

## Curie Point Depth Estimates from Aeromagnetic Data from Death Valley and Surrounding Regions, California

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**Abstract**—Aeromagnetic data were analyzed to determine the Curie point depth (CPD) by power density spectral and three-dimensional inversion methods within and surrounding Death Valley in southern California. We calculated the CPD for 0.5° regions using 2D power density spectral methods and found that the CPDs varied between 8 and 17 km. However, the 0.5° region may average areas that include shallow and deep CPDs, and because of this limitation, we used the 3D inversion method to determine if this method may provide better resolution of the CPDs. The final 3D model indicates that the depth to the bottom of the magnetic susceptible bodies varies between 5 and 23 km. Even though both methods produced roughly similar results, the 3D inversion method produced a higher lateral resolution of the CPDs. The shallowest CPDs occur within the central and southern Death Valley, Panamint Valley, Coso geothermal field and the Tecopa hot springs region. Deeper (>15 km) CPDs occur over outcropping granitic and Precambrian lithologies in the Panamint Range, Grapevine Mountains, Black Mountains and the Argus Range. The shallowest CPD occurs within the central Death Valley over a possible seismically imaged magma body and slightly deeper values occur within the Panamint Valley, southern Death Valley and Tecopa Hot Springs. The shallow CPD values suggest that partially molten material may also be found in these latter regions. The CPD computed heat flow values for the region suggest that the entire area has high heat flow values (>100 mW m<sup>-2</sup>), on the other hand, locally extremely high values (>200 mW m<sup>-2</sup>) occur within the Panamint Valley, the southern and central Death Valley and Tecopa Hot Springs region. These locally high heat flow values may be related to midcrustal magma bodies; but additional geophysical experiments are needed to determine if the magma bodies exist.

**Key words:** Aeromagnetic anomalies, Curie point depth, heat flow, inversion, spectral methods, Death Valley.

### 1. Introduction

The thermal structure of the Earth is an important parameter in determining the tectonic environment of a region (CHAPMAN and FURLONG 1992). However, in determining the thermal structure of the crust or lithosphere, it is common to use borehole measurements to directly determine the heat flow. The problem with these measurements is that they are more than 1 km deep and not uniformly spaced, and if the measurements are more than 100 km apart then heat flow values could be affected by near surface features (e.g., groundwater flow). One solution to the lack of heat flow measurements is to use geophysical measurements including magnetics, magnetotellurics (MT) and seismic velocity estimates to indirectly infer the presence of high heat flow. Magnetotellurics and seismic velocity measurements only provide indirect evidence of potential low electrical resistivities or seismic velocities that may indicate high heat flow but do not provide estimates of temperatures. However, the magnetic method can be used to estimate the CPD by determining the bottom of magnetic sources (e.g., SPECTOR and GRANT 1970; BHATTACHARYYA and LEU 1975; SHUEY *et al.* 1977; BLAKELY 1988; TANAKA *et al.* 1999; ROSS *et al.* 2006; ESPINOSA-CARDENA and CAMPOS-ENRIQUEZ 2008; BOULIGAND *et al.* 2009). The use of the CPD in determining the regional heat flow is still controversial as it may depend upon composition, Curie temperature of the magnetic minerals, and accuracy and resolution of the depths determined from magnetic interpretation methods (TANAKA *et al.* 1999; RAVAT *et al.* 2007).

The determination of the depth to the Curie point using magnetic data can be accomplished by two different methods. The most popular method is to

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calculate the spectrum of the magnetic data by using an isolated anomaly and one-dimensional spectral methods (e.g., BHATTACHARYYA and LEU 1975) or using the two-dimensional (2D) spectrum of a region of magnetic data (SPECTOR and GRANT 1970). In both cases, the spectrums are used to estimate the top and bottom of a magnetic source, with the bottom of the source assumed to be at the CPD. The other method used is forward modeling or inversion methods to model isolated magnetic anomalies (BYERLY and STOLT 1977; HONG 1982; MICKUS 1989) to determine the depth of the magnetic sources. In both methods, the depth to the bottom of the source is assumed to be at the Curie temperature of a magnetically susceptible mineral (e.g., magnetite at 580 °C). However, this depth may be caused by lithological variations (ROSS *et al.* 2006).

In the present study, we applied the 2D power density spectral method and three-dimensional (3D) inversion of aeromagnetic anomalies within and surrounding the Death Valley region of California to determine the depth to the bottom of magnetic sources. The Death Valley region is a site of extensive continental extension with the possibility of elevated heat flow. Seismic reflection studies (DE VOOGD *et al.* 1986) have shown that a series of strong reflectors at 15 km in depth may be caused by a midcrustal magma chamber. Due to the lack of heat flow data within or nearby Death Valley (Fig. 1), any elevated heat flow that may be caused by the potential magma chamber is unknown. The results of the spectral and inverse methods will be analyzed to determine if there is higher heat flow within and surrounding Death Valley and relate these findings to their cause of the higher heat flow.

## 2. Tectonic and Geophysical Setting

Death Valley (Fig. 1), a deep topographic basin that extends for about 200 km in a north-northwest direction in southeastern California, is a highly extended continental basin whose origin has been controversial (NORTON 2011). BURCHFIEL and STEWART (1966) suggested that due to strike-slip faulting within the topographic low of Death Valley, Death Valley formed as a pull-apart basin. However, with

the recognition of low-angle detachment faults in the 1970s and 80s numerous authors (e.g., WRIGHT and TROXEL 1973; HAMILTON 1988; WERNICKE *et al.* 1988; HODGES *et al.* 1989) have incorporated extensional models into explaining the structural origin of Death Valley. MILLER and PAVLIS (2005) divided the strike-slip and detachment faulting models into two groups: (1) one where detachment faulting is dominant and (2) another where strike-slip faulting is the main mechanism in forming Death Valley. The detachment faulting models (STEWART 1983; WERNICKE *et al.* 1988; SNOW and WERNICKE 1989) suggest that Death Valley formed mainly by a low-angle detachment fault that moved the Panamint Range 80 km to the west of its original position east of the Black Mountains with the strike-slip faults occurring in upper crust edges of the detachment faults. The strike-slip fault models (WRIGHT and TROXEL 1984; SERPA and PAVLIS 1996; MILLER and PRAVE 2002) suggest that Death Valley formed as a pull-apart basin between the terminations of deep crustal strike-slip Northern Death Valley-Furnace and Southern Death Valley strike-slip faults. In this model, the detachment faults are normal faults linking the strike-slip faults.

The above models assume that the strike-slip and detachment faulting occurred at the same time. A recent model of the formation of Death Valley by NORTON (2011) invoked the regional tectonic setting of southern California. Death Valley resides within the overlap of three tectonic regimes: (1) Basin and Range extensional province (BURCHFIEL *et al.* 1992), (2) Walker Lane belt (STEWART 1988) and (3) the Eastern Mojave Shear Zone (DOKKA and TRAVIS 1990). The Basin and Range province is characterized by extensional tectonics with metamorphic core complexes that bring middle crustal rocks to the surface (DAVIS 1980) with a number of metamorphic core complexes being found south of Death Valley in the Colorado River Extensional Corridor (DAVIS 1980). The Walker Lane belt and Eastern Mojave Shear Zone are characterized by north to northwest trending topography with active strike-slip and normal faults (NORTON 2011; OLDOW *et al.* 2008; DOKKA and TRAVIS 1990). NORTON (2011) used the above tectonic provinces and detailed studies of the sedimentology and stratigraphy, volcanology, structural geology, and geochronology to propose a two-stage

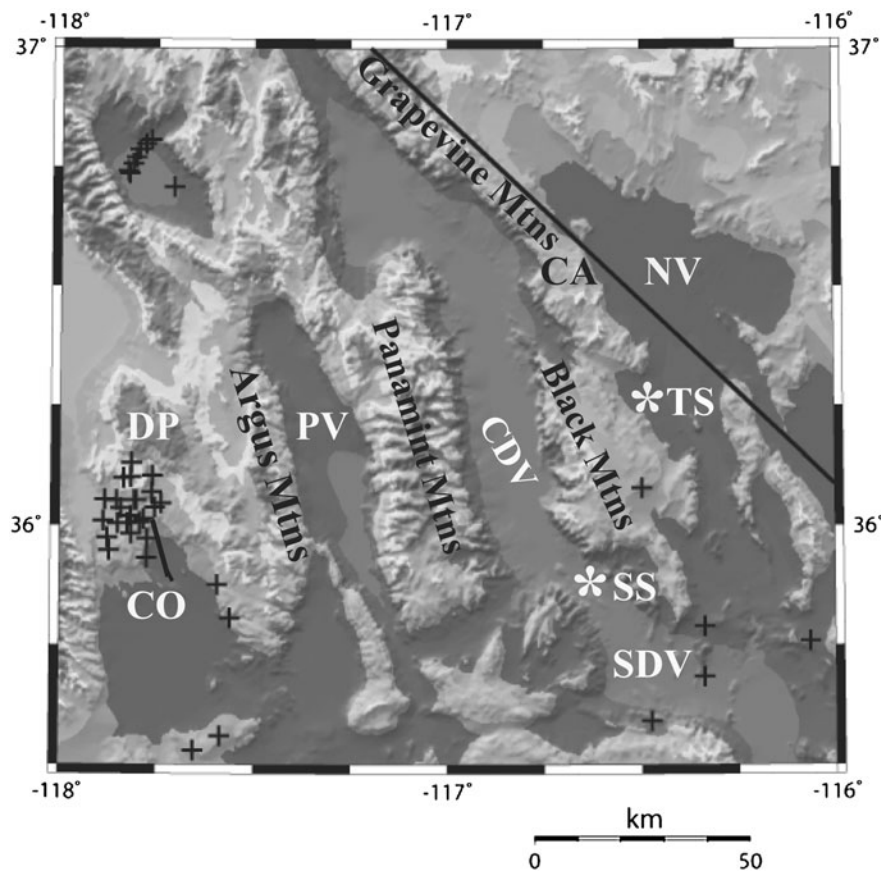


Figure 1

Location and topographic map of Death Valley and surrounding region. *CDV* central Death Valley, *CO* Coso geothermal field, *DP* Darwin Plateau, *OH* Owlheads Mountains, *SS* Saratoga hot springs, *SDV* southern Death Valley, *TS* Tecopa hot springs. + represents the location of the available heat flow data (BLACKWELL and RICHARDS 2004)

formation of Death Valley. Norton suggested that the basin first formed by Basin and Range extensional processes from 18 to 5 Ma that created the low-angle detachment faults and produced an exposed metamorphic core complex at the northern end of the Black Mountains. Then, after the extensional faulting ceased, the detachment faults were covered by a variety of volcanic rocks and sediments. At approximately 3 Ma, strike-slip faulting contemporaneous with the formation of the East Mojave Shear Zone, formed a pull-apart basin within Death Valley. This faulting segmented the older extensional faults (NORTON 2011) which aided the formation of the topographic depression of Death Valley.

The above basin formation models have been supported by numerous geophysical experiments performed within Death Valley. The most important

studies have been the seismic reflection and refraction studies of the Consortium for Continental Reflection Profiling (COCORP) project (DE VOOGD *et al.* 1986, 1988; GEIST and BROCHER 1987; SERPA *et al.* 1988). These studies determined the thickness (3 km) and the shape (asymmetrical and steeper to the west) of the sediments within Death Valley (GEIST and BROCHER 1987), the thickness of the crust (approximately 30 km) (SERPA *et al.* 1988), and the existence of high amplitude reflectors (bright spots) at approximately 15 km within central Death Valley. The bright spots have been interpreted to be caused by a magma chamber (DE VOOGD *et al.* 1986, 1988).

Magnetotelluric studies by PARK (2004) and PARK and WERNICKE (2003) in eastern California included four broadband stations within Death Valley. The investigation by PARK and WERNICKE (2003) compared

an electrical resistivity section to a geologic section extending across eastern California including Death Valley. They found that within Death Valley, the crust is characterized by low resistivities from the surface to 20 km in depth but the lowest resistivities were found in the upper 5 km. They concluded that the present day strike-slip faults in and surrounding the Death Valley region are characterized by a vertical low resistivity zone to depths of about 20 km in the crust with no subhorizontal layers that would be indicative of lateral flow. PARK (2004) concluded that partial melt is relatively uncommon beneath the Sierra Nevada and the California Basin and Range except for isolated regions beneath Miocene or younger basalt eruptions.

Detailed gravity studies have provided constraints on the Death Valley basin thickness and geometry (KEENER *et al.* 1993; BLAKELY *et al.* 1999) and regional gravity studies combined with receiver function studies have been used to determine the crustal structure of the Death Valley region (HUSSEIN *et al.* 2011). KEENER *et al.* (1993) and BLAKELY *et al.* (1999) analyzed Bouguer gravity anomalies and determined that the Death Valley basin has thicknesses varying between 3 and 5 km with steep sides along the edges of the basin. BLAKELY *et al.* (1999) modeled thicknesses of all the basins surrounding Death Valley to conclude that these basins represent about 10 km of extension and that the remaining regional extension must have been accommodated beneath the basins. HUSSEIN *et al.* (2011) created regional gravity and magnetic models constrained by a receiver function analysis and showed that the crust is thinnest (24 km) beneath the central Death Valley basin and thicken to approximately 31–33 km to the west and east of Death Valley. Additionally and important to this study, they modeled a low density region beneath 15 km that extends to approximately 26 km under Death Valley which corresponds to location of the Death Valley Bright Spot (DE VOOGD *et al.* 1986).

### 3. Aeromagnetic Data

Aeromagnetic data were obtained from the US Geological Survey with a grid spacing of 1 km (BANKEY *et al.* 2002). This data set was compiled

from numerous surveys of various line spacings that covered the US. The original data were reprocessed for diurnal variations, flight heading, and errors in flight elevation. Then the individual surveys were merged and regridded into regional compilations at the US state level (BANKEY *et al.* 2002). The gridded data had the Definitive Geomagnetic Reference Field removed for the date of the original survey. The regional grids were resampled to a grid spacing of 1 km and the original grids were either downward or upward continued to a constant 0.305 km above the Earth's surface. Finally the regional grids were blended together to produce a final grid of the US. The original survey line spacings varied from less than 1 km to over 8 km that makes detailed interpretation difficult in some areas. Within the Death Valley region, the original flight spacings were less than 1 km. However, in the southwest portion of the study area, the line spacing is between 4.8 and 8 km, and in Nevada, the line spacing is between 1.1 and 2 km. The magnetic anomaly map is shown in Fig. 2.

Magnetic anomalies usually reflect lateral variations in magnetic mineralogy (most commonly magnetite) of the crustal rocks to mid to lower crustal depths depending on the heat flow in the region. Shorter wavelength anomalies can be correlated with surface or near surface geology; however, longer wavelength anomalies may be caused by either deeper magnetic mineralogical variations or variations in the CPD caused by regional heat flow differences. Within the Death Valley region, the magnetic anomalies generally reflect the location of the granitic or Precambrian basement rocks, or Cenozoic volcanic rocks. This observation is similar to studies in nearby areas (e.g., LANGENHEIM *et al.* 2009 and MICKUS and JAMES 1991). Death Valley is characterized by a magnetic low in the central Death Valley graben (anomaly 1, Fig. 2) between a magnetic high within the Black Mountains (anomaly 2) and the northern Panamint Mountains (anomaly 3). The magnetic highs mainly occur over Precambrian lithologies, Mesozoic granites and Tertiary volcanic rocks in the Black Mountains (JENNINGS 1977). Within the northern Panamint Mountains, the magnetic anomalies occur mainly over Precambrian lithologies with the highest amplitude anomaly occurring over Mesozoic granites (JENNINGS 1977). A detailed description of all the magnetic anomalies is beyond this study.



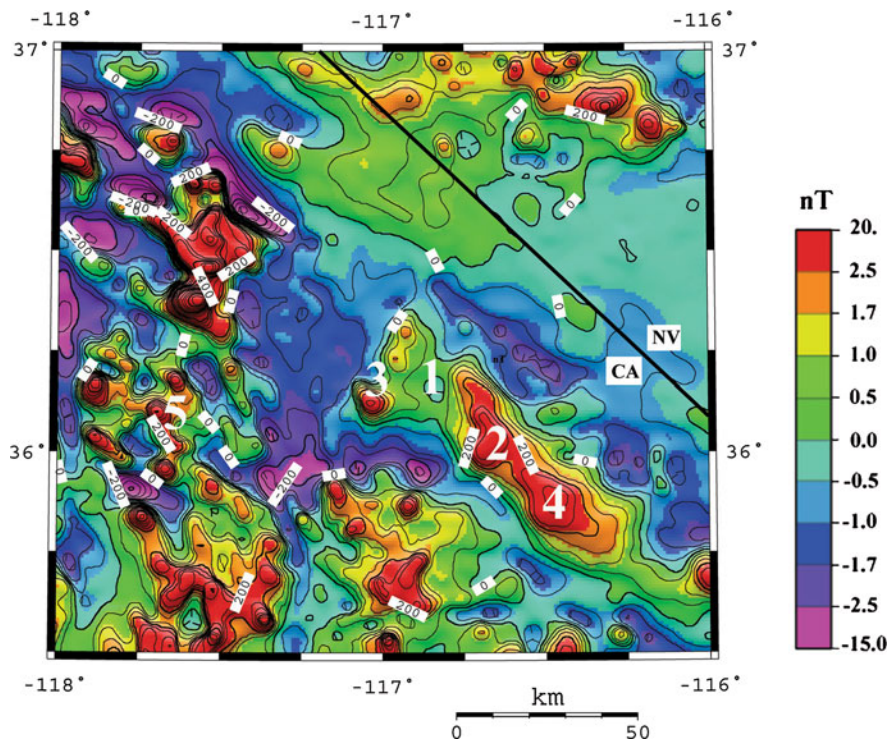


Figure 2

Magnetic anomaly map of the Death Valley region. *Bold numbers* refer to anomalies discussed in the text. Contour interval is 50 nT

Figure 2 shows that the southern Death Valley graben corresponds to a magnetic low (anomaly 4), and contrasts with anomaly 1 in the central Death Valley graben which is a local low that is superimposed on a regional magnetic high. The location of anomaly 1 corresponds to the location of the midcrustal magmatic body that was described by DE VOOGD *et al.* (1986) and another magmatic body that ends at the southern end of anomaly 1. The lowering of the magnetic anomaly's amplitude across the central Death Valley region may be caused by the thick sediments (2–3 km, GEIST and BROCHER 1987), and a lowering of the CPD by the implied magmatic body, this study will assist in determining if the later explanation is possible.

One problem with using aeromagnetic data in determining the CPD is that any given magnetic anomaly may be caused by either increasing temperature that causes the magnetization of the mineral to disappear or by the lack of magnetic minerals at a certain depth (ROSS *et al.* 2006). Without detailed heat flow data and/or drilling information, this is difficult to determine. There are no existing heat flow data within

Death Valley with only sparse data surrounding it (BLACKWELL and RICHARDS 2004) (Fig. 1) and analyzing aeromagnetic data may be the best way to estimate the heat flow variations within the Death Valley region. To assist in determining if there are deep magnetic sources, we made a residual magnetic anomaly map (Fig. 3) by constructing an upward continued grid (50 m above the flight line elevations) and subtracting it from the total field magnetic grid. BLAKELY *et al.* (2011) used this method, which is equivalent to the vertical derivative technique, as a residual magnetic anomaly map to emphasize anomalies due to shallow sources along the western margin of the Columbia River Plateau Basalts in central Washington. The residual magnetic map also shows most of the anomalies have a northwest trending component that is parallel to the known strike-slip faulting in the region. We did not show the resulting regional magnetic anomaly map as it is identical in shape and amplitude of the anomalies seen on Fig. 2 but this map indicates that there are several magnetic anomalies that may be related to deep magnetic sources.

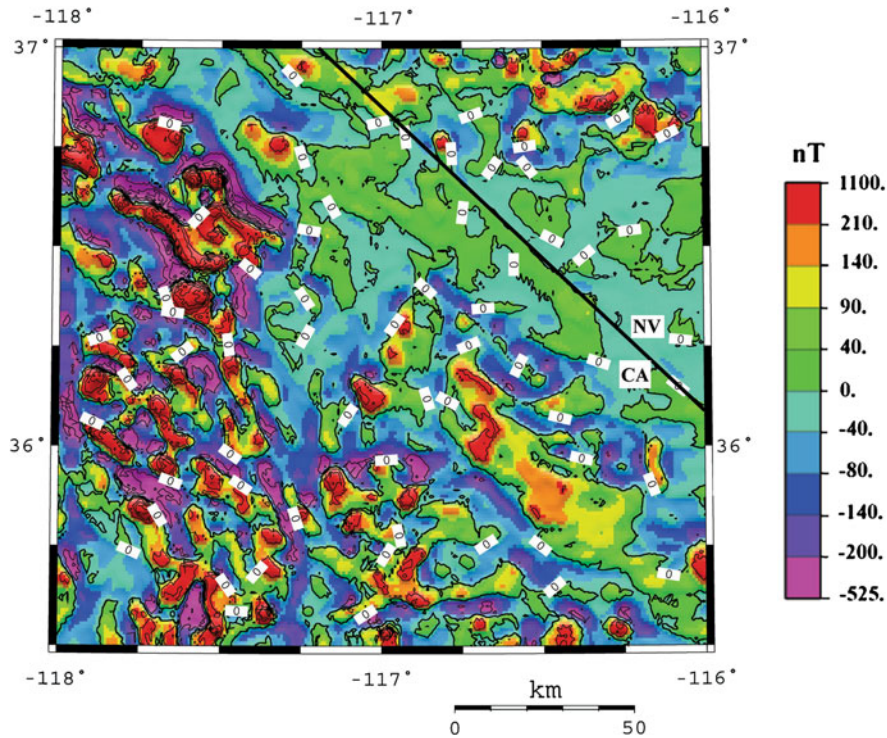


Figure 3

Residual magnetic anomaly map of Death Valley and surrounding regions. Contour interval is 5 nT

#### 4. CPD Analysis

##### 4.1. Spectral Analysis

Spectral methods have been the most commonly used method in determining the depth to the Curie isotherm. These methods are best in determining the regional CPD by examining the spectral properties of the magnetic anomalies over relatively large regions (SHUEY *et al.* 1977; BLAKELY 1988). The main problem with these methods is that small scale variations in the CPDs, and the depth to the bottom of a magnetic source are difficult to determine (BLAKELY 2012, personal communication). In general, the area analyzed to determine the depth to the bottom of a magnetic source must be at least three to four times the depth to that source (BOULIGAND *et al.* 2009). The CPD within the Death Valley region may be shallow as large scale CPD studies that covered the state of California (ROSS *et al.* 2006) and the western US (BOULIGAND *et al.* 2009) showed that the Death Valley

region is between a region with CPDs ranging from 5 to 9 km and 10 to 16 km. The shallower depths may allow for a more detailed study by spectral methods.

To estimate the bottom of magnetic sources, the method of TANAKA *et al.* (1999) and MANEA and MANEA (2011) was used. As suggested by RAVAT *et al.* (2007) the data were not filtered to remove regional fields or the lowest wavenumbers of the spectra were used in the analysis. TANAKA *et al.* (1999) and MANEA and MANEA (2011) based their studies on the methods of BHATTACHARYYA and LEU (1975) and OKUBO *et al.* (1985). TANAKA *et al.* (1999) showed that by calculating the radially averaged 2D power density spectra of the magnetic anomalies of a region, the depth to the bottom of a magnetic source could be estimated. Determining the top of a magnetic source can be done by plotting the radially averaged power density spectra ( $\ln [\Phi_{\Delta T} (kl)^{1/2}]$ ) and fitting a straight line through the higher wavenumber portions ( $0.5\text{--}0.8 \text{ rad km}^{-1}$ ) of the curve. The depth

to the centroid of a magnetic source is determined in a similar fashion by plotting  $(\ln [\Phi_{\Delta T} (|k|)^{1/2}]/|k|)$  and then fitting a straight line through lower wavenumbers ( $0.02\text{--}0.3 \text{ rad km}^{-1}$ ). The basal depth of the magnetic source is then calculated using  $Z_b = 2Z_0 - Z_t$ , where  $Z_t$  is the top, and  $Z_0$  is the centroid of a magnetic source, respectively.

Since we are attempting to determine CPDs of relatively small features (e.g., Death Valley magma chamber), we need to use small windows to estimate the radially averaged power density spectra. Previous studies (ROSS *et al.* 2006; BOULIGAND *et al.* 2009) that included the Death Valley region used a  $100 \times 100 \text{ km}$  window to show that the CPDs ranged from 8 to 18 km. However, such a large window is too large to analyze small scale CPD variations (RAVAT *et al.* 2007), so a  $55 \times 55 \text{ km}$  window was used that may provide reliable estimates of the CPDs of less than 15 km. Additionally, as suggested by TANAKA *et al.* (1999) to provide more consistent results, we overlapped our analysis regions by 10 km on each side. However, such a window will not be able to separate depths in a given region if there are depths to magnetic bodies both less and greater than 15 km.

Figures 4 and 5 show two examples of the power spectrum analysis from two different regions to determine the depths to magnetic sources within and surrounding Death Valley. One problem with the spectral methods is determining exactly where to measure the slope as slight variations in the location of the slope can lead to different depths (RAVAT *et al.* 2007). This is especially true when trying to estimate the centroid of the magnetic source from the lower wavenumbers. To test the error in our results, we measured the high and low wavenumber slopes at three different locations and determined the CPD. The range in values for the top of the magnetic body varied in most cases by 0.2 km while the range in depth values for the centroid varied by 1.0–1.5 km. These above errors would lead to potential errors between 1.0 and 3.0 km in the CPDs shown in Fig. 6.

Figure 6 shows the results of the power spectrum analysis to determine the bottom of magnetic sources within and surrounding Death Valley. The number in the center of each half degree blocks represents the depth to the magnetic source. The estimated depths

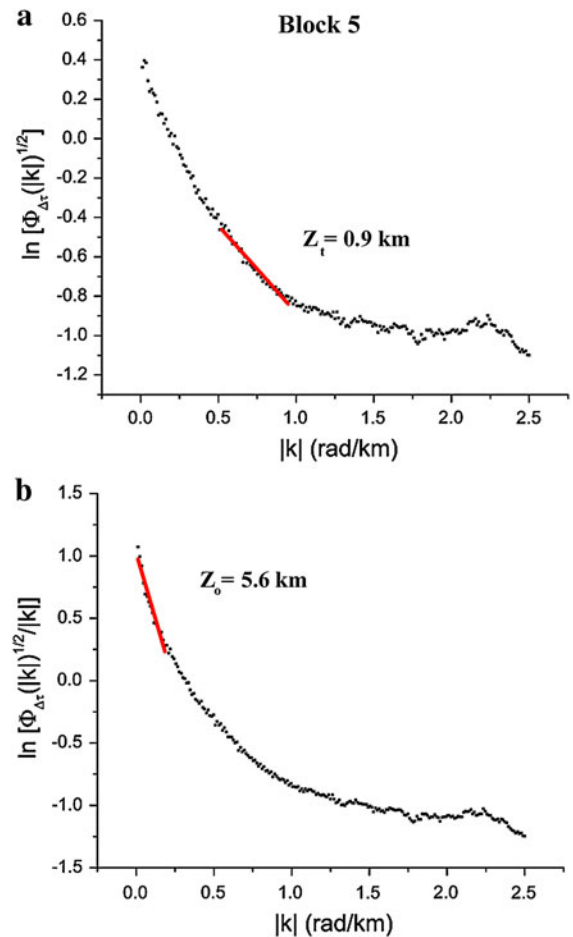


Figure 4

Example of the spectra **a** for the centroid of the magnetic source and **b** for the top of the magnetic source that were used to estimate the depth to the Curie point using the magnetic data shown in Fig. 2. The data are from block 5 (Fig. 6)

range from 7.0 km in block 1–16.1 km in block 12. These numbers roughly agree with the results of BOULIGAND *et al.* (2009) who found using a larger window that the east and northeast portion of our study area had depths greater than 15 km while those to the west averaged less than 12 km. Of particular interest is block 8 where a depth of 14.5 km for central Death Valley was determined. This depth is surprising considering there may be a magma chamber at 15 km in depth (DE VOOGD *et al.* 1986) and shows the limitation of the spectral method in imaging spatially small crustal CPD anomalies. The  $55 \times 55 \text{ km}$  window encompassed the large amplitude magnetic anomaly over the Black Mountains (anomaly 2, Fig. 2) which is probably due to a deeper

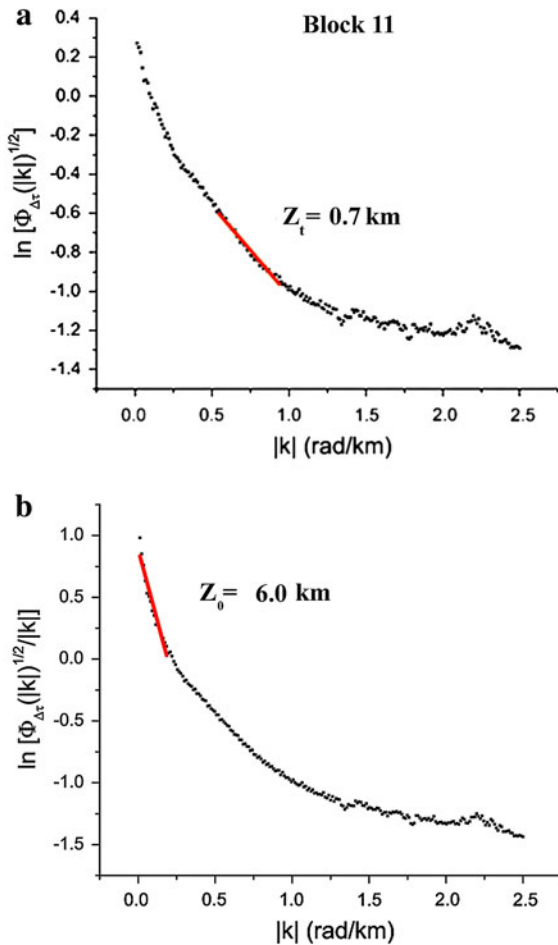


Figure 5

Example of the spectra **a** for the centroid of the magnetic source and **b** for the top of the magnetic source that were used to estimate the depth to the Curie point using the magnetic data shown in Fig. 2. The data are from block 15 (Fig. 6)

source (this will be discussed below). The resulting spectral analysis thus averaged the suspected shallow depth over central Death Valley and the deeper depths over the Black Mountains. However, the 7.8 km depth found for block 2 agrees with 2D MT models (WAMALWA 2011) within the Coso geothermal region who found a low resistivity region at approximately 7.0 km that corresponds to a partially molten region. Additionally, the shallow depths (10.3 km) found in block 7 correspond to a region with known large hot springs (WAMALMA *et al.* 2010) that suggests the existence of a heat source within the upper crust. However, given the limitations in delineating smaller scale variations of the CPDs using the

spectral methods, we will explore inversion methods in determining these depths.

#### 4.2. Inversion

The second method that is commonly used in determining the CPD is modeling magnetic anomalies due to isolated magnetic bodies. This approach has been used by BHATTACHARYYA and LEU (1975) who used flat bottomed vertical prisms; BYERLY and STOLT (1977) who modeled bodies of rectangular or cylindrical shapes; SHUEY *et al.* (1977) who modeled vertical prisms, and HONG (1982) and MICKUS (1989) who used inversion to determine the bottom of arbitrarily shaped 2D and two and one-half dimensional bodies, respectively. The above methods, except HONG (1982) and MICKUS (1989), used a flat upper and lower surface that may be an oversimplification of the problem and produce errors in any depth calculations. Additionally, another problem with the above methods is that they model an anomaly due to an isolated body that requires performing a regional-residual anomaly separation that usually introduces some sort of error in determining the true anomaly.

The above methods of modelling individual positive magnetic anomalies to determine the CPD involves selecting anomalies that may correspond to deep sources. HONG (1982) and MICKUS (1989) selected positive magnetic anomalies that occurred over granitic and/or metamorphic lithologies and not over volcanic rocks whose thickness may not be great enough to extend to the CPD. In some regions, there may not be enough suitable anomalies to accurately determine regional CPD variations. To overcome the above limitations on the modelling methods, a 3D inversion of the magnetic anomaly data (Fig. 2) and elevation data using the algorithm of LI and OLDENBURG (1996) was performed to estimate the depth and geometry of the sources of the magnetic anomalies. To obtain reliable solutions without outside constraints, different inversion parameters (e.g., weighting of the data, data errors, choice of objective function, starting model and size of model mesh) must be and were considered. These parameters were varied to test the consistency of our models with the geology. Wrong choices of these parameters could lead to results that



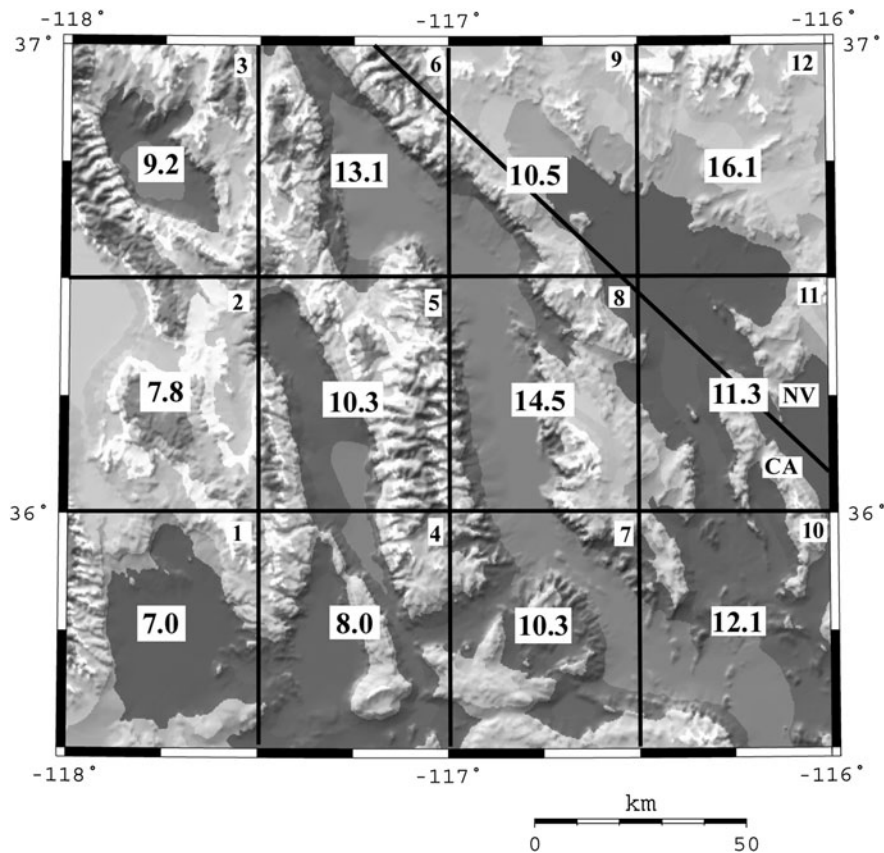


Figure 6

Topographic map of Death Valley and surrounding areas. The **bold numbers** in the center of each  $0.5^\circ$  by  $0.5^\circ$  squares represent the bottom of magnetic sources as determined by the power spectrum analysis. The **bold lines** in the *upper right corner* of each  $0.5^\circ$  by  $0.5^\circ$  squares represent the reference number of the block

have no relationship to the actual geology despite a low RMS error (LI and OLDENBURG 1996).

The 3D inversion of potential field data may require a large amount of memory, and thus time, if a large number of body cells and data points are used. Since we are trying to model a large area, we broke the model into two regions. The regions which overlapped by  $0.5^\circ$ , range from  $118.25^\circ\text{W}$ ,  $35.5^\circ\text{N}$  to  $116.75^\circ\text{W}$ ,  $37.25^\circ\text{N}$  for model 1, and  $117.25^\circ\text{W}$ ,  $35.5^\circ\text{N}$  to  $115.75^\circ\text{W}$ ,  $37.25^\circ\text{N}$  for model 2. For each model, the minimum sized cell block is 300 m which gradually increases toward the edges and bottom of the models. The maximum depth of the blocks was set at 40 km. We tried several starting models (magnetic susceptibilities) in order to determine which features in the model produced by the inversion process were consistently determined. To show the final models,

various slices were made (Fig. 7) to illustrate the main features of the models. The various slices through the final models are shown in Figs. 8, 9, 10, 11. The observed and calculated magnetic anomalies due to the two magnetic models are shown in Fig. 7. As with all geophysical methods and especially potential field methods the resolution of the boundaries decreases with depth so depth weighting is necessary in order to avoid having the bodies being concentrated near the surface (LI and OLDENBURG 1996). This is especially true for unconstrained inversions. To test the resolution of our models, we inverted the data using different starting models with and without depth weighting. For each model we ran ten inversions and determined the depth to the bottom of the magnetic bodies under central Death Valley, the Black Mountains and the Panamint Range. Under the central Death Valley, the

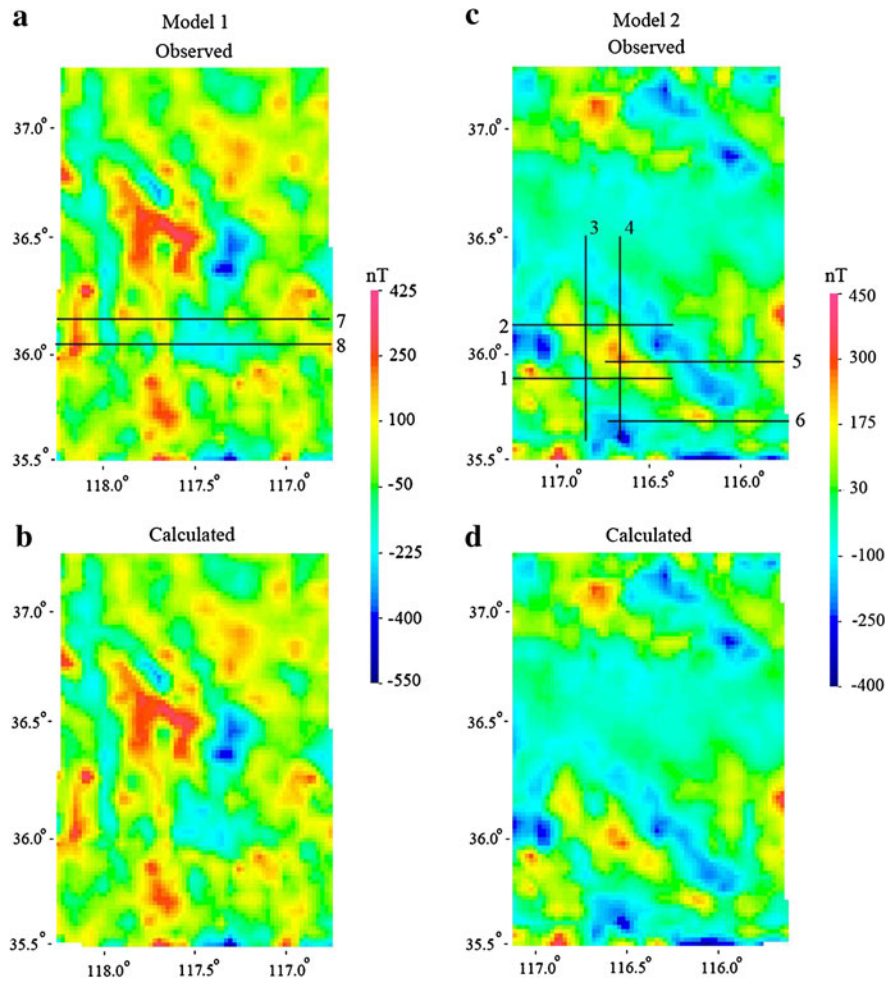


Figure 7

Observed and calculated magnetic anomalies of model 1 (a and b) and model 2 (c and d). Also shown are the locations of the cross-sections (1–8) used to illustrate the 3D magnetic inversion model

depth varied by 1.5 km while under the Panamint Range, the depth varied by 2.5 km.

Figures 8, 9, 10, 11 indicate that the depth to the bottom of magnetic sources range from 4 to 5 km to approximately 23 km (Fig. 5b). In general, the deeper magnetic sources are found under the larger amplitude magnetic anomalies (Fig. 2). Additionally, the deeper magnetic sources are located under Precambrian lithologies (JENNINGS 1977) (e.g., Panamint Mountains, southern Argus Range, and northern Black Range) or Mesozoic intrusive rocks (northern Argus Range). The one exception is the Precambrian lithologies in the southern Black Range associated with shallower depths (<10 km) which may indicate that the depth may be related to a lithological

boundary. The shallowest depths (5–7 km) are found within Death Valley and the Panamint Valleys. The central Death Valley region (Fig. 6) has depths of approximately 5–7 km while the southern Death Valley also has shallow magnetic depths but in general, they are deeper (8–9 km). Similar depths are found in the Panamint Valley to the west while the shallow depths (6–7 km) are associated with the Coso geothermal field and regions to its north-northeast.

### 5. Discussion

Curie point depth analyses can be used to estimate the thermal and/or geologic structure of a region. Our

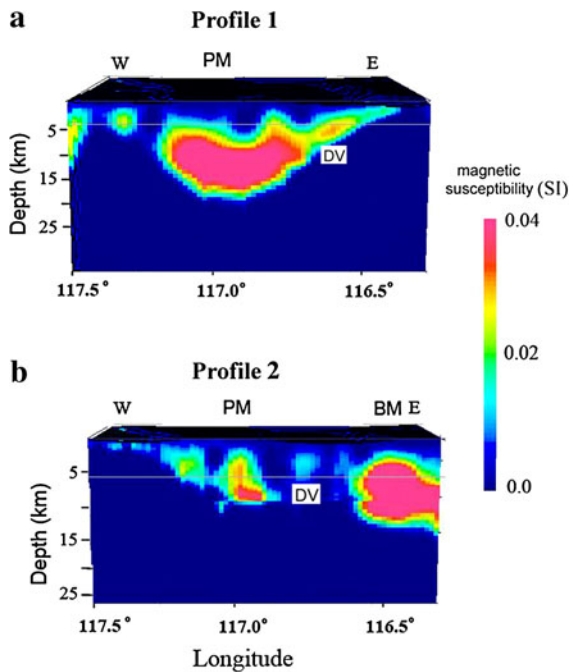


Figure 8

East–west slices (a profile 1, b profile 2, Fig. 7) of the 3D inversion model for the region centered on Death Valley. *DV* Death Valley, *PM* Panamint Mountains, *BM* Black Mountains

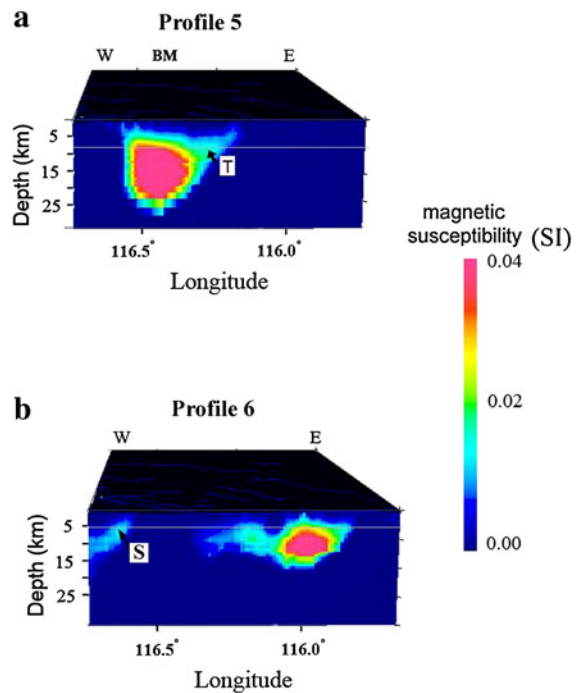


Figure 10

East–west slices (a profile 5, b profile 6, Fig. 7) of the 3D inversion model east of Death Valley. *S* Saratoga Springs, *T* Tecopa Springs, *BM* Black Mountains

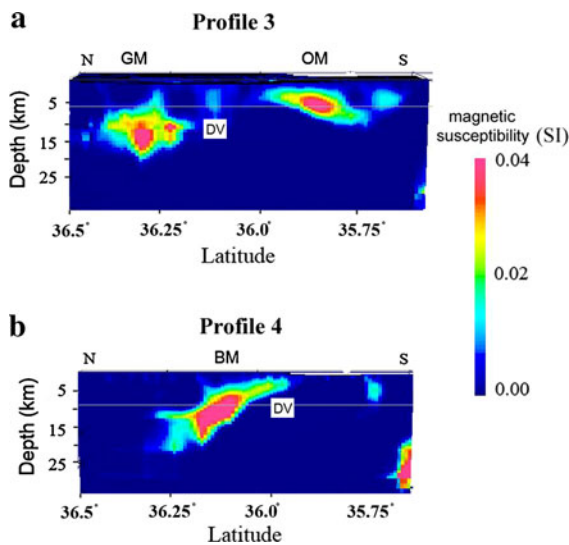


Figure 9

North–south slices (a profile 3, b profile 4, Fig. 7) of the 3D inversion model for the region centered on Death Valley. *DV* Death Valley, *GM* Grapevine Mountains, *BM* Black Mountains, *OM* Owlhead Mountains

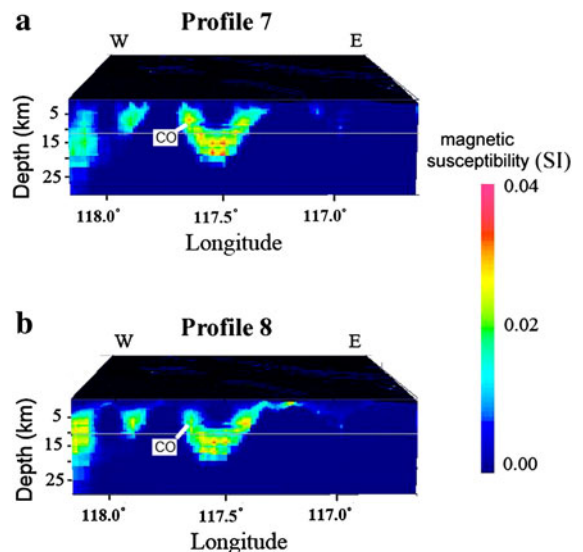


Figure 11

East–west slices (a profile 7, b profile 8, Fig. 7) of the 3D inversion model west of Death Valley. *CO* Coso geothermal field

analysis of the CPD in the Death Valley region was attempted with the traditionally used power density spectrum methods and by inverting magnetic data for 3D magnetic susceptibility distributions. The power density spectrum method roughly estimated the CPDs determined by the inversion (Fig. 12) in several regions but probably overestimated these depths in several regions including Death Valley (14.5 km, Figs. 6, 12) and the Panamint Valley (10.3 km, Figs. 6, 12). However, in other regions such as the Coso geothermal region and the southern Death Valley region, the spectral methods produced depths similar to the inversion results given the error range of both methods. The problem with the power density spectrum methods is that they cannot separate the depths to the top and bottom of magnetic sources unless the region analyzed is larger than the maximum depth to the bottom of a body (BLAKELY, personal communication, 2012) and thus cannot image small scale variations within the CPDs. This limitation has been noted by other authors (e.g., TANAKA *et al.* 1999; BOULIGAND *et al.* 2009). However, the power density spectrum method did produce results that roughly agreed with other investigations in the region (ROSS *et al.* 2006; BOULIGAND *et al.* 2009) with shallower depths (<10 km) in the central and southwestern portions of the study area and depths greater than 15 km elsewhere. The shallow CPDs (block 2, 7.8 km, Fig. 6) in the Coso geothermal region agrees with the high heat flow values (>200 mW m<sup>-2</sup>) (Fig. 3).

The 3D inversion models (Figs. 8, 9, 10, 11) provided more spatially detailed depths to the bottom of the magnetic sources than the power spectrum method. Assuming that most of these depths represent the Curie point, the CPDs of the Death Valley and Coso geothermal region are shown in Fig. 12. The values were selected by determining the maximum depths of the bodies shown in Fig. 8, 9, 10, 11. Additional depths were selected from other profiles that are not shown. Clearly, the shallowest depths (<8 km) are in Death Valley and the Panamint Valley to the west. The shallowest values are associated with the central Death Valley and overlie the possible magma chamber (DE VOOGD *et al.* 1986). If these depths are due to elevated temperatures then the existence of a magma chamber is likely. The Coso

geothermal region is also associated with shallow CPDs; however, shallower depths occur to the northwest that suggests high heat flow also exists in this region. Additional shallow CPDs are found (~8.5 km, Fig. 12) in the southern Death Valley and the Tecopa Valley where they occur over with hot springs that lie at the intersection of north–south and east–west trending faults (WAMALWA *et al.* 2010). The shallow CPDs in these regions imply that more extensive elevated temperature regions lie below each region.

The estimate of heat flow from CPD analyses is dependent on the temperature used for the most common magnetic mineral, magnetite. The commonly used value is 580 °C (HAGGERTY 1978), we used the one-dimensional conductive heat flow equation where the temperature gradient is constant. The equation (Fournier's law) is

$$q = k \, dT/dz, \quad (1)$$

where  $q$  is the heat flux,  $dT/dz$  is the temperature gradient and  $k$  is the thermal conductivity. TANAKA *et al.* (1999) showed the Curie temperature,  $C$ , can be defined as

$$C = (dT/dz)D, \quad (2)$$

where  $D$  is the CPD. Provided that there are no heat sources or sinks between the earth's surface and the CPD, the Curie depth becomes

$$D = kC/q. \quad (3)$$

An additional variable that affects the estimated heat flow is the thermal conductivity. Thermal conductivity normally ranges between 1.3 and 3.3 W m<sup>-1</sup> K<sup>-1</sup> for granites to 2.5–5.0 W m<sup>-1</sup> K<sup>-1</sup> for metamorphic rocks (LILLIE 1999). TANAKA *et al.* (1999) used a range of  $kC$  (1,000–2,500 W m<sup>-1</sup>) values to show that for high heat flow values (>150 mW m<sup>-2</sup>) in spatially small areas (e.g., individual composite volcanoes) the power density spectrum method may not be able to image local CPDs.

However, the 3D inversion results imply that spatially small CPDs may be estimated. Using Eq. 3, a CPD of 7.8 km and heat flow value of 220 mW m<sup>-2</sup> [from the Coso geothermal region (BLACKWELL and RICHARDS 2004)], the thermal conductivity



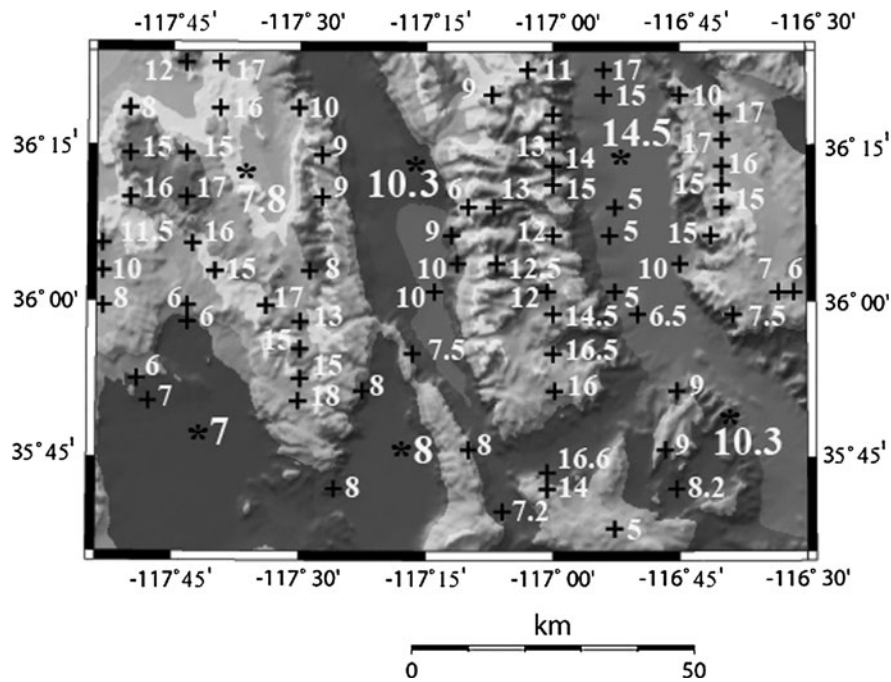


Figure 12

Topographic map showing the Curie point depths in kilometers (+) within the Death Valley region estimated from the 3D magnetic models (Figs. 7, 8, 9, 10, 11). Also shown are the location (\*) of the CPDs in kilometers determined from the spectral analysis (Fig. 6)

for this region is estimated to be between  $3.1$  and  $3.9 \text{ W m}^{-1} \text{ K}^{-1}$ . Using these thermal conductivities and a CPD of  $6.0 \text{ km}$ , the estimated heat flow within the central Death Valley region varies between  $262$  and  $338 \text{ mW m}^{-2}$ . The similar CPDs found in Panamint Valley, southern Death Valley and in the Tecopa Hot Springs region suggest that these regions will also have heat flow values over  $200 \text{ mW m}^{-2}$ .

The determination of the CPDs (Figs. 8, 9, 10, 11) indicates that if the bottom of the magnetic sources is indeed the CPD, then the shallow CPDs may be related to elevated heat flow values within Death Valley, Panamint Valley, and the Tecopa Hot Springs region. These values occur within relatively narrow regions and suggest that the higher heat flow values are concentrated within the faulted basins. The overall heat flow of the Death Valley region has been interpreted to be high ( $>100 \text{ mW m}^{-2}$ ) (Sass *et al.* 1994) and our results suggest that the heat flow regime in the Death Valley region may be more complicated. There seems to be areas with narrow regions of very high heat flow values in between regions (CPDs between  $15$  and  $20 \text{ km}$ ) of more

moderate but still relatively high heat flow values ( $90\text{--}135 \text{ mW m}^{-2}$ ). The areas of very high heat flow in central Death Valley and the Coso geothermal region are probably related to the shallow magma chamber that has been imaged by seismic reflection (central Death Valley, de Voogd *et al.* 1986) and MT data (Coso, Wamalwa, 2011). Based on our CPD results the other areas with very high heat flow (e.g., southern Death Valley, Panamint Valley, Tecopa Hot Springs) may have magma chambers (or a partially molten intrusive body) at shallow ( $\sim 15 \text{ km}$ ) depths. However, Serpa *et al.* (1988) suggested that the high amplitude seismic reflectors in the southern Death Valley region are not related to a magma body but to deep detachment zones. The deeper CPD depths ( $9 \text{ km}$ ) in the southern Death Valley, Panamint Valley, and Tecopa Hot Springs may suggest that even though the heat flow may be elevated it may not be due to a magma body. A CPD analysis cannot determine between these two models and additional detailed geophysical investigations (e.g., MT and seismic reflection) are needed to determine if there is some type of partially molten body exists at midcrustal depths within the Death Valley region.

## 6. Conclusions

The aeromagnetic field of Death Valley and surrounding regions was analyzed to determine the bottom of magnetic bodies and relate these to the depth to the Curie isothermal point. Two methods were applied: (1) the traditionally used 2D spectral methods and (2) 3D magnetic inversion. The spectral methods determined that the CPD varied between 7 and 16 km with the deeper values being east and northeast of Death Valley. Within the central Death Valley region, the CPD is 14.5 km but the analysis area included both central Death Valley and Precambrian outcrops within the Black Mountains. Even though these values agreed with more regional studies, the spectral methods could not image smaller scale variations in the CPD as seismic reflection studies indicated that a shallow (15 km) magma body underlies the central Death Valley region and such a body should lower the CPD in this region. The lateral resolution limitation of the 2D spectral methods in determining small scale variations in the CPD led us to use the 3D inversion method. The results of the 3D inversion showed that the CPD was shallowest (5 km) over the central Death Valley while shallow depths (7–9 km) also occur over the Panamint Valley, southern Death Valley, Coso geothermal field, and the Tecopa hot springs. Deeper CPD values (14–23 km) were found over granitic and Precambrian lithologies in the Black Mountains, Panamint Range, Argus Range, and the Grapevine Mountains. Assuming that the CPD depths are truly related to the Curie isotherm temperature and not magnetic lithological boundaries, the estimated heat flow for the 5–8 km depths was determined to be over  $200 \text{ mW m}^{-2}$  and between 100 and  $150 \text{ mW m}^{-2}$  for the deeper CPD values. The very high heat flow values in the central Death Valley region supports the existence of a magma body at 15 km depth. While the slightly deeper CPD values in the southern Death Valley, Panamint Valley and Tecopa Hot Springs region also implies very high heat flows, magma may not be present in these based on limited seismic reflection data in southern Death Valley. To determine if magma is present at midcrustal levels in these region, additional geophysical analyses including MT and seismic reflection are needed. While the spectral

and 3D inversion methods produced similar CPDs in several regions, the 3D inversion method produced higher lateral resolution of the CPD.

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