THE USE OF PLATE MOTION VECTORS TO PREDICT THE ORIENTATION OF HIGHLY PERMEABLE STRUCTURES IN ACTIVE GEOTHERMAL FIELDS RELATED TO SUBDUCTION

I. BOGIE[1]

[1]Sinclair Knight Merz, Auckland, New Zealand
IBogie@skm.co.nz

SUMMARY – Subduction produces deformation of the upper tectonic plate in a manner that can be predicted from plate motion vectors to indicate whether subduction is perpendicular, weakly oblique or strongly oblique. Perpendicular subduction produces reverse faults parallel to the arc and arc-normal faults, which when the intersection is within a volcanic arc, may localise intrusives with geothermal systems hosted by intrusion margin permeability. Where subduction is slightly oblique, faults with an element of strike-slip motion that strike parallel to the direction of obliqueness can intersect the arc and have associated permeable structures in orientations that can be determined from the strike of the fault and its sense of movement. Where subduction is strongly oblique and subduction is steep, arc-parallel strike-slip faults can form. These frequently run along the volcanic arc and have associated permeable secondary structures whose orientations can be determined similarly. The latter is the optimum tectonic environment for the development of permeable geothermal fields and is found in Sumatra, east-central Philippines, Colombia, Ecuador and southern Chile.

1. INTRODUCTION

The subduction of an oceanic tectonic plate beneath another plate produces a volcanic arc on the overlying plate (Gill, 1981) that provides the heat source for geothermal systems (Giggenbach, 1988). Subduction also causes deformation of the overlying plate (McCaffrey, 1996), which can create highly permeable structures that allow major fluid flow in the systems. These are prime targets for geothermal drilling.

The style of deformation varies according to the geometry of the collision of the plates. Knowledge of the plate motion vectors allows the geometry of collision to be determined, from which the style of deformation can be established. Once the style of deformation is known the orientation of potentially highly permeable structures can be predicted and used to target geothermal wells (Bogie and Lawless, 2000). This concept is further developed and discussed here.

2. CONSIDERATIONS

The main form of deformation in the volcanic arc is shearing (Nakamura and Uyeda, 1980). This is because there is a partitioning of the thrust and shear components of the downward moving plate (McCaffrey, 1996), the stronger the coupling between the plates the stronger the partitioning (Jarard, 1986). Most of the thrusting is taken up in the underlying plate's downward movement, although some can be expressed in fore-arc thrust-fold belts. The shearing takes the form of strike-slip faulting. Associated with it are secondary structures with a specific orientation to the strike-slip fault (Figure 1) such that if the strike and sense of movement of the strike-slip fault are known, the orientation of the secondary structures can be predicted. Where the secondary structures are most strongly developed along dilational jogs pull-apart basins form.

Any fault may be permeable, because faults are not perfectly planar features and movement on the fault can juxtapose non-parallel rock surfaces, thereby creating open space. However, where there has been strong shearing, comminuted wall rock can fill these open spaces and block permeability. Wall rock comminution is most strongly developed in strike-slip faults where there has been significant movement because of strong shearing. Hence, the major strike-slip faults produced by shearing of the upper plate are usually not especially permeable but the associated secondary structures are. Potentially the most permeable of the secondary structures are normal faults and tensional gashes because there can be a moving apart of the fault walls to create open space. Both have the same orientation in relation to the strike-slip faults.

The reason why the structures are only "potentially" highly permeable is that they are not perfectly planar features. Even very permeable structures will pinch and swell and if only a pinch is intersected by a geothermal well, permeability will not necessarily be high. The probability of drilling a pinch is dependent upon the geometry of the well-structure intersection. The further away from a perpendicular intersection of the well with the fault the better providing that the intersection is not so oblique that bitwalk occurs and the well fails to penetrate the structure. This is because the longer the intersection the less likely the well will only intersect a pinch. As the majority of highly permeable structures are near vertical,

vertical wells or deviated wells with low drift angles drilled from a structure's footwall will give long intersections and potentially better permeability. Deviated wells, particularly those with high drift angles, drilled from the hanging wall will have shorter intersections and a lower probability of intersecting high permeability, but have a higher probability of hitting a structure.

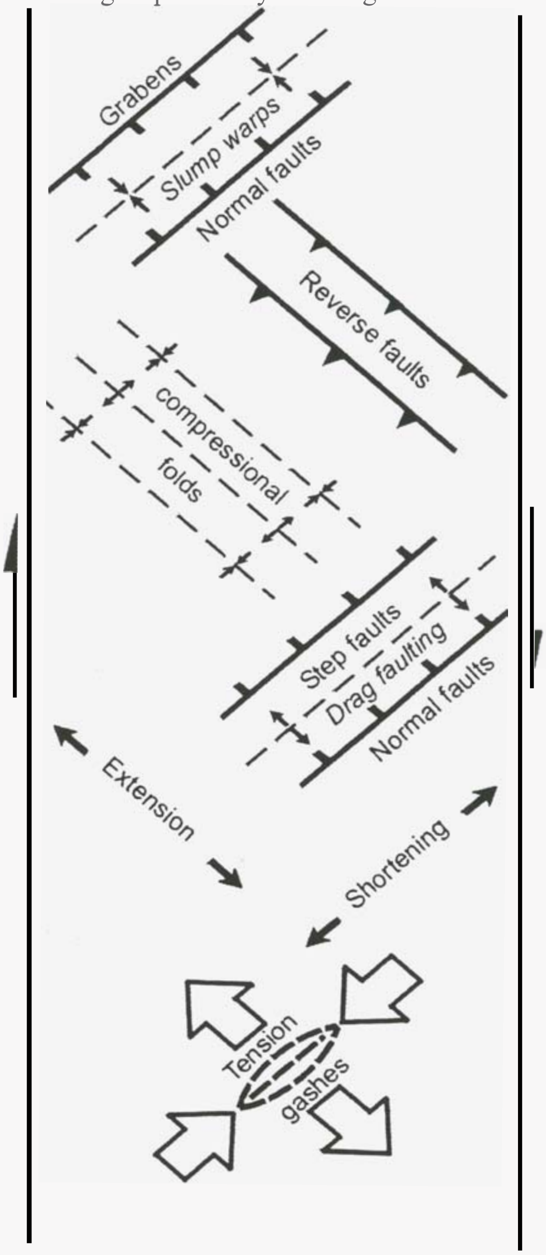

Figure 1. The structural pattern associated with a dextral strike-slip fault. The pattern associated with a sinistral strike-slip fault will be a mirror image.

Likewise the greater the horizontal angle of obliquity the longer the intersection. Therefore the targeting of preferred structures requires not only identifying the structure's orientation but also being able to drill the well in the most advantageous way to gain greatest benefit from it. As actual intersection choices may be limited by well pad locations, not all intersections with the potentially permeable structures will yield high permeability, and thus this approach does not guarantee that every well will be a success. A further factor is that the intersection must take place in competent rocks such that there is brittle failure to provide fractures. However, there is likely to be better overall results in a number of wells targeted into preferred structures than not targeting them.

There are other consequences of the requirement for both intersecting a preferred structure and maximising the length of intersection. Long intersections with generally less permeable structures may produce high well productivity and simple analysis of well results in terms of azimuth plotted against production to establish which are preferred structures in a field is unlikely to yield useful results unless some measure of the length of fracture intersection is considered. This is not only because some of the better wells may include those with some generally less permeable structures that have long intersections but also there will be two general azimuths for any particular well where length of intersection (without producing bitwalk) is maximised for each structure. If there are parallel structures there will be four favoured azimuths for each well, which will vary for each pad, depending upon the relative position of the pad and the structures. As reliable indicators of lengths of intersection are not generally available utilising the results obtained from using plate motion vectors is likely to give better results than simple azimuth analysis in fields where there has already been drilling and is the only approach available to target exploration wells.

3. METHOD

In using plate motions to predict permeability in active geothermal systems both the vector of movement of the host plate and the underthrust plate are required for the zone of interest. Given that the earth is not flat, strictly these vectors should be expressed and manipulated as relative rotation vectors utilising polar coordinates, (e.g. Minster and Jordan, 1978). However, this degree of accuracy is probably not justified in terms of possible uncertainties in the data and what is required to obtain a useful result. Thus, the vectors can be treated comparatively simply. The vector of movement of the host plate and the underthrusting plate are subtracted to give the relative plate movement. The other pieces of information that are required are the strike and dip of the subduction zone.

The angle perpendicular to the strike of the arc is taken as the subduction angle and compared to the angle of relative plate movement to give the angle of obliquity. If the two angles are the same subduction is perpendicular and the arc will be compressional. Deformation of the upper plate is thereby mainly by thrusting which produces reverse faults parallel to the arc. However, since the collision is occurring on the surface of a sphere there will still be some shear that expresses itself in faults normal to the arc. Where reverse and arc-normal faults intersect within the volcanic arc, intrusions can be localised, for example the Cu-porphyry deposits of northern Chile (Sillitoe, **1998).** Permeability in associated hydrothermal systems may however be largely controlled by fracturing around intrusion margins (Bogie and Lawless, 2000) rather than being purely fault related. However, this is not to say that intrusion related permeability is restricted to this tectonic environment.

It is more common for subduction to be oblique (McCaffrey, **1996)** and strike-slip faults with possible dilational jogs may be present. If the angle of obliquity is low **(< 45°)** and the dip of subduction is low **(<45°)** (Jarrard, **1986)** it is likely that these faults will be oriented semi-parallel to the vector of relative movement and hence cut the volcanic arc obliquely. Their sense of movement will be the same **as** the sense of obliquity. Once the sense of movement is known, the orientation of secondary dilational structures associated with these faults can be determined. Generally **as** the angle of obliquity decreases less strike-slip movement will be found and faults cutting the arc will have oblique rather than purely strike-slip movement.

Where the angle of obliquity is high, or the dip of the subduction zone is high, it is likely that there will be strong coupling between the upper and lower plates (Jarrard, **1986)** and strong partitioning. This results in strike-slip faults that run parallel to the **arc** and may overlap or strike along the arc. Their sense of movement will be the same **as** the sense of obliquity. As the arc is only a small part of the upper plate, the frequent Occurrence of strike-slip faults along arcs is not coincidental. The volcanic front has a high heat flow and this weakens rocks at depth, thus strike-slip faults preferentially form along the arc (Jarrard, **1986).** This should be most common where there is a long history of magmatism on the same arc. The situation where the arc and the strike-slip fault overlap or strike along the arc is found in Sumatra, Indonesia; the east-central Philippines; Colombia; Ecuador and southern Chile (Jarrard, **1986).** This is obviously a very advantageous situation **as** the intersection between a structure that can host dilational jogs and the volcanic arc **is** maximised.

4. EXAMPLES

4.1 Sumatra and Java

Moving south from Sumatra to Java there is a change from oblique to perpendicular subduction. The Australian and Eurasian plates meet along the Sunda arc with a relative movement of **6.5** cm yr^{-1} at **15°,** with a strike of **235"** (McCaffrey, **1996),** resulting in an angle of obliquity of 35". The subduction zone dips at **60°** (Gill, **1981)** and there has been a long history of magmatism on the arc. Consequently a major strike-slip fault, the Sumatran Fault, runs along the arc at a strike of **315** to **325°** with a dextral movement (Figure 2). Potentially highly permeable structures associated with it should strike at approximately 0 to **10"** (see Figure **1).** Gunderson ***et al.*,** (1995) and Santoso ***et al.*, (1995)** have mapped north striking faults and identified half graben and graben structures, possibly dilational jogs, in which geothermal fields are localised along the Sumatra fault at the Sarulla and Muaralaboh-Talang areas respectively. It is also interesting to note that mineralised veins produced earlier under the same tectonic environment preferentially strike north (Van Bemmelen, **1949).**

During pre-Miocene times the same tectonic environment extended onto Java (Hall, 1996) giving rise to the West Java epithermal gold deposits (Van Bemmelen, **1949).** However, the collision of the Australian continent with the Sunda arc has bent the arc around such that the arc now strikes at **295°** in West Java and the angle of obliquity is now **10°.** In Central Java the arc strikes at **285°** such that subduction is perpendicular, as the strike of the relative plate movement remains the same **as** that at Sumatra at **15°.** Therefore, between the most western part of Java and Central Java there should be faults cutting the arc with a strike of 0 to 10°, which will have an element of strike-slip movement and associated potentially permeable structures at approximately **45** to **55°.** There should be an eastward diminution of the degree of strike-slip movement and development of potentially permeable secondary structures.

At the Darajat geothermal field in West Java two predominant fault strike directions are found (Whittome and Salveson, **1990).** The most common strike direction is 50°, corresponding to potentially permeable structures with the less common strike at **10°,** which corresponds to faults with some degree of strike slip movement. A similar pattern is found at Awibengkok geothermal field in West Java (Stimac and Sugiaman, 2000). Dieng, the only Central Java geothermal field to be developed so far, is less likely to have well developed structural permeability but may have intrusion margin related permeability given the Occurrence of shallow intrusives (Fauzi, **1987).**

4.2 Taupo Volcanic Zone (TVZ)

The TVZ in the North Island of New Zealand has been formed as the result of the subduction of the Pacific plate beneath the Australian plate. The Pacific plate is moving to the northwest and the Australian plate is moving to the north with a resultant relative motion to the west **(265°).** The relative velocity increases northward along the plate boundary, but directly opposite the TVZ it is **4.5** cm yr^{-1} (DeMets et al., **1994),** (Figure **3).** The

TVZ itself strikes at **40"** and hence there is a 15" angle of obliquity. As subduction is steep, 50° (Gill, 1981), the resulting deformation structures in the overlying plate are dextral strike-slip faults parallel to the arc. These are best

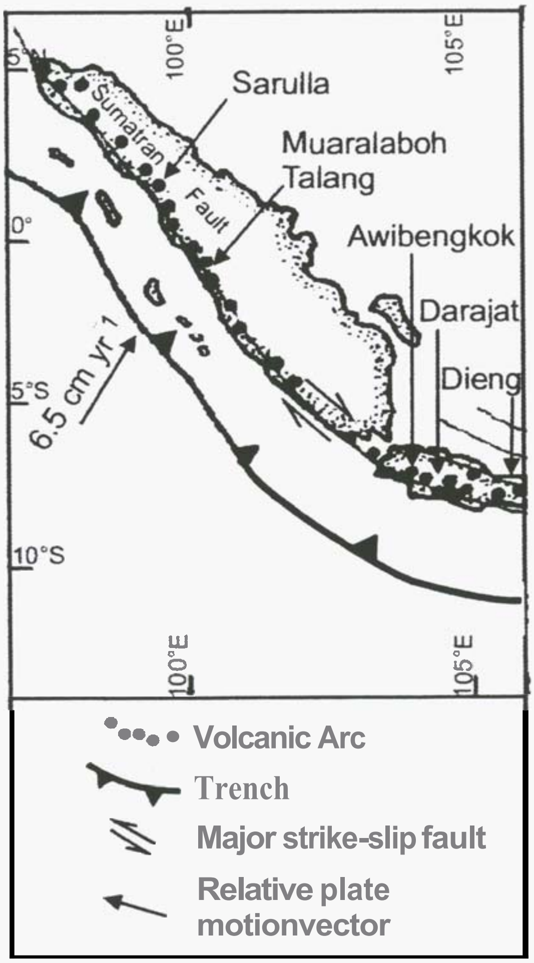

Figure 2. The plate tectonic environment of Sumatra and Java. Adapted from Gill (1978) and McCaffrey (1996).

developed along the North Island Dextral Fault Belt (NIDFB) to the east of the TVZ with increasing amounts of slippage moving to the south (Beanland and Haines, 1998). To what degree this movement is restricted to the NIDFB is not entirely clear, and the majority of faults within the TVZ are considered to be normal (Beanland and Haines, 1998). However, the very high heat flow and presence of normal faulting within the TVZ may have sufficiently weakened it such that there is an element of dextral movement on major normal faults and there may be some development of associated dilatant structures that may provide high permeability. If this is the case strike-slip movement should become stronger to the south with such dextral strike-slip movement producing associated highly permeable structures striking at approximately 80" (see Figure 1). Directional production drilling so far undertaken in geothermal systems in the TVZ has been approximately parallel to this trend (Wood, 1996; Wood and Braithwaite, 1999) and has not been

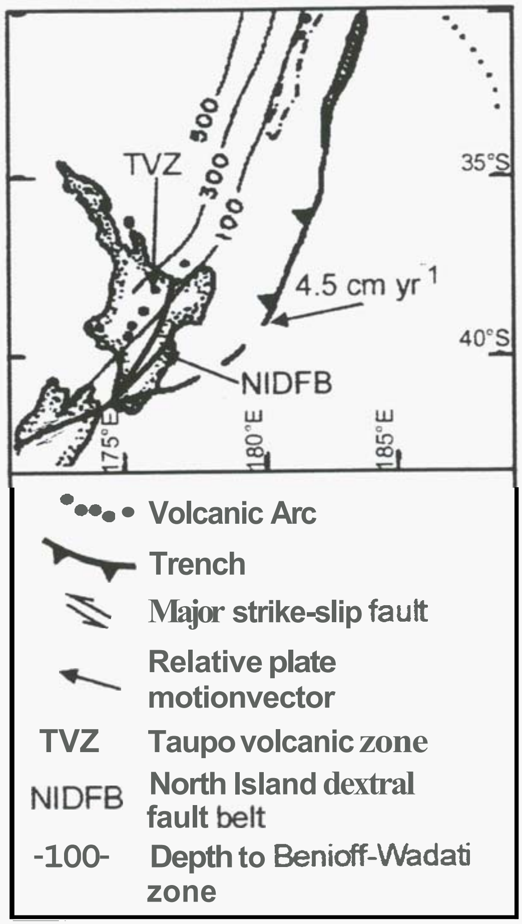

Figure 3. The plate tectonic environment of the North Island of New Zealand. Adapted from Gill (1981), McCaffrey (1996) and Beanland and Haines (1998).

particularly successful; possibly the failure to intersect these potentially permeable structures has been a factor.

4.3 East-central Philippines

The Philippines is the meeting point of the Philippine and Eurasian plates, which is complicated by the presence of a variety of allochthonous terrane blocks between them. Overall, in the east-central Philippines the plate boundary can be treated comparatively simply with the Philippine plate having a relative vector of movement of 8 cm yr^{-1} in the north and 10 cm yr^{-1} in the south at a strike of approximately 300° (Rangin *et al.*, 1996), (Figure **4).**

This produces more oblique subduction in the north, with an angle of obliquity of 45°, than in the south, where it is 30". The dip of subduction is 45° (Gill, 1981). This means that there is an intermediate situation between arc-parallel and arc-oblique strike-slip faulting and both are found. The Philippine fault, parallel to the Philippine trench, accommodates part of the lateral component of this movement (Rangin *et al.*, 1996). It only intersects the active volcanic arc on the island of Leyte, partly due to the north-south change in obliquity and partly because

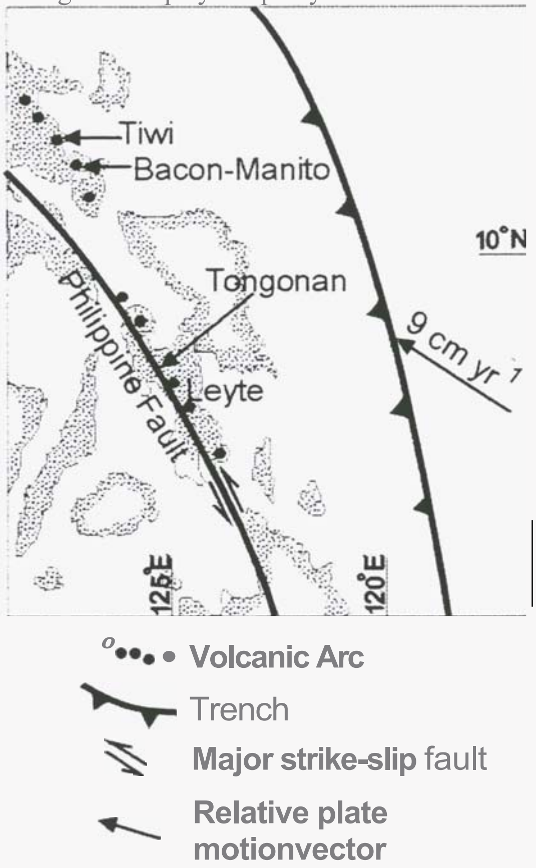

Figure 4. The plate tectonic environment of the east-central Philippines. Adapted from Gill (1981), McCaffrey (1996) and Rangin (1996).

subduction is too young in the southern Philippines for the volcanic arc to have formed. However, there is a set of faults running between the Philippine fault and the Philippine trench that strike at approximately 300° and is oblique to the arc. These have sinistral strike-slip movement. They intersect the Philippine volcanic arc along the Bicol Peninsula. The Tiwi and Bacon-Manito geothermal fields lie on such faults and if there has been the development of secondary structures associated with them, the structures with the highest potential for permeability should strike at approximately 75". Structures of this orientation are mapped at Tiwi (Gambil and Beraquit, 1993) and Bacon-Manit0 (Solis *et al.*,1998). On Leyte, where the Philippine fault is parallel to and within the volcanic arc, en echelon dilational jogs host the main Tongonan geothermal field and the smaller separate Mahanagdong field to the southeast. As the Philippine fault is sinistral and strikes at 330" in this area the structures with the greatest potential for permeability should strike at 105".

4.4 Ecuador and Colombia

In northern Ecuador and Southern Colombia the relative plate motion of the Nazca and South American plates is 8 cm yr^{-1} with a strike of 75° (Jarrard, 1986), (Figure 5). This gives an angle of obliquity of 47°, favouring arc-parallel strike-slip faulting even though the dip of subduction is low at 35°. The Guayaquil-Dolorres strike-slip fault runs along the volcanic arc in this area, where this fault has a dextral movement and a strike of 30". Potentially permeable structures should strike at 255". Possible geothermal prospects where this may be the case are Negro de Mayasquer on the Ecuador-Colombia border and Azufral in Colombia.

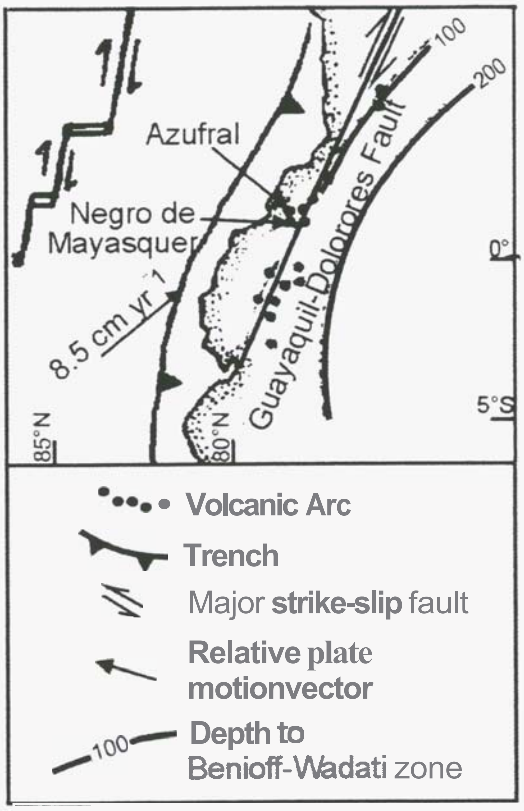

Figure 5. The plate tectonic environment of northern Ecuador and southern Colombia. Adapted from Gill (1981) and Jarrard (1986).

5. CONCLUSIONS

Plate motion vectors can be used to determine the orientation and sense of movement of major strike-slip faults produced by shearing of the upper plate during oblique subduction. Where the strike-slip faults cut the associated volcanic arc, or most favourably run along the arc, dilatational jogs can host geothermal systems in which the orientation of the potentially highest permeability structures is fixed in relationship to the strike and sense of movement of the major fault.

Where major strike-slip faults do not cut the volcanic arc there may still be some strike-slip movement on otherwise normal faults parallel to the strike-slip faults and the orientation of associated potentially highly permeable structures determined accordingly. Where subduction is perpendicular permeability in associated geothermal systems may be dominated by intrusion margin fracturing.

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