FAULT SET ANALYSIS OF REINJECTION AREAS IN THE MAHANAGDONG GEOTHERMAL FIELD, LEYTE, PHILIPPINES

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Abstract

An analysis of brittle deformations in the Bao Valley and Cambantog reinjection areas of the Mahanagdong Geothermal Field was conducted to determine the tectonic signature of the structures. Stress computations indicate wells MG-IRD and MG-4RD in Bao Valley and wells MG-5RD and MG-6RD in Cambantog intersected extensional structures. Both areas show intense fracturing and intense alteration, and are hosts for numerous hot springs Theoretically, structures under extension should exhibit good subsurface permeability. However, the wells in Bao Valley have very limited permeability whereas the wells in Cambantog exhibited very good permeability and high reinjection capacitiies. Stratigraphic correlation shows that the wells in Bao valley encountered formations that are inherently impermeable owing to their 'plastic' character whereas the wells in Cambantog were drilled through formations that lend themselves to good fracturing. Fault set analysis should therefore be incorporated with data from other disciplines such as subsurface lithological characteristics and well-fault intersection correlation to effectively determine structures that are more likely permeable.

1.0 INTRODUCTION

Fault set analysis allows for the reconstruction of different tectonics events that have transpired and are still occuring in an area. The direction of the paleostress tensors determine the fault's behaviour whether it is under compressional or extensional stress regime. Theoretically, faults formed by extension are more permeable than those formed by compression. Fault set analysis allows for surface fault data to be projected on the subsurface using models drawn from experiments employing a homogenous rock body. It is, however, known that lithologic inhomogeneities are always present in a stratigraphic succesion and even in a single formation itself. Uncertainties are therefore expected in projecting the geometry and the behaviour of faults at depth.

This paper aims to show that structures having the same surficial tectonic signature will not necessarily exhibit the same subsurface permeability characteristics. This paper also attempts to show that a fault's subsurface behaviour and, consequently, its permeability are constrained by the lithology it transects. Focus will be on two reinjection areas, MGRE pad in the Bao Valley and MG-RD1/B pad in Cambantog in the Mahanagdong sector of the Greater Tongonan Geothermal Field (Fig. 1).

1.1 Brief background on fault set analysis

In fault set analysis, centimetric to decametric tectonic structures with strike and dip directions such as faults, joints, tensions gashes, folds, beds, foliations and others are measured and *analyzed.*

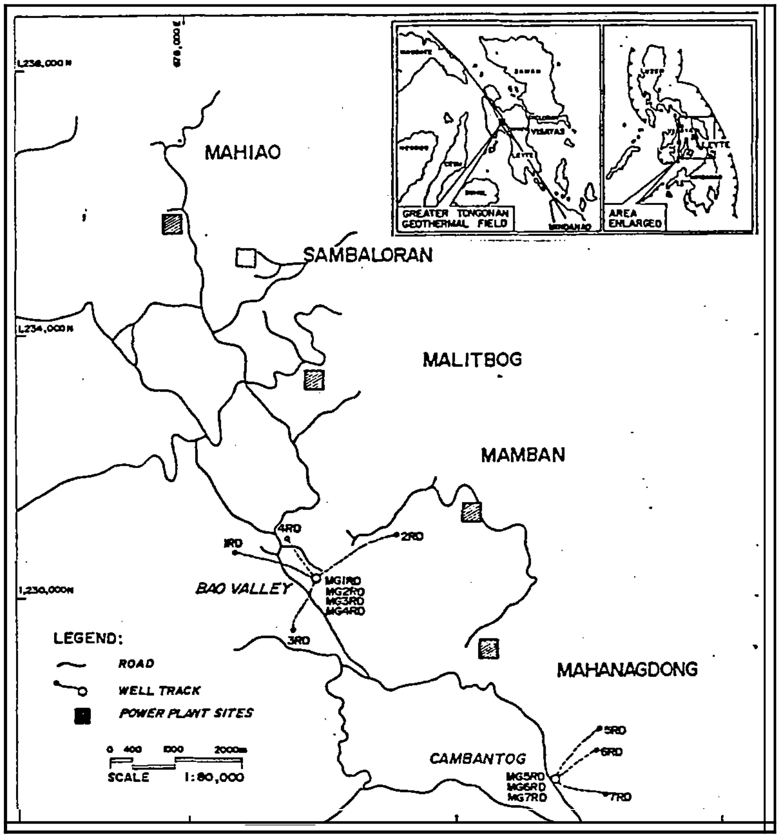

Fig. 1. The Greater Tongonan Geothermalfield Open square show: the location ***of*** *the existing Tongonan-]Power Plant. Shaded block are the location of the plants being constructed. Lower portion show. the two reinjection areas of the Mahanagdong sector.*

Contemporaneous events in a distinct fault population are plotted on an equal area stereographic **net** where the main **stress** axes are reconstructed. The direction of the three principal axes σ1 (maximum stress), 02 (intermediate stress) and **a3** (minimum stress) defines the faults behaviour, whether it is under a compressional or an extensional **stress** regime. Figure 2 shows a plot of fault populations in the Bao Valley and Cambantog areas.

1.2 Tectonic Setting

The Greater Tongonan Geothermal Field (GTGF) in the island of Leyte, the site of the largest geothermal power development in the **country,** is traversed **by** the ***NW-SE*** trending Philippine Fault. The Philippine Fault is a major sinistral fault that *can* **be** classified, on the **basis** of Sylvester's (1988) classification of strike-slip faults, as a trench-linked transform fault since it is located parallel to a trench (Philippine Trench) and within or immediately bordering a magmatic arc.

As the fault enters the GTGF it subdivides into several branches and forms a complex fault system. The Philippine fault zone in Tongonan **as** mapped **by** Panem (1992) consists of five major structural **lines,** the **West** Fault Line (WFL), Central Fault Line (CFL), **East** Fault line (EFL), Mahiao-Malitbog-Janagdan faults and the Litid North-Laao-Alto faults, which are oriented **between** N30°-65°W and spaced at 1-1.5 km interval.

1.3 Stratigraphy

According to the generalized stratigraphy recently proposed **by Delfin** *et* **al.**, (1995), the rock units in the GTGF **from** the oldest to youngest are the Basement Complex, Mahiao Sedimentary Complex, Mahanagdong

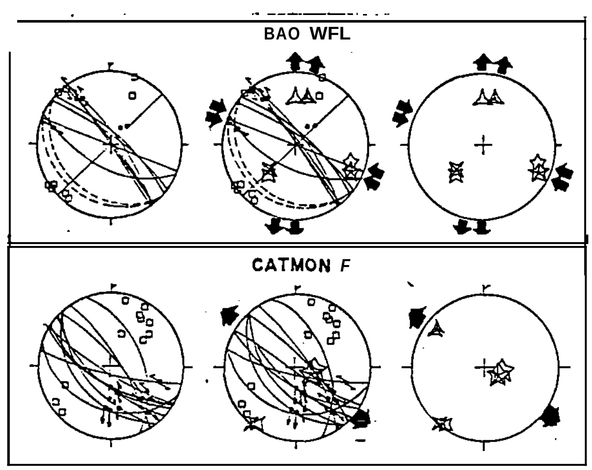

Fig. 2. Fault populations with the interpreted stress ***axes*** *plotted on an equal area schmidt stereographic net. Upperfigure shows a W-SE compression along the CFL* **as** *a consequence of its lef-lateral movement. Lower figure shows W-SE trending extension along Catmonfault.*

Claystone. Mamban Formation. Bao Volcanics and the North Central Leyte Formation (Fig. 3).

The oldest unit in the GTGF is the pre-Tertiary Basement Complex (BC) composed of an underlying serpentinite body overlain by a chaotic mixture of serpentinized peridotite, hornblende diorite, hornblendite, minor hornfels, schists and gneises. The chaotic mixture is without any discernible matrix but contains rare limestone and siltstone inclusions.

The second oldest formation is the Mahiao Sedimentary Complex (MSC), though no stratigraphic contact with the BC has been established. This formation is essentially a sedimentary breccia/conglomerate containing boulder-sized clasts of microdiorite, quarts monzodiorite and minor volcanics set in an arenaceous to argillaceous matrix and with minor interbeds of sandstone. siltstone and claystone.

Overlying the MSC is a thick sequence of predominantly fine clastics such as claystone, siltstone and sandstone with minor conglomerate, limestone and chert. This unit is termed the Mahanagdong Claystone (MC). The dominant claystone member consists of very finely laminated clay minerals and carbonaceous minerals with angular silt-sized fragments of quartz, feldspar, calcite and pyrite whde the conglomerates contain clasts of diabase, basalt. diorite, serpentinite, quartzite, minor andesite, hornfels. quartz monzodiorite and microdiorite set in an argillaceous matrix.

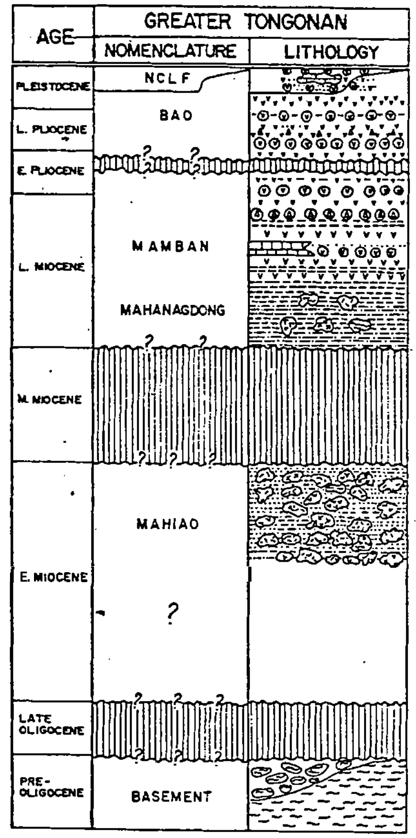

Fig. 3. Generalized stratigraphy of the Greater Tongonan Geothermal Field (after Delfin et al., 1935).

The MC is overlain by the water-laid Mamban Formation (MF) which is a thick sequence of predominantly biotite-bearing hornblende-pyroxene andesite lavas, hyaloclastites and tuff breccias consisting of andesite and dacite clasts set in an argillized matrix. The MF also contains interbeds of claystone, siltstone, sandstone and fossiliferous limestone occuring as lenses.

Lying unconformably above the Mamban Formation is the Bao Volcanics (BV) consisting of fresh to slightly weathered hornblende/oxyhornblende andesite lavas and glassy tuffs.

The youngest rock unit in the GTGF is the North Central Leyte Formation (NCLF) which is composed of ashfall, pyroclastic flow and lahar deposits interbedded with some conglomerate and minor limestone.

2.0 RESULTS OF FAULT DATA SET ANALYSIS

Two reinjection areas at the GTGF, the Bao Valley near MG-RE pad and the Cambantog area within MG-RD1/B pad, were studied using fault set analysis. Stress computations indicate that the structures intersected by wells MG-1RD and MG-4RD in Bao Valley and wells MG-SRD AND MG-6RD in Cambantog are dominantly dominantly under extensional stress regimes. Theoretically, considering perfectly indentical physical conditions, structures under extensional stress regimes are more permeable than structures under compressional stress regimes.

2.1 Bao Valley near MGRE pad

The trace of the West Fault Line (WFL) in Bao Valley is depicted by a **steep** scarp carved **on** the volcaniclastic sequence of the North Central Leyte Formation (NCLF). Fault set analysis revealed an almost E-W compression along CFL whde a dominant NW-SE trendmg extensional **stress** regime was observed along Banati and Banati-A faults (Fig. **4).** The left-lateral movement of the WFL allows extension along the Tongonan and the Banati family of faults while permitting compression along WFL's segment **in this area.** Numerous chloride **springs** and intense fracturing were **observed** along the banks of the Bao river and **within** the intersection **of** the two major structures. WFL and Banati-A faults. The welldeveloped subsurface fracturing due to the prevailing extensional stress regime was *already* confirmed **by sodium** fluorescein tracer testing when TGE-5A's permeable zone **was** detected to have a communication with the chloride **springs** further downstream. It is however, interesting to note that the **area** west of WFL is characterized by low degree of alteration whde numerous **springs** and intense fracturing are present **only** on the eastern side of the WFL.

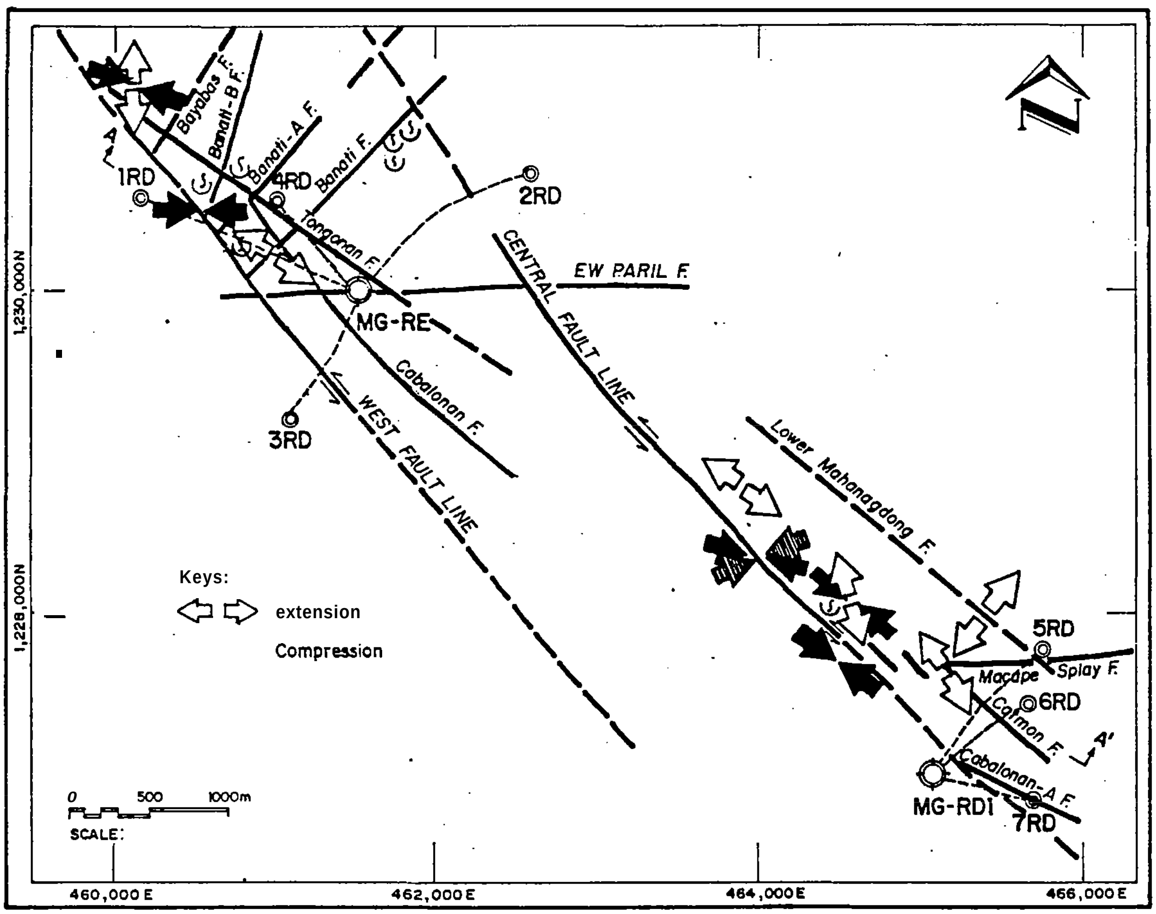

*Fig. 4. **Wells drilled from MG-RE (Bao Valley) and MG-RD1/B pad (Cambantog) showing the structures intersected. (See text for** discussion)*

2.2 Cambantog area

Field observations and measurements in the Cambantog area of the Mahanagdong sector revealed the behaviour of the Central Fault Line (CFL). the middle segment of the Phlippine Fault. **Its** presence is strongly indicated northwest of pad MG-RD1/B but do not show strong indication on its projected trace just north of this pad. **Instead,** an **almost** parallel structure believed to be a displaced segment of the CFL was **mapped** north. of the pad. This fault was recently **named** Catmon Fault. Intense fracturing and mineralization about 30 meters wide is associated to this fault which, fiom fault set analysis, shows a left-lateral displacement nith a significant dip-**slip** component. The present location of the fault *can* be described as a left-stepping left-lateral system produced **by** an extensional stress regime. This system is characterized **by** a hybrid **strike-slip** and normal fault movement typical in the formation of pull-apart structures (Aurelio et al., **1995). This** explains the absence of CFL at **its** projected trace **near** MG-RD1/B pad. The presence of **springs,** well developed **gypsum** veins and intense alteration just about NW of the pad further **supports** the transtensional regime characteristic of the area. This area southwest of the Mahanagdong-A Power Plant site along CFL is more **likely** related to a releasing bend while the portion on the northwestern part of the plant is within a restraining bend (Fig. ***5).*** Ideally along a single strike slip fault, releasing bends are extensional while restraining **bends** are compressional.

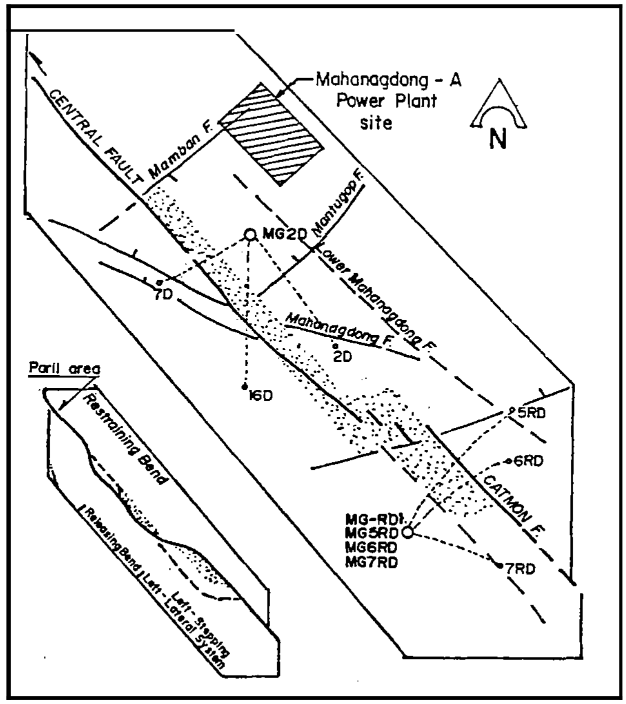

Fig. 5. The left-stepping left-lateral system produced by extensional stress regime. Lower figure shows the restraining and releasing bends produced along the CFL.

3.0 SUBSURFACE PERMEABILITY CHARACTERISTICS

The Bao **Valley** and Cambantog areas were intended for the reinjection of **fluids** that will come fiom the Mahanagdong Power Plants. The following section **highlights** the results of the wells **dnlled** with emphasis on their overall permeability and reinjection potential.

3.1 MGRE pad, Bao Valley

Prior to our ***study,*** wells have already been drilled from MG-RE pad primarily **aimed** at intersecting the extensional structures in Bao Valley. These wells were: MG-IRD, directed beneath the Bao hot **springs** towards Banati faults and CFL and MG-4RD, directed towards Tongonan Fault beneath the springs and **highly** fractured zones.

Well MG-IRD, supposedly intersected six structures in the open section of the borehole (Camit, 1993). Though geological indications such as veins, mylonites and intensity of alteration indicate the presence of the structures, they did not manifest circulation losses during drilling nor were there any permeabilty detected after the completion tests. These indicate the tightness, underdevelopment and limited permeabihty of the structures.

Well MG-4RD was directed beneath the Banati family of faults (beneath the springs) adjacent to MG-1RD to determine the shallow reinjection potential of the Bao Valley. Results showed that the northwestern portion of the Bao Valley has limited shallow permeability as high pump pressure are required to inject fluids at desired rates (Santos, 1994).

3.2 MG-RD1/B pad, Cambantog area

Well MG-5RD was the first well drilled from the pad prior to the conduct of the *study.* The *study* was then used as an aid in the design of the next reinjection well MG-6RD.

Well MG-SRD penetrated Catmon, Macape and Lower Mahangdong faults. Catmon fault exhibited good permeabilty as evidenced by shearing drusy vein minerals and circulation losses during drilling. Likewise, Macape Splay and Lower Mahangdong faults exhibited similar permeability characteristic. Blind drilling commenced upon the well's intersection with Lower Mahanagdong Fault (Vicedo and Medrano, 1995). The well's injectivity index was estimated at 21-22 li/s-MPa at zero WHP with an equivalent reinjection capacity of 95 kg/s at wellhead (Saw and Aleman, 1995).

Well MG-6RD was drilled towards the northeast targetting Catmon Fault, the structure interpreted to be under extensional stress regime. Despite the premature TD of the well, it exhibited good permeabdity having an injectivity index of 36.5-39.6 li/s-MPa at vacuum wellhead condition and a computed reinjection capacity of 112-115 li/s (102-105 kg/s) using a line separator pressure of *0.7* MPa (Gozon, 1995). The main source of permeability of the well is Catmon fault as it is the only structure intersected in the open hole (Leynes, 1995). Catmon Fault in this well was characterized by shearing, drusy vein minerals, intense alteration, drilling breaks and partial and total circulation losses. The recorded permeable zone at 1550-1650 m (Gozon, 1995) during the completion *tests* correlates to the intercepts of Catmon Fault.

4.0 DISCUSSION OF FAULT SET ANALYSIS DATA vs DRILLING RESULTS OF WELLS ON MGRE AND MG-RD1/B PADS

Fault data sets indicate that the structures intersected by wells MG-1RD and MG-4RD in Bao valley and wells MG-SRD and MG-6RD in Cambantog are under extensional stress regimes. Both areas also showed intense fracturing, high degree of alteration and are host for numerous hot springs. It was therefore expected that the structures will show the same subsurface permeabdity characteristics. However, drilling results of the wells drilled on the two areas are contrasting. Wells in MG-RE pad (MG-1RD and MG-4RD) have limited, almost nil, permeability whereas those wells drilled on pad MG-RD1/B (MG-5RD, MG-6RD) have significantly high reinjection capacities.

Subsurface geologic data reveal that the wells on MG-RE pad encountered formations different from those encountered by wells in MG-RD1/B pad Wells MG-IRD and MG-4RD penetrated through the Basement Complex and the Mahanagdong Claystone (Fig. 6). Based on their composition, these formations are inherently impermeable. The BC is composed mostly of serpentinites which is impermeable due to its plastic nature. Open fractures are minimal in these types of rocks as they react plastically to deformation. The MC is dominated by claystones consisting of very finely laminated clay minerals with silt-sized fragments of *quartz,* feldspar, calcite and pyrite. This makes the MC relatively impermeable or has very limited permeability due to its plastic character. The interpreted extensional *stress* regime on the surface was not manifested in the subsurface as no permeability was shown from the borehole data.

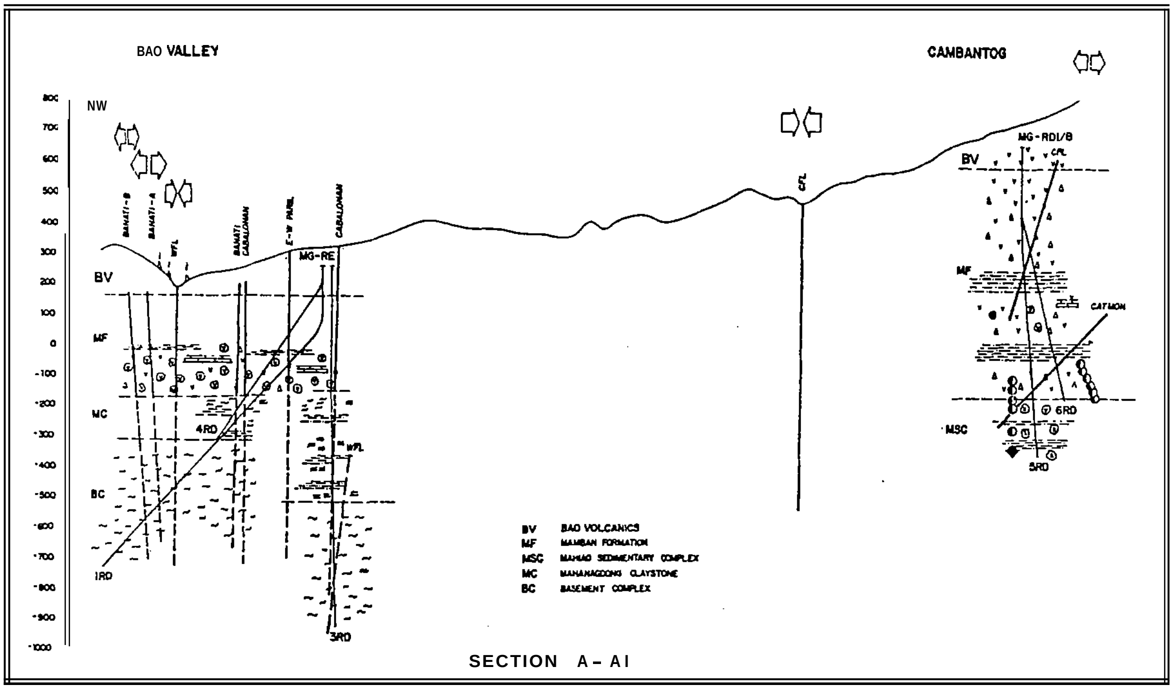

*Fig. 6. Cross **section along Bao Valley and Cambantog areas showing the lithology and structures intersected** by **the wells drilled. See textfor discussion.***

On the other hand, the wells drilled on pad MG-RD1/B in Cambantog did not encounter the BC and the MC but rather the Mamban Formation (MF) and the Mahiao Sedimentary Complex (MSC). These formations lend themselves to good fracturing due to their compositions, whch are breccia dominated (Fig. 3). Thus the predicted permeability related to the releasing bend formed **by** the left-stepping left-lateral fault system associated with CFL and Catmon Fault was proven to exist in the subsurface. This was clearly mamfested **by** the good permeability of the structures intersected **by** wells MG-SRD and MG-6RD.

5.0 CONCLUSIONS

Fault **data** set analysis can be used to pinpoint areas where permeability is more likely to exist. Although theoretically structures formed **by** extension are more permeable than those formed **by** compression (provided identical physical conditions exists), the preceding section clearly demonstrated that this is not always the case. The underlying lithology greatly affects the permeability of **an** area. Wells MG-IRD and MG-4RD in Bao Valley and wells MG-SRD and MG-6RD in Cambantog intersected structures under extensional stress regime. The wells in Bao Valley are impermeable while the wells in Cambantog are very pemeable owing to the differences in the composition and character of the encountered lithology. Thus, an area's response to the prevailing stress regimes appear to be dictated by the character or rheology of the underlying formations.

6.0 ON THE FUTURE USE OF FAULT SET ANALYSIS

Fault set analysis could be used as a tool in determining areas which are more likely permeable provided it is correlated with subsurface lithological characteristics and well-fault intersection correlation. The technique could also be of great use dunng the exploration stages in siting structural targets but should be incorporated with the regional stratigraphy and tectonics. It is therefore necessary that a multidisciplinary approach be followed to have a more precise assessment of the permeability potential of an area.

Acknowledgments:

The authors would like to *thank* A. C. Licup. Jr, H. P. Ferrer and F. G. Delfin, Jr for their comments and review of the paper. Great gratitude is also extended to E. G. Mendoza for drafting the figures.

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