Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Effective Tools for Exploring the Tectonic Evolution and Sub-surface Permeability of the Southern Negros Geothermal Field

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Keywords: fractures, palaeostress, fracture attributes, topology, exploration, brittle deformation

ABSTRACT

A fieldwork-based approach has been used to evaluate the potential fracture permeability characteristics of a typical high-temperature geothermal reservoir in the Southern Negros Geothermal Field, Philippines. Based on fault rock characteristics, alteration type, relative age of deformation, and associated thermal manifestation, two fracture groups have been identified with the youngest fractures mainly related to the development of the current geothermal system. Fault kinematics, cross-cutting relationships, and palaeostress analyses suggest at least two distinct deformation events under changing stress fields since probably the Pliocene, herein proposed to be influenced by the development of the Cuernos de Negros Volcano and the northward propagation of a major neotectonic structure located to the northwest, the Yupisan Fault. A combined slip and dilation tendency analysis of the mapped faults indicates that NW-SE structures should be particularly promising drilling targets under the inferred current stress regime. Frequency versus length and aperture plots of fractures across six to eight orders of magnitude can be described by a power law distribution, with a change in scaling exponent in the 100 to 500 m length-scale range. An evaluation of the topology of the fracture branches shows a dominance of Y-nodes that are mostly doubly connected suggesting good connectivity and permeability within the fracture networks. The self-similarity of the fracture size distribution of the outcrop and borehole datasets suggests that the fracture network mapped in the surface are good analogues for the fracture system at reservoir depths. This work illustrates how a range of desk-based tools can effectively be applied to improve understanding of a geothermal system and reduce uncertainties during the exploration and development phases of a field.

1. INTRODUCTION

Understanding fracture permeability is critical in exploitation of a typical subduction-related geothermal system like that in the Philippines, where the reservoirs are mostly hosted by crystalline and clastic rocks, resulting in permeability arising mostly from fractures, and less from the intrinsic permeability of the host rocks (Dobson, 2003). This involves the characterization of fractures, delineating the fracture development history, and understanding how these faults are related to past and present regional and local stress conditions. This is never straightforward, however, particularly during the early phases of exploration where borehole data is still not available. The challenge is to maximize surface geological data and the amount of information that can be derived from such sources and use them to inform exploration strategies, and even the targeting of drilling.

This work aims to illustrate how a well-targeted structural fieldwork can be fully utilized to understand the structural character and controls of the Southern Negros Geothermal Field (SNGF) which is being exploited by the Energy Development Corporation (EDC) located in Negros Island, Philippines (Figure 1), a classic example of an andesitic high-enthalpy geothermal system hosted by the andesitic to dacitic Cuernos de Negros volcano. A multiscale structural model for the field will be constructed to characterize fractures, identify controls, understand the fracture evolution, and evaluate the applicability of using the regional and local surface fractures as analogues of the SNGF reservoir in the subsurface. The intention is that the tools and methodology used here can be applied in other exploratory geothermal fields in equivalent geothermal and tectonic settings (e.g. Indonesia, Philippines), lowering exploration risks and hopefully improving the intersection of permeable structures during drilling of future wells.

2. GEOLOGICAL SETTING

2.1. Regional Geology

The Philippines is marked by complex and active tectonism, composed of the largely aseismic Palawan - Mindoro Continental Block to the west – a fragment that rifted from mainland Eurasia in the mid-Tertiary, and to the east, the seismically active Philippine Mobile Belt on which the majority of the country is located (Gervasio, 1966; MGB, 2010; Yumul *et al.,* 2005; Sarewitz and Karig, 1986; Aurelio, 2000). The Philippine Mobile Belt is an actively deforming zone composed of terranes of various affinity (i.e. from the ancient Philippine Sea Plate and the Indo-Australian margin; Yumul, 2005) that is bordered by subduction zones of opposing polarities: the west-dipping Philippine Trench and Luzon Trough to the east; and the east-dipping Manila, Negros, Sulu and Cotabato Trenches to the west (Gervasio, 1966; MGB, 2010). Shallow earthquakes are dispersed across the Philippine Mobile Belt indicating its continued active deformation due to plate tectonic forces (Cardwell, 1980).

Traversing from northwest Philippines to the southwest of the archipelago is the >1200km long sinistral Philippine Fault (Figure 1a) that formed from the oblique convergence of the Philippine Sea Plate with the Philippine Mobile Belt (Aurelio, 2000). The Philippine Fault has a slip rate of 2 to 3cm/yr (Aurelio, 2000; Barrier, 1991) or 2.4 to 4cm/yr (Yu, 2013) from GNSS techniques. This represents a third of the oblique convergence of Philippine Sea Plate, the remaining two-thirds being accommodated along the Philippine Trench and other major structures across the country (Aurelio, 2000). Maximum compression, σ_1, in the Luzon area is oriented between 90 to 110° in Luzon (Yu, 2013) and approximately east-northeast in Bicol region (Lagmay, 2005).

Negros Island is part of the Philippine Mobile Belt in central west Philippines (Figure 1a). It forms part of the Negros Trench arc system that is dominated by subduction processes in the south, but becomes more collision-dominated towards the north in Panay, where the collision of the Palawan microcontinent with the western margin of the Philippine Mobile Belt is observed (Yumul, 2013; Yumul, 2005; Rangin, 1989}. The GPS data analyses and focal mechanism solutions suggest that, in general, Negros Island is experiencing a WNW-ESE to NW-SE compression (Rangin, 2016; Lin, 2013; Kreemer, 2000, Rangin, 1999) consistent with the results of limited borehole breakout data of SNGF wells suggesting a maximum horizontal compression oriented 286° (Pastoriza, 2017).

The Negros Trench is associated with weak seismicity (Cardwell, 1980; Archaya, 1980) andweaker volcanism compared to the eastern side of the Philippine Archipelago. Its last destructive earthquake was a M6.7 in February 2012 centered in the central part of the island (USGS, 2012), generated by the NNE-SSW-trending NW-dipping Yupisan Fault (Aurelio *et al.,* 2017; Figure 1a). The Yupisan Fault runs to the west of the Cuernos de Negros Volcano, and represents part of an active fold-thrust system together with the Pamplona Anticline in the southern part of the island (Pastoriza, 2017; Aurelio *et al.,* 2017) consistent with WNW-ESE compressional tectonic regime.

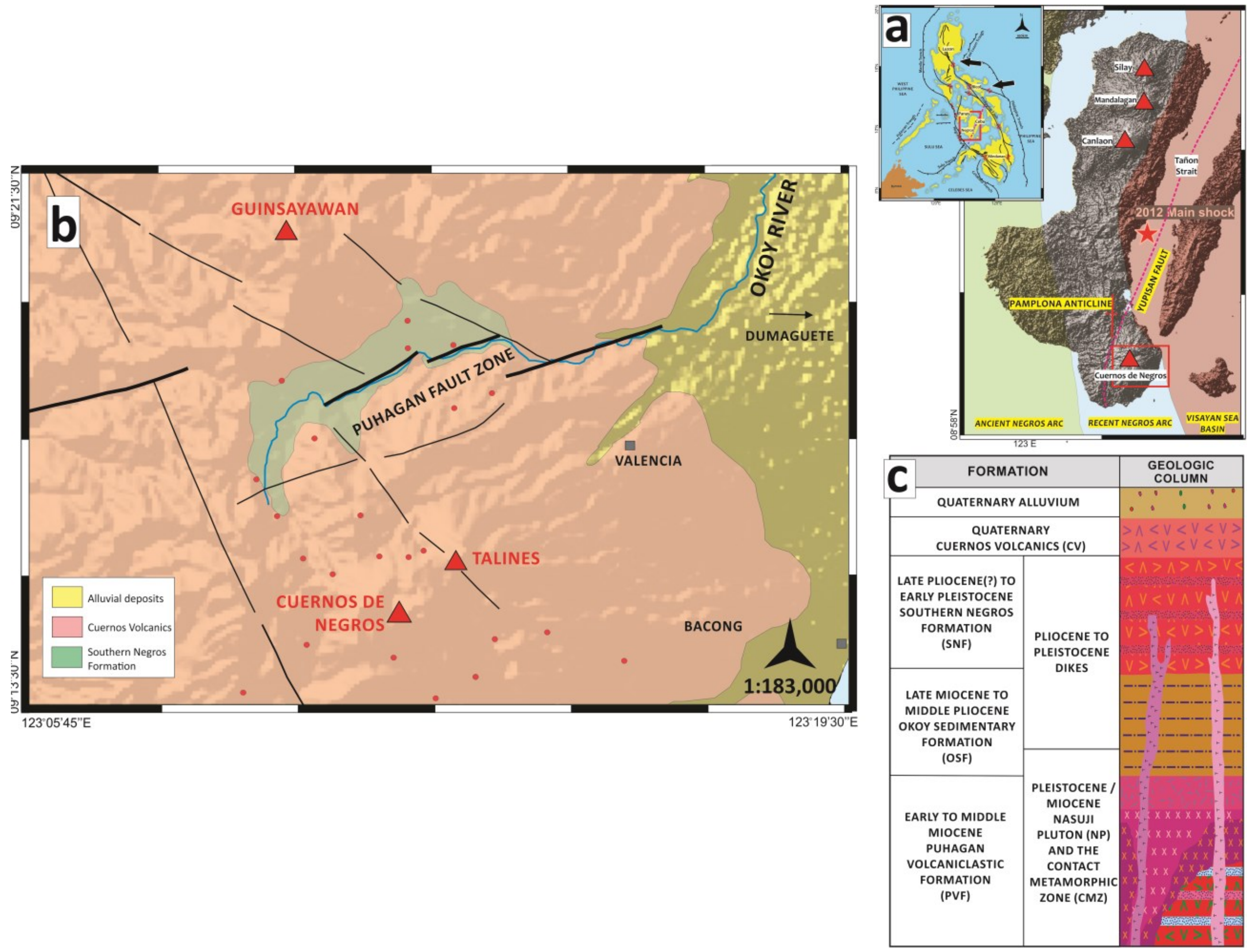

Figure 1: Geology of the Southern Negros Geothermal Field. (a) Negros Island, showing the Negros volcanic arc (red triangles) and the estimated trace of Yupisan Fault in dashed dark pink, overlain by the approximate boundaries of the tectono-stratigraphic terranes of the Negros subduction system. Red box represents the location of Figure 1b. Inset shows the major tectonic structures of the Philippines after Aurelio (2000). (b) Simplified map of the SNGF encompassing the CDN volcanic complex showing the key lineaments identified in Pastoriza (2017), location of the Okoy River (blue), volcanic edifices within the complex (red triangles), and estimated location of thermal manifestations (red dots), overlain by a simplified geological map of the field from Rae et al. (2004) and PNOC-EDC internal reports (modified from Pastoriza, et al., 2018).

2.2. Sub-surface Geology

The oldest rocks drilled beneath the Cuernos de Negros volcano are Miocene volcanic sequences of altered andesites intercalated with tuffs and calcarenites and occasional volcanic and sedimentary breccias, known as the Puhagan Volcaniclastic Formation (Figure 1b). They are intruded by the Nasuji quartz monzodiorite to micromonzodiorite pluton, that is reported to be either Miocene (10.5 Mya using K-Ar in Ariceto-Villarosa (1988) and Zaide (1984)) or Pleistocene (0.7 to 0.3 Mya using Ar-Ar in Rae (2004)) in age. By the Early Pliocene, the Okoy Sedimentary Formation and overlying undifferentiated andesitic volcanics and pyroclastics of the Southern Negros Formation were deposited. All the above-mentioned formations have been intruded by at least two dyke events during the Pliocene. These rocks are overlain by the Quaternary-aged andesitic Cuernos Volcanics, which can be subdivided into different members depending on which volcanic edifice of the CDN volcanic complex they are associated with. Radiocarbon dating of charred wood within the Cuernos Volcanics suggests a youngest eruption age of 14,450 years (Zaide, 1984). These young volcanics cover much of the surface of the present-day CDN volcanic complex, with exposures of the older Southern Negros Formation limited to the downstream river valley area of the E-W Okoy River (Pastoriza et al., 2018; Figure 1c).

3. METHODS

The methods applied in this work can generally be categorized into four phases – desk study, fieldwork, laboratory work, and a final analysis to compile and synthesise information (Pastoriza, 2017). The desk study includes carrying out a lineament picking analysis utilizing digital elevation models of various resolution – 30 m, 10 m, and 1 m, mainly within the ArcGIS environment. The results were used to guide the development of the field work strategy wherein more time was spent in areas where regional and suspected critical structures are located. Two field seasons involved collection of fracture data that includes fault rock types, kinematic indicators, and cross-cutting relationships, which were carried out both in 1D (linear transects) and 2D (circular scanlines). Stress inversion was done on cross-cutting fractures using MyFault v.1.05 fault analysis software following the minimized shear stress variation model of Michael (1984) and Michael (1987). All the mapped fractures where then analysed for their slip and dilation tendencies (Ferill, 1999) to identify which fractures are most likely critically stressed and permeable at the present-day, using 3DStress developed by the Southwest Research Institute. Finally, cumulative frequency plots were created following the methods detailed in Ortega (2006) to characterize the distribution models of fracture networks from the lineament maps, outcrops, cores, and thin section samples. This was accompanied by a topology analysis, following the methodology of Sanderson and Nixon (2015) and Manzocchi (2002). The topology characteristics describes the connectivity of the fracture network, and thus by implication,, their effectiveness as a potential fluid transport system.

4. LOCAL STRUCTURAL GEOLOGY

As detailed and discussed in Pastoriza (2017) and Pastoriza et al. (2018), exhumed fractures within the Southern Negros Geothermal Field can be divided into two groups, termed Group 1 and Group 2 fractures. They are characterized in terms of their fault infills, key alteration minerals, kinematics, and the age of host rocks which they generally cut as summarized in Table 1. Group 1 fractures are mostly E-W-trending sinistral faults - or structures related to them - which are limited to outcrops of the older Southern Negros Formation. Group 2 fractures, on the other hand, are mostly associated with NW-SE-striking oblique dextral faults and with recent alteration related to presently active and inactive past thermal manifestations. They occur both in the older and more recent volcanic rocks and consistently, where they are observed together, Group 2 cut the Group 1 features. This strongly suggests that the Group 1 set of fractures developed earlier than Group 2, during what is termed as the Stage 1 of deformation (Pastoriza et al., 2018). Moreover, in some outcrops, some Group 2 fractures crosscut other Group 2 features, and on several occasions, overprinting of slickenlines, mostly horizontal lines overprinting steep ones, have been observed. Thus, it is proposed that more than one deformation event may have occurred to form the Group 2 set of faults, herein refer to as Stage 2a and Stage 2b, with Stage 2b mostly related to reactivation rather than involving new fracture formation (Pastoriza et al., 2018).

	Group 1	**Group 2**
Fault rocks	Cohesive and cemented (cataclastic)	Generally non-cohesive/poorly cemented Open fractures in some case
Key alteration minerals	Abundant pyrite Amorphous silica Quartz Rare Cu-sulphides	Abundant clays Quartz Sulphur Zeolites, calcites, gypsum
Kinematics	Mostly E-W (+/-) sinistral	Mostly NW-SE oblique dextral
Host rocks	Older Southern Negros Fm. Host has been completely altered previously	All lithologies Both altered and fresh rocks

Table 1: Summary of field characteristics of the two fracture groups mapped in the area of study (after Pastoriza et al., 2018).

Stress inversion analyses on the three stages of crosscutting features indicate that the prevalent stress regime at the time of each deformation event has changed over time (Figure 2). Stage 1 likely occurred under a pure strike-slip to transpressive tectonic regime where the maximum horizontal stress, S_{hmax}, was oriented NE-SW. The stress conditions completely shifted from a wrench faulting to strongly extensional regime when the Group 2 fractures formed and the second and possibly dominant stage of deformation developed. New structures have formed, mostly major WNW-ESE to NNW-SSE-trending normal, dextral, and oblique (normal/reverse) and rare ENE-WSW-oriented normal faults. Associated NNW-SSE tensile fractures and smaller faults offset the earlier fractures of Stage 1. The principal extension direction, σ_3, is oriented E-W for Stage 2a, consistent with the poles of the mapped N-S oriented tensile fracture planes, whilst the principal compression direction, σ_1, is vertical. By Stage 2b, σ_1 remained steeply plunging, whilst S_{hmax} shifted to the NW-SE, consistent with the modern stress regime of Negros Island (Heidbach, 2008) and borehole breakout data, but with a swapped σ_1 and σ_2 axes (Pastoriza et al., 2018).

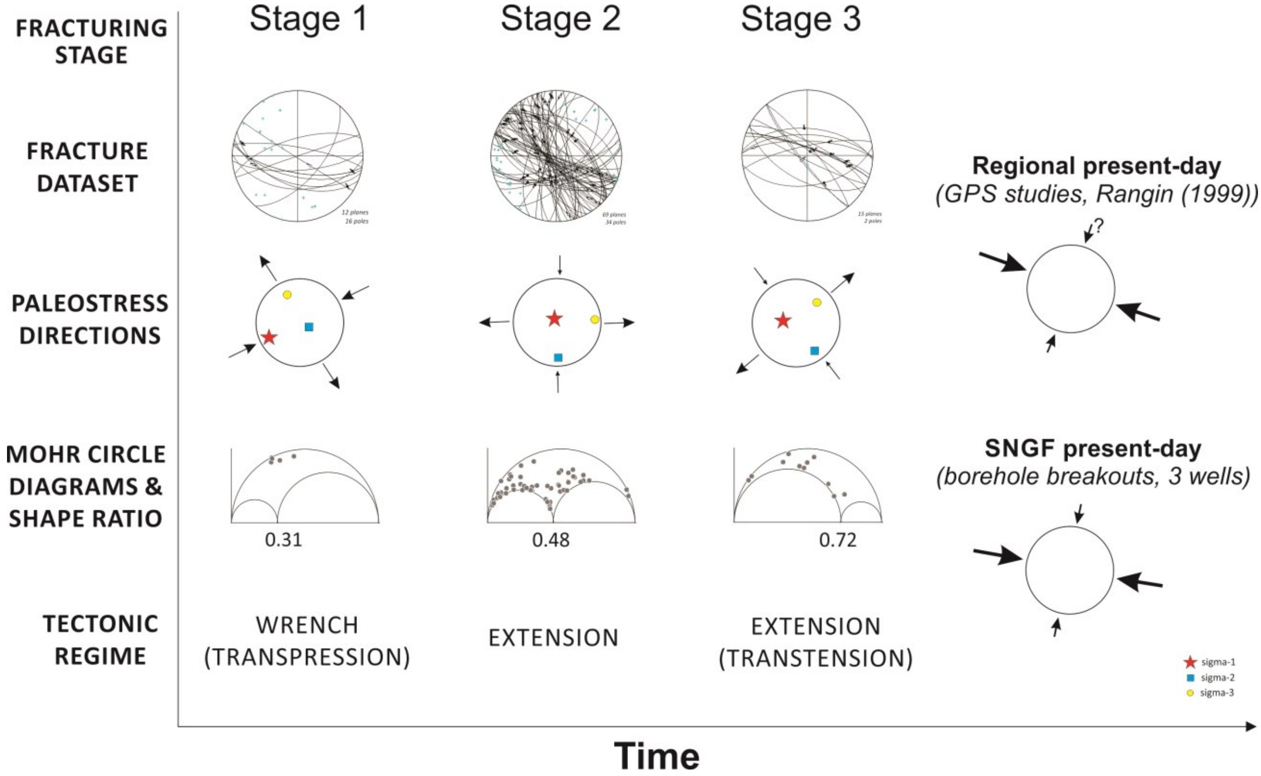

Figure 2: Summary of the palaeostress analysis results per stage of deformation (Pastoriza et al.,, 2018). The upper row shows stereographic projections of the key faults per stage with their corresponding slickenlines, where observed. The illustrated Stage 2 and Stage 3 palaeostress results (second and third rows) are from the data which have been weighted by both the fault thickness and length. The compression arrows in Stage 2 and Stage 3 are intended to be smaller to highlight that the associated stress regime is generally extensional. The question mark in the regional present-day direction indicates that only the maximum compression direction is given in the cited study. The smaller horizontal stress direction is inferred.

This observed stress rotation, as discussed in detail in Pastoriza et al. (2018) is suggested to reflect small-scale changes in the stress field related to the propagation of the NNE-SSW sinistral-reverse Yupisan Fault, traversing the southeastern area of Negros Island. This can be illustrated by a displacement vector model wherein a progressive local clockwise block rotation can result from the northward propagation of the Yupisan Fault. Further, the dominant extensional regime during Stage 2a and Stage 2b may well be a temporal effect of the activity of the ancestral Cuernos de Negros volcano. As volcanism progressed, intrusion heightened which affected the alteration type and the propagation of heat, presently being tapped by the SNGF.

Slip and dilation tendencies of all mapped fractures indicate under the present-day stress conditions, the orientation of fractures within the SNGF are more likely to dilate than to slip (i.e. slip tendencies are quite low <0.20 whilst dilational tendencies are close to 1.0). Steeply dipping to vertical NW-SE fractures have the highest dilation tendency and thus, are the most unstable under the modern stress conditions, followed by moderately dipping NW-SE-striking features. These ultimately suggest that NW-SE fractures are likely to be active at present, and thus, may have higher permeability than other fractures of different orientations.

5. FRACTURE NETWORK ANALYSES

A total of 40 linear scanlines and 70 circular transects were carried out on lineament maps, field rock exposures, core samples, rock slabs, and thin sections. Model fitting of the fracture intensity versus length plots based on maximum likelihood estimation criteria suggest that large-scale lineament networks ($5x10^2$ to $1x10^5$ m long fractures) are well described by a log-normal distribution whilst outcrop and core samples fracture networks ($1x10^{-3}$ to $\sim 5x10^1$ m in length) are strongly power law (details in Pastoriza, 2017). Plotting them altogether in log-log space, a clear break in the slope between the digital elevation model-based fractures and the field and borehole-based fractures are noted with the former having steeper regression slopes than the latter (Figure 3a). This suggests that there is a non-continuity of statistical properties across eight magnitudes of scale, but a clear continuity within the borehole and outcrop fracture networks (0.001 to 100 m). This continuity between the outcrop and borehole fracture transects is also observed in cumulative frequency versus aperture plots. Aperture sizes from $2x10^{-5}$ to 6.5 m collected here are also well described by a power law (Figure 3b). Both fracture length and aperture characteristics demonstrate that the surface fracture network of the SNGF is a good proxy for the subsurface fracture network.

Examination of the nodal types of the various fracture networks observed at multiple scales within SNGF shows that X-nodes are generally low in abundance (Figure 4). Instead, a significant proportion of the circular scanline results plot close to the Y-node apex, where Y-nodes comprise at least 60% of the observed intersections. This concentration is composed of the majority of the outcrop datasets, three core samples, and two slab scanlines. Most of the core samples, together with a few outcrop data, plot in the central area of the diagram, where there is a fairly equal proportion of X- and Y-nodes and just a slightly higher proportion of isolated nodes. The dominance of Y-nodes suggests that fractures tend to form abutments and splays, rather than intersecting each other. This observation may be related to the presence of different episodes of fracture formation within the SNGF where cross-cutting or abutting relationships are enhanced when fractures of different ages are present. Consequently, a high number of either X- or Y-node implies a high number (maximum being 2.0) of average connections per branch, which is a better measure of connectivity (Sanderson and Nixon, 2015). Outcrop fractures, for example, in this work have an average of 1.6 to 2.0 connections per branch (Pastoriza, 2017). Such a highly connected system is optimal for effective fluid storage and transport in the subsurface, provided that the fractures have remained completely to partially open.

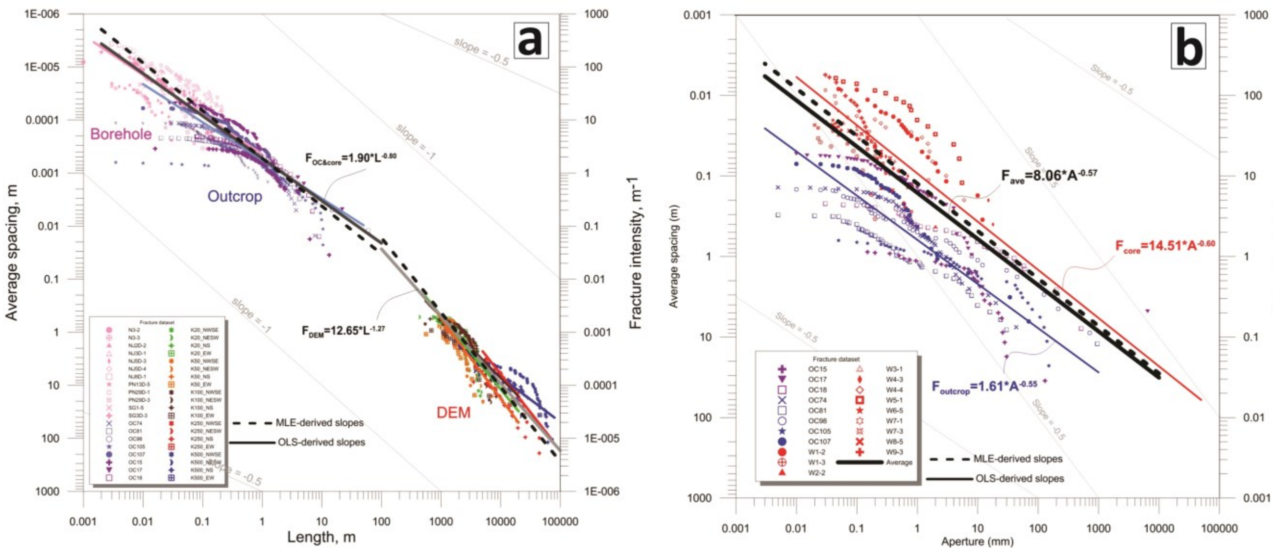

Figure 3: (a) Fracture intensity (right y-axis) versus length (x-axis) plots of all fracture transects carried out in the Negros and SNGF areas, fitted using a power law distribution (log-log). (b) Fracture intensity (right y-axis) versus aperture (x-axis) plots of all fracture transects carried out in both the mesoscale and the macroscale, fitted using a power law distribution (log-log). In both plots, average spacing is also shown on the left-hand y-axis. Fractures are coloured by scale they are collected. Trendlines for each scale are generated following the colours of the symbols. Average trendline in solid black is generated from the OLS method whilst the black broken line is from the MLE method. The regression equations are written only for the OLS trendlines.

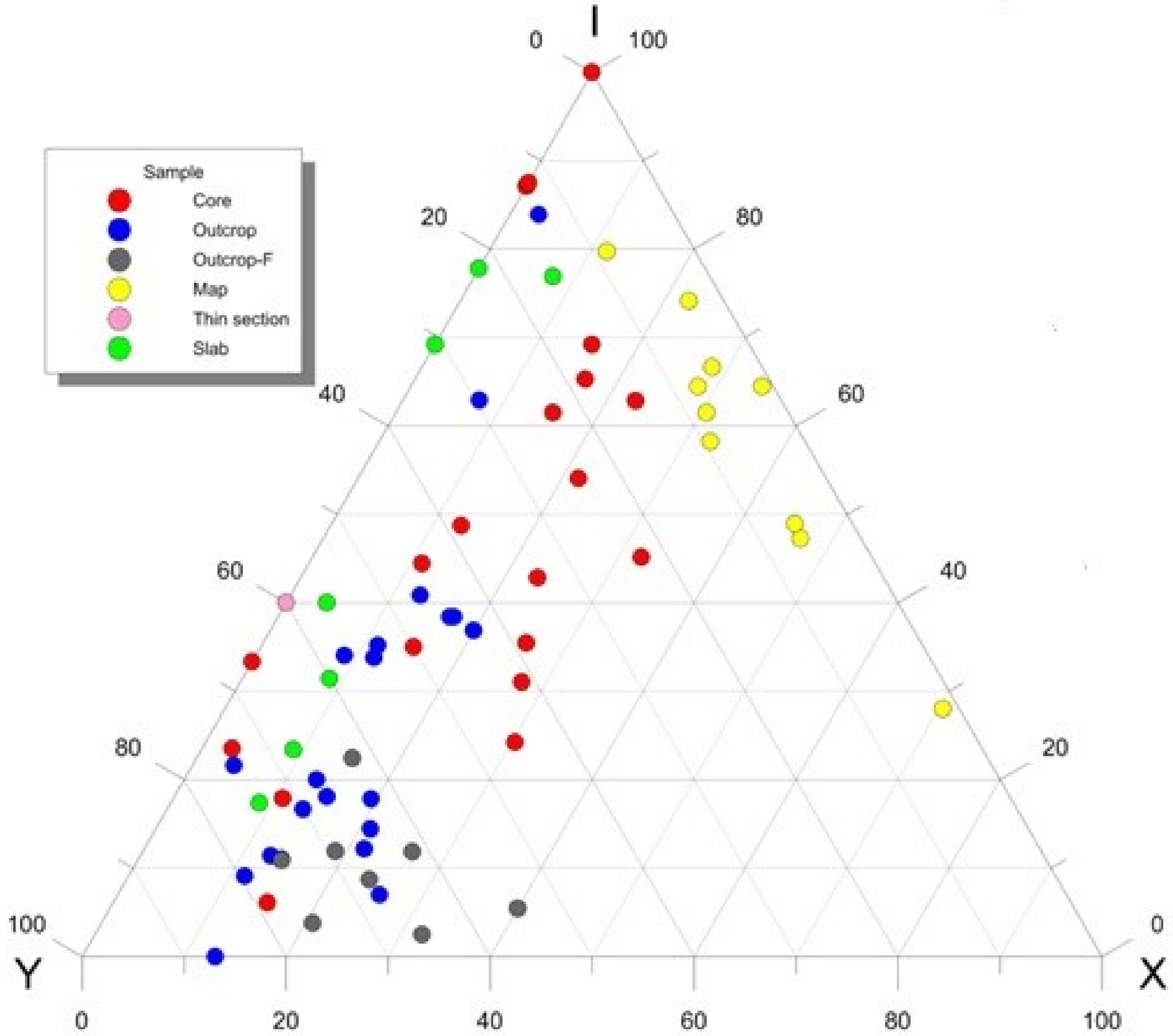

Figure 4: Node type ternary diagram of all the fracture intersection data populations, collected from the lineament maps (yellow), outcrops (grey for field-based and blue for photo-based), well cores (red), slabs (green), and thin section (pink).

6. DISCUSSION

This paper illustrates an approach that maximizes the analysis of geological data collected during the fieldwork through the application of several table-based tools that enable an improved understanding of a geothermal field. It is clear that a robust geological understanding of a field is critical in order to better predict one of a geothermal field's most important components – permeability.

Permeability of fractures is a temporal characteristic (Caine, 1996) - a damaged zone of rock densely cut by open tensile fractures at *time 1* may be permeable, and can by *time 2* become much less permeable due to mineral precipitation along fractures. Similarly, presently active faults are likely associated with fractures that are well-oriented relative to the modern stress regime and have a higher chance of increased open fracture density, thus enhanced permeability (Ferrill, 1999). A higher capacity to transport fluids is also more probable when a structure is more prone to dilate, since fault aperture is likely to enlarge. Thus, fractures with higher slip and dilation tendencies are ideal to target for drilling. These concepts have been effectively applied, for example, in assessing fault reactivation potential in deep enhanced geothermal systems in Germany (Moeck, 2009) and in understanding anisotropic transmissivity of the groundwater in the Yucca Mountain in Nevada (Ferrill, 1999). Thus, it is important to not just understand where the faults are, but more importantly, how these faults are related to past and present-day stress regimes.

In order to understand the deformation history of the mapped fractures in a field such as the SNGF, it is critical to carefully document cross-cutting relationships, their kinematics, and related alteration and fill mineralogies. The classification of these fractures revealed that not all surface faults are affected by hydrothermal alteration, and consequently, are least likely to be channeling or have channeled geothermal fluids. These are the older set of fractures, Group 1. By carrying out a palaeostress analysis, it was shown that this group of fractures has deformed during Stage 1 prior to the development of the present day geothermal regime and that this was associated with a different stress configuration from the modern one. Relating this to the temporal characteristic of permeability, this means that they are least likely to be permeable. This is consistent with field observations. Slip and dilation tendencies further support this suggestion that NE-SW-oriented fractures are mostly kinematically stable at the present-day stress regime, and thus, permeability will also likely to be low.

On the other hand, the younger fractures, Group 2, as observed in the field, show widespread evidence of recent channeling of fluids, which may be confined along the fracture plane or diffuse, indicating they are still active at the present-day. Similarly, the results of the stress inversion indicate that stress conditions at the regional scale during Stage 2 fracturing are already consistent with the present-day, locally perturbed by volcanism and the development of regional features like the Yupisan Fault. Thus, those formed during this stage are likely still well-oriented relative to the modern stress conditions, and may well be active, consistent why calculated dilation tendencies are high. Considering the age of their deformation, some may still be far from maturity and so tensile and smaller fractures are still enhanced and open, and thus, permeability is expected to be relatively high.

In addition, the application of a multiscale fracture attribute analysis to the SNGF demonstrates that the surface networks are good analogues for the subsurface. This is a critical finding as mostly, at the early stages of exploration where drilling has not taken place, the similarity of surface features and subsurface structures is simply assumed. The results of this study validate this common assumption. The multiscale approach used here also very much increases the confidence in estimating properties of fractures which are not directly observed – a key limitation when trying to model the subsurface. Information on the fracture network and the individual fracture attributes will be of the utmost importance in the creation of a realistic fracture model of the reservoir. Although not attempted here, a fracture network model allows the visualisation of how the fractures interact and are spatially located to support fluid flow modelling, better understand reservoir processes, and guide drilling strategies.

Actual drilling results within the SNGF prove that the model proposed here where NW-SE-trending faults are permeable structures is valid (Bayon, 2005). However, NE-SW and NNE-SSW-oriented structures are also important in the known fluid flow regime of the SNGF (Bayon, 2005). These large-scale NE-SW faults could have been original tensile fractures during Stage 1, and evidence for this is observed in some exposures (e.g. SNG-118 in Pastoriza, 2017). In most existing surface exposures, these have been sealed by mineral fills but could have been reactivated during succeeding fracturing events. This reactivation may have re-opened these structures as tensile fractures in the predominantly extensional regime of Stage 2, with or without a component of shearing. As the geothermal system was already developing during Stages 2a and 2b, temperatures at the fracturing depths may well have been much higher, making rapid cementation/sealing of the fracture planes less likely. This reactivation model may explain why some larger NE-SW faults have remained opened until the present day.

The overprinting of several fracture events within the SNGF may have also led to additional permeability. The topology analysis showing that Y-nodes are more prevalent than X-nodes in the majority of the fracture datasets analysed suggests that abutting or offsetting fractures contribute significant connectivity in the fracture network.

Finally, we proposed a methodology (Figure 5) that should supplement existing workflows on building geothermal resource conceptual models at the exploration stage (e.g. Cumming, 2009), which requires the integration of of geochemical, geophysical, and hydrological data and with geology-specific workflows, for fault zone permeability estimation proposed by Houwers (2015), for example.

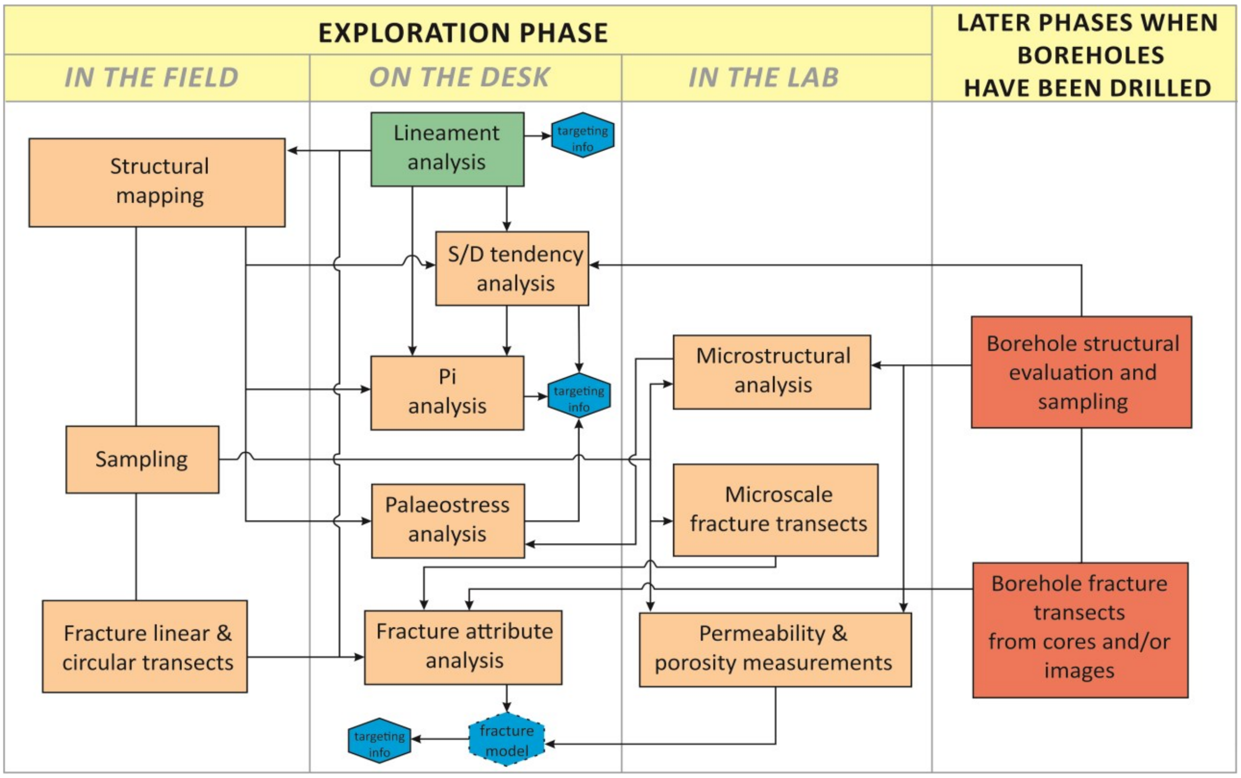

Figure 5: Schematic diagram of the workflow applied in this project aimed at characterising fracture networks. The green box refers the start of the process whilst blue hexagons represent stages where drilling strategies can be evaluated, the confidence levels of which increase as one opts to go through the entire workflow with the input of additional information. Processes in red are those not rigorously carried out in this project whilst those outlined by dashed lines indicate the process/output have not been attempted here.

Figure 5 summarises the methods that have been applied with some recommended extensions, in characterizing fracture networks even at the onset of the exploration phase where datasets are limited to surface information. A lineament analysis of the field often marks the start of the structural characterization, the results of which can then be verified by specifically-targeted fieldwork to carry out fracture transects, collect kinematics data, and observe crosscutting relationships. Deformation history can be deduced following a careful classification of fractures according to their relative ages prior to a stress inversion analysis, which then enables an understanding of the stages of the fault development. It is then potentially possible to explore how changes in the local and regional stress conditions may have affected the mapped fractures, and consequently, their permeability evolution. Likewise from the field information, one can already start building a preliminary fracture model of the subsurface, using this as an initial means to identify potential well targets for exploration drilling. This can be enhanced by calculating slip and dilation tendencies and carrying out common fault intersection, or pi, analysis (see Pastoriza et al., 2018 following Woodcock, 1983). These tools help to identify critically stressed fractures orientations and where fractures mostly intersect, respectively, and thus regions of likely enhanced permeability (Person, 2012; Ferrill, 1999; Sibson, 1996). Models may be revisited and further improved as microscale work (i.e. microstructural analysis, transects on thin sections) are carried out and actual information from the borehole are made available (Figure 5). Quantitative permeability assessment may also be conducted in the laboratory, which may be particularly useful if the interpreted reservoir rocks are composed of different lithologies, and where observed, faults fills may differ.

7. CONCLUSIONS

In this work, the key role of brittle structures within a high enthalpy geothermal system dominated by crystalline rocks has been analysed and assessed. These brittle structures provide the permeability, which is one of the critical components for a geothermal system to exist and perhaps be successfully exploited. Different aspects of the importance of fractures have been evaluated throughout this work and it was shown:

(1) That a well-constrained deformation history based on field observations and associated palaeostress analysis is necessary to understand the development of the fracture systems and how they are correlated with other structures in a geothermal reservoir.
(2) That fracture systems can be studied based on their topology, attributes, and physical permeability characteristics, and that each of these aspects has implications for the understanding of the permeability at the reservoir level,
(3) That the quantitative observations of the fracture network made both in the surface and sub-surface in the SNGF are similar and constrained by a power law distribution, and thus
(4) The exposed fracture networks are good analogues, therefore be used as basis to evaluate those attributes in the subsurface across a broad range of scales (mm to km)

Finally, we illustrate that when a wider picture of the characteristics of the fracture networks in a geothermal system is incorporated with a good understanding of the past and present-day stresses utilizing several tools, it can provide valuable information as to which faults and fractures may be conduits or barriers to fluid flow, similar to how these tools are widely applied in petroleum resources. This has direct implications for the drilling strategy, should a geothermal area be developed.

REFERENCES

Ariceto-Villarosa, H.G., et al., 2000. The subsurface geology and alteration mineralogy of Nasuji-Sogongon Sector, Southern Negros Geothermal Field, 1988, PNOC-Energy Development Corporation Internal Report.Aurelio, M.A., Shear partitioning in the Philippines: constraints from Philippine fault and global positioning system data. The Island Arc, 9: p. 584-597.

Barrier, E., P. Huchon, and M. Aurelio, 1991. Philippine fault: A key for Philippine kinematics. Geology, 19(1): p. 32-35.

Bayon, F.E.B. and M.S. Ogena, 2005. Handling the problem of rapid reinjection returns in Palinpinon-I and Tongonan, Philippines. in World Geothermal Congress. Antalya, Turkey.

Caine, J.S., Evans, J.P. and Forster, C.B., 1996. Fault zone architecture and permeability structure. Geology, 24(11): 1025.

Cardwell, R.K., B.L. Isacks, and D.E. Karig, The spatial distribution of earthquakes, focal mechanism solutions, and subducted lithosphere in the Philippine and Northeastern Indonesian Islands, in The tectonic and geologic evolution of Southeast Asian seas and islands, D.E. Hayes, Editor 1980, American Geophysical Union. p. 1-35.Lagmay, A.M.F., A.M.P. Tengonciang, and H.S. Uy, Structural setting of the Bicol Basin and kinematic analysis of fractures on Mayon Volcano, Philippines. Journal of Volcanology and Geothermal Research, 2005. 144(1–4): p. 23-36.

Cumming, W., 2009. Geothermal resource conceptual models using exploration data, Thirty-Fourth Workshop on Geothermal Reservoir Engineering Stanford, California.

Dobson, P.F., et al., 2003. Porosity, permeability, and fluid flow in the Yellowstone 687 geothermal system, Wyoming. Journal of Volcanology and Geothermal Research, 688 2003. 123(3–4): p. 313-324.

Ferrill, D.A., et al., 1999. Stressed rock strains groundwater at Yucca Mountain, Nevada. GSA Today, 9(5): p. 2-7

Gervasio, F.C., 1966. The age and nature of orogenesis in the Philippines. The Philippine Geologist, 20(4): p. 121-140.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeb, D. and Muller, B., 2008. The World Stress Map database release.

Houwers, M.E., Heijnen, L.J., Becker, A. and Rijkers, R., 2015. A workflow for the estimation of fault zone permeability for geothermal production a general model applied on the Roer Valley Graben in the Netherlands, Proceedings World Geothermal Congress, Melbourne, Australia.

Kreemer, C., Holt, W.E., Goes, S. and Govers, R., 2000. Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data. Journal of Geophysical Research: Solid Earth, 105(B1): 663-680.#84#322;Lin, 2013 #331;

Mines and Geosciences Bureau (MGB) , 2010. Geology of the Philippines, M.A. Aurelio and R.E. Pena, Editors : Quezon City.

Michael, A.J., 1984. Determination of stress from slip data: Faults and folds. Journal of Geophysical Research: Solid Earth, 89(B13): 11517-11526.

Michael, A.J., 1987. Use of focal mechanisms to determine stress: A control study. Journal of Geophysical Research: Solid Earth, 92(B1): 357-368.

Moeck, I., G. Kwiatek, and G. Zimmermann, 2009. Slip tendency analysis, fault reactivation potential and induced seismicity in a deep geothermal reservoir. Journal of Structural Geology, 31(10): p. 1174-1182.

Ortega, O.J., Marrett, R.A. and Laubach, S.E., 2006. A scale-independent approach to fracture intensity and average spacing measurement. AAPG Bulletin, 90(2): 193-208.

Pastoriza, L.R., Holdsworth, R.E., McCaffrey, K.J.W. and Dempsey, E., 2018. Tectonic Evolution of the Southern Negros Geothermal Field and Implications for the Development of Fractured Geothermal Systems. Geofluids, 2018: 20.

Pastoriza, L.R., 2017. The geological characterisation and permeability evaluation of fractures in the Southern Negros Geothermal Field, Negros Island, Philippines, in Earth Sciences, University of Durham.

Person, M., Hofstra, A., Sweetkind, D., Stone, W., Cohen, D., Gable, C.W. and Banerjee,A., 2012. Analytical and numerical models of hydrothermal fluid flow at fault intersections. Geofluids, 12(4): 312-326.

Rangin, C., Rigid and non-rigid micro-plates: Philippines and Myanmar-Andaman case studies. Comptes Rendus Geoscience, 2016. 348(1): p. 33-41.Rangin, C., et al., Plate convergence measured by GPS across the Sundaland/Philippine Sea Plate deformed boundary: the Philippines and eastern Indonesia. Geophysical Journal International, 1999. 139(2): p. 296-316.

Rangin, C., C. Muller, and H. Porth, 1989. Neogene geodynamic evolution of the Visayan Region, in On the geology and hydrocarbon prospects of the Visayan Basin, Philippines, H. Porth and C.H. Von Daniels, Editors. Geologisches Jahrbuch. p. 7-28.

Rae, A.J., Cooke, D.R., Phillips, D. and Zaide-Delfin, M., 2004. The nature of magmatism at Palinpinon geothermal field, Negros Island, Philippines: implications for geothermal activity and regional tectonics. Journal of Volcanology and Geothermal Research, 129(4): 321-342.

Sarewitz, D.R. and D.E. Karig, 1986. Geologic evolution of Western Mindoro Island and the Mindoro Suture Zone, Philippines. Journal of Southeast Asian Earth Sciences, 1(2): p. 117-141.

Sanderson, D.J. and Nixon, C.W., 2015. The use of topology in fracture network characterization. Journal of Structural Geology, 72(0): 55-66.

Sibson, R.H., 1996. Structural permeability of fluid-driven fault-fracture meshes. Journal of Structural Geology, 18(8): 1031-1042.

Woodcock, N.H. and Naylor, M.A., 1983. Randomness testing in three-dimensional orientation data. Journal of Structural Geology, 5(5): 539-548.

Yumul, G.P., C.B. Dimalanta, and R.A. Tamayo, 2005. Indenter-tectonics in the Philippines: Example from the Palawan Microcontinental Block - Philippine Mobile Belt Collision. Resource Geology, 55(3): p. 189-198.

Yumul Jr, G.P., Dimalanta, C.B., Tamayo Jr, R.A. and Faustino-Eslava, D.V., 2013. Geological features of a collision zone marker: The Antique Ophiolite Complex (Western Panay, Philippines). Journal of Asian Earth Sciences, 65(0): 53-63.

Zaide, M., 1984. Interpretation of rock-dating results in the Southern Negros Geothermal Field. PNOC-EDC Internal Report.

Aurelio, M.A., et al., Seismotectonics of the 6 February 2012 Mw 6.7 Negros Earthquake, central Philippines, 2017. Journal of Asian Earth Sciences, 142: p. 93-108.

USGS, 2012. Magnitude 6.7-Negros-Cebu Region, Philippines. United States Geological Survey Retrieved from http://earthquake.usgs.gov/earthquakes/eqinthenews/2012/usb0007wgq/