inversion in regions with reversely magnetized rocks the scalar inversion code would output non-geological results which commonly took the form of large, cone-shaped regions of zero magnetic susceptibility co-located with the reversely magnetized rocks.

Over the past several years, significant advances have been made in developing 3D magnetic inversion codes that can properly model both normal and reversely magnetized rock bodies using magnetic survey data. One example of such a code is the Magnetic Vector Inversion (MVI) algorithm in the SimPEG family of inversion codes (Fournier et al. 2020). The MVI code can model both the magnitude (i.e. magnetic susceptibility) and direction (i.e. inclination and declination) of the magnetization in rock units from magnetic survey data.

To provide examples of this type of modelling, I performed both 3D scalar modelling and 3D MVI modeling in an area with known reversely magnetized rocks located in northern Nevada ~20 km SE of the town of Battle Mountain. The study area is in the eastern part of the Argenta Rise project area; Argenta Rise is one of the DOE-funded INGENIOUS project study sites.

5.2 Methodology

Both the scalar and MVI modelling codes were provided the following datasets as input:

- High resolution magnetic survey data (including sensor height)
- High resolution topographic data (i.e. a 10 m DEM)
- A rough 3D geology model of the expected distribution of rock units
- Average rock properties for each rock unit (i.e. magnetic susceptibility, inclination, and declination)

The 3D magnetic inversion model volume is 5 km x 5 km x 2.2 km with a cell size of 40 m and it covers the area shown in Figure 4. Total Magnetic Intensity (TMI) data from the GeoDAWN project (Glen and Earney, 2024) with 100 m data spacing was used for the magnetic survey data. A rough 3D geology model was constructed from the east-west oriented B-B' geologic cross-section shown on the Geologic Map of the Mule Canyon Quadrangle (Figures 4A & 5). The 3D geology to the north and south of the B-B' cross-section was approximated, but generally honored the surface geologic map. Rock property data for the rock units in the 3D model volume were obtained from USGS (T. Earney, personal communication, 2024). The reversely magnetized rock unit in the 3D model volume is the Caetano tuff and the magnetic properties of this unit were determined from paleomagnetic measurements by USGS.

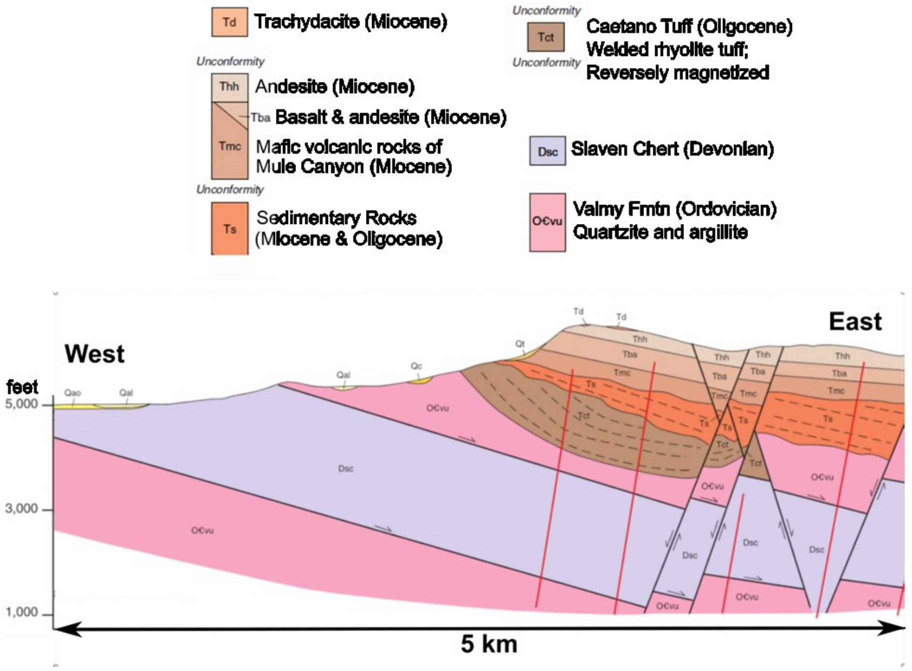


Figure 5: East-west oriented geologic cross-section B-B' (adapted from John and Wrucke, 2003) showing the reversely magnetized Caetano tuff as unit Tct in brown. This cross-section was used to create the rough 3D geologic model used in the 3D magnetic modelling. Depths of the thrust faults at the Valmy-Slaven contact were inferred by John and Wrucke (2003) and the dikes in the cross-section (red lines) were also drawn schematically. Location of B-B' is shown in Figure 4.

5.3 3D Magnetic Model Results

The scalar magnetic inversion model output (that assumes reversely magnetized rocks are not present) is shown in Figure 6. A cone-shaped region of low magnetic susceptibility is clearly present and it is co-located with the reversely magnetized Caetano tuff. These cones of low magnetism are geologically meaningless and an artifact of using the scalar magnetic inversion code in an area where reversely magnetized rocks are present. The results shown in Figure 6 indicate that a different inversion code (such as MVI) that can more effectively model reversely magnetized rocks is needed.

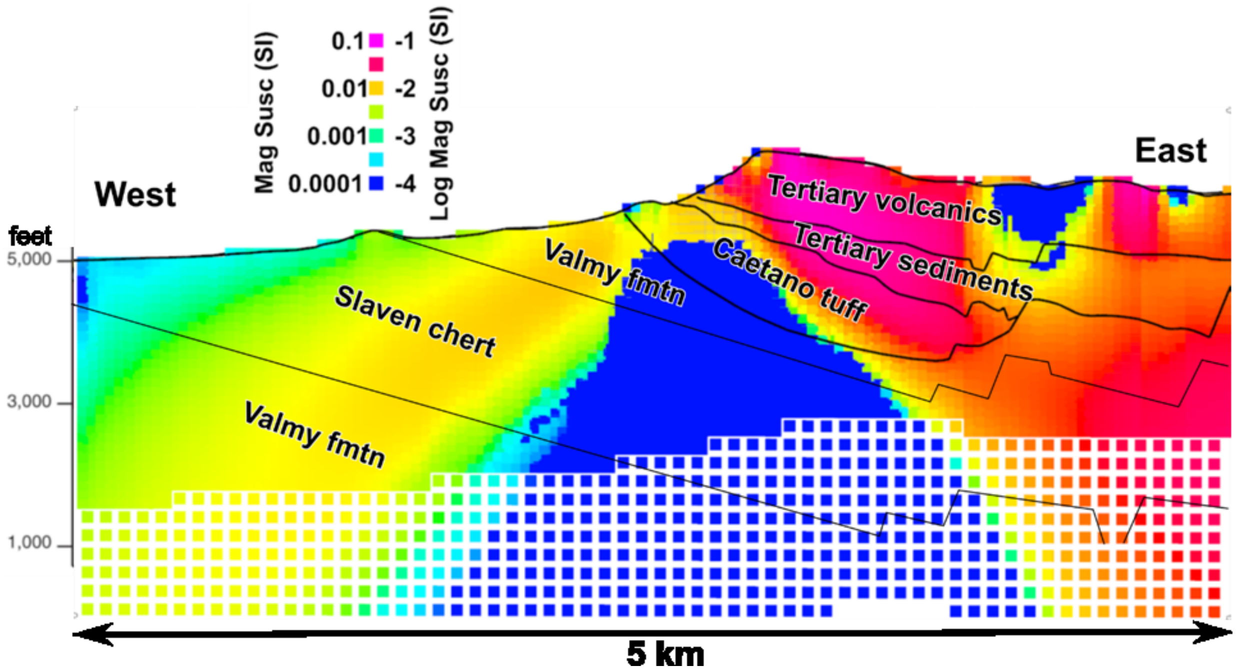


Figure 6: 3D magnetic susceptibility inversion model shown along section B-B'. This result was generated using a scalar inversion algorithm which assumes reversely magnetized rocks are not present. In an attempt to match the magnetic survey data, the inversion algorithm generated a model result that placed a cone of non-magnetic rocks (dark blue) that coincides with the reversely magnetized Caetano tuff and cuts across geologic boundaries. This magnetic model sharply disagrees with the existing geologic cross-section and is considered to be geologically-unreasonable. Such a result indicates that a different magnetic inversion algorithm is needed – one that can better account for reversely magnetized rock units.

MVI modelling was performed in two stages to work towards a geologically-reasonable solution. In MVI model #1 (Figure 7), an initial reference model with specific geologic boundaries and populated with magnetic properties, was used as input to test how closely it matched to the MVI model output. The reference model #1 consists of moderately magnetic Tertiary volcanics & sediment units as well as a more strongly magnetic Caetano tuff (Figure 7A). In addition, the basement Valmy and Slaven chert rock units on the west are weakly magnetic while the basement rock on the east side has been intruded by Northern Nevada Rift dikes and is modestly magnetic. This distribution of rock units is nearly identical to the geologic cross-section of John and Wrucke (2003) shown in Figure 5. In reference model #1, the only rock unit which is reversely magnetized is the Caetano tuff (Figures 7C and 7E) and it is assigned values of Declination, D = 156° and Inclination, I = -67°. All other rock units are normally magnetized with D = 13° and I = 64°.

If reference model #1 matches the magnetic survey data, then the three MVI model outputs (magnetic susceptibility, inclination, and declination) should look the same as the reference models. The MVI model outputs (Figures 7B, 7D, and 7F) match the reference models in some areas, but not in others. The match is particularly poor near the Caetano tuff. This suggests that the reference model is not accurate in the vicinity of the Caetano tuff and updates to the reference model are merited. An update to the reference model involves geologic interpretation to ensure that a new reference model is geologically-reasonable. Changes to the reference model generally involve three options:

A) Change the estimated rock properties for each rock unit
B) Adjust the boundaries of the rock units in the 3D geologic model
C) Add new rock units to the 3D geologic model

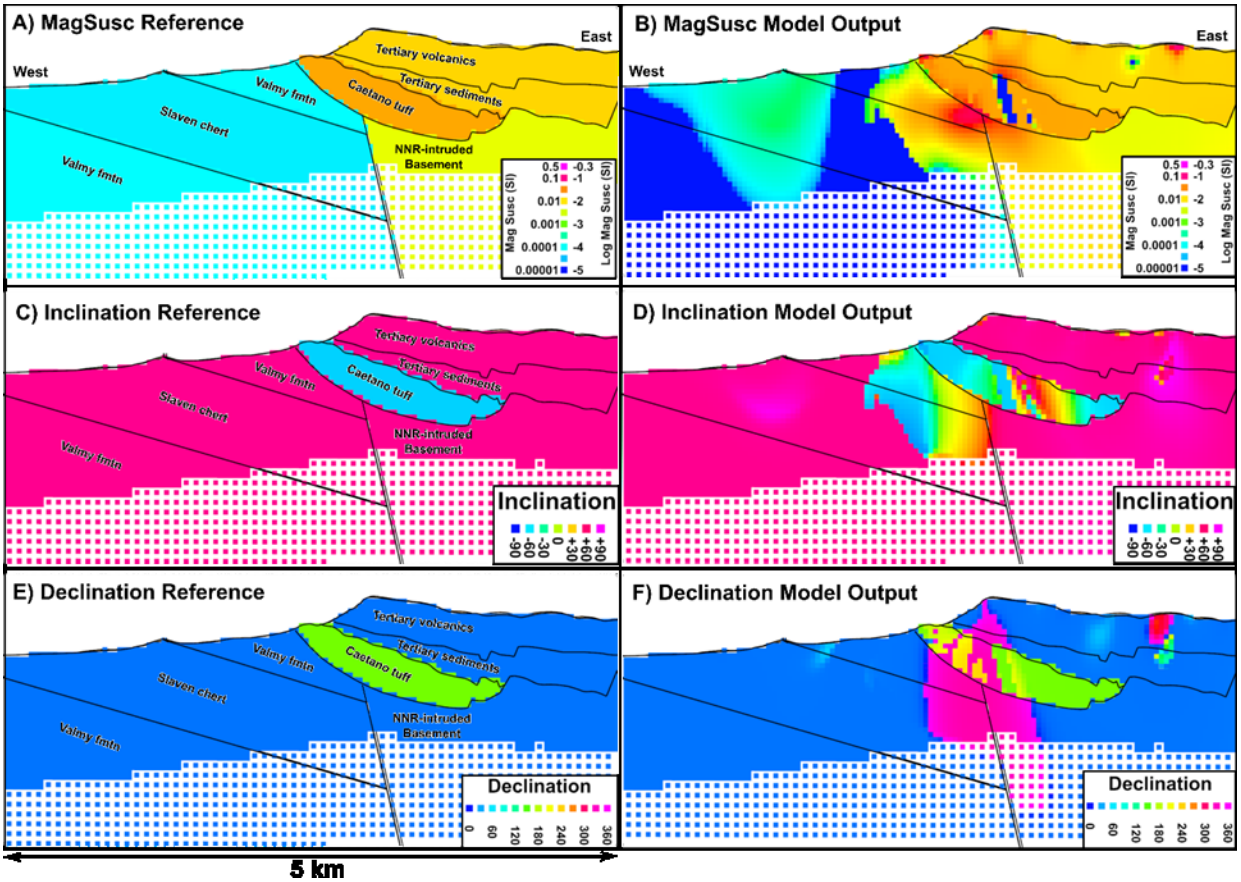


Figure 7: 3D Magnetic Vector Inversion output #1, which includes magnetic susceptibility, inclination, and declination reference models (left side) and inversion model outputs (right side). The output models on the right match the reference models in some areas, but not others. The match is particularly poor in the vicinity of the reversely magnetized Caetano tuff. This mismatch suggests that the reference models (i.e. the geologic boundaries and/or the rock properties) need to be changed to better guide the MVI algorithm towards a more geologically-reasonable output. Note that the output models (on the right) match the measured magnetic survey data within error (~5 nT).

For MVI model #2 (Figure 8), the reference model was updated based upon the results from MVI model #1 and re-run to test if the MVI model output is improved. Changes to the reference model included the following:

A) Move the geologic contact between the NNR-intruded basement and non-intruded basement further to the west
B) Insert a strongly magnetic, normally magnetized dike into the reference model that cuts through the Caetano tuff
C) Insert a second, moderately magnetic dike that has normal declination but reverse inclination at the boundary between the intruded and non-intruded basement

The two dikes added to reference model #2 may be analogous to mapped Tertiary basaltic intrusions that crop out along strike ~5 km north of the study area.

Comparison of the updated reference models (Figures 8A, 8C, and 8E) with the three new MVI outputs (Figures 8B, 8D, and 8F) show that the agreement is much better than that shown for the previous model #1 (Figure 7). This means that reference model #2 (with the dikes) is more likely a better representation of the subsurface geology than the model without the dikes. Note that the MVI model outputs shown in Figures 8B, 8D, and 8F still retain some areas of disagreement with the reference models. This suggests that further updates could be undertaken to refine the reference model and create an even better representation of the subsurface geology.

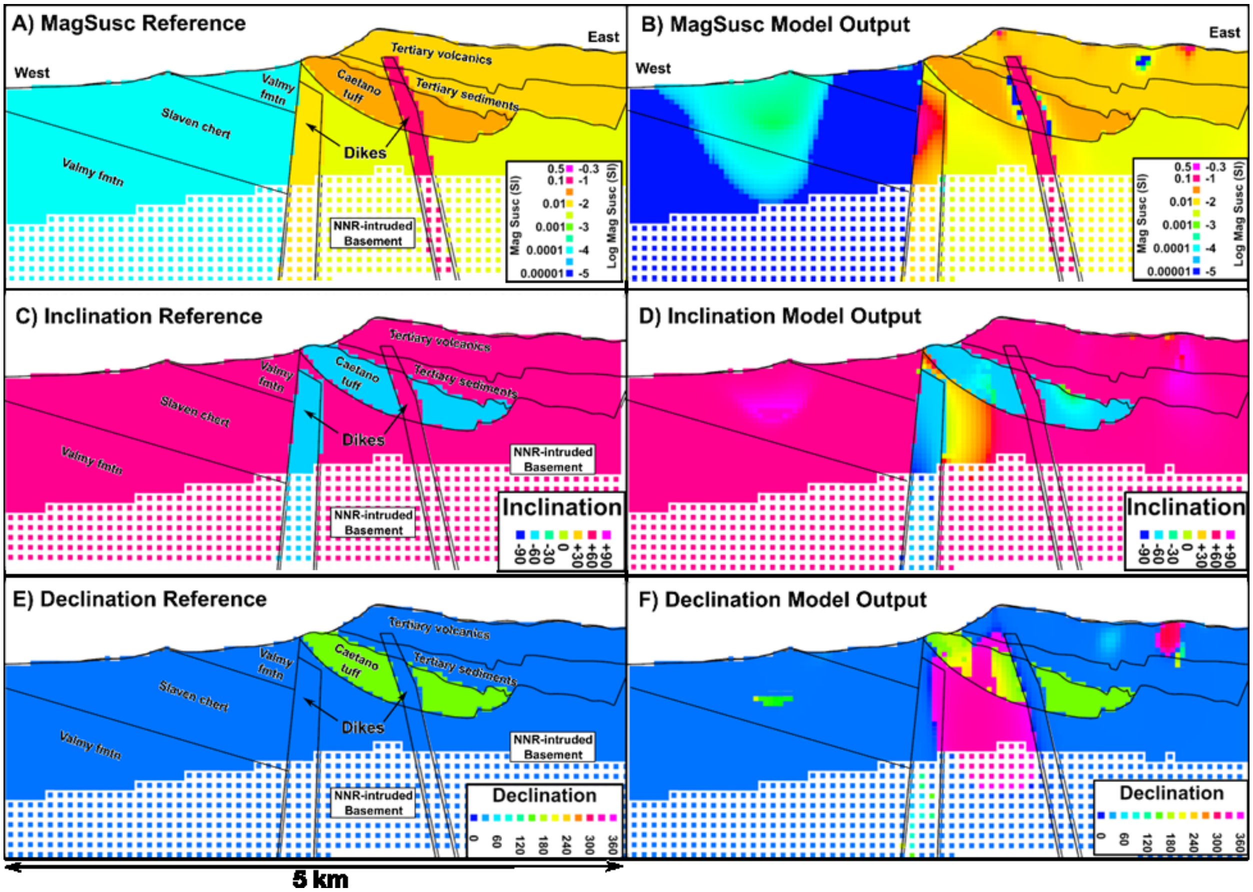


Figure 8: 3D Magnetic Vector Inversion output #2, with discrete dikes added. The magnetic susceptibility, inclination, and declination output models (right side) match quite well with the reference models (left side). In addition, the output models (on the right) match the measured magnetic survey data within error (~5 nT). This means that the geologic boundaries and magnetic property values shown in reference model #2 are more likely to represent the subsurface geology than model #1 shown in Figure 7.

6. DISCUSSION

The presence of reversely magnetized rocks in a study area complicates map-based interpretation of magnetic survey data which, if unrecognized, can lead to incorrect geological interpretations. For example, reversely magnetic rocks can generate strong magnetic "low" anomalies on magnetic survey maps, which could easily be misinterpreted as non-magnetic rocks. Alternatively, reversely magnetized mafic volcanic rocks (showing a magnetic "low") lying adjacent to normally magnetized mafic volcanic rocks (showing a magnetic "high") might lead the geologic interpreter to infer a major fault at the contact between the magnetic "high" and "low" when, in fact, no fault exists, but rather mafic volcanic rocks were simply erupted at different times imparting reverse or normal polarity on the rocks during their emplacement. Co-interpretation of magnetic survey data with geologic maps, magnetic susceptibility measurements, and analytic signal maps can be helpful to discern whether or not reversely magnetized rocks are present, and where they are located, in the event that paleomagnetic measurements are not available.

Reversely magnetized rocks also cause problems when interpreting the results of 3D magnetic inversion algorithms. Scalar inversion algorithms, that assume reversely magnetized rocks are not present, commonly generate modelling artifacts that take the form of cone-shaped regions of zero magnetism where the reversely magnetized rocks are located. Magnetic vector inversion algorithms, such as Fournier et al. (2020), are a significant improvement and should be utilized to investigate the 3D variations in rock magnetic properties (i.e. magnetic susceptibility, inclination, and declination) anytime reversely magnetic rocks might be present in a study area. Importantly, reference geology models, populated by either measurements or sensible estimates of magnetic properties should be employed to help guide the inversion algorithm towards a geologically-reasonable outcome. Without the guiding influence of the reference model, the non-uniqueness problem inherent in 3D potential field inversion modelling could easily lead the inversion algorithm to calculate a result that may match the measured magnetic survey data but would otherwise be geologically non-sensical.

7. CONCLUSIONS

Tertiary and magnetic volcanic rocks are abundant in Nevada and other areas of the Great Basin where exploration for geothermal resources occurs. Periods of reverse magnetic polarity have also been common during the Tertiary. This means that when interpreting magnetic survey data as part of a geothermal exploration program, one must be aware that the reversely magnetized volcanic rocks could greatly complicate matters and lead to incorrect geological and structural interpretations. An example from the Buffalo Valley volcanic field is presented where geologic maps, radiometric age dates, and the magnetic polarity timescale are used together to conclude that "low" anomalies on the magnetic survey map are likely due to reversely magnetized rocks.

Another example from the Argenta Rise project area is also presented in which the reversely magnetized Caetano tuff unit is clearly recognized in the magnetic survey data using analytic signal mapping. Subsequent 3D magnetic vector inversion modelling in the Argenta Rise area also shows that the subsurface geology around the Caetano tuff is likely more complicated than that depicted in a 2D geology profile constructed previously for the area. In particular, two dikes with different magnetic properties are needed to create a geologically-reasonable solution that matches the measured magnetic survey data. These two dikes are likely associated with Northern Nevada Rift intrusions that are found in outcrop a few kilometers north of the study area.

REFERENCES

Cande, S.C., and Kent, D.V.: Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic, Journal of Geophysical Research, 100 (B4), (1995), 6093–6095.

Cousens, B., Wetmore, S., Henry, C.D.: The Pliocene–Quaternary Buffalo Valley volcanic field, Nevada: Post-extension, intraplate magmatism in the north-central Great Basin, USA, Journal of Volcanology and Geothermal Research, v. 268, (2013), 17-35.

Fournier, D., Heagy, L.J., Oldenburg, D.W.: Sparse magnetic vector inversion in spherical coordinates, Geophysics, v. 85, no. 3, (2020), J33-J49.

Glen, J.M.G., Earney, T.E.: GeoDAWN: Airborne magnetic and radiometric surveys of the northwestern Great Basin, Nevada and California: U.S. Geological Survey data release, https://doi.org/10.5066/ P93LGLVQ, (2024).

John, D.A., Wrucke, C.T.: Geologic Map of the Mule Canyon Quadrangle, Lander County, Nevada, Nevada Bureau of Mines and Geology, Map 144, plate 1, (2003).

John, D.A., Henry, C.D., Colgan, J.P.: Magmatic and tectonic evolution of the Caetano caldera, north-central Nevada: A tilted, mid-Tertiary eruptive center and source of the Caetano Tuff, Geosphere, v. 4, no. 1, (2008), 75-106.

Li, Y., Oldenburg, D.W.: 3-D inversion of magnetic data, Geophysics, v. 61, no. 2, (1996), 394-408.

Tingley, S.L.: Generalized Geologic Map of Nevada, modified from the Nevada Bureau of Mines and Geology Map 57, Million-Scale Geologic Map of Nevada by John H. Stewart and John E. Carlson; and fault maps by Craig M. dePolo, 1998, Educational Series 30, Nevada Bureau of Mines and Geology, 1 plate, (1999).

Roest, W.R., Verhoef, J., Pilkington, M.: Magnetic interpretation using the 3-D analytic signal, Geophysics, 57, (1992), 116-125.