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Fossil Multiphase Normal Faults - Prime Targets for Geothermal Drilling in the Bavarian Molasse Basin?

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ABSTRACT

Foreland basins with their increasing depth towards the orogenic belt are ideal geologic systems as host for geothermal resources. The Bavarian Molasse Basin is the only basin worldwide where geothermal energy is being successfully developed by industry in conduction dominated heat transport environment. However, the predicted productivity is not achieved in all projects because either temperature or flow rate or both are lower than expected. The utilized reservoir rock consists of Upper Jurassic fractured carbonates, and reservoir quality is governed by fracture and fault frequency, dolomitisation degree, karstification and facies type. From these controlling factors only fracture density can be reliably assessed before drilling because generally highest fracture density is found in the vicinity of faults which can be in turn clearly identified in reflection seismic. In contrast facies and dolomitic domains can be reliably detected only after drilling and seismic-well log correlation. From this perspective faults seem to be the most reliable target in geothermal exploration in the Molasse Basin. A particular fault system, however, might have experienced a complex kinematic history from Jurassic to the present-day state, eliciting the question which fault among many detected faults might be the best drilling target. The geothermal site Mauerstetten in the Western Bavarian Molasse Basin is an example where drilling into a fault zone did not result in high flow rates. This article tries to identify the effects on the lacking reservoir permeability by detailed geological well data and advanced structural geological interpretation. The results are set into context with successful geothermal drilling projects in the Molasse basin where high flow rates were achieved by fault zone drilling.

1. INTRODUCTION

The Bavarian Molasse Basin is one of seven Alpine foreland basins in Europe (Fig. 1). The 3-5 km deep Upper Jurassic Malm formation of the Molasse Basin (Fig. 1) is explored as an fractured and faulted carbonate reservoir rock recently for geothermal and - to a minor degree - in the last decades for hydrocarbon resources. Faults play a major role in reservoir exploration of carbonate reservoirs. Critical questions are addressed to the hydraulic properties of faults and their ability to channel fluids while matrix properties are interactively affected by depositional environment, karst evolution, pressure solution, early and late diagenetic processes, metasomatic dolomitisation and changes in diagenetic grade during basin subsidence. The different respond of faults on paleostress regimes causes open (mechanically or secondary opened by dissolution), cemented sealed (dissolution and precipitation), kaciritic cohesion less, tectoclastic (kataclastic) lithified, authigenic clay mineral or fault gouge filled, and discrete decollated or disperse brecciated, fossilized or migration active cuts. The fault style has thus a strong controlling factor on the hydrostatic, hydro-pressured (gas over-pressured), hydrothermal and telethermal setting of the fluids (volatiles) involved. The Upper Jurassic Malm formation in particular is well studied for facies types (Kott, 1989; Meyer & Schmidt-Kaler, 1996; Koch et al. 2010), karst formation, diagenesis and dolomitisation (e.g. Michel 1999), paleontology including microfossils and paleogeography (e.g. Pomoni-Papaioannou et al., 1989) in outcropping sections of the Franconian Alp.

Since geothermal exploration has been started in the Upper Jurassic Malm Fm., open questions address physico-chemical properties of rock type, reservoir quality, the impact of faults on deep hydrogeology, fluid flow patterns, discrimination of meteoric advective and deep thermal convective cycles, rock-water interaction and cement precipitation as also authigenic clay-mineral formation and reaction progress, dolomitisation and karstification processes with the ultimate goal to determine optimal drilling targets for geothermal production wells. It is known from fractured carbonate reservoirs that a cluster of faults channelling fluids and an enhanced matrix porosity increases the storage capacity for fluids thus leading to favourable reservoir rock qualities (Lian and Ma, 2012). Due to the deep burial setting of the Malm reservoir in contrast to lithofacies changes and the occurrence of high porosity domains, only faults can be reliably detected in the dataset of seismic sections during green field exploration, i.e. before drilling without well-log and seismic correlation. Thus, the characterisation of faults, the better knowledge about their kinematic and diagenetic evolution together with the better understanding of syn-kinematic processes controlling permeability structures obtain a primary role in exploration. The dominating E-W to ENE-WSW striking normal faults in the carbonate reservoir (i.e. the Malm formation) must have been generated in a stress regime with a minimum horizontal stress direction Sh ≈ N-S (Moeck et al., submitted). The present-day stress field is however 90° rotated to this normal faulting stress regime with a present-day minimum horizontal stress direction Sh ≈ E-W and a maximum horizontal stress direction SH ≈ N-S (Fig. 1) (Reinecker et al., 2010). This inconsistency between the fault geometry and the recent stress regime indicates the existence of fossil normal faults in a present-day stress regime.

This article addresses the question on normal faults in the Upper Jurassic formation of the Bavarian Molasse Basin. The elementary focus relates to the formation time, the time spans of a potential tectonic reactivation and the implications on permeability structure in faulted carbonate reservoirs.

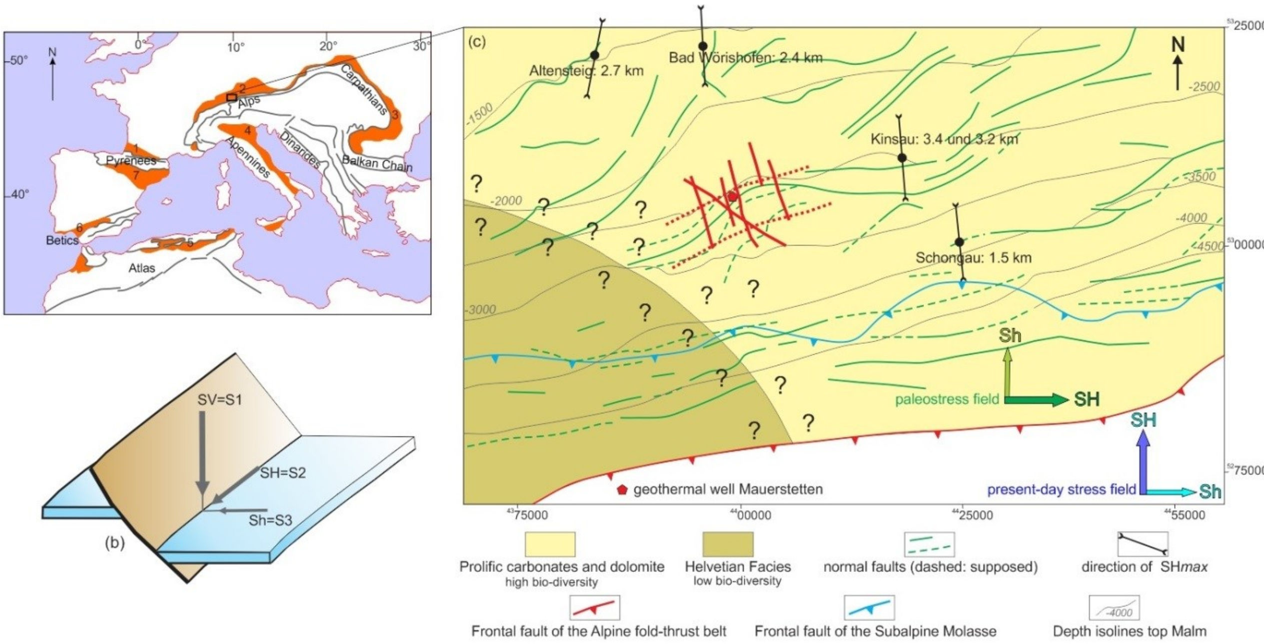


Figure 1: (a): The seven Alpine foreland basins with 1-Aquitaine Basin, 2-Molasse Basin, 3-Carpathian Basin, 4-Apenninic basins and Po Basin, 5-Atlas Basin,6-North Bethic Basin, 7-South Pyrenean and Ebro Basin. (modified from Allen et al., 1986). 1(b): Andersonian stress field/faulting regime relation for normal faults. 3(c): Map of the Upper Jurassic (Malm) carbonate formation. Red polygone: well GT1, red solid lines: 2D seismic profiles used in this study, dashed red lines: 2D seismic profiles used for 3D geological modeling but not used for the stratigraphy related fault throw analysis. Question marks indicate the transition region from prolific carbonate facies to Helvetian facies. Back dots: neighboring wells with depth range of borehole breakouts indicating the direction of SH from the present day stress field. Green Sh-SH arrows: stress field causing the normal faults, blue Sh-SH arrows: present day stress field causing the Alpine frontal fault (modified from Moeck et al., submitted; Reinecker et al., 2010; Bayerischer Geothermie-Atlas, 2010).

2. GEOLOGICAL SETTING

The Molasse Basin and its substratum underwent four major evolutionary stages, termed as syn-rift (Permo-Carboniferous), epicontinental (Triassic-Middle Jurassic), passive margin (Middle Jurassic to Late Cretaceous-Palaeocene) and Alpine foredeep (Oligocene to Pliocene), illustrated in an updated standard stratigraphic profile of the basin. At the basis of the Molasse sediments (Oligocene to Miocene) a large hiatus is testifying a basal unconformity evolving from the Helvetic European shelf domain to the Molasse Basin (Schmid et al., 1996, 2008) from the south in the Palaeocene to the north in the Oligocene (Chattian). The Molasse is underlain by 500-1,000 m thick Mesozoic shelf sediments that represent the passive margin basin of the Neotethys (Stampfli & Borel, 2004). The predominantly Mid to Late Jurassic carbonate beds are deposited on Variscan basement that is locally segmented by Permo-Carboniferous troughs containing clastic sediments of largely unknown thickness and composition (Lemcke, 1988; Lüschen et al., 2011). After several marine transgression and regression phases from Permian to Early Cretaceous, prior to continuous deepening due to increased shelf subsidence evidenced by neritic to pelagic sediments (mostly eroded in the Palaeocene to Eocene emersion phase, Trümpy 1960) in Late Cretaceous and progressing to Early Eocene, the deposition of marine and freshwater Molasse from Late Eocene to Late Miocene represents the foreland basin period where sedimentation was controlled by erosion and uplift cycles of the Alpine fold and thrust belt (Lemcke, 1977; Kuhlemann & Kempf, 2002).

The involved faulting processes may be identified by a quantitative fault zone analysis in seismic sections measuring specifically the fault throw on individual seismo-stratigraphic horizon cut-offs on seismic profiles. The six 2D seismic sections of the Mauerstetten prospect cover a major ENE-WSW trending discontinue offset of normal fault array with an absolute throw of 270±10 m and a length of 20 km (Fig. 2). The fault zone truncates from Upper Jurassic to Miocene strata. However, the fault throw seems larger in the Mesozoic strata than in the Cenozoic strata and declines towards the Miocene in the upper section. A stratigraphy related fault throw analysis is therefore chosen to identify intra-formational fault throws to detect a fault activity at a certain time slot.

3. GEOTHERMAL DRLLING AND ADVANCED STRUCTURAL INTERPRETATION OF SEISMIC DATA

The well Mauerstetten GT1 hits the fault zone of the afore mentioned undulating E-W striking normal fault array at a depth of 3.763 m TVD (i.e. below ground level) encountering the Malm aquifer (Figs. 1 and 2). The well is deviated along ESE direction (120° azimuth), inclined with an angle of 50° and has a total length of 4.523 m MD (4.085 m TVD). The well path is placed into the hanging wall block of the fault zone and truncates three branches of synthetic normal faults evidenced by repeating strata in the lithostratigraphic section of well GT-1. The sidetrack GT1a is placed into the hanging wall of the second fault branch and is drilled in fault dip direction along ESE-WNW (108° azimuth) with an inclination of 57° to 4.052 m MD (3.572 m TVD) depth with a lateral distance of 513 m to GT1 in 289° azimuth. The temperature in 3,675 m depth TVD is 132°C shortly after reaching the target horizon in the side track GT1a. The drilled imbricated normal fault zone is visible in the 2D seismic sections as one fault zone, obviously with the synthetic parasitic fault branches not detected below seismic resolution. The seismic sections originate from 2007 and were adjoined to older seismic sections from 1989, 1990 and 2003. A total of 12 seismic sections were processed or re-processed and interpreted to build a 3D geological model (Loske and Witte, 2008).

3.1 Stratigraphy related fault through analysis

Two methods were employed for advanced structural interpretation of the 2D seismic data to determine the growth history of the studied fault zone (Fig. 3): (i) the fault throw was measured sequentially through all mapped seismic horizon from the uppermost faulted layer with an identifiable cut-off in the lower Neuhofener Formation down to the Purbeck Formation that represents the top carbonate geothermal reservoir. The throw measured on each seismic horizon was subtracted from the throw of the next lower horizon in order to detect the differential offset for each layer instead of only measuring the cumulative offset. The differential offset is referred as to Quantitative Fault Expansion Index (QFEI) and is given in meter; (ii) the thickness variation of seismic stratigraphic intervals were measured in the footwall and hanging wall adjacent to the fault dislocation plane. The thickness of the seismic horizon in the hanging wall was compared with the thickness of the same layer in the footwall at the intersection of the horizons with the fault dislocation plane. The thickness variation from hanging wall to footwall is expressed in percent and referred as to Expansion Index. In the case that the horizons have the same thickness in hanging and foot-wall, the Expansion Index is 1. Has the hanging wall horizon a 10% higher thickness than in the footwall, the expansion index is added by 10% resulting in 1.1, with a 20% higher thickness from hanging to footwall layer the expansion index is 1.2. The thickness is measured vertically to the horizon base, respectively, so that an apparent thickness in rotated fault blocks can be excluded. This second method aims to discriminate syn-sedimentary growth faulting from post-sedimentary faulting while the first method aims to identify the fault activity at a certain period.

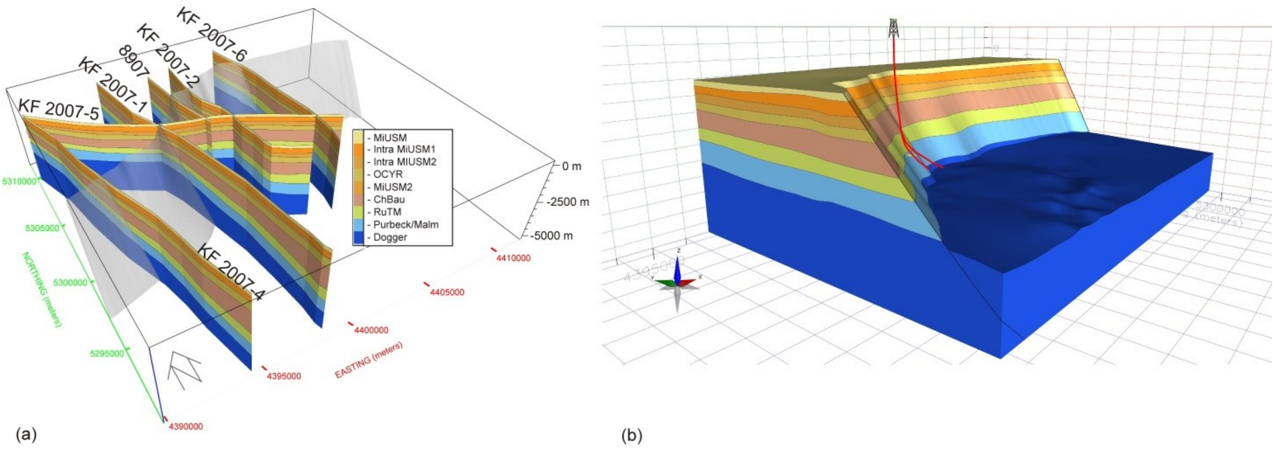


Figure 2: (a) 2D seismic lines of the Mauerstetten prospect, gray shaded is the dominating multiphase normal fault. (b) 3D geological model developed from 2D seismic sections with well path of main well and side track in the hanging wall of the fault zone (modified from Moeck et al., submitted).

4. RESULTS

The QFEI derived from the fault throw analysis indicates the inactivity of the fault since the Middle Miocene (17 Mio years) confirmed by the absence of natural seismicity in the present-day stress field (Barnikel & Geiss, 2008). Depending on strike and dip azimuth fault segments exhibit a different fault kinematic evolution. While E-W oriented segments underwent a multiphase normal faulting history from Jurassic to Miocene due to rifting in the Helvetic-European shelf and subsequent lithospheric bending in the foreland of the evolving orogeny during Alpine nappe thrusting (Moeck et al., submitted), NE-SW trending fault segments acted as Jurassic normal faults presumably reactivated first as normal faults in the lower Cretaceous and as strike-slip faults in the Upper Cretaceous due to subduction in the Valais ocean (e.g. Stampfli, 1994). The culmination of normal faulting was in the Lower Oligocene obviously related to lithospheric bending associated with the lithospheric load of the Alpine fault-thrust belt. Normal faulting continued on the Mauerstetten fault to Miocene and died out in the Burdigalian (Moeck et al., submitted) (Fig. 3a).

The present-day stress state of the faults and its likelihood for fault slip can be estimated by the slip tendency and derived fault reactivation potential (Morris, 1996; Moeck et al., 2009a) following the concept of limiting stress ratios and the Mohr-Coloumb failure criterion extended by the Hoek-Brown parameters (Moeck et al., 2009b; Cacace et al., 2013). Two important facts can be addressed: (i) the orientation of fault segments with high slip ratio; (ii) the conditions for slip referring to rock strength and fluid pressure. Assuming a present-day strike-slip stress regime in the Mesozoic succession (Cacace et al., 2013; Reinecker et al., 2010) with a maximum horizontal stress direction SH ≈ 170° (±15°) (Moeck, 2011), an estimated fair rock mass quality with fracture spacing at 0.3-1 m (Moeck et al., 2009a) accounting for the fractured fault damage zone as indicated by the lithology of the well GT1, and hydrostatic conditions of 35 MPa for the Malm reservoir in Mauerstetten, the slip tendency on any segment of the normal fault is below the friction coefficient of the rock mass. This result is another indicator for a fossil normal fault with no probability of reactivation in the current stress field. E-W trending fault segments with dip angles >42° cannot be reactivated as reverse faults in the current stress field. With a dip angle <42° these faults could be re-activated as reverse faults. NNE and NNW trending faults could be reactivated as sinistral and dextral strike slip faults, respectively.

The observed normal fault with an E-NE trend in the Mauerstetten area has significant steeper dips (>45°). Thus, these fault segments undergo a frictional blockade and are unlikely to be reactivated. Therefore unusual high horizontal stresses would be necessary to reactivate these faults as reverse faults. Obviously this is not the case because no indication for reverse faulting reactivation (such as anticlinal bending of the hanging wall formations) is observed in the 3D geological model. An additional fluid pressure of 33 MPa would be required to reactivate NE-SW segments of the normal fault in fairly fractured rock (fracture spacing 0.3-1 m) indicating an inactive normal fault exhibiting fossil multiphase activity.

5. IMPLICATIONS ON FAULT ZONATION AND PERMEABILITY STRUCTURE

The hydraulic properties of the fault zone can be estimated from the well tests and the geologic profiles of the well GT1 and the sidetrack GT1a. The well GT1 has a minimum distance of 173 m to the mapped major fault surface while GT1a has a distance of 337 m to the main fault. The estimated flow rate from GT1a is 24 l/sec derived from an injectivity index of 25.2 m^3/h*MPa. However, injection tests always opened fractures to a larger extend than under production conditions resulting in smaller flow rates. GT1a provides 7 l/sec derived from a productivity index of 7.2 m^3/h*MPa. The well GT1 is located closer to the major normal fault and transects possibly synthetic minor faults, which cause a flow rate that is about 3 times higher than in the sidetrack GT1a (Fig. 4). Another reason for the higher flow rate derived from GT1 is that the injectivity can be three to five times higher than the productivity due to poro-elastic effects (Grant and Bixley, 2011). Garg and Comb (1997) suggest a 1:1 ratio of productivity to injectivity and assuming the linear relationship of injectivity to productivity GT1 is significantly more productive than GT1a. GT1 is located in the damage zones of the minor faults identified by the repeated lithologic and facies type sections from the well geological profile. The sidetrack GT1a is located out of the damage zone and is influenced by the matrix permeability of the host rock rather than the fracture permeability of the damage zone. The multiple phases of normal faulting may have generated a fault damage zone with higher fracture density with a positive effect on the permeability of the fault core and fault damage zone. Moreover, the Mauerstetten fault was active as normal fault up to the Miocene when the thrusting and compression in the Alpine orogeny started to decay in the Alpine front. Obviously this fault preserved its dilative character as an inherited fossil structure in the recent compressional stress field due to local extension and lithospheric bending in the Upper Eocene to Lower Miocene with possibly positive effects on its hydraulic properties in the damage zone containing parasitic synthetic normal faults indicated by the geologic profile of the well.

Since no image logs are available from the well, only suggestions can be drawn to fracture characteristics in fault core and damage zone. Calcite mineralisation in cuttings indicates healed fractures or slip planes acting as fluid barriers. No breccia is reported from cuttings as someone would expect from drilling along a multiphase normal fault zone. One reason might be that the spatial relationship between fault and borehole is not accurately defined because the fault geometry is mapped from 2D seismic profiles instead of a 3D seismic survey. A 3D seismic survey might deliver a modified structural pattern with rather a segmented normal fault than one coherent fault surface. The fault dip and bed thickness in the 2D seismic sections might be correct as the fault throw analysis is, however the uncertainty of strike and dip of the fault surface increases with distance to the seismic sections and interpolation effects from 3D model building influence the mapping result. Another reason for missing breccia in the carbonate section is that the repetition of the lithofacies types in the well profile can also be related to facies boundaries and not only to faulted boundaries. In this case the well GT1 is only crossing one minor synthetic fault with a small damage zone thickness. Under this circumstance a fractured reservoir should be combined with a stratiform lithofacies reservoir with hybrid pore types as vuggy fractures (Nelson, 2001). Vugs are identified in the cuttings from the well GT1. These vugs are associated with Cretaceous siliciclastics indicating a sediment filled karst in the Malm limestone obviously formed in the Lower Cretaceous during a terrestrial period posterior to the carbonate platform formation.

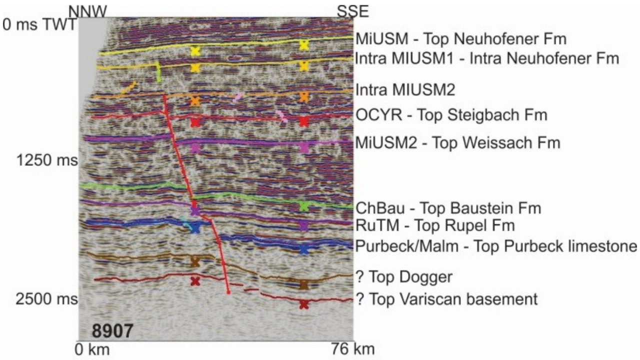
5.1 Controlling factors on permeability anisotropy in carbonate rock

Fluid flow in carbonate rock is however not only fractured controlled but is affected by a complex interplay between deposition, early and late stage alteration by diagenesis, hydrology including dissolution and karst, and tectonic overprint including healing of fractures. The challenges in carbonate reservoir exploration are associated with a complexity of multi-scale porosity and permeability distribution related to a wide range of biosediments on the carbonate platform (Ahr, 2008). Geothermal exploration has shown that highest recovery from the Malm formation in the Bavarian Molasse Basin are from reef detritus limestone of the profilic and highly bio-diversified carbonate factory of the outer carbonate platform with barrier reefs. In contrast low-diversity carbonate factory dominated by algo-microbal associations are less prospective (Ahr, 2008). According to the cutting analysis the Mauerstetten wells are located in the latter facies type exhibiting a minor degree on dolomitisation and vuggy pores generated by karst and dissolution. Dolomitisation and karstification seems to be facies-selective, however mechanisms on fabric-selective, texture-selective and facies-selective porosity and permeability development or pore space structure are not fully understood yet for the Upper Jurassic of the Molasse Basin.

The polyphase activity of the normal fault may have a positive impact on the fracture density however the low recovery might be related to poorly connected fractures, sealed fractures and/or low interstitial porosity in the low-biodiversity limestone. Fracture porosity scale is not only related to fracture spacing, width and length but also to the area size or reservoir thickness and interconnectivity of the fractures (Ahr, 2008; Youn and Gutierrez; 2011). The latter could be the critical factor for the Mauerstetten fault. Only synthetic normal faults are identified by the lithologic profile of the well and the 2D seismic sections. Mapped fractures and parasitic faults are parallel and may undulate in strike possibly generating steep or vertical intersection lines that could channel fluids. A higher degree in interconnectivity is however given by an array of synthetic and antithetic fractures forming an X-geometry. X-fractures are typically generated in Y-shaped graben situations or along listric normal faults. At an analogue outcrop in the front ranges of the Rocky Mountains in Alberta open channels could have been observed in the damage zone of a reactivated normal fault in carbonate rock. The channels were bound to intersections of X-shaped fractures (Fig. 3b). Intersection lines of X-shaped fractures or crossing normal faults are lateral and provide optimal channels for fluid flow along fault strike (Ferrill et al., 2009). Transferred to reservoir depth, these channels might be kept open even in a compressional stress field. Along the

Mauerstetten well only synthetic fractures are observed, X-fractures are lacking thus no lateral fluid channels can be expected with reduced fracture-assisted permeability and resulting low flow rate from the well GT1.

Reservoir productivity cannot be simply attributed to fast communication along faults cutting the top of the reservoir. However, faults are the only structural element that can be reliably detected through reflection seismic before drilling while diagenetic and depositional heterogeneities can only be identified after drilling and extensive well log – core analysis – seismic data correlation of a minimum of 20 wells in a 20 km^2 reservoir block (Spina et al., 2014). Before the 3D stratigraphic and sequential architecture of a carbonate platform can be simulated from information of a number of wells and 3D seismic data, identifiable seismic-scale faults may play a primary role in targeting of geothermal wells in a new prospect. The stratigraphy related fault throw analysis may help to select favourable faults bearing fluids from a complex fault pattern for the following reasons inferred from the hydraulic well tests from fault zone and off the fault zone in Mauerstetten.



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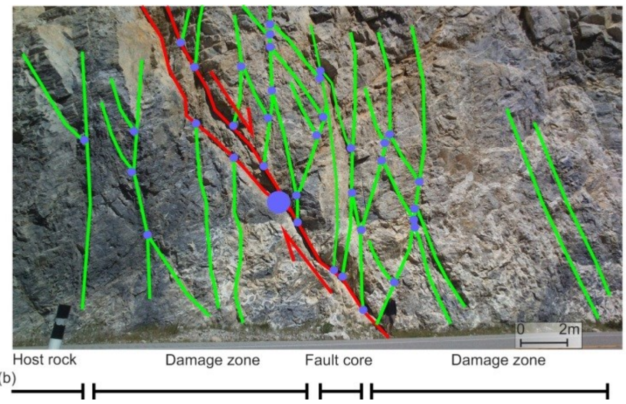

Figure 3: (a) Multiphase normal fault identified in the Mauerstetten prospect in the Bavarian Molasse basin. (b) Multiphase normal fault in the Middle Cambrian Cathedral carbonate formation in the Front Ranges of the Rocky Mountains, Alberta. Red are slip planes in the fault core zone, green are fracture planes in the damage zone, and blue are intersection points of X-fractures.

6. CONCLUSION

The geothermal prospect Mauerstetten in the southwestern Bavarian Molasse Basin is one of the industry projects where high temperature of over 150°C but insufficient flow rate due to tight carbonates in the Malm unit (i.e. Upper Jurassic) dragged down the overall project performance. In a subsequent research project, a detailed structural geological analysis of twelve 2D seismic profiles with a total length of 155 km has been performed to better understand fault kinematics with possible implications on fault core and damage zone formation over time. The applied approach for fault plane analysis is a stratigraphy related fault throw analysis to identify multiphase reactivation of detected normal faults. The normal faults are striking about E-W and obviously generated in a normal faulting stress regime with a minimum principal stress S3 in N-S. The present-day stress field has a maximum principal stress direction S1 in N-S, indicating fossil normal faults in a current stress field.

The results of seismic fault throw analysis show that the throw varies in different stratigraphic layers indicating different periods of faulting activity. A major fault activity occurred after deposition of the Upper Jurassic Malm unit presumable in the Lower Cretaceous. A second major faulting period occurred in the late Oligocene. All fault throws indicate normal faulting in the Mauerstetten prospect until Miocene period when the main fault-and-thrust activity in the Alpine orogen has terminated. Due to lithospheric bending these normal faults preserved obviously their dilative character in a plate tectonic compressional regime. Flow test data from different wells indicate that these multiphase fossil normal faults are loci of increased permeability due to high interconnected fracture density in a well-evolved fault damage zone. This example shows that stratigraphy related fault throw analysis in combination with stress field determination is an important addition in advanced seismic interpretation to identify reactivated faults.

Insufficient flow rates might be explained by three reasons: (I) Crossing X-fractures and their intersections are prime flow channels for flow along faults that are compressional in the present-day stress field. The dominating fault at the Mauerstetten prospect is a major southward dipping normal fault with an offset of more than 200 m. The fault damage zone – commonly a high permeability zone in carbonate rock fault zones – is built up by synthetic fault parallel secondary normal faults. Crossing X-fractures are lacking; (II) multiphase normal and presumably strike-slip faulting activity of the drilled NE-oriented fault segment started in Jurassic and decayed in the Miocene. The multiple fault activity might have caused sealed the fault zone by fault gouge; (III) low interstitial matrix porosity as effect of the formation of the carbonates at the outer slope of the carbonate platform.

However, technological treatments and reservoir engineering may help to develop sites as Mauerstetten provided the carbonate platform at depth is geologically characterized. Reservoir engineering can only be developed for carbonate reservoirs if the depositional, diagenetic and tectonic history and its impact on pore space, permeability distribution and the overall fluid-rock system are identified. In so far the case study Mauerstetten is an example that the Malm unit of the Bavarian Molasse Basin is not comprehensively understood yet.

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