Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 59 (2014) 351 – 358

Energy Procedia

European Geosciences Union General Assembly 2014, EGU 2014

Mapping the geothermal potential of fault zones in the Belgium-Netherlands border region

Sian Loveless[a,]*, Maarten Pluymaekers[b], David Lagrou[a], Eva De Boever[c], Hans Doornenbal[b], Ben Laenen[a]

[a]Flemish Institute of Technology,Boeretang 200,2400 Mol, Belgium
[b]Geological Survey of the Netherlands, Princetonlaan 6, 3584CB Utrecht, The Netherlands
[c]Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium.

Abstract

Faults can determine the success or failure of low enthalpy geothermal projects. This is due to their capacity to behave as pathways or baffles to geothermal water (or both simultaneously) and their prevalence throughout the subsurface. Here we present an initial assessment of the possibility for faults in the Northern Belgium (Flanders) and Netherlands border region to impact the geothermal potential of four selected reservoirs.

Peer-review under responsibility of the Austrian Academy of Sciences

Keywords: Geothermal energy; ArcGIS mapping; Fault zones; Regional assessment; Belgium-Netherlands border region

1. Introduction

The Flanders-Netherlands border region is located in the lowlands of northwest Europe. The region is far from tectonic plate boundaries, volcanoes, or other regions of high crustal heat flow. Yet over the last 10 years shallow and deep low-medium enthalpy geothermal (heat) energy has experienced growth in the region. In the Netherlands this growth is dramatic – geothermal energy is now the fastest growing RES (renewable energy source) [16], growing by nearly 25 % between 2012 and 2013 [9]. In Flanders the growth of geothermal looks set to follow that of the Netherlands in the coming years [20]. The GEOHEAT-App project, a 1.5 year cross-border project funded by

* Corresponding author. Tel.: +32 14 33 56 35.
E-mail address: Sian.loveless@vito.be

Peer-review under responsibility of the Austrian Academy of Sciences
doi:10.1016/j.egypro.2014.10.388

the European INTERREG IVa program for Flanders-The Netherlands, was undertaken in order to facilitate this growth. This project was designed to provide an initial assessment of the geothermal potential of the four provinces in the border region (Belgian Limburg and Antwerp, and Dutch Limburg and Noord-Brabant) (Fig. 1). Geothermal potential and above ground heat-demand were also assessed for six specific case study locations in these provinces (for further details about the project please visit www.vito.be/geoheatapp).

Geothermal resource potential was mapped for four intervals that are possible geothermal reservoirs in the region; the Upper Cretaceous Chalk Group (Houthem and Maastricht formations), Lower Germanic Triassic Group sandstones (Main Buntsandstein Subgroup – Volpriehausen, Detfurth, Hardegsen and Nederweert formations in the Netherlands and the Bree, Bullen and Gruitrode formations in Flanders), Upper Carboniferous, Westphalian D sandstones (Neeroeteren and Hellevoetsluis formations) and Lower Carboniferous, Dinantian limestones. The region was classified as having low, medium or high geothermal potential according to the transmissivity (Dm) (reservoir permeability*reservoir thickness) and temperature (according to the temperature gradients of the main intervals and reservoir depth).

The spatial extents of these reservoirs are related to the main structural elements within this region through paleogeographic depositional settings and fault controlled displacement (Fig. 1). Devonian-Carboniferous limestones were deposited in part of the Carboniferous basin of northwest Europe, a foreland basin of the Variscan Orogeny [17]. The transition from the Lower to the Middle Carboniferous is marked by a shift from a carbonate to a siliciclastic setting, becoming more continental in nature through the Upper Carboniferous, from the Namurian shales to paralic Westphalian sandstones and coal measures in the Campine Basin [17]. Basin development continued from the Permian through to the Middle-Triassic as a result of thermal subsidence, allowing deposition of thick sequences of sandstones and claystones in the centre of the Roer Valley Graben. In the early Cretaceous the region underwent extension along northwest trending extensional basins similar to today's basin orientation during which time thick sequences of chalk were deposited. Parts of the Roer Valley Graben and Campine basin subsequently underwent a crustal inversion phase from the Upper Cretaceous until around the end of the Paleogene, related to the Alpine Orogeny [11]. The current Roer Valley Graben is part of the European Cenozoic Rift system [18, 25]. The study area is today transected by a predominant set of (N)NW - (S)SE striking normal faults, which locally display a shear component (see Fig. 1). Most of these faults already existed during the Carboniferous. The largest faults were reactivated during the Jurassic, and some are still active today [17,26]. The faults resulting from this complex geological history impact the reservoir properties of each of the intervals assessed here.

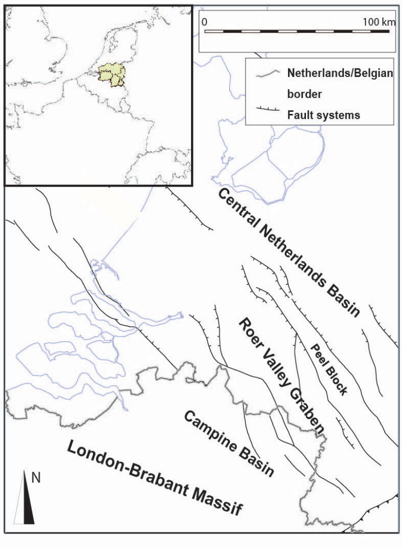

Fig. 1. The main structural features of the region; the Roer Valley Graben, the Campine Basin and the London-Brabant Massif, map adapted from [10]. Inset shows the four provinces of Northern Belgium and The Netherlands included in the GEOHEAT-App project.

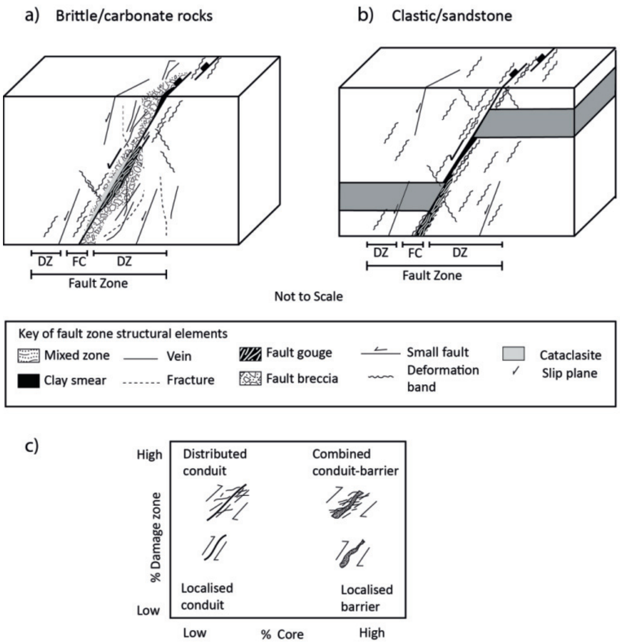

Fig. 2. Fault zone hydrogeological structure. Fault zones in brittle and clastic rocks typically comprise a fault core (FC) and damage zones (DZ). Conceptual model of fault zone structure in brittle/carbonate rocks (a) and clastic rocks (b). (c) Conceptual model of the hydraulic behaviour of fault zones in brittle rocks based on the relative proportion of fault zone structural elements, from [8]. Figure adapted from [19].

Faults are known to have a strong impact on the feasibility of geothermal projects, both in high enthalpy and medium-low enthalpy settings, due to the impact they can have on the permeability of the subsurface [28]. If faults behave as conduits (increase permeability) [13] they may improve geothermal prospects, but if they behave as barriers (decrease permeability) [14] they may cause compartmentalization of the reservoir, which can present difficulties for accessing the full geothermal resource.

Fault permeability structure is an important parameter for assessing whether or not fault zones will increase or decrease permeability, behaving as conduits or barriers, or a combination of both [5]. Specific lithologies can deform differently when subjected to stress, resulting in different permeability structures (Fig. 2). Fault cores in (macroscopically) brittle (generally crystalline) rocks can comprise a combination of fault gouge, cataclasites, breccias, mylonites, discrete slip surfaces, and relatively cohesive lenses or blocks of sediment [4,5,23] (Fig. 2a). Fault damage zones in carbonate rocks tend to fracture, creating breccia or joints, as described by [8] (Fig. 2a). Often, the damage zone around the fault core can be much more extensive and hydraulically more important, contributing more towards bulk permeability than the core (10's to 1000's of meters in thickness perpendicular to the fault strike compared with 0.1 to 10 m thickness). Fault hydraulic behaviour (conduit/barrier) can be determined from the ratio of fault zone elements (Fig. 2c)[8]. Fault zones in brittle rocks are often conduits to fluid flow [13].

In clastic rocks strain is often accommodated by (multiple) deformation bands in both the fault core and damage zone [1,2] (Fig. 2b). These are thin bands (<2 cm thickness) in which cataclasis and particulate flow occur (breakage and rolling/sliding of grains), acting to reduce pore space and thus permeability. If there is a sufficient proportion of clay in the protolith of siliciclastic and carbonate rocks clay can be smeared through the fault core, forming strong seals [27]. Fractures are much less common in these rocks. As a result of these processes faults in clastic rocks are likely to behave as barriers, decreasing permeability of the clastic reservoir units[14].

Certain lithologies – carbonates in particular – may also be karstified, whereby permeability is increased further by the dissolution of the rock along fractures [7,22]. This has been shown to have occurred within the Lower Carboniferous limestones in parts of the region of interest [12]. Large-scale dissolution is less common in fault zones with other mineralogical compositions. Conversely, over time, mineral-saturated fluids can precipitate cements in pores and/ or fractures and effectively become re-sealed, reducing fault permeability [21] and forming significant barriers to fluid-flow [15]. However, each time the fault deforms (is activated) fractures may open and permeability can increase again [23]. As a result, faults that have deformed more recently are more likely to be permeable. Barton et al. [3] also found that normal faults optimally oriented to the current stress field, i.e. "critically stressed" and therefore more likely to slip, were also more permeable than those not critically stressed.

Incorporating these factors into fault assessments is complex. However, we have produced regional scale maps that indicate the likelihood of fault zones to improve geothermal potential across the four provinces in Flanders and the Netherlands based on the main principles behind the fault behaviour, outlined in this paper.

2. Methodology

In order to assess the likelihood of fault zones improving geothermal potential we identified two key questions: 1. Are there faults, and if so where are they? 2. How will the faults affect the resource potential of geothermal projects (will they behave as conduits or barriers)? Analysis was completed using spatial data and the Geographical Information System software ArcGIS. It was not possible to directly assess fault zone structure for faults in this region because a) there are few outcrops and b) there are very many faults. Therefore parameters known to influence fault permeability (as described in the previous section) were used to make assessments at the regional scale.

2.1. Identification of areas with faults

Fault maps were compiled for the whole region. Faults have previously been mapped for key stratigraphic intervals in Flanders and the Netherlands (https://dov.vlaanderen.be and http://www.nlog.nl) based on seismic and borehole data. In some places the data coverage is quite good, and the fault locations well-known, however in other locations the data is sparse and for the deeper intervals the resolution can be quite poor. In addition, since data from different sources were used either side of the border the fault traces did not always match. This discrepancy had to initially be rectified with the correlation of faults across the border.

Fault maps were made for only the carbonate (Upper Cretaceous chalk and Lower Carboniferous limestone) groups, for reasons explained in section 2.2. Fault maps for the Upper Cretaceous chalk interval combined pre-existing maps of faults at the top of the chalk deposits in Flanders (from DOV) and the top Chalk Group in the Netherlands (from TNO). These faults have recently been re-mapped and jointly interpreted across much of the border region as part of the H3O project [10]. This newly mapped region was incorporated into the fault maps. Fault maps of the Lower Carboniferous limestone interval comprise faults mapped for the top of the Lower Carboniferous in Flanders (DOV) and the top of the Upper Carboniferous for the Netherlands (NLOG 2013). Faults were connected at the country border where there were discrepancies. A buffer of 10 km was applied to the faults. Areas >10 km from mapped fault zones (outside the buffered zone) were excluded from the analysis, assuming that those areas are not significantly faulted. This distance was chosen as a buffer in order to be confident that the excluded areas were outside of the influence of fault damage zones and thus smaller undetected faults would be included in the analysis.

2.2. Lithology

Lithology was used as a key factor with which to evaluate fault hydraulic behaviour [6]. The four potential geothermal reservoirs can be split into two key lithological categories; carbonate reservoirs comprising the Upper Cretaceous chalks and Lower Carboniferous limestones, and clastic reservoirs comprising Lower Triassic and Upper Carboniferous sandstones, according to their expected fault zone permeability structures (as described in the previous section). Diagenetic processes are also expected to differ between these groups. Faults were considered to be potential targets for geothermal energy in the carbonate reservoirs but not the clastic reservoirs therefore an assessment of possible improved geothermal potential was only completed for the Upper Cretaceous chalk and Lower Carboniferous limestone intervals.

2.3. Fault activity

Fault activity was used to identify faults that could have open fractures due to recent deformation (Table 1). Please note this is not an assessment of the seismic risk. Fault activity was also used as a proxy for the stress criticality since a good assessment of fault stress state requires a large number of contributing parameters, including stress measurements, that are not available the study area. Evidence for recent fault activity was collated from a number of sources, described below.

Recent work by Vanneste et al. [26] identified the seismically active regions of the Roer Valley Graben (Fig. 3a). Seismic sources were attributed to an unspecified number of sources (composite seismic sources) rather than to individual faults because surface ruptures are rarely found in this region. These composite seismic sources are mapped at the surface with polygons corresponding to the surface locations projected in the subsurface. Faults mapped as crossing the projection polygon were assumed to be related to the earthquake source. We also used these polygons to define a region in which faults are likely to have been active recently (Fig. 3b).

Table 1. Classification of the likelihood of fault zones to improve geothermal potential based on recent fault activity.

Likelihood of fault zones to improve geothermal potential	Classification parameters
No potential	Absence of Upper Cretaceous chalk group/Lower Carboniferous limestones or faults.
Possible potential	Faults mapped in Upper Cretaceous chalk group/Lower Carboniferous limestones but no evidence of recent activity.
Potential	Faults mapped in Upper Cretaceous chalk group/Lower Carboniferous limestones with proximal recorded historical earthquake *or* faults mapped in Quaternary layers
Good potential	Faults mapped in Upper Cretaceous chalk group/Lower Carboniferous limestones with proximal recorded historical earthquake *and* mapped in Quaternary layers, *or* areas mapped as seismically active by [27].

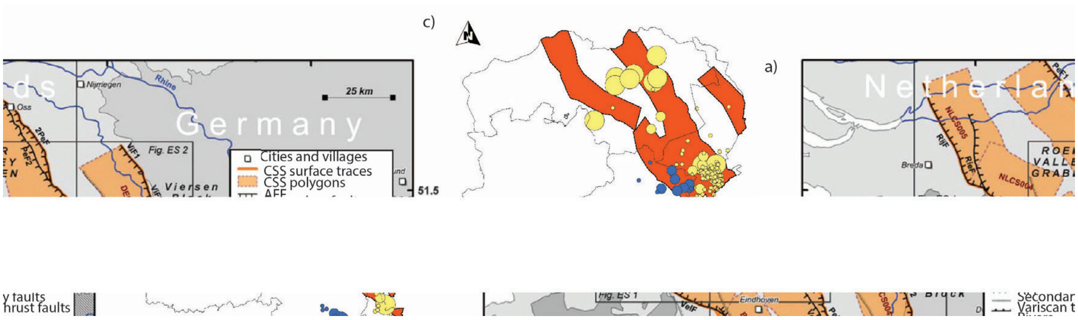

Fig. 3. Assessment of the likelihood of faults improving geothermal potential based on recent fault activity. a) Composite seismic sources indicating seismically active regions of the Roer Valley Graben from Vanneste et al. [26]. b) Area with mapped active faults in (a) transferred onto the regional map. c) Historical earthquakes, circle size indicates area of uncertainty (Table 2). d) Faults mapped in Quaternary sediment.

This seismic analysis was only available for the Roer Valley Graben therefore fault activity outside of this area was determined using a combination of historical earthquake location data and faults mapped cutting Quaternary sediment. Recorded earthquakes provide an indication as to the areas in which faults have been active since records began in 1904 (Flanders) and 1906 (Netherlands). Earthquake epicentres located by the Royal Observatory of Belgium for Flanders and KNMI for the Netherlands were combined, with duplicated recordings over the country borders removed. Epicenter locations were plotted on the fault maps. Because the accuracy with which epicentres can be located has improved considerably through time the epicenters were plotted as circles with the radius representing the uncertainty in epicenter location (Fig. 3c, Table 2). If the zone of epicenter uncertainty intersected with areas mapped as active [26] earthquakes were attributed to faults mapped as active in this region. Otherwise all fault segments (and connected fault segments) that crossed the zone of epicenter uncertainty were assumed to be possibly active. It is possible that earthquakes have not occurred in historical times along certain faults, yet their recent (Quaternary) geological activity may be relevant for indicating their diagenetic (cementation) state and also state of stress. Maps of Quaternary faults from VITO and TNO show a number of these areas (see figure 3d).

Table 2. Accuracy of epicenter locations over time [26].

Time period	Radius of uncertainty
Historical pre instrumental	20-50 km therefore disregarded
Instrumental pre 1958	10 km
1960-1985	3- 5 km
1985 onwards	< 2 km

3. Results

Maps showing the likelihood of fault zones improving geothermal potential for the Upper Cretaceous chalk group and Lower Carboniferous limestone group are shown in Fig. 4. The maps indicate that faults could enhance permeability in the Upper Cretaceous chalk and Lower Carboniferous limestone reservoirs across the majority of the provinces. Good potential is found along the flanks of the Roer Valley Graben (Fig. 1) and to the south in both the Dutch and Belgian Provinces of Limburg. Regions with potential improvements for geothermal energy border the areas with good potential, in the Campine Basin and North of the Roer Valley Graben. There remains a possibility for faults to improve the geothermal potential across much of the rest of the area of interest. In these areas faults have been mapped but are probably inactive. In these areas the diagenetic impacts (e.g. cementation or dissolution processes) will be very important for determining whether or not these fault zones experience enhanced permeability. To the west of the region for both the Upper Cretaceous chalk and Lower Carboniferous limestone there are areas in which fault zones are unlikely to improve geothermal potential either due to a lack of fault zones or an absence of the interval of interest.

4. Discussion

The maps produced as part of the GEOHEAT-app project (Fig. 4) provide a first assessment of the potential of fault zones as targets for geothermal energy in the Upper Cretaceous chalk and Lower Carboniferous limestone reservoirs. The boundaries of the zones of the different potential categories should not be regarded as definite.

At this point in time these maps can only be verified by wells drilled at the Venlo geothermal project, which targeted a karstified fault zone. However, this location does lie within the northerly region with an estimated good potential (Fig. 4). The maps can be further validated as more geothermal projects develop in the region.

Faults are likely to provide important regions of high permeability in these reservoirs in particular since primary permeability is generally low both lithologies and in fact may be considered the primary targets, providing the additional transmissivity necessary to reach the requirements for economic geothermal projects. Both reservoirs are found at greater depths and thus temperatures in the region with the best potential for fault zones to improve geothermal energy prospects, the Roer Valley Graben. Lower Carboniferous limestones are expected to reach depths of > 4 km in the centre of the Roer Valley Graben therefore sufficient transmissivity at this depth might even allow for electricity production (requirement of > ~120^o C). The Upper Cretaceous chalks are shallower but temperatures ~40^o C could easily allow for direct heat applications such as swimming pools or fish farms. The potential for fault zones to enhance geothermal potential in the less active faults that can be found across much of the rest of the region is likely to be strongly linked with secondary diagenetic effects. These vary regionally and locally [24] and therefore for each geothermal development it remains necessary to make site-specific assessments of the local geological structure and history (fault activity and diagenesis).

This assessment by no means incorporates all parameters that could point to fault zone permeability. Indeed, much more sophisticated methods exist to assess fault behaviour such as Allan diagrams to assess the juxtaposition of permeable/impermeable units either side of the fault zone [15], and methods to assess the sealing capacity, such as the Shale Gouge Ratio [27]. Such investigations were not possible with the scale of the work and the resources available. However, with the limited information about the nature of faults in the subsurface of this region there is no certainty that correct predications can be made about a fault's hydraulic behaviour.

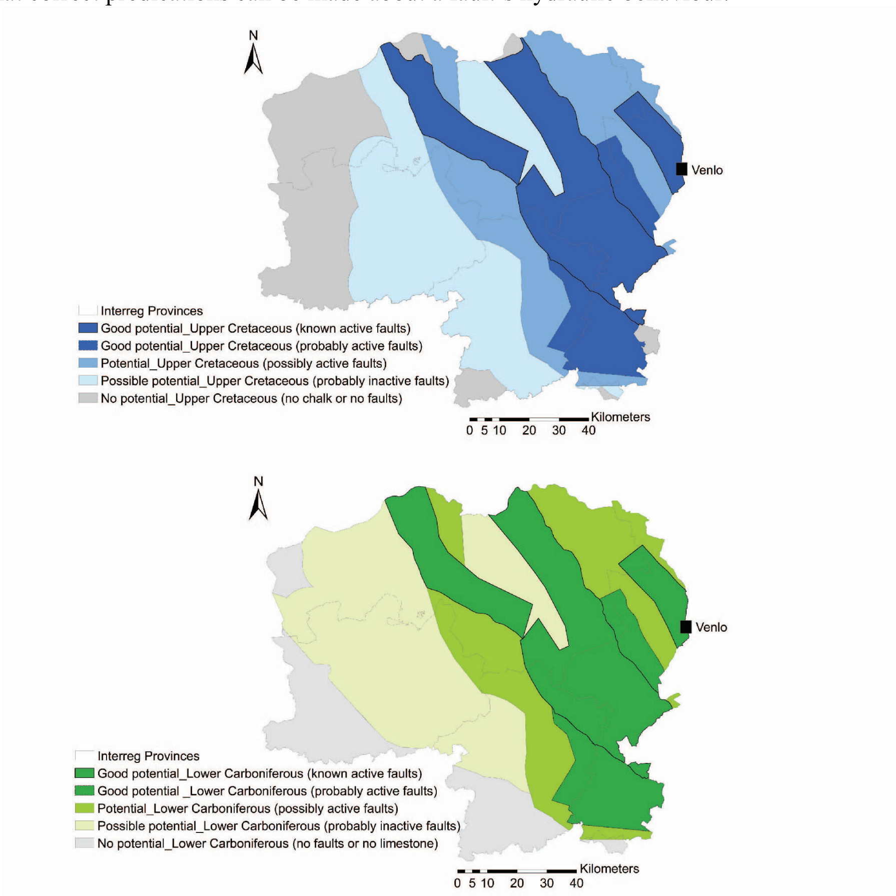

Fig. 4. Maps showing the likelihood of fault zones to improve geothermal potential in the a) Upper Cretaceous chalk reservoir and b) Lower Carboniferous reservoir. The black box indicates the location of the Venlo geothermal site that utilises a fault zone in the Lower Carboniferous.

5. Summary

A regional assessment of the possibility of fault zones to improve geothermal potential in four border provinces of Belgium and the Netherlands has been made according to principles of fault hydraulic behaviour. The assessment accounts for lithology cut by the faults and their recent fault activity. Assessments are presented on two maps, for the Upper Cretaceous chalk reservoir and Lower Carboniferous limestone reservoir. These maps show that faults may prove to be possible targets across much of the region but particularly so in the Roer Valley Graben. While these maps may provide an indication of possible targets, further site-specific feasibility and risk studies will always be required prior to exploration.

Acknowledgements

The authors would like to thank the European INTERREG IVa program for Flanders-The Netherlands for funding the Geoheat-app project that made this work possible and partners Grontmij.

References

[1] Antonellini M, Aydin A. Effect of faulting on fluid flow in porous sandstones: Geometry and spatian distribution. AAPG Bulletin 1995; 79.5: 642-671.
[2] Aydin, A. Small faults formed as deformation bands in sandstone. Pure and Applied Geophysics 1978; 116:913-930.
[3] Barton CA, Zoback MD, Moos D. Fluid flow along potentially active faults in crystalline rock; Geology 1995; 23:683-683.
[4] Bastesen E, Braathen A, Nottveit H, Gabrielsen RH, Skar T. Extensinoal fault cores in micritic carbonate – Case studies from the Gulf of Corinth, Greece. Journal of Structural Geology 2009; 31: 403-420.
[5] Bense V F, Person MA. Faults as conduit-barrier systems to fluid flow in siliciclastic sedimentary aquifers. Water Resources Research 2006; W05421.
[6] Bense VF, Gleeson T, Loveless SE, Bour O, Scibek J. Fault zone hydrogeology. Earth Science Reviews 2013; 10.1016/j.earscirev.2013.09.008.
[7] Billi A. Grain size distribution and thickness of breccia and gouge zones from thin strike-slip fault cores in limestone. Journal of Structural Geology 2005; 27 (10) 1823-1837.
[8] Caine J, Evans JSP, Forster CB. Fault zone architecture and permeability structure. Geology 1996; 24:1025-1028.
[9] Centraal Bureau voor Statistiek. Renewable energy in the Netherlands 2011. The Hague: Statistics Netherlands 2012.
[10] Deckers J, Broothaers M, Lagrou D, Matthijs J. The late Maastrichtian to Late Paleocene tectonic evolution of the Southern part of the Roer Valley Graben (Belgium). Netherlands Journal of Geosciences (In Press).
[11] Doornenbal JC, Stevenson AG. Petroleum Geological Atlas of the Southern Permian Basin Area. Houten: EAGE Publications; 2010.
[12] Dreesen R, Bouckaert J, Dusar M, Soille P, Vandenberghe N. Collapse structure at the Dinantian-Silesian contact in the subsurface of the Campine basin, N of the Brabant Massif (N-Belgium). Dixième Congrès International de Stratigraphie et de Géologie du Carbonifère; Compte Rendu, 1985; 7-14.
[13] Ferrill DA, Sims DW, Waiting DJ, Morris AP, Franklin NM, Schultz AL. Structural framework of the Edwards Aquifer recharge zone in south-central Texas. Geological Society of Americal Bulletin 2004; 116 (3-4): 407-418.
[14] Gibson RG. Physical character and fluid-flow properties of sandstone derived fault zones. Geological Society, London 1998; 127(1): 83-97.
[15] Knipe RJ. Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs. AAPG Bulletin 1997; 87(2): 187-195.
[16] Kramers L, Van Wees J-D, Pluymaekers MPD, Kronimus A, Boxem T. Direct heat resource assessment and subsurface information systems for geothermal aquifers; the Dutch perspective. Netherlands Journal of Geosciences - Geologie en Mijnbouw 2012; 91 (4): 637-649.
[17] Laenen B, Van Tongeren P, Dreesen R, Dusar M. Carbon dioxide sequestration in the Campine Basin and the adjacent Roer Valley Graben (North Belgium): an inventory. Geological Society, London 2004. 233: 193-210.
[18] Langenaeker V. The Campine basin. Stratigraphy, structural geology, coalifation and hydrocarbon potential from the Devonian to Jurassic. Aardkundige Medeedelingen 2000; 10: 1-142.
[19] Loveless SE. The hydrogeological structure of fault zones in porly lithified sediment, Gulf of Corinth, Central Greece. PhD Thesis. University of East Anglia 2013.
[20] Loveless S, Hoes H, Petitclerc E, Licour L. Country Update, Belgium. World Geothermal Congress. Australia and New Zealand: International Geothermal Association, 2015. In Press.
[21] Micarelli L, Benedicto A, Wibberley CA. Uplift, deformation and fluid involvement within an active normal fault zone in the Gulf of Corinth, Greece. Journal of the Geological Society 2006; 151(3):1214-1227.
[22] Roberts G, Stewart I. Uplift, deformation and fluid involvement within an active normal fault zone in the Gulf of Corinth, Greece. Journal of the Geological Society 1994. 151(3):531-541.
[23] Sibson RH. Fault rocks and fault mechanisms. Journal of the Geological Society 1977; 133:191-213.
[24] Smeester A, Muchez P, Swennen R, Keppens E. Diagenesis at Exposure Surfaces in a Transgressive Systems Tract in a Third Order Sequence (Lower Carboniferous, Belgium). Morad, S J, J M Ketzer and L F De Ros. Linking Diagenesis to Sequence Stratigraphy. John Wiley & Sons, Inc, 2013.
[25] Van Wijhe DH. Structural evolution of inverted basins in the Dutch offshore. Tectonophysics 1987; 137: 171-219.
[26] Vanneste K, Camelbeeck T, Verbeek K. A Model of Composite Seismic Sources for the Lower Rhine Graben, Northwest Europe. Bulletin of the Seismological Society of America 2013; 103(2A):984-1007.
[27] Yielding GB, Freeman B, Needham T. Quantitative fault seal prediction. AAPG Bulletin 1997; 81(6):897-917.
[28] Younger PLJ, Gluyas J, Stephens WE. Development of deep geothermal energy resources in the UK. Energy 2012; 19-32.