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Fracturing in Basement Reservoir Rocks: Case Study of the Norwegian and Scottish Basements, some Analogues for Deep Geothermal Reservoir

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ABSTRACT

The occurrence of naturally fractured basement reservoirs has been known within the E&P industry for many years. However, despite their proven commercial success, basement reservoirs are a globally underexplored field for geothermal research, with some exceptions such as in Rhine Graben where several plays are under investigation. Fluids accumulations in basement rocks are usually restricted to fault zone however accumulations may also arise in igneous bodies that have been intruded into sedimentary successions. In this kind of ultra-tight reservoirs, fluids are essentially confined into porous fractures within, or near, fault zones or may migrate significant distances from faults if the open fracture network permits. Weathered zones of basement, usually confined to the upper reaches of the palaeobasement surface, sometimes provide areas of increased upside volumes and the same can apply to sections of hydrothermally altered basement. However, this may not always hold true if, for example, porosity has been later filled by cements or weathering products. Natural geological features present within basement can be divided into two main categories: lithological elements and structural elements. Lithological elements include features such as foliation, intrusions and lithological changes. Structural elements include fractures/joints, faults and breccias. Basement is commonly considered to be an impermeable part of a geological system, but this assumption does not hold for weathered and fractured bedrock. Even though weathering and fracturing are common features of bedrock, their characterization and their mutual relationships are still an under explored and challenging issue. For the purpose of characterizing Norwegian and Scottish basement, a lineament analyses were conducted on the two basements using high resolution DEM on a GIS software

1. INTRODUCTION

The North Sea is the result, since the Permien, of the erosion and then the opening of a Precambrian orogenic zone: the Caledonian chain e.g. Sorensen et al (1992). The stigma of this mountain range is now found on both sides of the North Atlantic Ocean (Greenland in the West, Norway in the East, Scotland and Ireland in the South) e.g.Ziegler (1990) (fig 1), via the Caledonian front. The basement of these different regions is consequently very old, often more than 2 Ga (fig 2) e.g. Kalsbeek et al (1993). It can be assumed that the constituent rocks of these large units have been subjected to previous first-order tectonic events e.g. Gaal and Gorbatschev (1987), including several orogenesis e.g. Bingen et al (2005).

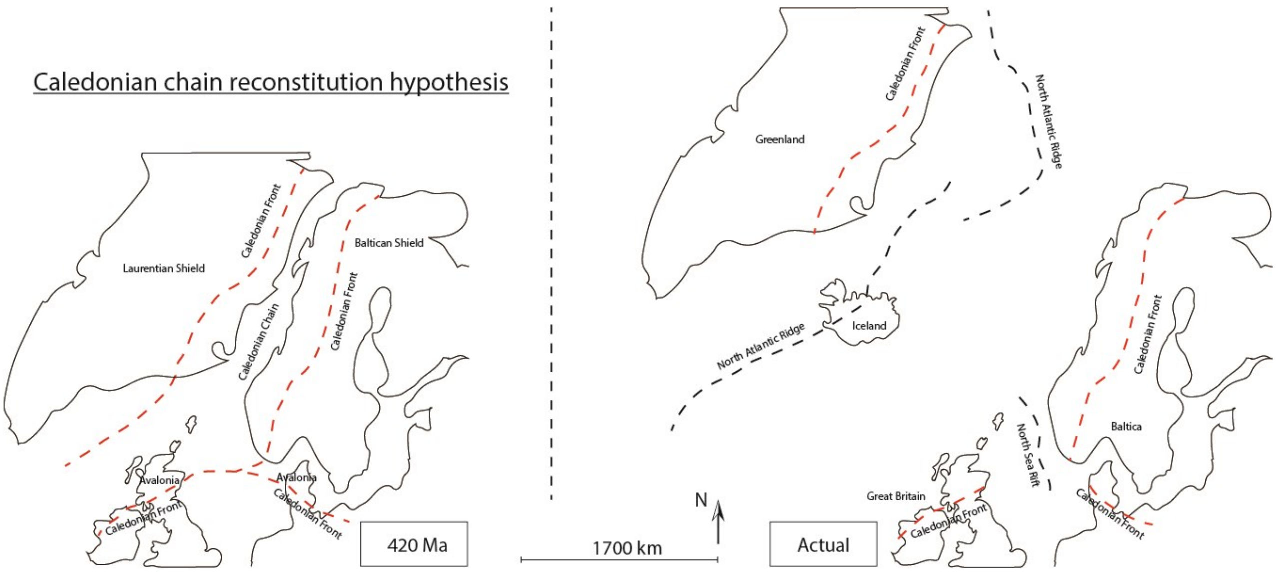

Figure 1: Caledonian chain reconstitution

The history of these different basements is indeed complex but also closely linked. Considering a single basement unilaterally can be very simplistic and will certainly prevent a global vision of the structural inheritance to ultimately allow a better characterization of the drains essential to geothermal energy in a basement domain.

This multi-scale lineament study, conducted in both Norway and Scotland, provides a small-scale overview of the importance of geological inheritance and opens the way for future field and sample studies.

2. GEOLOGICAL CONTEXT

The Caledonian chain formation began about 620 Ma ago and has been characterized by the convergence of the Laurasian and Baltican plates to the detriment of the Iapetus Ocean e.g. Van Berkel and Currie (1988), a process driven by oceanic subduction on both sides e.g. Fossen et al (2008) that will lead to the subduction of the Laurentian block below the Baltican block e.g. Root et al (2004), Gee et al (2008). In Norway, traces of this subduction are found in the successive stack of nappes with an increasingly continental affinity e.g. Fossen and Dunlap (1988). The convergence of the two blocks has also led to the accretion of island arcs and terranes of varying sizes, the largest of which is the Avalonia block e.g. Harper (1992). The latter is the result of the accretion of several secondary terranes in transtension e.g. Fossen et al (2008). The chain's hypercolision occurred around 420 Ma fig1 e.g. Gee et al (2008), as shown by the UHP and eclogitic zones (fig 2) e.g. Corfu et al (2014), particularly on the Seve nappe e.g. Corfu et al (2014). In the Devonian, the chain began to experience an extensive play e.g. Fossen and Dunlap (1988), basins with conglomeratic filling were created e.g. Osmundsen and Andersen (2001).

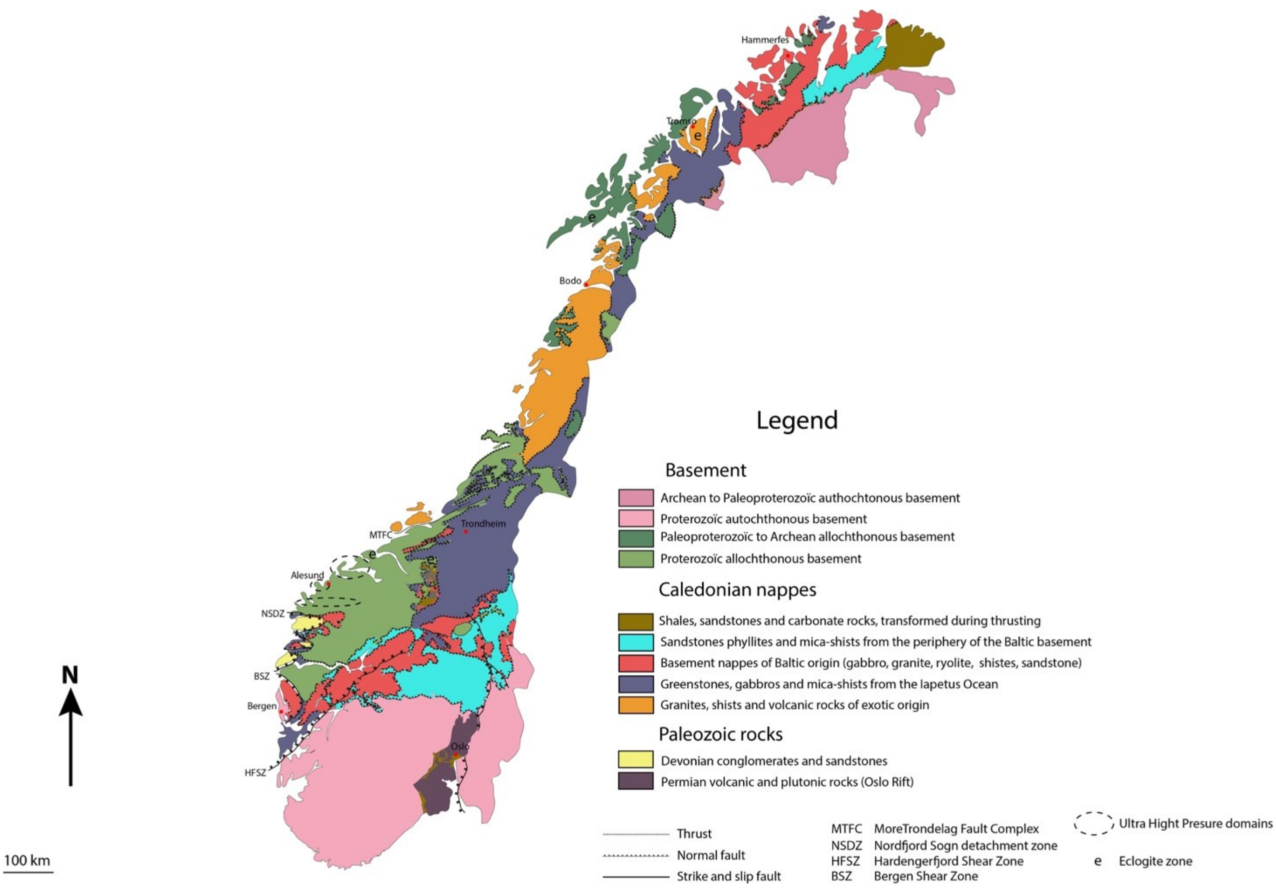

Figure 2: Structural map of Norway, e.g. Ramberg et al (2008), Corfu et al (2014)

In the Permian, the chain naturally follows its collapse and the suture area seems to be reactivated in normal play, the deposits are associated with deeper and deeper areas e.g. Deng et al (2017). In the North Sea the same evolution is described with a better preservation of the deposits. This sea is the result of several coalescing basins located offshore Norway and Scotland e.g.Duffy et al 2015. The North Sea also records large sequences of organic matter in the Mesozoic e.g. Fossen et al (2008), which after maturation will produce the large oil and gas deposits that are known. Hydrocarbons migrate into the higher sandstone formations e.g. Fossen et al (2008). A second type of hydrocarbon migration has been described in the basement, which leads to reconsidering the Caledonian basement as a powerful hydrocarbon reservoir. Consequently, making an analogy with the transfer of hot fluid within this same type of basement which has experienced in addition to many episodes of fracturing and episodes of alteration increasing the porosity and permeability as a result still consistent.

3.MATERIAL AND METHODS

The work focused on the Arcgis software, lineament processing was based for Norway on a DTM with a resolution of 10m by 10m and for Scotland on a DTM of 30m by 30m.

The protocol put in place for the tracing of lineaments was to work at three investigation scales (1:1,000,000; 1:750,000; 1:500,000). Each lineament line was checked under four different shading orientations (0°, 45°, 90°, 135°) allowing to discriminate as much as possible the effect of the exposure orientation e.g.Bertrand et al 2015.

The traces were then transferred to the Fracpac software e.g. Healy et al (2017) running under matlab, allowing preferential orientations to be deduced and interpretations to be made. The analyses were carried out in zones. Three areas have been selected for Norway, the first area is located around Trondheim, it has been chosen for its Caledonian structural history, the second area studied is located around Oslo, this is a site marked by an East-West extension in the Permian-Carboniferous region. The third zone chosen is located in the extreme North-East of Norway, the choice of this zone is justified by the oldest lithologies in Norway, the objective is therefore via this zone to determine the influence of structural heritage as regards to the development of the Caledonian chain. In the case of Scotland, the area studied is logically much smaller, a zonal distribution was not necessary.

4.RESULTS

In the case of Norway, nearly 9,000 lineaments could be treated (fig 3), and the total results show very few major trends other than fracture orientations N0-N10 and N60-N70 (fig 4). Considering now precise zones, it becomes possible to refine preferential orientations. For the first selected zone, around Trondheim (fig 5), this area is characterized in this study by three preferential fracture orientations, a first one strongly expressed N60-N70 (fig 6), a second one weakly expressed N150-N160 (fig 6) and a third one N0-N10 (fig 6). For the second zone studied around Oslo (fig 7), two fracture orientations emerge, the first is N0-N10 (fig 8) and is highly expressed, the second is present to a lesser extent and is rather oriented N150-N160 (fig 8). Finally, at the level of the third Norwegian zone located to the northeast (fig 9), the fracture orientations are much less marked, the N40-N50 (fig 10) direction is still present and diffuse.

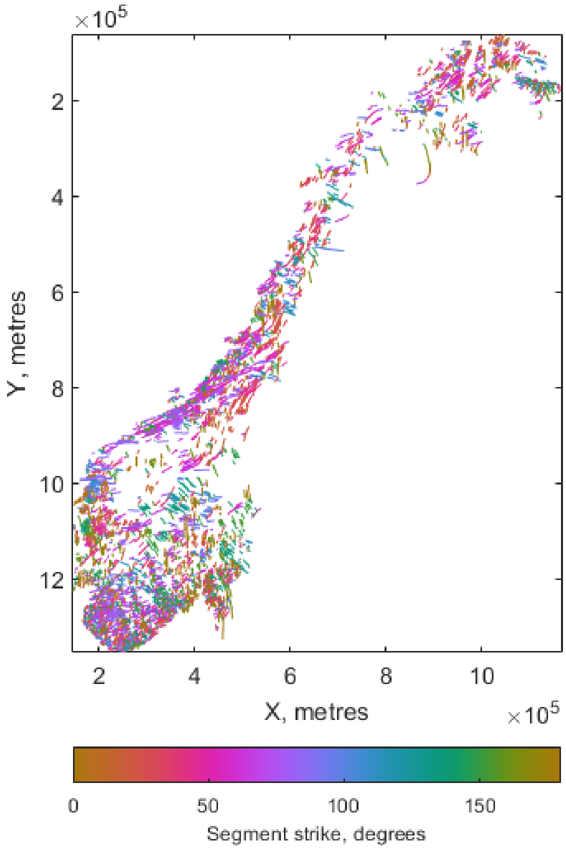

Figure 3: Segment strike map of Norway

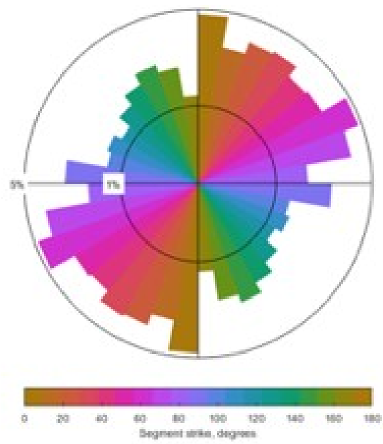

Figure 4: Segment angle (equal area, length weighted) of Norway

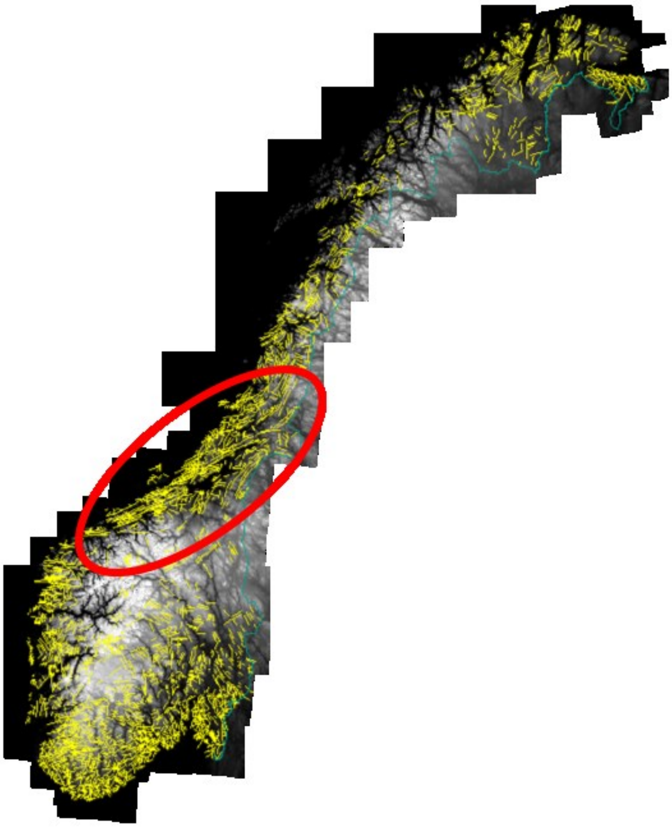

Figure 5: Lineament map of Norway. Red ellipsoid: Trondheim region, zone 1

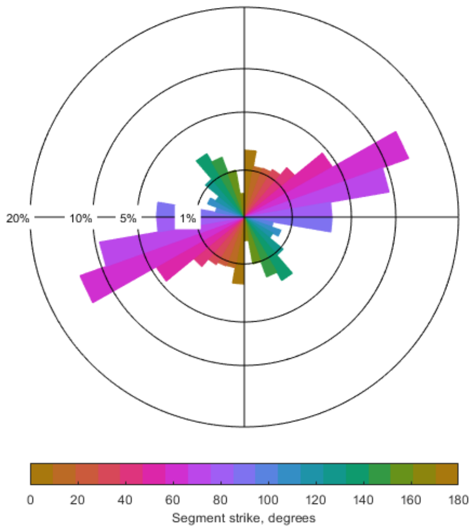

Figure 6: Segment angles (equal area, length weighted) of the zone 1

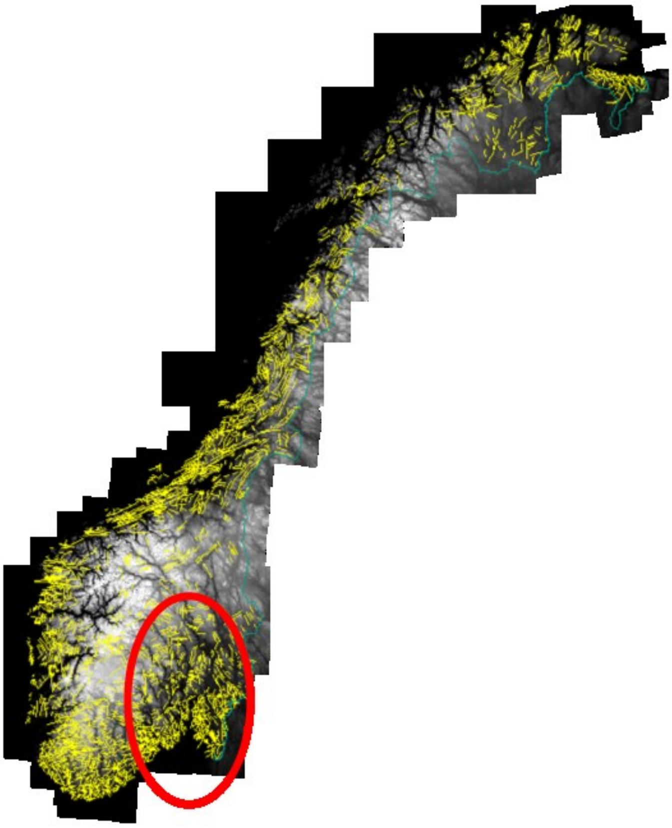

Figure 7: Lineament map of Norway. Red ellipsoid: Oslo region, zone 2

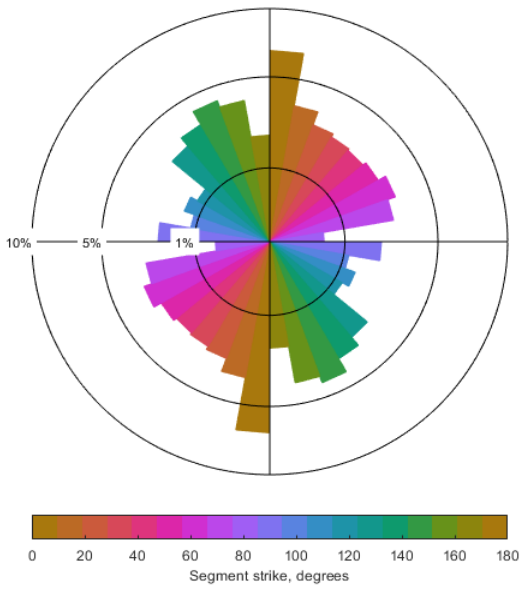

Figure 8: Segment angles (equal area, length weighted) of the zone 2

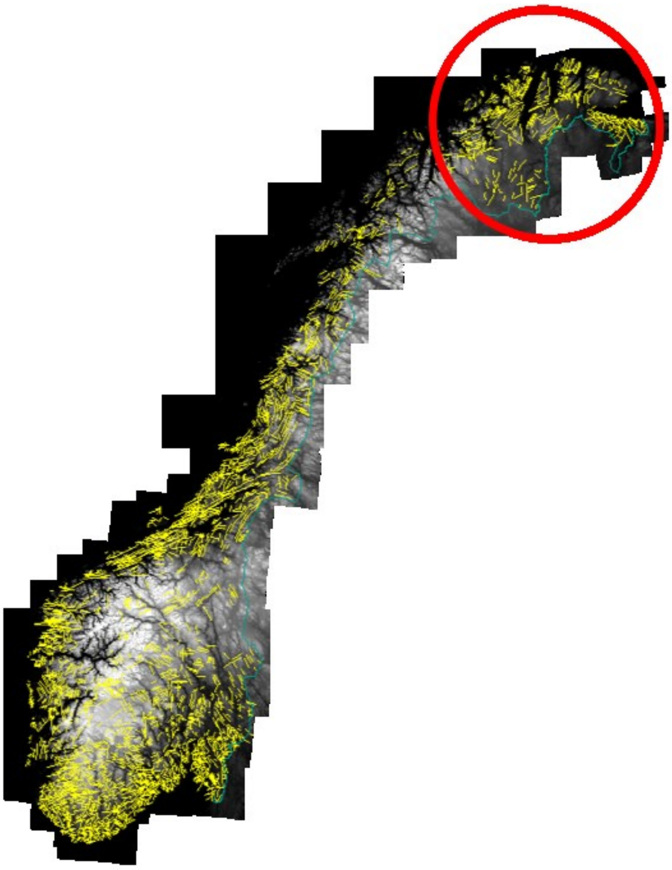

Figure 9: Lineament map of Norway. Red ellipsoid: North East region, zone 3

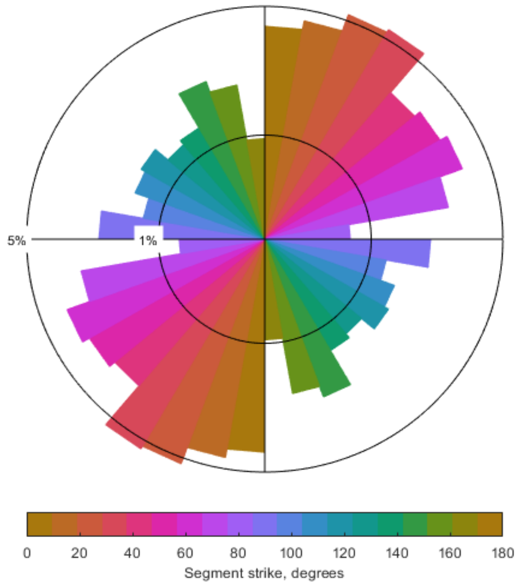

Figure 10: Segment angles (equal area, length weighted) of the zone 3

In Scotland, more than 1000 lineaments could be traced (fig 11). In Scotland, the lineament orientations are much less diffuse, and it becomes possible to extract two deformation directions, a first N60-N70 (fig 12) oriented and a second between N100 and N120 (fig 12).

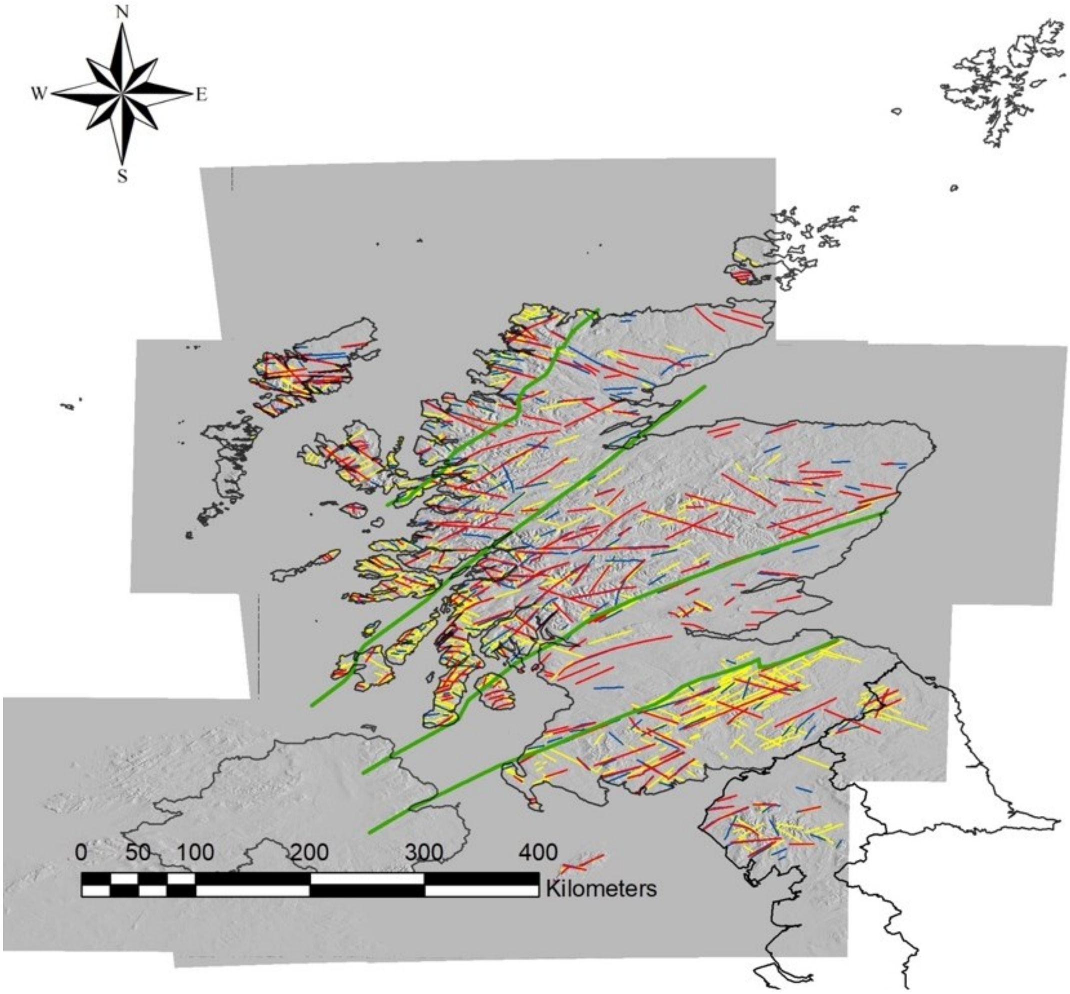

Figure 11: Lineaments map of Scotland

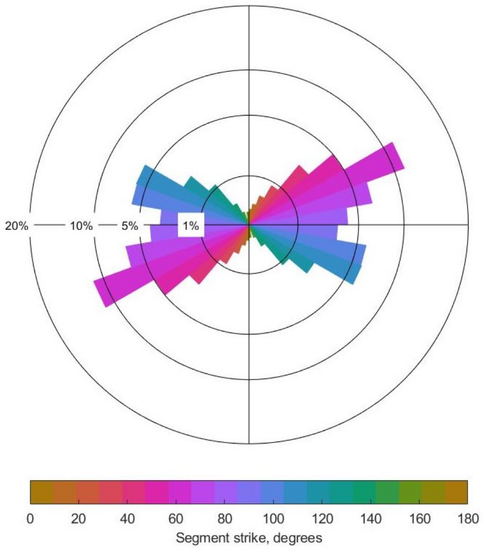

Figure 12: Segment angle (equal area, length weighted) of Scotland

5.INTERPRETATIONS

In view of the results obtained in Norway, several types of tectonic episodes stand out, first of all a complex history on old terrain as is the case in northeastern Norway. In the first zone, the rocks are of a younger age and have only known a compressive deformation epidose during the formation of the New Caledonian chain, this NE-SW Caledonian "direction" is blurred when the terrain attains a certain level of age. This area also underwent the opening of the North Sea, the North-South lineaments are present and therefore reflect the mezosoic rifting. The second zone is an equally old basement zone explained by a diluted signal crossed by a North-South orientation, it is explained by the opening of the oslo rift in the Permo-Carboniferous. In Scotland, as the terrain is a little younger, the influence of structural heritage is less present, so New Caledonian lineaments are expressed in a more prominent way. The regularity of the lineaments can also be explained by the presence of lithological limits.

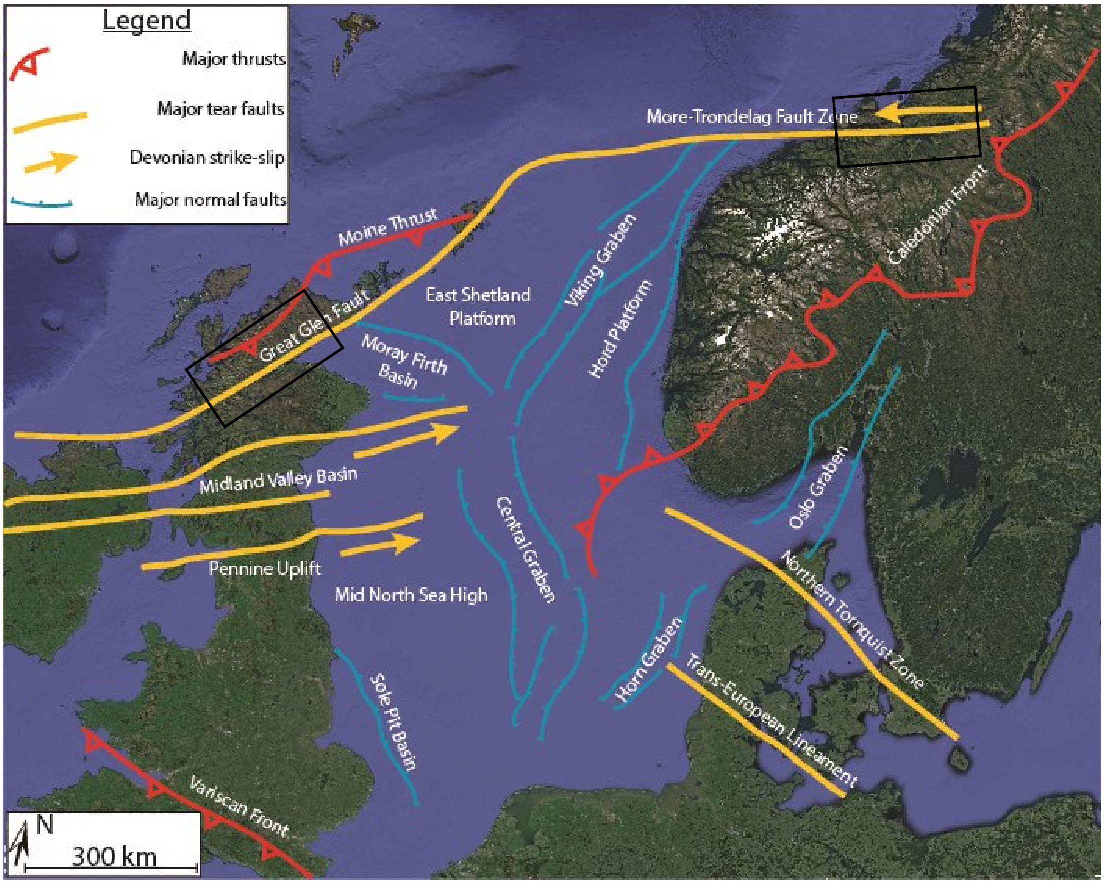

Figure 13: Tectonic framework of North-West Europe, e.g. Coward et al (1990), Armour et al (2003)

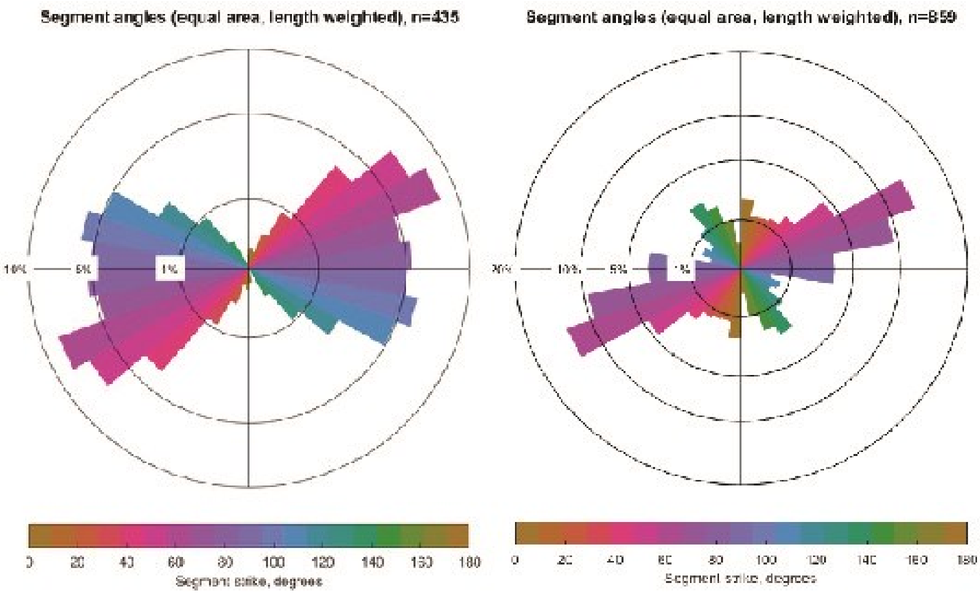

Figure 14: Segment angle (equal area, length weighted) of Scotland (left) and Norway (right)

The lineament orientations in Norway and Scotland can also be compared (fig 13) (fig 14). A correlation of lineament orientations can be established between the beams of the Great Glen fault and those of the More Trondelag fault complex. This correlation is explained by the Devonian transtensive play, so this detachment zone seems to have played a major role in the opening of the Caledonian chain.

6.CONCLUSIONS

The constituent rocks of the Norwegian and Scottish basement have therefore known a complex geological history marked by the formation of a major mountain range, the Caledonian Chain. The lineaments observed in Scotland and Norway testify to this polyphase history and show that if an economic exploitation is to be undertaken, an N50-N60 orientation should be preferred as a potential drain. These lineament observations can also be supplemented by field work and on a larger scale on sample.

REFERENCES

Bertrand, L., Géraud, Y., Le Garzic, E., Place, J., Diraison, M., Walter, B., Haffen, S.: A multiscale analysis of a fracture pattern in granite: A case study of the Tamariu granite, Catalunya, Spain, *Journal of Structural Geology*, **78**, (2015), 52-66.

Corfu, F., Andersen, T., Gasser, D.: The Scandinavian Caledonides: main features, conceptual advances and critical questions, *Geological Society, London, Special Publications*, **390**, (2014), 9-43.

Deng, C., Fossen, H., Gawthorpe, R., Rotevatn, A., Jackson, C., FazliKhani, H.: Influence of fault reactivation during multiphase rifting: The Oseberg area, northern North Sea rift, *Marine and Petroleum Geology*, **86**, (2017), 1252-1272

Duffy, O.B., Bell, R.E., Jackson, C. A. L., Gawthorpe, R. L., Whipp, P. S.: Fault growth and interactions in a multiphase rift fault network: Horda Platform, Norwegian North Sea, *Journal of structural geology,* **80,** (2015), 99-119.

Gee, D.G., Fossen, H., Henriksen, N., Higgins, A.K.: From the Early Paleozoic Platforms of Baltica and Laurentia to the Caledonide Orogen of Scandinavia and Greenland, *Episodes*, **31**, (2008), 44-51.

Fossen, H., Dunlap, W.J.: Timing and kinematics of Caledonian thrusting and extensional collapse, southern Norway: evidence from40Ar/39Ar thermochronology, *Journal of structural Geology*, **20**, (1988), 765-781.

Fossen, H., Pedersen, R.B., Bergh, S., Andersen, A.: Creation of a mountain chain. in Ramberg, I.B., Bryyhni, I., Nottvedt, A. Ragnes, K.: The making of a land-Geology of Norway. Norsk geologisk Forening, (2008), 178-231.

Harper, D.A.T.: Ordovician provincial signals from Appalachian- Caledonian terranes, *Terra Nova*, **4(2)**, (1992), 204-209

Healy, D., Rizzo, R.E., Cornwell, D.G., Farrell, N.J.C., Watkins, H., Timms, N.E., Gomez-Rivas, E., Smith, M.: FracPaQ: a MATLAB™ toolbox for the quantification of fracture patterns, *Journal of Structural Geology*, **95**, (2017), 1-16.

Kalsbeek, F., Austrheim, H., Bridgwater, D., Hansen, B.T., Pedersen, S., Taylor, P.N.: Geochronology of Archaean and Proterozoic events in the Ammassalik area, South-East Greenland, and comparisons with the Lewisian of Scotland and the Nagssugtoqidian of West Greenland, *Precambrian Research*, **62**, (1993), 239-270.

Osmundsen, P.T., and Andersen, T.B.: The Middle Devonian basins of western Norway: sedimentary response to large-scale transtensional tectonics, *Tectonophysics*, **332**, (2001), 51–68.

Root, D.B., Hacker, B.R., Mattinson, J.M., Wooden, J.L.: Zircon geochronology and ca. 400 Ma exhumation of Norwegian ultrahigh-pressure rocks: an ion microprobe and chemical abrasion study, *Earth and Planetary Science Letters*, **228**, (2004), 325-341.

Sørensen, S., Morizot, H., Skottheim, S.: A tectonostratigraphic analysis of the southeast Norwegian North Sea Basin, *Norwegian Petroleum Society Special Publications*, **1**, (1992), 19-42.

Ziegler, P.A.; Geological Atlas of Western and Central Europe, *Shell Internationale Petroleum Maatschappij BV*, 1990.