Targeting faults with geothermal wells – why bother?

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ABSTRACT

The principal objectives in drilling geothermal wells are generally to obtain permeability (injection wells), or permeability plus temperature (production wells). A significant number of exploration and production wells are unsuccessful, and that is often because they do not find sufficient permeability. Targeting faults can increase the overall success rate, and increase the productivity of individual wells, if the faults are accurately located and the local tectonics are properly understood.

1. INTRODUCTION

Convective geothermal systems can only exist if the rock units that host them are sufficiently permeable to allow fluids to flow. That fluid flow will utilise inherent primary matrix permeability, plus any secondary structural permeability. Targeting secondary permeability on faults has resulted in some highly permeable production and injection wells, but there are other cases where it has been a lot less successful. Possible reasons why only some wells have been successful when targeting faults are discussed here. The challenge is to accurately predict the locations of permeable zones within a well prior to drilling (Figure 1).

2. IDENTIFYING FAULTS

The major challenge with targeting faults is to accurately locate suitable faults. There are a number of methods that can be used to do this.

2.1 Geological maps

In addition to published and unpublished geological maps, some countries, including New Zealand and the USA, have produced databases of active and recently active faults that are freely available as kmz files for viewing in Google Earth. These might not be sufficiently accurate for well targeting, but are a great place to start. Anyone tasked with targeting wells should also be doing additional field mapping, especially of new road cuts and outcrops around a project site.

2.2 Satellite imagery/air photos

In parts of the world, the best imagery available is that from various satellites, including what is freely accessible on Google Earth. However, only major structures will be visible on satellite images.

2.3 Lidar

Lidar imagery is superior to satellite imagery or air photos because it can image the land surface through vegetation, and so gives an accurate topographic map even in thick forest, and can be artificially shaded using any angle of light to highlight different features.

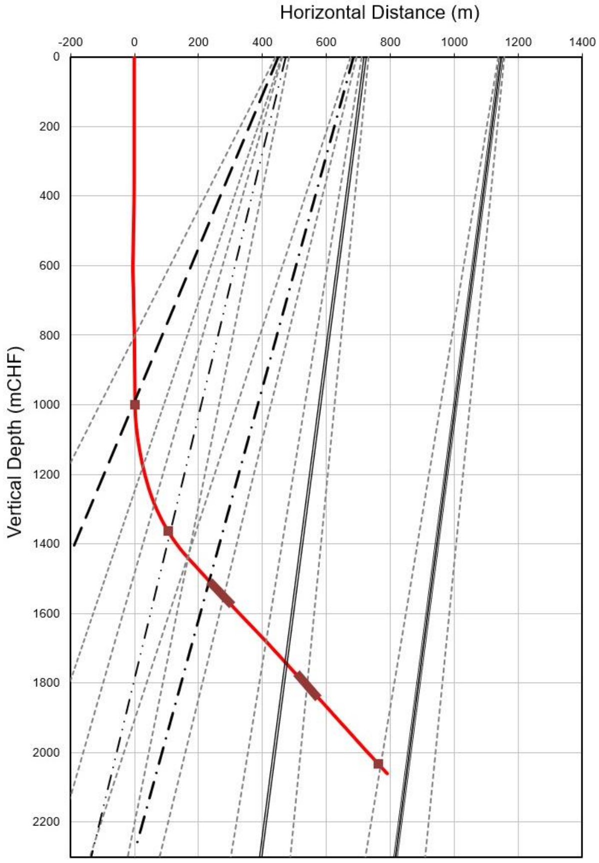

Figure 1: A simplified cross section showing fault projections from surface traces based on an assumed 80° dip on all faults (from the well prognosis), the drilled well track (red line), and permeable zones (from completion testing).

In parts of New Zealand (including Northland, Waikato and the Bay of Plenty), Lidar imagery of reasonable quality is now freely available on the web. Higher resolution imagery can be obtained from commercial companies at reasonable cost for an area the size of a geothermal system. High quality Lidar images are invaluable for accurately locating the surface traces of young and recently active faults.

2.4 Other methods

In some fields, major faults with significant offset will be revealed by geophysical methods including gravity and resistivity. However, usually this will just supplement and hopefully confirm the evidence from field mapping and/or Lidar.

Microseismic surveys might also indicate the location and orientation of active faults, although not to the level of accuracy that is needed for well targeting.

2.5 Determining the dip on a fault

In the volcanic arc and rift settings where most high temperature geothermal systems are found, the vast majority of faults have some combination of normal and strike-slip components. Accordingly, if it can be determined from topographic offsets which side of the fault has gone down, the fault will dip in that direction.

The faults in these settings tend to be steeply dipping, at least within 2 km of the surface, with dips generally close to 80° (±5°) from horizontal.

3. MISIDENTIFYING FAULTS

Locating faults can be a challenge, and many faults have been (mis)identified based on very tenuous assumptions. There are many ways by which lineations and other erosional or geological features can be misidentified as faults. Some possibilities include:

- Connect two or more thermal areas
- Connect two or more volcanic centres
- Connect two or more permeable zones in wells
- Draw a line along the edge of a lava flow
- Draw a line along radial streams around a volcanic centre
- Draw lines along parallel streams
- Draw a line anywhere

Identifying "fake faults" can be difficult, but features to look for include straight lines, lines at 90° to other lines, and lines that cross each other without offset. However, once a "fake fault" appears on a map, it can be very difficult to permanently remove it, especially if it has been given a name.

4. IDENTIFYING PERMEABLE FAULTS

Not every fault will be permeable, and not all parts of a fault will be equally permeable. In addition to locating faults, it is important to identify which of those faults are most likely to be permeable. Young (recently active) faults will be more permeable than old faults, and extensional faults will be more permeable than compressional faults. In addition, faults will be more permeable where they cut through harder and more brittle lithologies (*e.g.* Wallis *et al.* 2012).

4.1 Tectonic setting

On a large scale, the orientation of permeable structures can be predicted from plate motion vectors (*e.g.* Bogie, 2000). On a more localised scale, there may be small to quite significant variations from the regional extension directions, as shown by Rowland and Sibson (2001) for various parts of the Taupo Volcanic Zone.

4.2 Thermal Features

Where permeable structures within a geothermal system allow hot fluids to flow up through the clay cap, those fluids may reach the surface and form thermal features. Accordingly, thermal features may be aligned above permeable structures, *e.g.* at Silangkitang, North Sumatra (White *et al.* 2020). However, care is needed in inferring structures from the locations of thermal features, as hot fluids may flow laterally for some distance before reaching the surface.

4.3 CO_2 flux surveys

If steam is condensed and hot fluids flow laterally above a permeable fault, it is still possible for the geothermal gases to reach the surface. CO_2 gas flux surveys are a relatively inexpensive method to confirm the location and orientation of permeable structures within geothermal systems (*e.g.* Harvey *et al*. 2011).

4.4 Downhole image logging

Image logging can be used to identify the orientation and inclination of structures within a well. Analysing the structures within the feed zones identified in completion testing can confirm the orientation of permeable structures. Multiple permeable zones in a well can potentially have different orientations.

5. EXAMPLES

5.1 Sarulla, Indonesia

The Sarulla contract area in North Sumatra was explored in the 1990s by Unocal, and then developed by Sarulla Operations Limited (SOL) in the 2010s, with a 110 MWe unit at Silangkitang, and two 110 MWe units at Namora-I-Langit. After analysis of satellite imagery and extensive field mapping at Namora-I-Langit, Unocal produced a geological map with four subparallel faults (including the "principal strand" of the Sumatra Fault System) and another fault almost perpendicular to those (Figure 2). This map was used for constructing wellpads and planning the initial wells.

SOL then commissioned a Lidar survey in 2015, and using this, plus reprocessed MT and gravity data, a new structural interpretation was produced by WestJEC in late 2015, which was used for targeting subsequent wells. A second interpretation of the Lidar images revealed much greater complexity (White *et al.* 2020), and the targeting strategy changed again. The faults identified from Lidar can explain the permeability in many of the wells, and the drilling problems in some (Figure 2).

Lessons learned: use the best tools available to identify and locate faults. Lidar is far superior to the satellite imagery that was used in the 1990s, and should be obtained as early as possible. But interpretation is subjective and requires a critical eye.

5.2 San Jacinto, Nicaragua

The San Jacinto geothermal system was explored in the 1950s and 60s, and vertical wells were drilled in the 1990s. In 2007-08, Polaris Energy Nicaragua S.A. undertook further drilling and construction of a power plant. Drilling has continued in several phases since then, along with changes of management, drilling methods and targeting strategies.

When the 2007 drilling began, it used a structural model of NW-SE and E-W faults (Figure 3). However, regional tectonics with compression at 030° was more consistent with north-south oriented normal faults. With new results from drilling, geological mapping and an image log, the structural model was revised to one of predominantly NNE striking normal faults (Figure 2), and most wells targeted those faults. The wells that were drilled to the east or west include large (>20 MWe) producers, and those wells were generally more successful than the wells drilled to the southwest (SJ9-2 and SJ12-2). The revised structural model was later reinforced by the results of a soil CO_2 flux survey (Harvey and White 2011).

Lessons learned: Don't be afraid to question, and if necessary, revise the structural model as new data comes in.

5.3 Mita, Guatemala

The Mita geothermal system was discovered in 1997 during gold exploration, adjacent to an epithermal gold deposit. The gold deposit has been uplifted by several hundred metres on the Eastern Horst Fault (EHF) (Figure 4). Except for two warm springs, the EHF is indistinct at the surface, but it shows up clearly on gravity and resistivity profiles. The geothermal system was delineated by inclined slimholes and then standard sized 700-1120 m deep vertical geothermal wells (White *et al*. 2010). Those wells found that the EHF dips to the east at 70-80°, and varies from impermeable in the south (MG-08) to having good permeability in the central part (MG-05) (McDowell and White, 2011).

Lessons learned: Geophysics can help to define fault locations, and permeability can vary along a fault.

5.4 Corbetti, Ethiopia

The Corbetti geothermal system is located within Corbetti Caldera in the East African Rift system. It is being explored by Corbetti Geothermal PLC, but no drilling has been undertaken to date, other than shallow temperature gradient holes drilled in the 1980s. Outside the caldera, there are many rift-related north to northeast striking normal faults, but inside the caldera, these are largely obscured beneath young rhyolite lavas.

Lidar imagery of Corbetti had been examined and interpreted prior to the author being involved in the project. Accordingly, there are now two separate structural interpretations of the Lidar. While there is some agreement between the two structural maps, there are also some significant differences (Figure 5). Many of the lineations from the earlier work clearly follow contacts between lava flows of different ages, and some follow erosion channels that simply flow downslope.

Lessons learned: Drilling at Corbetti is still in the planning stage, but it is already apparent that not all of the inferred structures should be used for targeting wells.

6. CONCLUSIONS

Targeting geothermal wells to intersect faults can give highly productive wells when it is done well. Where targeting a fault is unsuccessful, it could be that the fault was not permeable, was not accurately mapped, or was not there at all.

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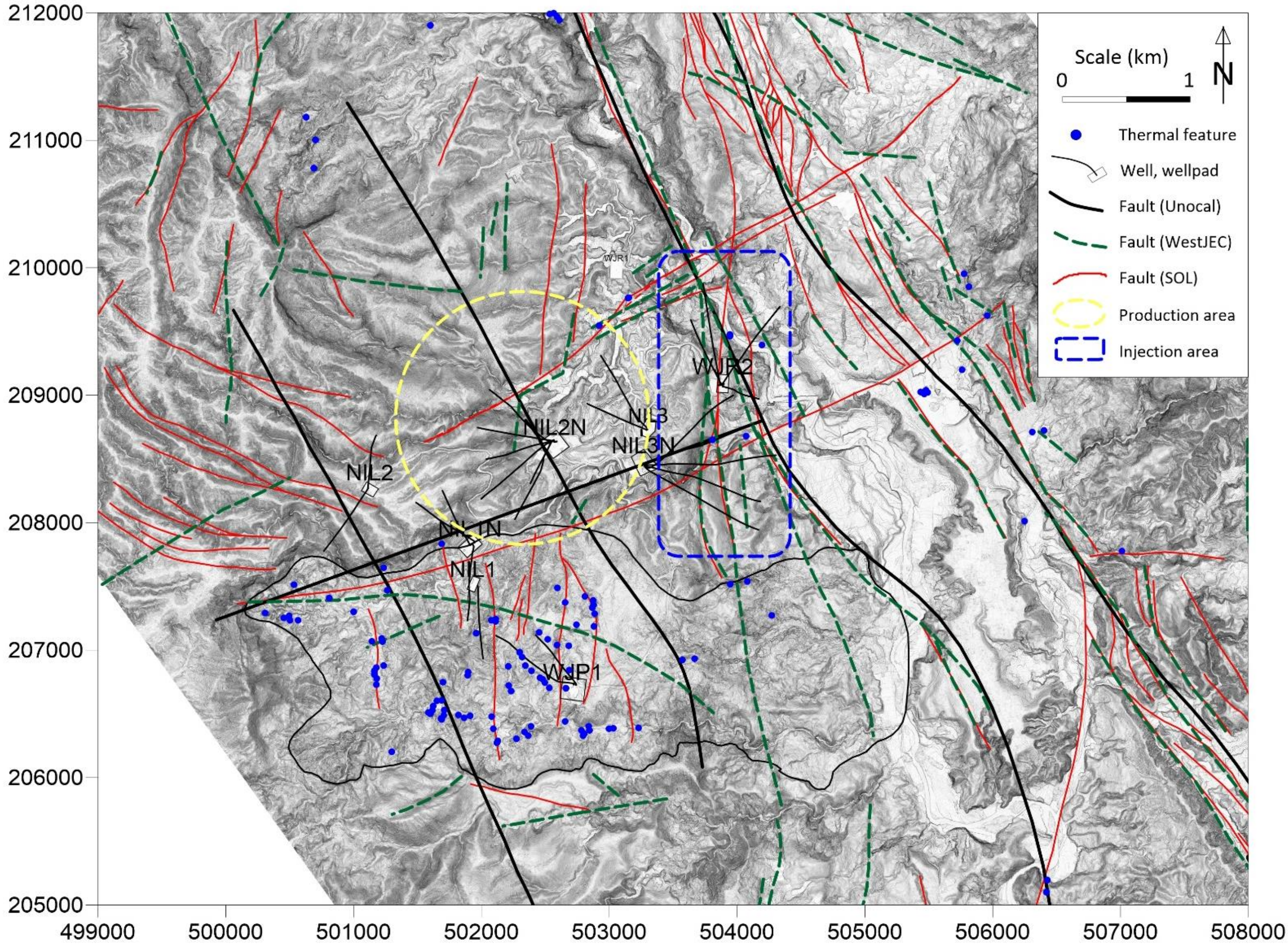

Figure 2: Lidar image of Namora-I-Langit area, Sarulla, showing production and injection areas, wells (to 2017), thermal features, and faults from Unocal (Ganefianto 1998), WestJEC (unpublished), and SOL. A large (5 km long) sector collapse immediately south of the production area is outlined in black (not discussed here). Modified after White *et al.* (2020).

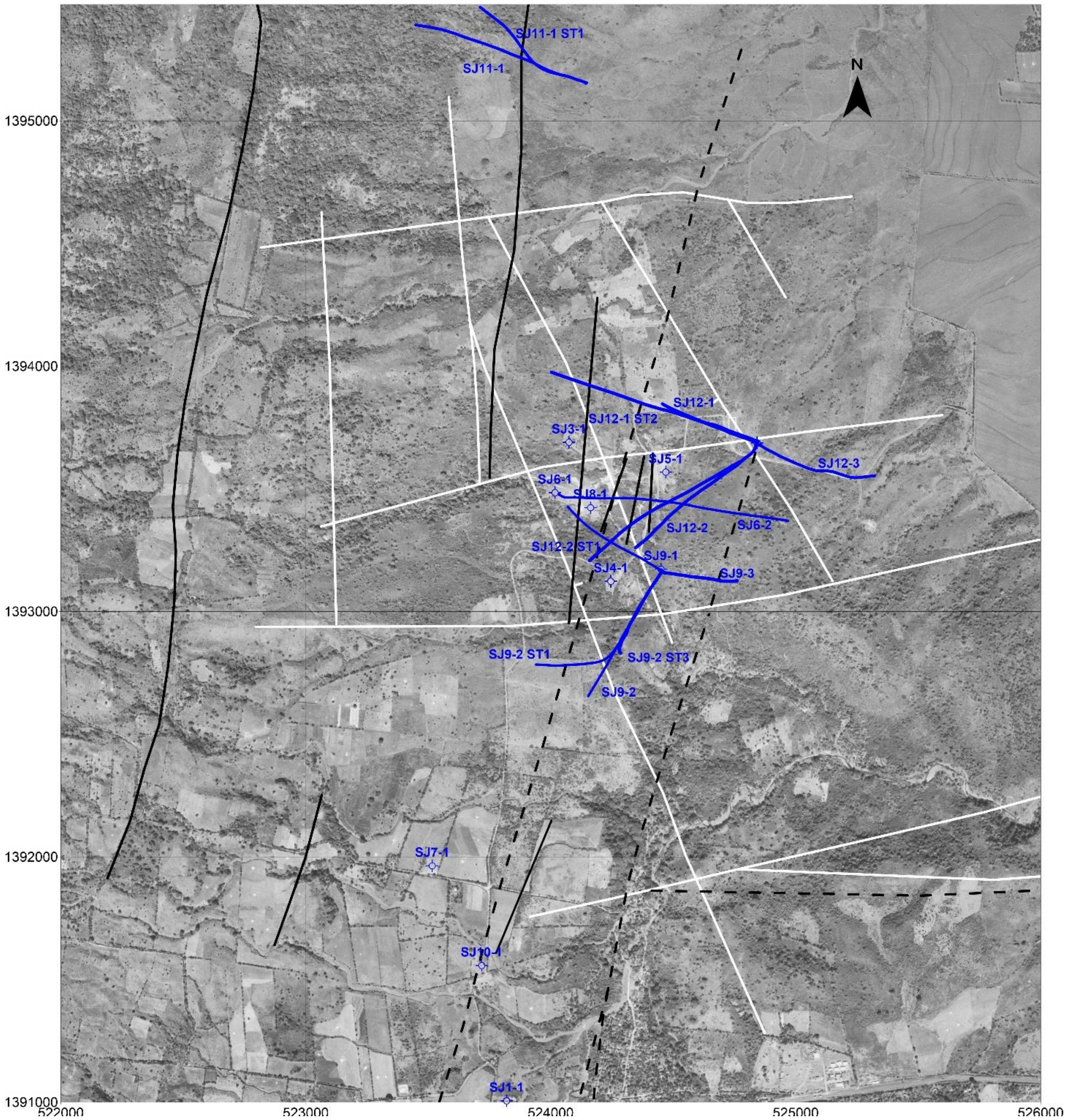

Figure 3: San Jacinto geothermal area, showing wells to 2011 (blue), the 2006 structural model (white lines) and the revised 2008 structural model (black lines).

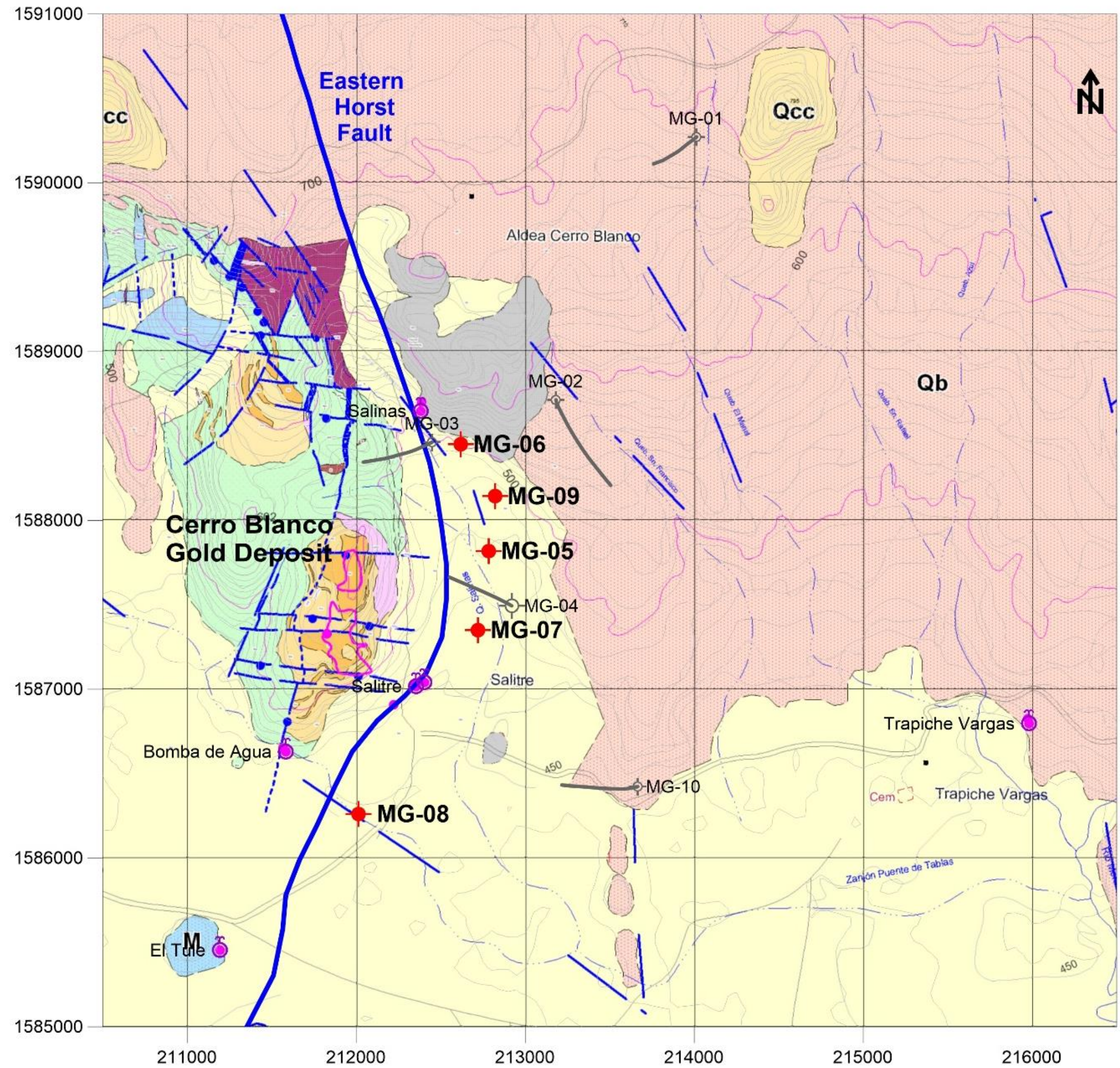

Figure 4: Simplified geological map of the Mita geothermal system. The inclined slimhole MG-04 and the vertical wells MG-05 to MG-09 all intersected the Eastern Horst Fault at depth but had varying permeability. After McDowell and White (2011).

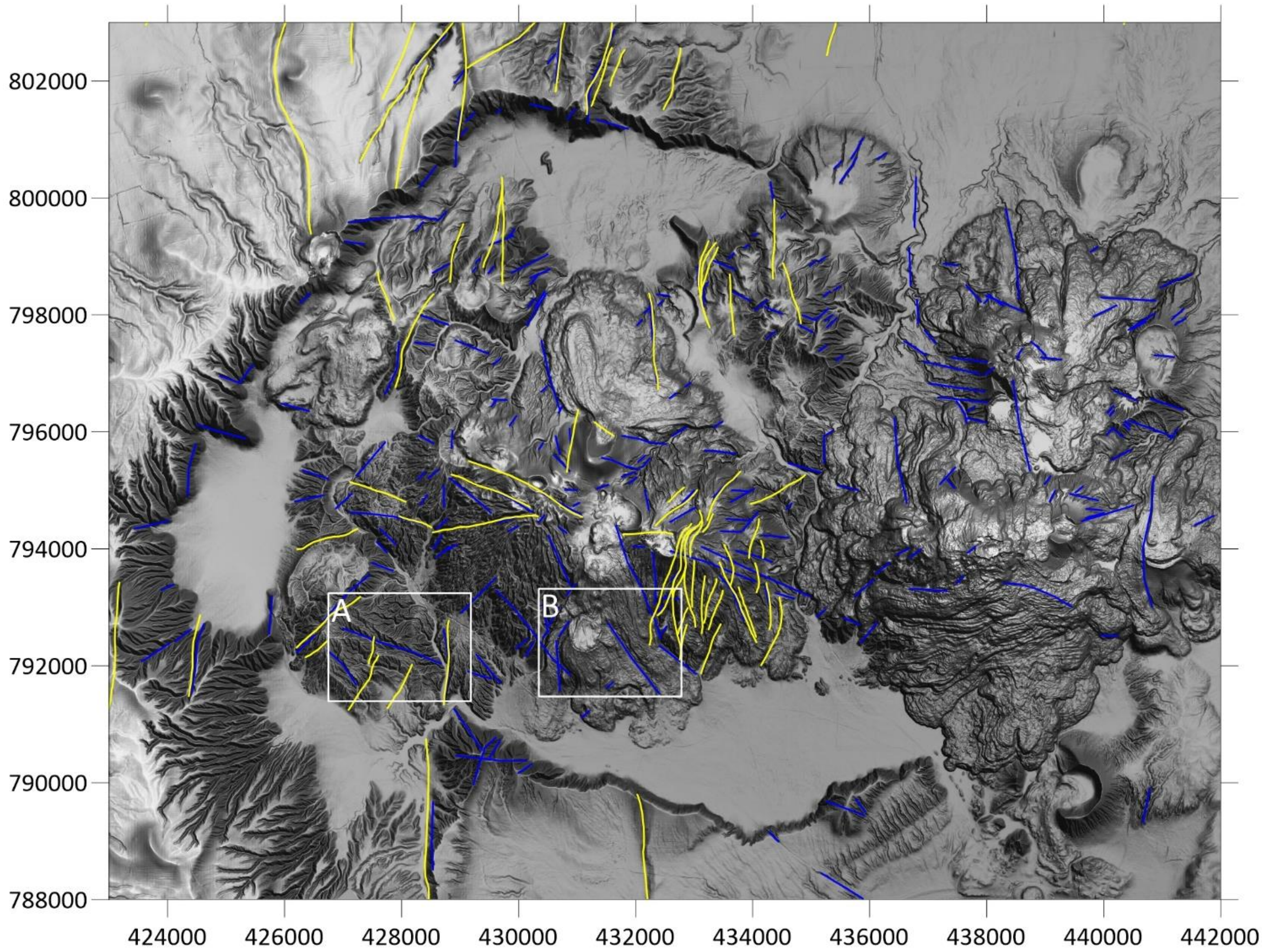

Figure 5: Alternative interpretations of Lidar images at Corbetti. Many of the blue lines follow lithological contacts (boundaries between lava flows), and some follow erosional channels, as highlighted in the enlarged maps below.

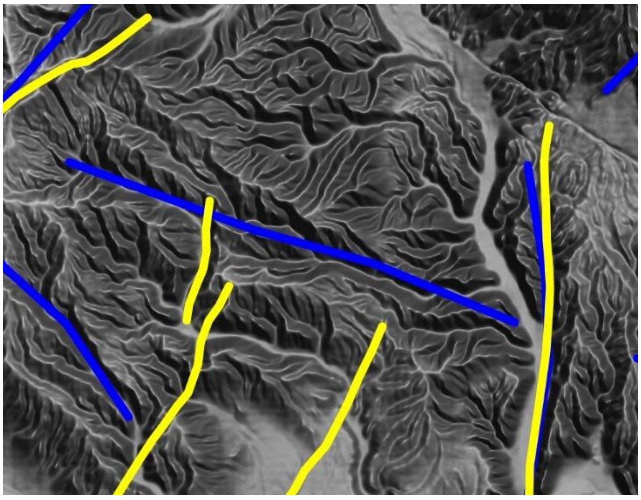

Figure 5A: Enlargement of Area A showing an ESE trending erosional channel (near centre) that is offset on NNE faults.

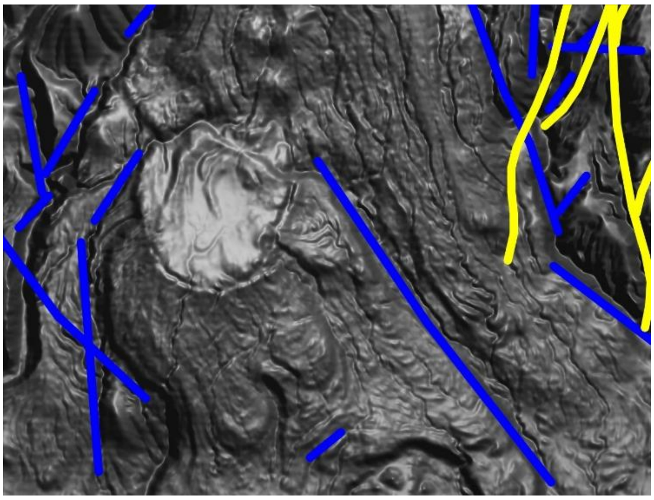

Figure 5B: Many of the lineations in Area B are contacts between lava flows, and have no structural significance.