Identifying Faults and Fractures at Different Depths from Airborne Gravity Gradient Surveys over Kujyu and Kirishima Geothermal Areas, Japan

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ABSTRACT

Airborne gravity gradiometer surveys were carried out by JOGMEC (Japan Oil, Gas and Metals National Corporation) to investigate the Kujyu and Kirishima geothermal areas in Kyushu (southern part of Japan). An interpretation of the gD_FOURIER_2p3 component of the airborne gradiometer data (equivalent to the Bouguer gravity anomalies) was carried out using some geophysical filtering methods available in the Geosoft Oasis Montaj software.

Low pass filtering with upward continuation was used to separate components of anomalies related to sources at different depths. Another filtering technique, first vertical derivative (1VD) was applied to the processed airborne gravity data to make enhance lineaments.

The lineaments of gravity anomalies are inferred to be associated with fault and/or fracture structures. The final result of this work is a geological structure map of Kujyu and Kirishima area showing the intense fault/fracture zones at four different levels: close to ground surface, +1,000 mRL, +500 mRL, 0 mRL, and -2,000 mRL.

1. INTRODUCTION

HeliFalcon™ Airborne gravity gradiometer surveys were carried out during October and November 2013 by CGG Aviation (Australia) Pty Ltd for the Japan Oil, Gas and Metals National Corporation (JOGMEC) over the Kujyu and Kirishima, Kyushu Japan (CGG Australia PTY Ltd, 2013). The average terrain clearance in the Kujyu area was 144 m and in the Kirishima area was 153 m. Geosoft database files of these surveys were available for this study from Prof T Tosha, the co-author of this paper. In this study we use only gD_FOURIER_2p3 (equivalent to gravity Bouguer anomalies reduced using terrain density of 2.3 g/cc) and DTM values listed in the database, as the purpose of this research was to develop and test a simple but useful interpretation technique that will also applicable to the gravity data obtained from ground gravity surveys. Ground gravity measurements are one of the most common geophysical surveys and had been carried out over almost all the world's geothermal areas.

Figure 1 shows the locations of Kujyu and Kirishima airborne gravity gradiometer survey areas in Kyushu, Japan.

A similar interpretation approach has been applied to ground gravity survey data over the Reporoa Basin, New Zealand (Soengkono, 2012)

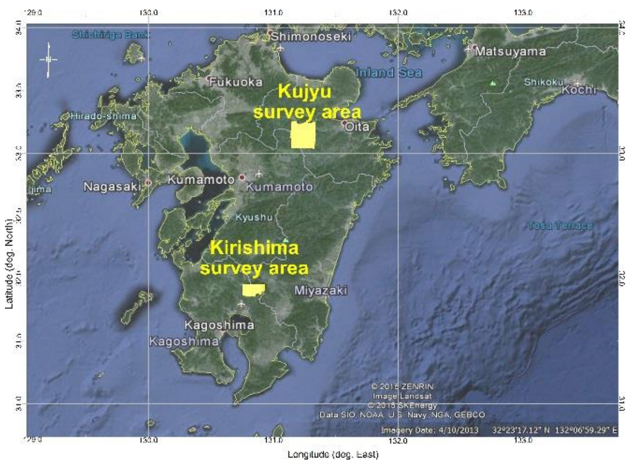

Figure 1: Location map of Kujyu and Kirishima survey areas, Kyushu, Japan.

2. DATA PROCESSING

2.2 Gravity anomalies maps of Kujyu and Kirishima

As mentioned in the introduction, we use the gD_FOURIER_2p3 available in the geosoft database from JOGMEC to represent the Bouguer gravity anomalies over Kujyu and Kirishima study areas.

The gD_FOURIER_2p3 values were gridded at 100 m grid size listed in the geosoft database for the Kirishima and Kujyu survey areas are gridded using the Geosoft Oasis Montaj software at 100m grid size. These gridded data are used to create the Bouguer gravity anomalies maps of Kujyu and Kirishima areas, which are presented in Figures 2 and 3.

The Bouguer gravity anomalies shown in Figures 2 and 3 were progressively upward continued from 0th level (0m = original data) to the 10th level (3462 m) to provide ground information to about 2,000 m depth (Table 1).

We introduce here a parameter "*diffUpc*" for each layer which is equal to data upward continued to the layer level subtracted by data upward continued to the level directly higher. We interpret the diffUpc to be the component of Bouguer gravity anomaly caused by anomalous bodies within the layer with top and bottom also listed in Table 1. For example, the *diffUpc* values of layer no 4 (data upward continued to 253 m subtracted by data upward continued to 483 m) are caused by anomalous bodies located within a layer with top at depth 94 m and bottom at 184 m beneath the mean ground level of the entire survey area (assuming that the survey area does not contain extreme topography). These depths are transformed to RL ("reduced level"; positive RL for the levels above the sea level, negative RL for below sea level). For this, we used the mean ground level of 755 mASL (m above sea level) at the Kujyu area, at the Kirishima area it is 725 mASL.

2.1 Apparent density

From the grids of *diffUpc* values of each layer, we estimate approximate density contrasts, or "apparent density contrasts" ($\Delta\sigma_{app}$), within each 100 m grid cells using equation from "Bouguer plate Formula" (see, for examples, Dobrin and Savit, 1984; Kearey and Brooks, 1984; Telford et all, 1976):

$$\Delta\sigma_{app} = diffUpc/(0.04185*\Delta h), \qquad (1)$$

where: Δh is the thickness of layer

Equation (1) uses *mixed units*: *metres* for ΔH and *mgals* $(10^{-5}$ *N/kg)* for *DiffUpc*; the $\Delta\sigma_{app}$ obtained from equation (1) is in *grams/cubic centimetres (g/cc)*. The apparent density is the apparent density contrasts plus (or minus) the terrain density used for the processing of the Bouguer anomalies (ie. 2.30 gram/cc for the Kujyu and Kirishima areas).

3.1 Determination of sub-surface apparent density of the Kujyu and Kirishima areas

The sets of diffUpc obtained for Kujyu and Kirishima areas (Section 2.2) were transformed to apparent density contrasts using equation (1). Using the Oasis Montaj software, the apparent density contrasts were gridded 3D with the UTM zone 52 Easting and Northing (transformed to metres) as X (easting) and Y (northing) axes and the depth of RL of each layer (see Sub-Section 2.2) as Z (vertical axis) to obtain apparent density contrasts voxels of 100 m size for Kujyu and Kirishima areas which, in this study where we are dealing with density gradients, are essentially equivalent to the apparent density voxels.

Once we obtain the 3D voxels, it become easy to extract lateral section of apparent densities at any level. In this study, we extracted the lateral sections at levels to obtain maps of apparent densities at -2,000, 0, +500 , and +1,100 m RL to obtain maps that show variation of apparent density at those levels for both Kujyu and Kirishima areas.

Horizontal gradients were computed for each map to show the patterns of density changes that can indicate lateral lithological changes or vertical faulting within each layer.

Further filtering using first vertical derivative (1VD) (available in the Geosoft Oasis Montaj software) was applied to each horizontal gradient of apparent density maps to enhance gradients within each leyer. These processing provided maps of detailed lateral lithological changes and/or vertical faulting in each layer, which are useful to interpret zones of intense sub-surface vertical permeability in the Kujyu and Kirishima areas.

Table 1. Level of upward continuation and inferred depths of sources.

Layer no.	Level of upward continuation (m)	Depth of mid-level (m)	Depth of top level (m)	Depth of bot level (m)
0	0	3	0	6
1	25	13	6	21
2	58	29	21	46
3	124	62	16	94
4	253	127	94	184
5	483	242	184	338
6	867	434	338	583
7	1463	732	583	946
8	2321	1161	946	1446
9	3462	1731	1446	2079
10	4854	2427	2079	2912
11	6794	3397	2912	4077
12	9514	4757	4077	5708
13	13319	6660	5708	7991
14	18647	9323	7991	11188

Table 2. Kujyu grids' statistics of the first vertical derivative of the lateral gradient of the apparent density (*1VD App Den Gradient*) of the layers at -2,000mRL, -1,500mRL, -1,0000mRL, 0mRL, +500mRL, +1,000mRL and +1,500mRL. All *1VD App Den Gradient values* are in 10^{-9} mgal/m/m (E-09 mgal/m/m).

Mid-Level	**Min value**	**Max value**	**Mean value**	**SD value**	**SD value** *subtracted by* **Mean value**	**Mean value** *subtracted by* **SD value**
-2000 mRL	-0.4079	0.7259	0.0000	0.0252	**0.03**	**-0.03**
-1500 mRL	-0.6798	1.2086	0.0000	0.0336	**0.03**	**-0.03**
-1000 mRL	-1.1325	2.0356	-0.0001	0.0585	**0.06**	**-0.06**
-0 mRL	-4.2654	6.4725	-0.0019	0.2431	**0.25**	**-0.25**
+500 mRL	-21.0486	20.4204	-0.0203	1.8206	**1.84**	**-1.84**
+1000 mRL	-13.8022	15.2517	0.0029	2.7147	**2.71**	**-2.71**
+1500 mRL	-13.4015	15.8166	0.0201	4.7577	**4.74**	**-4.74**

Table 3. Kirishima grids' statistics of the <u>first vertical derivative of the lateral gradient of the apparent density</u> (*1VD App Den Gradient*) of the layers at -2,000mRL, -1,500mRL, -1,0000mRL, 0mRL, +500mRL, +1,000mRL and +1,500mRL. All *1VD App Den Gradient values* are in 10^{-9} mgal/m/m (E-09 mgal/m/m).

Mid-Level	Min value	Max value	Mean value	SD value	SD value *subtracted by* Mean value	Mean value *subtracted by* SD value
-2000 mRL	-0.0711	0.0610	0.0002	0.0091	**0.01**	**-0.01**
-1500 mRL	-0.1772	0.1161	0.0002	0.0159	**0.02**	**-0.02**
-1000 mRL	-0.3661	0.2982	0.0002	0.0301	**0.03**	**-0.03**
0 mRL	-0.8401	0.9388	-0.0013	0.0675	**0.07**	**-0.07**
+500 mRL	-8.0643	12.5739	0.0035	1.0640	**1.06**	**-1.06**
+1000 mRL	-12.4297	17.9716	0.0004	2.4611	**2.46**	**-2.46**
+1500 mRL	-1.6980	3.8651	0.0013	1.7476	**1.75**	**-1.75**

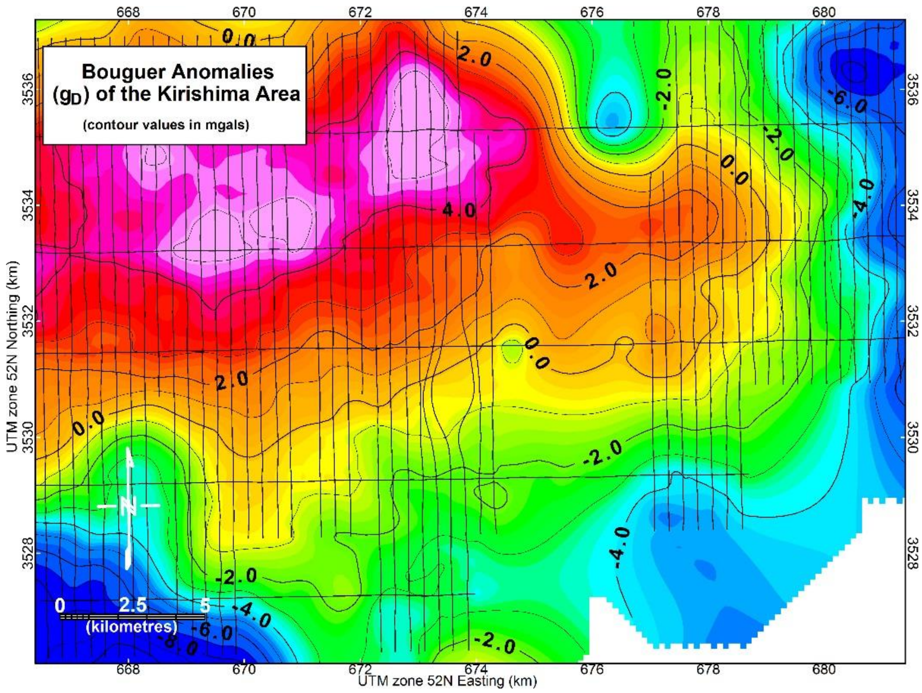

Figure 2: Bouguer Anomalies (gD_FOURIER_2p3) of the Kirishima area. Contour values are in mgals; the flight lines of airborne gravity survey are shown by black lines

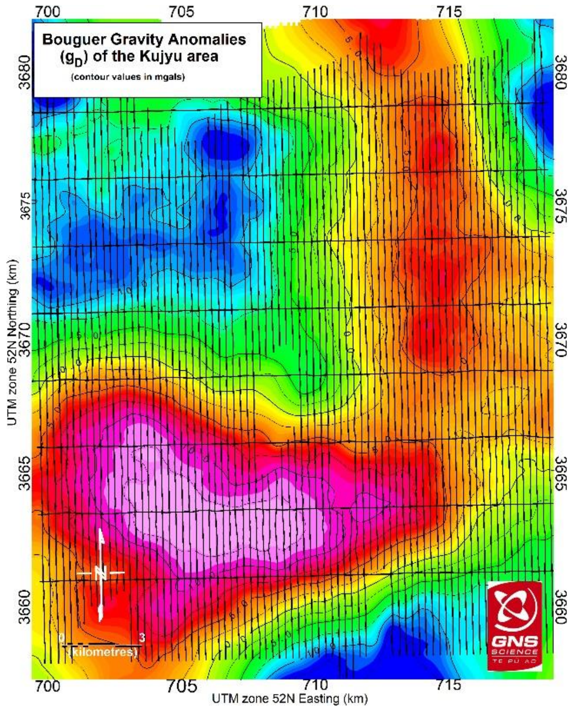

Figure 3: Bouguer Anomalies (gD_FOURIER_2p3) of the Kujyu area. Contour values are in mgals; the flight lines of airborne gravity survey are shown by black lines

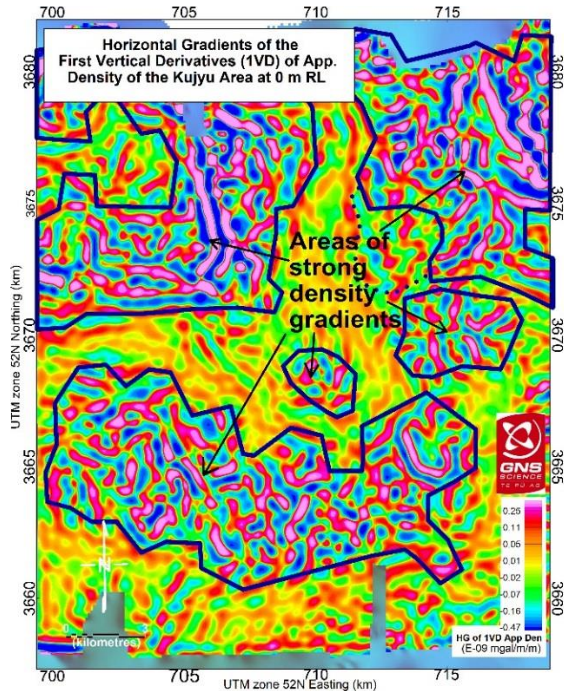

Figure 4: Horizontal gradients of the First Vertical Derivatives (1VD) of App. Density Gradient of Kujyu Area at 0 m RL. The thick blue polygons represent area with strong density gradients, inferred as area with intense vertical lithology boundaries and/or faulting (therefore, high vertical permeability).

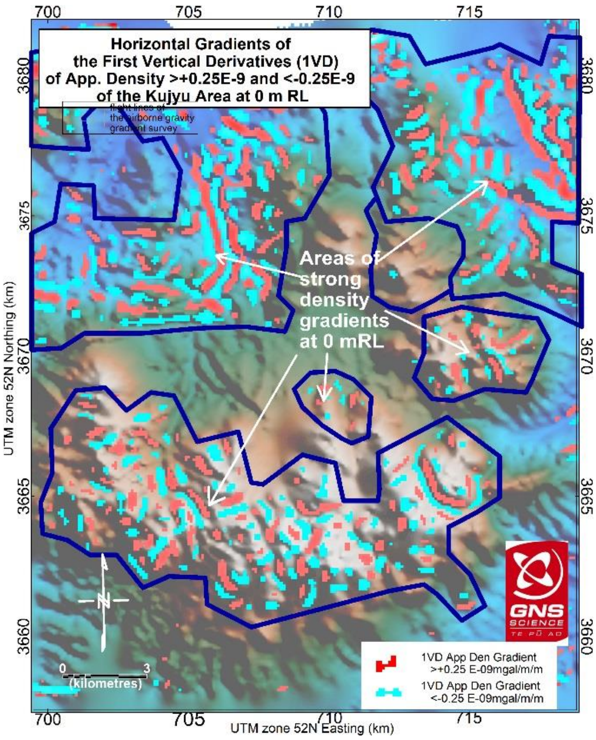

Figure 5: Polygonal enclosures of Strong Horizontal Gadients of the First Vertical Derivatives (1VD) of App. Density Gradient of Kujyu Area at 0 m depth The same polygons are also shown in Figure 4.

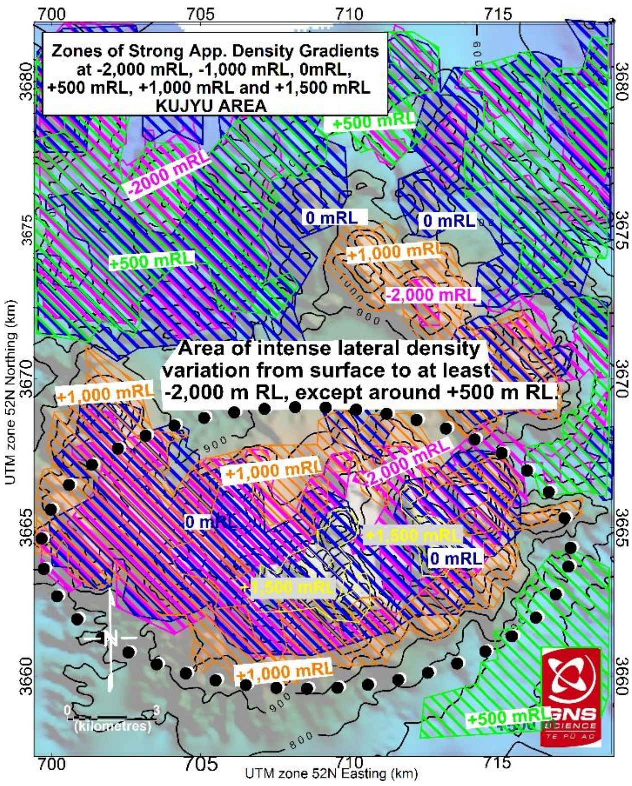

Figure 6: Zones of strong lateral density variations (vertical lithological contacts and/or faulting) which could represent area with intense vertical permeability in Kujyu area at -2,000 mRL, 0 mRL, +500 mRL, and +1,000 mRL. The black contour lines represent topography (contour values in metres).

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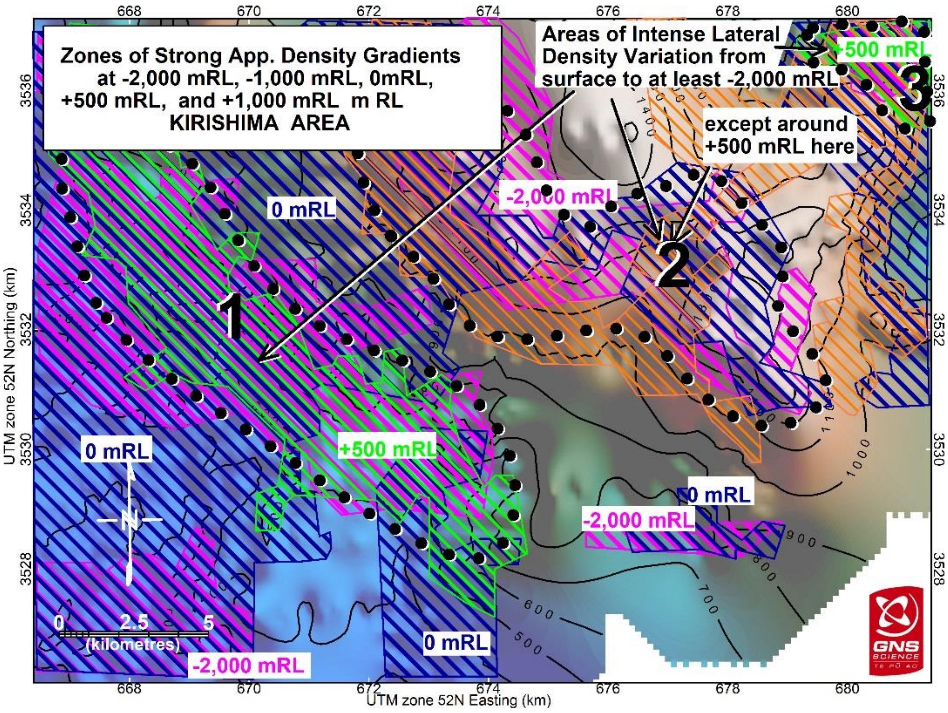

Figure 7: Zones of strong lateral density variations (vertical lithological contacts and/or faulting) which could represent area with intense vertical permeability in Kirishima area at -2,000 mRL, 0 mRL, +500 mRL and +1,000 mRL. The black contour lines represent topography (contour values in metres).

3. DISCUSSIONS

To describe our study at Kujyu and Kirishima area, an example of the determination of zones of intense lateral lithological variation and/or vertical faulting at layer of 0 m RL mid-level at the Kujyu area are discussed below.

We show the horizontal gradients of apparent density at 0 m RL that have been enhanced by 1VD filtering in Figure 4. In Figure 5, only zones of horizontal gradients less than $-25x10^{-9}$ mgals/m/m and greater than $+25x10^{-9}$ mgals/m/m are shown ($\pm 25x10^{-9}$ is the standard deviation of the whole horizontal gradients of layer 0 mRL). We interpret these strong density gradients zones in Figure 5 (marked by the blue polygons) as representative of intense vertical lithological contacts and/or faulting at 0 mRL beneath Kujyu area.

The same process was applied to all other layers (-2,000 mRL, +500 mRL, +1,500 mRL and +1,500 mRL) of the Kujyu area. All the polygons representing zones of strong horizontal gradient at all these levels are plotted together in Figure 6. One area of strong horizontal density variations from the ground surface down to -2,000 mRL in the Kujyu area is shown in Figure 6.

The strong horizontal density variation from ground surface to about -2,000 m RL are also plotted beneath the Kirishima area in Figure 7. Three areas of strong lateral density variations from surface to -2,000 m RL are shown in Figure 7.

These zones of strong lateral density variations in Kyjyu and Kirishima areas can indicate the zones of intense vertical permeability. If deep thermal sources are present beneath these areas, these zones could indicate geothermal up-flows zones that may be targeted by drilling.

It is interesting to note that strong lateral density variation at 500 mRL does not exist in the one area of intense lateral density variation in Kujyu (Figure 6) and in the area 2 in Kirishima (Figure 7). This could reflect the nature of lithology at +500 mRL in these two areas.

4. CONCLUSION

A simple and easy method to identify fault and fractures at different depths from airborne gravity data using data filtering methods available in the Geosoft Oasis Montaj software over Kujyu and Kirishima area, Kyushu, Japan, are introduced and presented in this paper. It appeared that the method can be used to identify areas of intense vertical permeability beneath these two areas.. In many other geothermal areas in the world, airborne gravity survey may not have been carried out because of cost and logistical problems. However, these other geothermal areas are likely to have been surveyed by ground gravity measurements.

The method used in this study would also be directly applicable for the interpretations of data collected from any ground gravity measurements, although the resolution of the results may be less than that obtained over area where data from airborne gravity survey are available.

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