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A Workflow for the Estimation of Fault Zone Permeability for Geothermal Production A General Model Applied on the Roer Valley Graben in the Netherlands

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ABSTRACT

A high permeable medium allowing groundwater flow is needed for the production of geothermal energy. Permeability can be enhanced by the presence of natural fractures and faults. Permeability prediction of fault damage zones and fracture corridors simply by extrapolation or up-scaling of reservoir characteristics is de-validated by the heterogeneity, anisotropy and scale variation of these features. In addition, the evolution of damage zones in time may cause changes in the porosity-permeability due to changes in the tectonic deformation style and geochemical processes. In the hydrocarbon industry, fault zones are generally considered for their sealing capacity, however (hot) springs and fumaroles are natural evidence of extended upward flow along faults. Geothermal activity in for example western Turkey and the Basin and Range province (USA) is related to regional extension with deeply penetrating faults and recent geothermal drilling towards several fault damage zones in the Upper Rhine Graben near Landau, Insheim, Brühl, and Bruchsal in Germany even resulted in better flow results than expected compared to the overall porosity and permeability of the Buntsandstein reservoir. Previous studies showed that mainly the host rock lithology, fault activity, magnitude of displacement, pre-existing structures, the depth, the tectonic stress field and the width of the damage zone are considered to be essential parameters in predicting the conductivity of fault damage zones. In order to make a valid but simple model of the conductivity of fault damage zones, these are the most relevant parameters which can be obtained relatively straightforward. These parameters should be measured and taken into a quantitative approach. They include fault plane orientation, displacement, intersections, the width of the damage zone, and the local stress field. Next to the measurable parameters, available geological and geomechanical parameters such as lithology, shear and tensile strength and clay content should be combined with the results from algorithms provided to obtain an indication of the potential flow along a fault damage zone. This approach results in a workflow that predicts permeability in fault damage zones by quantification of damage zone and rock properties. This approach can be used to select potential drilling targets. The workflow provides an overall first step in the exploration of potentially high productivity targets in fault damage zones.

1. INTRODUCTION

Within sedimentary basins, low enthalpy geothermal energy is in general produced from aquifers. Not all of these aquifers have the required reservoir properties to extract sufficient flow rates for an economical project. Fault zones are considered as an additional target since high geothermal production rates are being produced in geothermal projects related to active fault zones worldwide. The productivity of an aquifer can be quantified before drilling when sufficient well data in the surrounding are available. Prediction of the productivity from fault zones before drilling is however difficult as the permeability of the faults are hard to predict due to the complexity of fault zones.

Fault zones can be both sealing and permeable. In the hydrocarbon industry the faults are assessed for their sealing capacity and examples where faults are sealing are numerous. However, in the geothermal industry permeable faults are targeted. Natural evidence of extended upward flow along faults are for example (hot) springs and fumaroles. Geothermal activity in for example Western Turkey and the Basin and Range province (USA) is related to a regional extensional geologic setting with deeply penetrating faults. Predicting whether a fault zone will behave like a conduit or seal is complex, since it depends on a great variation of factors, see figure 1.

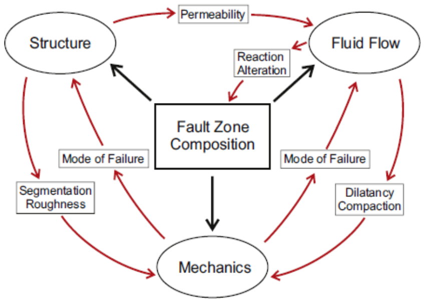

Figure 1: Flow diagram showing interactions of main topics of structures, mechanics and fluid flow. Mode of failure refers to whether or not seismic slip occurs (Faulkner, 2010).

The question rises if and how the value of fault zone permeability predictions can be quantified. In this paper, several factors are investigated for their role in fault behaviour and the prediction of fault permeability. The focus will be specifically on sandstone reservoirs as finally these factors will be used in an example study in Dutch fault systems in Triassic sediments within the Roer Valley Graben.

2. FAULT ZONE ELEMENTS

Fault zones can be subdivided into several elements which each have a different permeability. Fault zone architecture is generally considered the following way; the host rock is the unaltered rock, the fault core is the plane along which the displacement occurred and the damage zone is the ellipse shaped area surrounding the fault core with a higher fracture density than the host rock. These elements must be considered for localization of the zone with highest potential for fluid flow by enhanced permeability in the damage zone (fig.2).

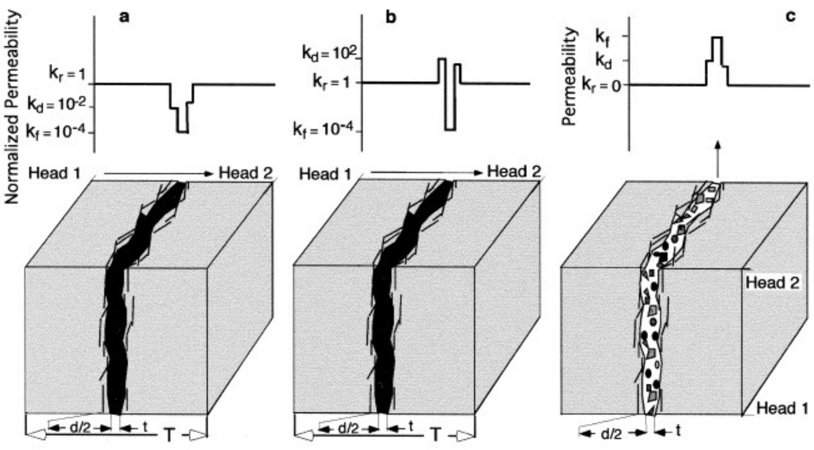

Figure 2: Showing normalized permeability along a fault zone; a) Deformation band fault zone results in reduced permeability b) A fault developed by shearing across a joint zone. Fault rock formed by this process is similar to that of the deformation band process but it is surrounded by a damage zone, more permeable than the parent rock. (c) A brecciated fault zone of increased permeability (Rawling, 2001).

In each of the fault zone elements discussed, the grain size differs due to mechanical compaction and chemical alteration. Most importantly, the grain size is significantly reduced in the fault core due to shearing of the rock, resulting in clays that strongly reduce the fault zones permeability. The fault zone then forms a barrier for flow perpendicular to the fault, but the damage zone enables flow parallel to the fault. The presence of a fault therefore can change local anisotropy significantly and stratigraphy affects local permeability (fig.3). Stronger anisotropy develops in sedimentary rock than in crystalline rock (Bense, 2013) (fig.3), this will be discussed in more detail in section 3.4.

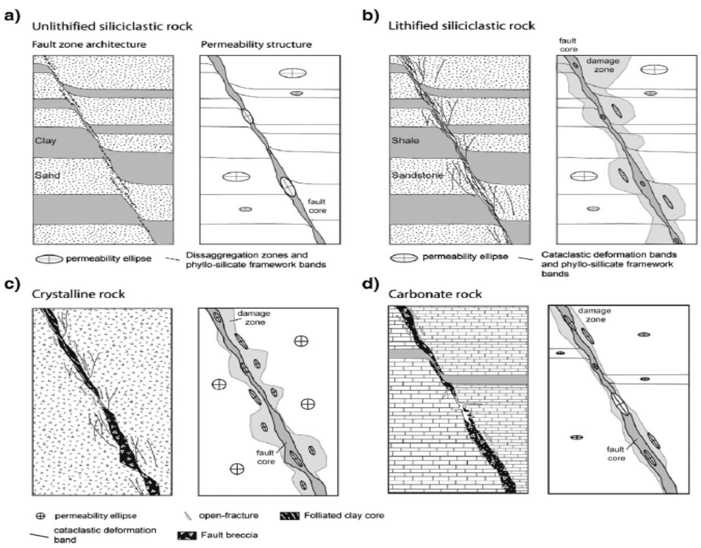

Figure 3: Fault structure in terms of fault core and damage zone affecting anisotropy (Bense, 2013).

3. FACTORS CONSIDERED

The complexity of fault zones is mainly caused by local variations in terms of size, orientation and sub structures. The host rock could change within short distances due to for example sedimentary features or an intrusion. Variation of host rock and conditions (e.g. temperature and pressure), will result in different alterations. Shear strength as well as clay content and resulting fault slip and flow behaviour are related to depth (fig.4). Each combination results in fluid-rock interactions specific for a geological setting, altering rock through geological time. Prediction of upward fluid flow in fault zones can for these reasons not be predicted with high certainty. Only local well data and samples can confirm predicted values and therewith the models used.

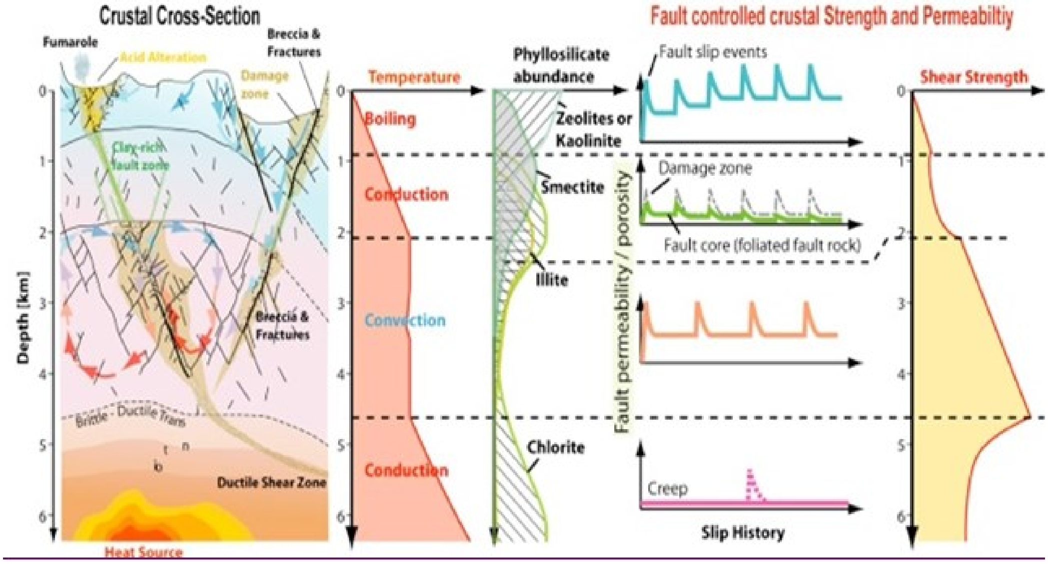

Figure 4: Fault zone behaviour and properties over depth (Faulkner, 2008).

Factors affecting fault rock properties have been modelled and tested in different settings and are therefore taken as expected indicators of local enhanced permeability. Factors that are not considered in this study involve lithological characteristics like grain size and grain size variation, mineral composition, bed thickness and geometric characteristics like fault length and fracture connectivity. These are not taken into account in this paper since they are not discussed and studied in detail in available literature or only consider a very specific geological setting and therefore have a lower predictive value in general.

General indicators along with their relation to permeability are combined in a workflow which can be used to assess an area for its best location to produce geothermal energy. The workflow involves analysis of observable features as fault plane orientation, displacement, intersections and the regional stress fault. These will be related to geological and geomechanical characteristics like lithology, tensile strength and clay content. These factors will be discussed more extensively below.

3.1 Active faults and regional stress field

First of all, the presence of active fault zones should be determined. Active regions and older fault zones can be located using 3D seismic imaging and natural seismicity. Fault zones are considered active when the latest activity was within the last 10000 years, i.e. the Holocene. Seismic images combined with surface data (Lidar) can be used to analyse whether a fault zone penetrates formations of this age or younger. Active fault zones contain more fluid pathways than ancient faults since fractures will not have yet been sealed by other processes like mineral precipitation. Strike slip faults and normal faults occur in extensional stress situations and are therefore most likely to be open and host fluid flow.

In order to determine the occurrence of active fault zones in the area around the test area Tilburg (The Netherlands), 3D seismic data has been interpreted. From the seismic data, it can be observed that faults in the area penetrate late Miocene and younger sediments. These faults are considered as active fault zones. Fault trenching in the area confirms that the Gilze-Rijen Fault zone is active (van Balen et al, 2003).

When active faults are present in the area, the next step is to estimate the behaviour of the fault zone relative to the regional stress field**.** The prevailing stress field determines the tendency of a fault to slip and to be open for fluid flow. Dilation of a fault is required for a fault to act as a flow path. According to the orientation and magnitude of the principal stress axis relative to the fault plane the tendency to slip of the fault plane is determined using the following relations (Morris, 1996);

$$T_{s=\frac{\tau}{\sigma_n}>\mu} \quad (1)$$

$$T_{d=\frac{\sigma_1-\sigma_n}{\sigma_1-\sigma_3}} \quad (2)$$

Where Ts is the slip tendency, τ is the shear stress, σ_n is the normal stress, μ the friction coefficient, Td is the dilation tendency, and $\sigma_{1\text{-}3}$ are the principle stress magnitudes.

The slip tendency indicates whether a fault is likely to move. The slip tendency is directly related to the stress field relative to the fault plane orientation.

In normal faulting and strike slip faulting stress regimes, the minimum principal stress is in the horizontal plane and thus being a net tensional force. If this stress is perpendicular or slightly oblique to the fault plane, it will result in an opening of the fault.

3.2 Fault zone kinematics

Besides the slip and dilation tendency of fractured rock to accommodate fluid flow, fracture density is a primary indication for permeability. This is related to the size of the damage zone of a fault. Displacement of a fault indicates the deformation intensity of the fault and therewith gives an indication of the fracture density and width of the damage zone (fig.5) (among others Schueller, 2013; Bense, 2013). Since displacement might be directly observed from seismic data, this is a useful indicator.

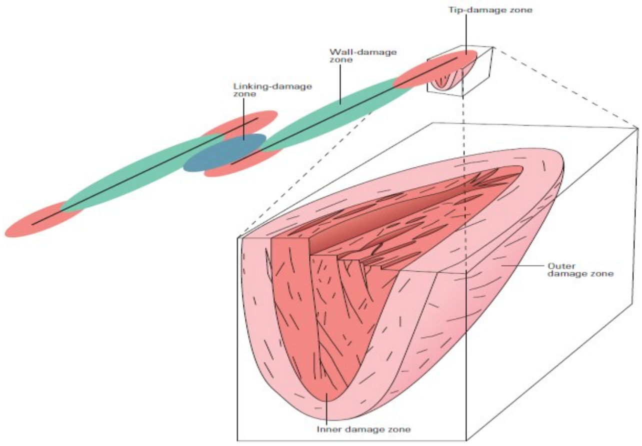

Figure 5: Damage zone width is the widest point of the ellipse shaped damage zone. The inner damage zone shows a varying off set along the fault (Cerveny, 2005).

A power law relation exists between the fault displacement and the width of the damage zone. This relation has been studied by several authors (Schueller, 2013; Childs, 2009; Bense, 2013, Shipton and Cowie, 2001), but no general relation has been found. As part of this study, results from available literature have been compared and fitted to a power law:

$$W = aT^b \tag{3}$$

Where *W* is the damage zone width, *T* is displacement (fault throw) and *a* and *b* are constants (Bense, 2013; Schueller et al, 2013). The values of *a* depends on the clay volume of the host rock while the value of *b* relates to the dip of the fault.

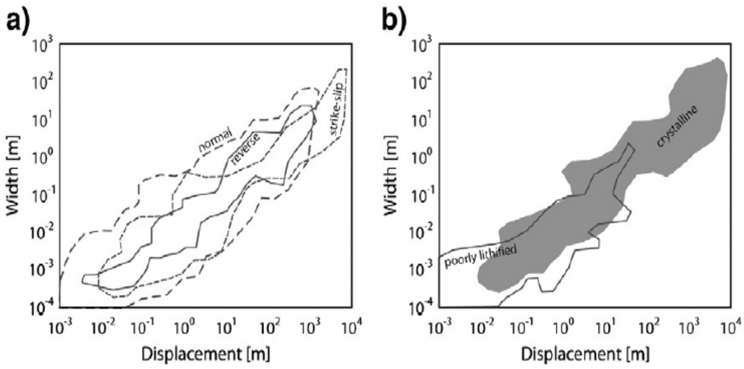

Figure 6: Displacement vs damage zone width wherein a: shear sense does not seem to effect the damage zone width, b: an effect of the rock type seems to exist (Bense, 2013).

The most significant effect on the development of the damage zone width was shown by the clay content of the host rock and the dip of a fault zone. An example is shown in figure 7 in which the negative effect of clay content on the development of damage zone width can be seen. The following values were determined for relation (3):

Clay < 5% a= 7.9 (R^2=0.14)
Clay > 20% a= 0.3 (R^2=0.66)
Dip > 70 b= 0.58 (R^2=0.64)
Dip < 70 b= 0.25 (R^2=0.76)

It should be noted that the amount of studies which is compared is limited due to different definitions and measurements. Since for both for the clay content and dip only two ranges are defined, application of the power law will be a rough estimate and therefore not very accurate. Deformation intensity might be changed by reactivation of a fault zone, which could occur along the initial sense of shear but also as inversion. This should be taken into account during analysis of seismic data. However the total displacement which is related to deformation intensity could be harder to determine.

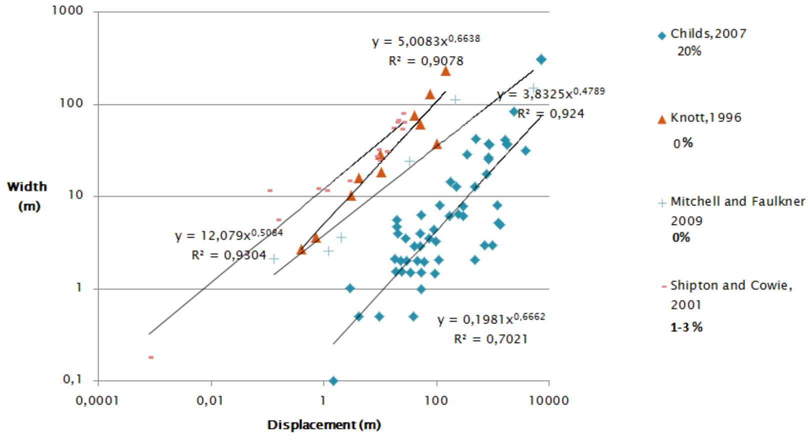

Figure 7: Comparing the effect of different factors on the development of damage zone width. Clay volume of the host rock (% given below authors) is related to a damage zone width difference of 2-3 orders of magnitude.

3.3 Interaction of fault zones and reservoir curvature

Due to fracture density higher permeability is expected within the damage zone, compared to the host rock. Not just local factors affect the permeability of individual fault zones, also the interaction of multiple faulted or fractures zones can affect fluid path ways. Crossing fault zones or opposite half graben systems are related to high ground water fluxes (Faulds, 2001). Also reservoir curvature can potentially enhance fracture density in anticlinal areas.

Many geothermal systems are found in extensional fault systems at places where faults interact. Also different numerical modelling show an increase of the fracture density in intersecting damage zones (fig.8A). The assumption of these regions being favourable for fluid flow seems also likely since extension in these areas will be high, causing fractures to be open for flow. Since major fault structures might be mapped or could be obtained from seismic data, zones of interaction can be identified. Fault systems from which geothermal heat are produced are in many cases related to interacting fault systems.

Curvature of the formation can result in dilatant fractures in the top of anticlinal structures as well as the bottom of synclinal structures. These areas are therefore also interesting for well targeting of geothermal systems. An example is given in figure 8B.

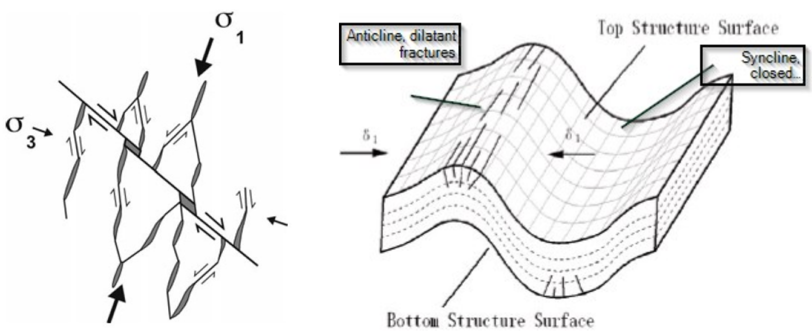

Figure 8: A: fault structures developed adjacent to a pre-existing fault in an extensional stress regime, faults are shown with arrow indicating relative movement Person (2012); B: Curvature affecting the tendency of fractures to be open in anticlinal parts (Suo, 2012).

3.4 Lithology

The rock assemblage in general affects the mechanical and chemical behaviour of the rock and thus the fault rock development. The initial permeability differs strongly because of the high primary porosity of sandstone (2-20%), whereas crystalline rock and limestone mostly have no initial porosity.

The development of deformation bands in porous sandstone will reduce permeability and enhance the anisotropy and heterogeneity of the rock. Due to the low initial porosity this process is less relevant in volcanic rock. In shallow crust brittle failure is dominant and results in cataclasis. Due to increasing temperature and pressure, diffusion mass transfer and plasticity are the main failure mechanisms with increasing depth they help explain ductile behaviour (White, 2001; Sibson, 1977). The low permeability of clay is the main cause of fault zones considered to be sealing. The Shale Gouge Ratio (SGR) (Yielding, 1997) is used as indicator of the relative clay volume in a fault zone (4).

$$SGR = \frac{(V_{clay} \times z)}{T} \qquad (4)$$

In which V_{clay} is the clay percentage, z the bed thickness and T the throw of the fault.

Even though in the upper crust brittle behaviour is dominant, ductile behaviour also has been observed (Billi, 2010; Brogi, 2008; Tesei et al., 2013). Ductile behaviour due to pressure solution increases with clay content which has been confirmed in experiments (Niemeijer and Spiers, 2005;Tesei et al., 2013). The brittle ductile transition is predicted to be at a depth of 3-5 km in clay bearing lithologies. Under the (low) P–T conditions rocks with higher clay content tend to quickly develop pressure-solution fabrics to accommodate whereas in pure limestone grain size reduction is energetically favourable when exposed to tectonic stresses. For this reason dilation and overpressure within fractured rock is more favourable in high strength pure limestone compared to siliciclastic rock (Billi, 2010).

Chemical alteration of fault zones is mostly the result of fluid flow along the fault. Chemical reactions can occur and affect fracture surfaces by precipitation and dissolution of minerals. The depth relates to local temperature which in turn affects these reactions. Upward fluid flow might also cause local temperatures changes that could trigger alteration of the host rock. Whether reactions will occur depends on the available elements and pressure and temperature conditions. Sandstones in the North Sea studied by Fisher (2001) show compaction of quartz grains by pressure solution strongly affecting the permeability at depths over 2.5 km.

3.5 Seismic risk

The injection of geothermal water along fault zones enhances the pore pressure in a fault zone. As a result, the effective stress is reduced causing rock to fail at lower shear stress, referred to as induced seismicity. This risk is a complex matter by itself and should be taken into account when developing a project in a fault zone. The details go beyond the scope of this paper. However, the increased hazard of induced seismicity has to be kept in mind when exploring fault zones for geothermal use.

4 PERMEABILITY PREDICTION – A CASE STUDY

Within some areas of the Roer Valley Graben in the South East part of the Netherlands, the primary reservoir properties of the Buntsandstein reservoirs are such that only low flow rates can be achieved. The Roer Valley Graben (RVG) is the north-western branch of the European Cenozoic Rift system. The most active faults during the Quartenary are the border faults of the RVG; the Peel Boundary Fault zone in the northeast and the Feldbiss Fault Zone in the southwest (fig. 9). These active faults are NW-SE orientated, and a second set of faults is present with a NE-SW tot N-S orientation (Houtgast, 2000). The faults are investigated for their potential for higher geothermal production rates.

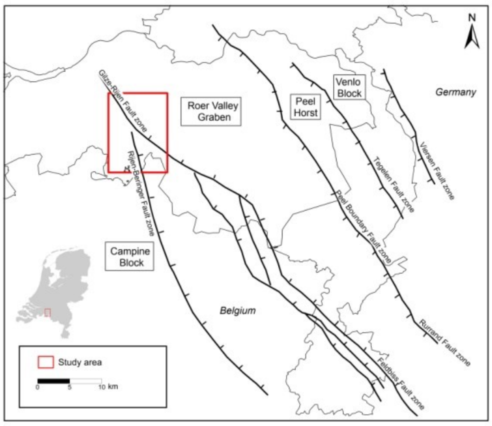

Figure 9: The tectonic units of the Roer Valley Rift System (after van Balen, 2004).

4.1 Stress, orientation and kinematics

Active faults are present and the neotectonic faulting mode is normal-slip (van Balen, 2004). The stress orientation from borehole breakouts and focal mechanisms were taken from the world stress map (2008) and stress magnitudes were calculated based on wellbore data. At the approximate reservoir depth of 2.5 km, the effective stress magnitudes are: S_{Heff} = 22.0 MPa (105/00), S_{heff}=12.9 MPa (015/00), S_v= 28.0 MPa.

Relative position of the faults to the present stress field and slip and dilation tendencies can be determined using the fault orientation, stress orientation and magnitudes.

Slip and dilation tendency calculations resulted in very low slip tendency (0.4) and medium dilation tendency (0.5). Enhanced vertical permeability by open fracture system might therefore be expected. The most favorable conditions are high dilation tendency (DT>0.7) and a low slip tendency (ST<0.3).

The low slip tendency and high dilation tendency are promising for both permeability and fault activity. Fault activity should be considered since changing pore pressures could trigger activity of the faults .. The presence of potentially active or large faults near the prospected area is therefore also considered as a hazard.

4.2 Lithology

The lithology could be analysed assuming lateral equivalence of the formation. Haffen (2013) performed extensive analysis of the reservoir in the Lower Germanic Triassic Group. Clay volume is estimated at 20 % (Haffen, 2013) and fluid circulation in the

Buntsandstein sandstone is controlled by the fracture network of a comparable fault zone as the RVG. Also braided river facies are important for macroscopic fluid flow (Haffen, 2013). Other identified fluid circulation zones are controlled by sedimentary properties. Since cataclasis is dominant in the crust at depth greater than 1 km (Fulljames et al. 1997), grain size reduction and related permeability reduction will become more important in the RVG setting. Also smearing of the present clay into the fault zone will become important. Extensive quartz cementation in the North Sea basin is found at depths of 2.5-3.0 km at temperatures of 90-100 °C (Bjorlykke and Egeberg, 1993) and thus might also be significantly reducing the permeability in the RVG. Other analysis of the Bundsandstein by Frottier (2013) concludes similar to this report that not the major fault zones but the fractured Bundsandstein formation are should result in thermal conductivity.

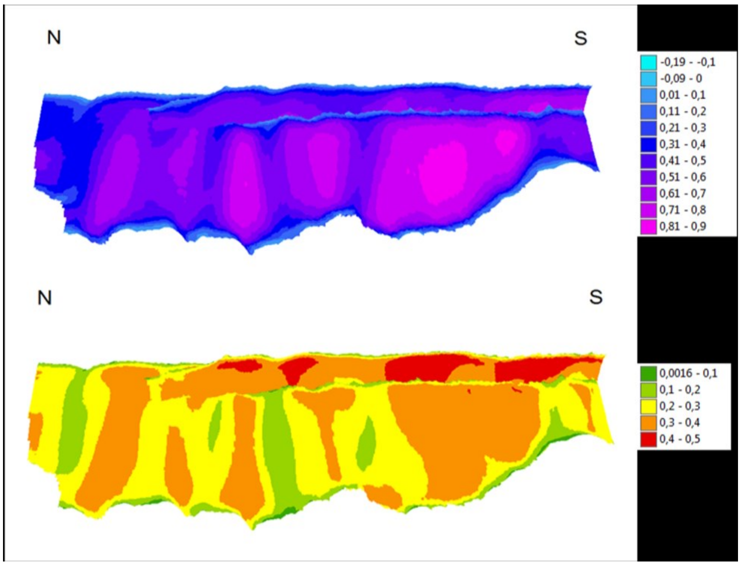

Figure 10: Dilation tendency (DT) and slip tendency (ST) of a N-S trending fault in the Tilburg area, The Netherlands (Rijkers et al., 2014).

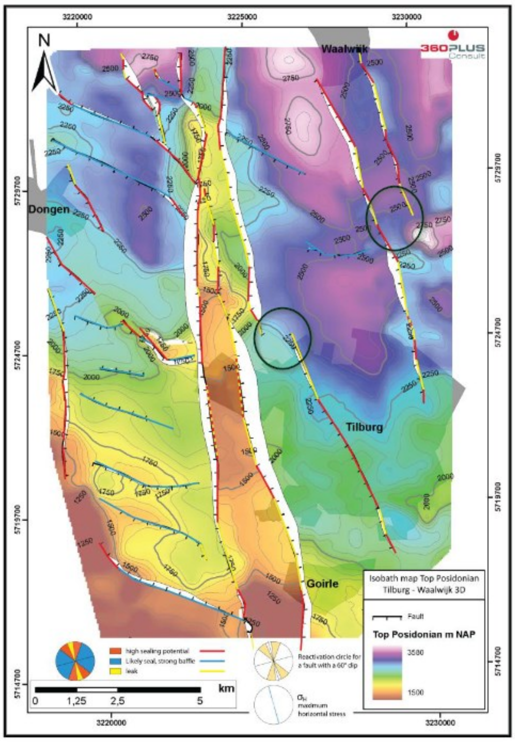

Figure 11: Potential fault seal and leak analysis according to the orientation of the faults relative to the stress regime (Rijkers et al., 2014). The yellow faults show potential conduit behaviour. Black circles indicate fault intersections related to potential upwelling.

Damage zone width calculations result in a range of W (100) = 7.6 m and W (200) = 15.2 m. The damage zone width obtained by the proposed relations seems small, but might be a good illustration of relative small damage zone width due to the high clay content. This corresponds to literature as the occurrence of clay induces shear weakening resulting in strain concentration (Faulkner, 2010).

4.3 Curvature and intersections

In seismic cross sections, high curvature regions can be found. On smaller scale this needs to be determined. For example on the fault side of footwall block, drag causes local curvature. Regions were fault tips approach (not necessarily touch) are the best prospective since fracture density will be high and no (sealing) fault rock will be formed. Examples are marked in fig (11).

5. DISCUSSION

Geological conditions, time and scale interact and this way affect local and regional permeability. As a result, this makes the prediction of flow along fault zones complex. The factors chosen in the workflow, although not complete, give a rough indication of potential permeability due to fractures and faults. This seems valid since the factors considered in the workflow have been studied in varies settings. Even though their predictive value might be generally valid, the effect on a specific setting is not known. Using the slip and dilation tendency values and displacement-damage zone width power law are effective to filter the relatively better areas. The use of the latter method has only been roughly determined in this study. For both variables affecting the damage zone width, only two and fairly rough ranges have been determined. The power-laws established here therefore give only an indication and cannot be used in a quantitative way. New data will have to be obtained using the same methodology to increase the reliability of the relationship. However, using the workflow does provides a relative estimation of the best potential area for enhanced permeability to occur along fault zones.

Overall the method provides a first step to indicate potential areas of a fault zone for geothermal production. The next steps in order to make a general model for quantification of fault zone permeability will include increasing the reliability of the relationships, defining a relation between the permeability and the expected production volumes. Furthermore, research is necessary to determine whether other factors should be included. For example vertical reservoir stratifications (juxtaposition of sandstone or permeable sediments) is not yet included in this model. Including an algorithm for quantification of the production rate as well as the seismic risk becomes essential in the economic liability of geothermal projects.

6. CONCLUSIONS

It is difficult to calculate potential geothermal flow rates from fault zones; however fault characterization is very useful. Lithologies of the juxtaposed fault blocks and the stress situation strongly influences the permeability of the fault (zone). Prediction of processes affecting the permeability is complex due to interaction of many factors related to lithology, deformation processes and the geological setting, both in the past and present. The highly fractured damage zone surrounding a fault plane is considered most promising for geothermal exploitation in terms of its enhanced permeability. A general workflow is recommended to assess an area for its most promising faulted area before detailed work is necessary. Estimations can be made based on active faults and regional stress field and fault zone kinematics including estimation of the damage zone width using the displacement of a fault; lithology and fault zone interactions. It should be noted that this is a first step, further research is necessary since the market would like to determine the expected flow rate and its uncertainty range before drilling.

Applying the workflow on the Tilburg area delivered useful results. Using the available 3D seismic data , the dilation and slip tendencies have been calculated for specific faults. The workflow has been used for the selection of the area with the highest potential. However, the lithological characteristics led to the conclusion that both the high clay content en depth are not favourable for the permeability.

7. ACKNOWLEDGEMENTS

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