A basin thermal modelling approach to mitigate geothermal energy exploration risks: The St. Gallen case study (eastern Switzerland)

OMODEO SALE, Silvia, et al.

Abstract

In sedimentary basins geothermal resources may coexist alongside hydrocarbon resources. The latter can represent a risk to geothermal exploration as experienced during the drilling of the deep St. Gallen geothermal well in eastern Switzerland. In this case, the unexpected occurrence of substantial amounts of natural gas, along with other external factors, prevented the continuation of the geothermal project. Therefore, this work aims at resolving the origin of the gas alongside evaluating the processes activating the petroleum system in the study area. In order to characterize the petroleum system of St. Gallen, we performed a basin analysis study aimed at reconstructing the thermal history of the basin and quantifying the main variables controlling the temperature in the basin: the paleo-heat flow and the magnitude and timing of the most relevant erosion events. The findings from this study indicate that the thermal conditions attained in the area were mostly controlled by the deposition of the Molasse units during the Oligocene-Miocene time. Older thermal events could not be detected by organic paleothermometers. An [...]
A basin thermal modelling approach to mitigate geothermal energy exploration risks: The St. Gallen case study (eastern Switzerland)

S. Omodeo-Salé, O.E. Erutey, T. Cassola, A. Baniasad, A. Moscariello

GE-RGBA Group, Department of Earth Sciences, University of Geneva, Switzerland
Schlumberger GmbH, Aachen, Germany
Institute of Petroleum and Coal, RWTH, Aachen University, Germany

ARTICLE INFO

Keywords:
Thermal modelling
Geothermal energy
Exploration risk
Petroleum system
Geological Modelling
Northern Alpine Foreland Basin
St. Gallen

ABSTRACT

In sedimentary basins geothermal resources may coexist alongside hydrocarbon resources. The latter can represent a risk to geothermal exploration as experienced during the drilling of the deep St. Gallen geothermal well in eastern Switzerland. In this case, the unexpected occurrence of substantial amounts of natural gas, along with other external factors, prevented the continuation of the geothermal project. Therefore, this work aims at resolving the origin of the gas alongside evaluating the processes activating the petroleum system in the study area.

In order to characterize the petroleum system of St. Gallen, we performed a basin analysis study aimed at reconstructing the thermal history of the basin and quantifying the main variables controlling the temperature in the basin: the paleo-heat flow and the magnitude and timing of the most relevant erosion events. The findings from this study indicate that the thermal conditions attained in the area were mostly controlled by the deposition of the Molasse units during the Oligocene-Miocene time. Older thermal events could not be detected by organic paleothermometers. An erosion thickness of 1800–2000 m was estimated for the Molasse deposits, related to the uplift of the Northern Alpine foreland, occurring in the area most likely at 8–5 Ma.

Results of thermal modelling revealed favourable conditions for the activation of a petroleum system in the St. Gallen area. The source rocks, located most likely in the Permo-Carboniferous grabens, are in the gas window. The model suggests that most of the hydrocarbons generated in the study area migrated northward, because of the southward dipping of the basin. According to the model only a small percentage of hydrocarbons were trapped in reservoirs, mostly located in the uppermost Permo-Carboniferous and basal Mesozoic units. Accumulations were simulated a few hundred meters below the final depth reached by the geothermal St. Gallen GT-1 well. From here the gas likely migrated into the overlying Mesozoic units, the target area of the well, where effectively the model predicts high petroleum saturation levels. This work demonstrates that the basin-scale thermal modelling approach adopted in this study should be incorporated into the feasibility and planning phase of future geothermal exploration campaigns to de-risk the subsurface manifestation of hydrocarbons.

1. Introduction

Sedimentary basins are favourable settings for the formation and accumulation of geo-energy resources, such as water and hydrocarbons. Sedimentary basins also offer suitable temporary and permanent storages for heat, CO₂, methane, toxic and nuclear waste, etc. (cf. Chapman, 1987; Goff and Williams, 1987). The potential interplay between the geo-resources naturally occurring and/or anthropogenically stored in a sedimentary basin can represent a risk during their exploitation, firstly in the sense of environmental pollution and secondly with respect to safety challenges during drilling operations. Geothermal exploration can be impeded by the risk associated with the occurrence of hydrocarbons in the subsurface (Moscariello et al., 2020a). In Switzerland, this situation is well-known, as it has been the cause of significant incidents while drilling geothermal wells. In the case of the St. Gallen deep geothermal well (St. Gallen GT-1; Fig. 1), a 3.5 magnitude earthquake was triggered while containing the over-pressure in the drill pipes and annulus induced by of natural gas kick (Diehl et al., 2017; Moeck et al., 2015; Wolfgramm et al., 2015). In the case of the Schlattingen hydrothermal well, situated in north-eastern
Switzerland, the hot water discharged into the Rhine river while testing was found to contain substantial amounts of oil (Frieg et al., 2015). This discharge generated serious water contamination concerns (Hilzinger, 2018). In order to prevent these types of incidents, extended multiscale and multiapproach studies aimed at de-risking geothermal exploration with respect to subsurface hydrocarbon occurrence should be envisaged before the commencement of drilling operations. 

This work aims to understand the petroleum system associated with the St. Gallen deep geothermal well, which was initially designed as part of a hydrothermal doublet in the year 2011–2012 and realized throughout the year 2013. The main goal of the well was to introduce geothermal energy as a main heat source for the existing local district heating network and possibly also for electricity production (Moeck et al., 2015). The drilling target was a regional and complex fault zone – the St. Gallen Fault Zone (Heuberger et al., 2016) – affecting the Mesozoic layers at depths of around 4–5 km where potential hydrothermal resources (water at temperature of 130–170 °C) were predicted. The primary target was the Upper Jurassic carbonates (Malm) and with the Triassic (Muschelkalk) and/or Permian reservoirs (Moeck et al., 2015; Wolfgramm et al., 2015) as secondary objectives. A 3-D seismic survey was acquired in the area in order to define the main structural framework and the geometry of the stratigraphic units (Heuberger et al., 2016). By considering the regional geological framework and the data from deep wells in the region located in a similar tectonic position (Entlebuch-1, Luzern Canton, Fig. 1a, and in the Sulzberg well, in Austria, Vollmayr and Wendt, 1987; Müller and Nieberding, 1996), the presence of hydrocarbons flows in the subsurface of the St. Gallen GT-1 well area was envisaged (Naef, 2012). However, the lack of pre-drilling data made it difficult to estimate the magnitude, pressure, and exact locations of potential gas accumulations (Naef, 2012).

The geothermal well “St. Gallen GT-1” reached the depth of 4450 m below ground level in summer 2013, when an injection test and a subsequent acidizing of the target zone within the Mesozoic units was initiated, leading to substantial losses of drill mud (e.g. Diehl et al., 2017; Moeck et al., 2015; Wolfgramm et al., 2015). A few days later, natural gas started to enter the borehole producing a gas kick. To
control the sudden increase of gas inflow, heavy drill mud, freshwater and lost-circulation materials were pumped into the well. This operation triggered microseismicity around the area mainly below target depth, resulting in a series of earthquakes ML 3.5, widely felt by the population in northeastern Switzerland (intensity IV on the European Macroseismic Scale EMS-98, Diehl et al., 2015, 2017; Edwards et al., 2015). The drilling operation was paused for evaluation during several weeks, before resuming testing activities with another acidizing job and a drill-stem test in fall of 2013, which produced both water and natural gas. As a consequence of the resulting very low productivity of hot brine encountered in the targeted reservoir intervals, the high productivity of natural gas, and a high risk of induced seismicity associated with injection of fluids a decision was reached to stop the project and temporarily abandon the well in May 2014 (Moeck et al., 2015).

The natural gas in the St. Gallen GT-1 well consists mostly of thermogenic methane (Eichinger, 2014; Jurisch, 2013). The isotopic data indicate the gas was generated by a mature source rock, composed of Type II and Type III kerogens (Eichinger, 2014; Jurisch, 2013; Wolfram-fermer et al., 2015). Coaly shales, confined within the Permo-Carboniferous grabens, were designated as potential source rocks. Pressure/depth-factor analysis following short flow tests (Anshah et al., 2000) gave an estimate of the volume of gas initially in place as between 4 and 11 million cubic meters (Horne, 2015). However, a pressure decline analysis derived from a longer flow test could not be carried out, therefore high uncertainties are associated with these values.

The St. Gallen incident raised several questions for planning deep geothermal projects, particularly in relation to predicting unexpected high-pressures. To detect the occurrence of hydrocarbons in the subsurface, the petroleum potential of an area needs to be explored. This involves a basin-scale characterization of the petroleum system elements (e.g. source rock, reservoir, seal and trapping mechanisms) and processes such as hydrocarbons generation, migration and accumulation be investigated (Magoon and Dow, 1994). The petroleum system in the Swiss Molasse Basin is still not completely understood (Leu and Gautheli, 2014; Misch et al., 2017). Despite the occurrence of several hydrocarbon shows at the surface demonstrating the presence of an active petroleum system in the Swiss plateau, only a few accumulations have been found at present. This includes gas in the Entlebuch-1 deep well (Lahusen and Wyss, 1995; Vollmayr and Wendt, 1987; Greber et al., 2011) and oil and asphalt mostly in western Switzerland (Girard and Buman, 1913; Lagotola, 1932; Meia, 1987; Vollmayr, 1983; Weidmann, 1991). The lack of extensive direct information on the subsurface (e.g. core, seismic and ditch cuttings) impedes a complete assessment of the extension and effectiveness of the Swiss plateau petroleum system.

Thanks to the exceptional quality of subsurface data acquired during the GT-1 geothermal well planning and drilling campaign a detailed analysis of the hydrocarbon potential and the origin of the gas can now be performed in the St. Gallen area. To achieve this objective, this work applies the thermal modelling approach (e.g., Welte and Yalcin, 1987; Welte and Yukler, 1981; Welte et al., 1997), which allows the integration of a large set of multidisciplinary data. In order to investigate the evolution of the petroleum system of St. Gallen, the geodynamic and stratigraphic evolution of the study area was firstly analyzed, as the latter control the temperature attained in the stratigraphic record and thus the thermal maturation of the source rocks and timing of hydrocarbon generation (Welte et al., 1997).

The thermal modelling approach adopted in this study could find application in the development of similar geothermal projects and in de-risking with respect to unexpected occurrence of hydrocarbons. This can help project developers make an informed decision and manage the risks associated with such geo-energy projects. Importantly, this will help avoid a negative impact on society’s perceptions, leading to more support for the transition towards the use of geothermal energy.

2. Geological setting

The study area is located in the eastern part of the Swiss Plateau, west of the Lake of Constance and 4 km from the St. Gallen city centre (Fig. 1a). It forms part of the North Alpine Foreland Basin (NAFB), which formed during the Paleogene from the flexural bending of the European plate under the0 thrusts and crustal thickening of the Alpine orogeny (Burkhard and Sommaruga, 1998; Dickinson, 1974; Kuhlemann and Kempf, 2002; Pfiffner, 2014; Price, 1973; Stampfl et al., 2002; Turcotte and Schubert, 2014). Eocene-Miocene siliciclastic deposits filled the foreland, eroded from the uplifting of the Alpine nappes (Berger et al., 2005; Kuhlemann and Kempf, 2002; Pfiffner, 2014). The NAFB is separated into the northern external slightly tilted Plateau Molasse and the southern internal Subalpine Molasse, characterized by thrust sheets and folds (Pfiffner, 1986) (Fig. 1a). The study area is located in the Plateau Molasse, a few kilometres from the northern border of the Subalpine Molasse (Fig. 1b). The northern Subalpine Molasse in this area is characterized by partially blind thrust planes with opposite vergence, forming a triangular zone structural style (Fig. 1b), which extends up to the Austrian foreland basin (Berge and Veal, 2005; Ortnner et al., 2015; Pfiffner, 1986; Von Hagke and Malz, 2018). These structures, formed in the late Miocene (10 – 6 Ma) in the Subalpine deformation phases, have been linked to the Jura mountain formation and to the inner Alpex exhaustion events (Von Hagke et al., 2012). Since the latest Alpine thrusting phases, from the Miocene up into the Pliocene, part of the NAFB was gradually uplifted and eroded, forming a diachronous hiatus with the Quaternary cover of approximately 10 My (Kuhlemann and Kempf, 2002). In the western NAFB most of the younger Molasse units are missing whereas they are still present in the eastern sector (Trümpy et al., 1980).

2.1. Stratigraphic evolution

The stratigraphic record constituting the NAFB and its substratum can be grouped into four mega-sequences, corresponding to the geodynamic evolution cycles of the area (Burkhard and Sommaruga, 1998) (Fig. 2): (1) crystalline basement; (2) post-Variscan sequence; (3) Mesozoic sequence; and (4) Cenozoic-Quaternary sequence. The crystalline basement of the Molasse Basin formed during three major orogeneses: the Pan-African Cycles on Gondwana, the Caledonian orogeny in northwestern Europe and the Variscan orogeny in central Europe (Pfiffner, 2014; Ziegler et al., 2004). The Variscan orogeny ends with the Westphalian (Upper Carboniferous) (Ziegler et al., 2004). The following dextral translation of Gondwana and Laurussia and the reorganization of the asthenospheric flow patterns resulted in the collapse of the orogeny and thinning of the lithosphere (Von Raumer and Neubauer, 1993; Cortesogno et al., 1998; Von Raumer, 1998; Ziegler et al., 2004). The transtensional and transpressional tectonic regime and the strong regional thermal subsidence controlled the formation of a narrow and elongated array of pull-apart basins, mostly oriented WNW-SSE, which were rapidly filled by coarse siliciclastic deposits from the eroded orogen relief (Ziegler et al., 2004). In the transgressive phases, coal and carbonaceous shales were deposited in floodplain and swamp depositional environments (Capuzzo and Wetzol, 2004). An intensive intrusive and extrusive magmatic activity characterised this period (Schönlaub, 1997), which was followed by a long-term thermal subsidence up into the Triassic.

The Permo-Triassic thermal subsidence was overprinted by the Mesozoic rift events related to the opening of the Tethys Ocean between the Eurasian and African plates (Ziegler et al., 2004). The Triassic sediments record the transition from continental to shallow marine conditions. They consist of continental sandstone deposits (Buntsandstein facies), intertidal dolomites, limestones and evaporites (Muschelkalk facies) and marine and lagoonal sandstones, marls and shales (Keuper facies). Toward the central-western and north part of the NAFB, the Keuper is composed of dolomite, anhydrite and salt, making this unit a
decollement layer for the last Alpine thrust sheets. In the southeastern part, sevaporites are not found (e.g., Opfenbach and Sulzberg wells; Naef, 2012). The Jurassic succession is mostly composed of shallow water platform facies and is generally subdivided into the Lias, Dogger and Malm units. The Lias and Dogger deposits are marls, shales limestones and sandstones, whereas the Malm deposits are predominantly micritic limestone. The Lias is poorly represented in the eastern NAFB (Bachmann et al., 1987) and is entirely absent northward, in the Helvetic realm. The presence of a structural high, the Zurich High (Trümpy et al., 1980), could be the cause of this stratigraphic hiatus. The Cretaceous record is completely missing in the eastern sector of the NAFB, whereas in the western part it is limited to the Early Cretaceous (Lemcke, 1974; Schegg and Leu, 1998; Wildi et al., 1989).

During the Alpine orogeny, when the NAFB formed, the entire Paleozoic and Mesozoic sequence was tilted and covered by mostly siliciclastic deposits. In the internal part of the foreland, Paleocene-Eocene aged flysch sediments were deposited, followed by the Oligocene-Miocene marine to freshwater Molasse deposits (Bachmann et al., 1987; Pfiffner, 1986, 2014). The Molasse deposits are subdivided into four units representing two under-filling/over-filling megacycles, composed of two marine sequences each followed by sequences of mostly terrestrial deposits (Allen et al., 1986; Bachmann and Müller, 1992; Kuhlemann and Kempf, 2002; Lemcke, 1988; Schlunegger et al., 1997; Schlunegger and Willett, 1999). The age of these two mega-sequences has been defined as between 33−20 Ma and 19−12 Ma respectively (Kuhlemann and Kempf, 2002).

In the eastern sector of the NAFB, the entire Molasse sequence reaches a maximum thickness of 4000 m in the proximal position close to the Alpine border (Linden-1 well) whereas a minimum thickness of 1500 m is present in the northern distal margin (Herdern-1 well; Vollmayr, 1983). The Lower Marine Molasse (LMM, Rupelian), predominantly composed of marine shales, is poorly represented in the study area. The overlying unit of the Lower Freshwater Molasse (LFM, Chattian-Aquitanian) is a thick sequence formed by littoral and fluvial systems (Kuhlemann and Kempf, 2002). The LFM in the study area is represented by the LFM I unit, comprising the Untere Bunte Molasse and the Karbonatreiche Molasse units, and the LFM II unit, comprising the Granitische Molasse and the Oberaquitaine Mergelzone (Fig. 3). The back-thrust planes bounding the “triangle zone” separate the LFM I to the LFM II. Renewed subsidence deepened the basin with the deposition of the Upper Marine Molasse (UMM, Burdigalian), which in the study area includes the Luzern and the St. Gallen Formations comprising sandstones and conglomerates. In the subsequent overfill phase, the fluvial Upper Freshwater Molasse unit (UMF, Langhian-Serravalian)
was deposited; in the study area it is formed by the Obere Süßwasser Molasse, constituted by marls and sandstones (Fig. 3).

3. Data and methods

To evaluate the risk of hydrocarbons in the subsurface, an extensive understanding of the processes that permit the generation, expulsion and accumulation of oil and gas in a sedimentary basin must be investigated. This results in the definition of the elements and processes of the petroleum system. Thermal basin modelling is applied to reconstruct the timing of the hydrocarbon generation and expulsion, and the areas where migration and accumulations can most likely occur.

The thermal modelling workflow encompasses the construction of a geological model, definition of the boundary conditions that control the heat transfer in the basin and the assignment of the source rocks and their geochemical properties (Littke et al., 2008; Tissot et al., 1987; Tissot and Welte, 1984; Welte and Yukler, 1981; Welte et al., 1997). The PetroMod software (Version 2018, Schlumberger) was used to evaluate the thermal maturity of the hydrocarbon source rocks and to reconstruct possible hydrocarbon migration pathways and accumulation zones.

3.1. Conceptual geological model

The conceptual geological model provides the main input data. It defines the geometry of the main stratigraphic units, the ages, the lithologies and the eventual structural elements (e.g., faults, thrust planes). The model was derived from the interpretation of previous studies that analyse the three-dimensional seismic reflection dataset integrated with borehole logs from the St Gallen GT-1 well (Eruteya et al., 2019; Heuberger et al., 2016; Naef and Schlanke, 2014). The seismic dataset covers approximately 270 km² of the St. Gallen area (Fig. 1a). Key stratigraphic horizons were used to build the geological model, which results in the definition of ten units: Upper Freshwater Molasse (UFM), Upper Marine Molasse (UMM), Lower Freshwater Molasse 1 and 2 (LFM1 and LFM2), Triangle zone, Malm, Dogger-Lias-Keuper, Muschelkalk, Permo-Carboniferous and Basement (Fig. 3). Importantly, the fault planes forming the triangular zone and limiting the Permo-Carboniferous troughs were mapped, converted to depth, and introduced in the model (Eruteya et al., 2019).

A consecutive sequence of depositional, non-depositional and/or erosional events was defined in order to simulate the chronological basin history (Table 1). The depositional events were represented by physically existing sedimentary units, defined as layers in the model, which correspond to the units into which the stratigraphic record has been subdivided (Fig. 3). In respect to the GT-1 stratigraphic log, the Lower Marine Molasse (LMM) was not considered (Fig. 3), as its limits cannot be clearly identified in the seismic. For the same reason, a unique layer was considered for the combined Dogger, Lias and Keuper units and another one for the Muschelkalk and Buntsandstein units (Fig. 3). An additional layer was assigned to the triangle zone. To simulate the formation of the latter, a paleo-thickness of zero has been assigned to this layer, up to the time when the triangular zone starts to be formed. At that time, the paleothickness has been gradually increased, in order to achieve the present-day geometry.

The lithologies assigned to the defined layers were based on the description of well-cuttings recovered from the St. Gallen GT-1 borehole (Molasse to Dogger, Naef and Schlanke, 2014). We relied on literature to account for the lithologies of the lowermost units (Lias to Permo-Carboniferous; Diebold et al., 1991; Madritsch et al., 2018; Matter et al., 1987; Naef, 2012; Thury, 1989; Thury et al., 1994), since the borehole did not penetrate these intervals. The facies assigned to the model at each layer were expressed as the percentage of the different lithologies, as indicated in Table 2. The petrophysical properties of the mixed lithologies were proportionally calculated by the modelling software package (Hantschel and Kauerauf, 2009).

3.2. Boundary conditions

Thermal boundary conditions have to be defined to simulate the temperature attained over time in the basin infill. The upper boundary is the sediment-water interface temperature (SWIT). Paleo-temperature distribution maps are automatically calculated by PetroMod, which defines the evolution temperature at sea level considering variations of...
global mean surface temperature and latitudinal variation of the study area through time (Wygrala, 1988). The lower boundary condition is the heat flow at the bottom of the basin, which mostly comes from the asthenosphere. It is strictly related to the geodynamic setting where the basin forms and evolves, which controls, among other processes, the original lithosphere thickness, the stretching forces, the magmatic activity, and the circulation of deep fluids (Allen and Allen, 2017; Poelchau et al., 1997; Royden and Keen, 1980; Tissot et al., 1987).

To assess the variation of the heat flow over time the main geodynamic phases affecting the Swiss Foreland Basin, and its Mesozoic substratum were considered. Literature data were mostly used to constrain this data (Loup and Wildi, 1994; Marchant et al., 2005; Mazurek et al., 2006; Pfiffner, 2014; Schegg and Leu, 1998; Stampfl et al., 2002; Wildi et al., 1989; Ziegler, 1987; Ziegler et al., 2004). In order to evaluate the main lithosphere stretching and thermal relaxation phases (Allen and Allen, 2017; Royden, 1986; Royden and Keen, 1980; Sclater and Christie, 1980), the backstriped tectonic subsidence curves of the main representative wells of the NAFB stratigraphic sequence were used (Loup, 1992; Marchant et al., 2005; Stampfl et al., 2002; Ziegler et al., 2004). In the extensional regimes, the steeper indicators define subsidence acceleration pulses, interpreted as periods dominated by stretching and/or thinning of the crust. Gentler gradients represent subsidence deceleration, interpreted as periods dominated by lithosphere thermal relaxation (Allen and Allen, 2017; Royden, 1986; Royden and Keen, 1980; Sclater and Christie, 1980). A heat flow peak was considered for each subsidence acceleration phase, as it is assumed that they correspond to lithosphere thinning, and thus an uprising of the asthenosphere. The heat flow peak values were estimated by considering the thermal subsidence magnitude (Royden, 1986) and the range of values proposed in the literature for different geodynamic settings (Allen and Allen, 2017). In contrast, in the compressional regime, subsidence acceleration is the expression of thrust loading, which creates accommodation space in the forming foreland basin (Allen and Allen, 2017; Royden, 1986; Royden and Keen, 1980). During the orogeny formation, the lithosphere gets thicker and colder. Because of that, lower values of heat flow are assigned to this geodynamic phase.

The present-day heat flow (Q) was calculated as follow:

\[ Q = k \cdot \frac{dT}{dz} \]

where \( \frac{dT}{dz} \) is the geothermal gradient measured in the well and \( k \) the thermal conductivity of the rock. The geothermal gradient was

---

**Table 1**

D observational and erosional events defined in the conceptual model. A facies is assigned to each layer (see facies properties in Table 2). When a layer is represented by more than one facies, the single layer was split and the corresponding facies were assigned to the generated sub-layers. (*) indicates the uncertainty of the age of the top of the UFM and of the uplift and erosion of the basin. Different scenarios with the three ages indicated were simulated.

<table>
<thead>
<tr>
<th>Age at the top (Ma)</th>
<th>Event no.</th>
<th>Event type</th>
<th>Layer</th>
<th>Facies assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17</td>
<td>Deposition</td>
<td>Quaternary</td>
<td>Quaternary</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>Hiatus</td>
<td>Hiatus Pliocene-Pleistocene</td>
<td>–</td>
</tr>
<tr>
<td>10-8.5*</td>
<td>15</td>
<td>Erosion</td>
<td>Erosion Molasse</td>
<td>–</td>
</tr>
<tr>
<td>10-8.5*</td>
<td>14</td>
<td>Uplift</td>
<td>Triangle zone</td>
<td>–</td>
</tr>
<tr>
<td>10-8.5*</td>
<td>13</td>
<td>Deposition</td>
<td>UFM</td>
<td>UFM</td>
</tr>
<tr>
<td>15.97</td>
<td>12</td>
<td>Deposition</td>
<td>UMM</td>
<td>UMM</td>
</tr>
<tr>
<td>20.44</td>
<td>11</td>
<td>Deposition</td>
<td>LFM-1</td>
<td>LFM</td>
</tr>
<tr>
<td>23.03</td>
<td>10</td>
<td>Deposition</td>
<td>LFM-2</td>
<td>LFM</td>
</tr>
<tr>
<td>35.9</td>
<td>9</td>
<td>Erosion/Hiatus</td>
<td>Erosion/Hiatus Cretaceous-Eocene</td>
<td>–</td>
</tr>
<tr>
<td>113</td>
<td>8</td>
<td>Deposition</td>
<td>Lower Cretaceous</td>
<td>Lower Cretaceous</td>
</tr>
<tr>
<td>145</td>
<td>7</td>
<td>Deposition</td>
<td>Malm</td>
<td>Malm</td>
</tr>
<tr>
<td>163.5</td>
<td>6</td>
<td>Deposition</td>
<td>Dogger-Lias-Keeper</td>
<td>Dogger; Lias; Keuper</td>
</tr>
<tr>
<td>237.00</td>
<td>5</td>
<td>Deposition</td>
<td>Muschelkalk</td>
<td>Muschelkalk</td>
</tr>
<tr>
<td>253.00</td>
<td>4</td>
<td>Erosion/Hiatus</td>
<td>Erosion/Hiatus Permian-Triassic</td>
<td>–</td>
</tr>
<tr>
<td>272.3</td>
<td>3</td>
<td>Deposition</td>
<td>Permian</td>
<td>Permian source rock</td>
</tr>
<tr>
<td>298.9</td>
<td>2</td>
<td>Deposition</td>
<td>Carboniferous</td>
<td>Perm-Carboniferous Fine./Coarse; Carboniferous source rock</td>
</tr>
<tr>
<td>307</td>
<td>1</td>
<td>Deposition</td>
<td>Basement</td>
<td>Basement</td>
</tr>
</tbody>
</table>

---

**Table 2**

Petrophysical properties assigned to the facies defined in the model. (Cgl) is used for conglomerates, (Sdt) for sandstones and (Lmt) for limestones.

<table>
<thead>
<tr>
<th>Facies name</th>
<th>Lithology (%)</th>
<th>Initial Porosity (%)</th>
<th>Athy’s factor k (depth) (1/ km)</th>
<th>Permeability at porosity of (log mD)</th>
<th>Heat Capacity (Ical kg⁻¹ K⁻¹)</th>
<th>Thermal Conductivity (W m⁻¹ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cgl</td>
<td>Sdt</td>
<td>Others</td>
<td>Shales</td>
<td>Marls</td>
<td>Lmt</td>
</tr>
<tr>
<td>Quaternary</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UFM</td>
<td>10</td>
<td>90</td>
<td>49.12</td>
<td>0.48</td>
<td>–1.67</td>
<td>–0.16</td>
</tr>
<tr>
<td>UMM</td>
<td>10</td>
<td>30</td>
<td>53 (siltstone) 5 28</td>
<td>47.20</td>
<td>0.43</td>
<td>0.11</td>
</tr>
<tr>
<td>LFM</td>
<td>20</td>
<td>80</td>
<td>48.20</td>
<td>0.46</td>
<td>–1.20</td>
<td>0.24</td>
</tr>
<tr>
<td>Malm</td>
<td>10</td>
<td>100</td>
<td>51.00</td>
<td>0.52</td>
<td>1</td>
<td>1.52</td>
</tr>
<tr>
<td>Dogger</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>57.60</td>
<td>0.63</td>
<td>–0.68</td>
</tr>
<tr>
<td>Liaa</td>
<td>10</td>
<td>90</td>
<td>67.10</td>
<td>0.78</td>
<td>–2.4</td>
<td>–0.7</td>
</tr>
<tr>
<td>Keuper</td>
<td>20</td>
<td>50</td>
<td>48.50</td>
<td>0.47</td>
<td>–0.22</td>
<td>0.93</td>
</tr>
<tr>
<td>Muschelkalk</td>
<td>30</td>
<td>40</td>
<td>52.50</td>
<td>0.54</td>
<td>0.29</td>
<td>1.51</td>
</tr>
<tr>
<td>Perm-Carbon</td>
<td>10</td>
<td>70</td>
<td>45.70</td>
<td>0.41</td>
<td>1.70</td>
<td>3.17</td>
</tr>
<tr>
<td>coarse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perm-Carbon</td>
<td>20</td>
<td>80</td>
<td>64.20</td>
<td>0.73</td>
<td>–1.80</td>
<td>–0.29</td>
</tr>
<tr>
<td>fine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permian</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>source rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carboniferous</td>
<td>40 (coal)</td>
<td>60</td>
<td>71.60</td>
<td>0.67</td>
<td>–2.79</td>
<td>–1.01</td>
</tr>
<tr>
<td>source rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement</td>
<td>Gneiss</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.19</td>
<td>0.22</td>
</tr>
</tbody>
</table>
calculated from borehole temperature data (Naef and Schlanke, 2014). For k, an average value of 2.5–2.7 W/m/k was used for the entire stratigraphic section.

### 3.3. Erosion

In the NAFB, three erosional unconformities have been identified (Schegg and Leu, 1998): (i) the Early Permian-Early Triassic unconformity related to a phase of uplift and peneplanation of the Variscan relief, (ii) the Jurassic-Cenozoic unconformity, related to the non-deposition or erosion of the Cretaceous record, and (iii) the Miocene-Quaternary unconformity related to the uplift and erosion of the NAFF at the end of the Alpine collision. In this work, the Permian-Triassic erosional event could not be calibrated because of the lack of paleothermal data for these deep deposits. For the two remnant unconformities, different thicknesses and timing of the erosion were tested.

The magnitude of the erosion has an influence on the thermal conditions attained in the basin, as it controls the maximum burial depth attained by the sedimentary record and thus the maximum temperature. On the other hand, the timing of the end of the deposition of the youngest unit and of the onset of the erosion defines the interval of time during which the basin infill remains buried at maximum depth. The erosion magnitude and timing have an influence on the thermal maturation of the organic matter, as the latter is a function of both temperature and time (Barker, 1989; Lopatin, 1971; Sweeney and Burnham, 1990; Tissot and Welte, 1984). Therefore, evaluation of both is necessary to properly calibrate the modelling results. Several scenarios were proposed and evaluated by the modelling calibration in an iterative approach (see Section 3.4).

### 3.4. Model calibration

In order to validate the thermal conditions simulated by thermal modelling, the model results have to be calibrated with paleo-thermal data, which indicate the maximum thermal conditions attained by the rocks (Welte and Yalcin, 1988; Welte et al., 1997). The latter was estimated by considering the degree of organic matter maturity, firstly by means of vitrinite reflectance data and secondly by the molecular study of the aromatic fraction. Analyses were performed on the St. Gallen GT-1 well cutting samples richest in organic matter.

Vitrinite reflectance (%Ro) was measured in ten samples, representing the entire drilled stratigraphic record, from the Molasse to the Dogger unit. Analyses were performed at the LEK laboratory at the Aachen University (Germany), using an optical microscope in incident white light, following the ASTM-D7708-11 (2011) and the ISO-7404-7405 (2009) norms. A mean vitrinite reflectance value was obtained from random measurements. In order to estimate the correct representative value for each sample, the standard deviation and the frequency distribution of the measurements were considered.

The molecular study of the aromatic fraction was performed on three Dogger samples, located from 4422 to 4445 m, (values of measured depth MD; true vertical depth TVD below ground level was from 3656 to 3667 m), at the LEK laboratory RWTH Aachen University (Germany). Extraction of organic matter was performed on around 5 g of pulverized rocks by Accelerated Solvent Extraction (ASE) using the DIONEX ASE 150 device. Extracted materials were then separated into aliphatic, aromatic and polar compounds using liquid chromatography by a micro column filled with 2 g of silica gel 40 μm. The column was activated in the oven at 200 °C overnight prior to fractionation. The fractions were eluted with an n-pentane, n-pentane/dichloromethane mixture (40/60 v/v) and methanol. A detailed molecular study was performed on the aromatic fraction using a quadrupole mass spectrometer Trace MS linked to a Mega Series HRGC S160 gas chromatograph equipped with a 30 m × 0.25 mm i.d. × 0.25 μm film Zebron ZB-S fused silica capillary column. The chromatographic condition was set to a 270 °C injector temperature, 1 µL split/splitless injection at 80 °C, 3 min isothermal hold, and then programmed at 3 °C/min to 230 °C, 20 min isothermal hold. Helium was used as the carrier gas at a velocity of 30 cm/s. The mass spectrometer was operated in single ion mode. Identification of compounds was based on reference materials and published gas chromatographic elution orders. Calculation of different ratios is based on the integration of peak areas from the specific ion chromatograms.

To calibrate the model, the measured and estimated vitrinite reflectance data were compared to the theoretical curve calculated by the software. The latter considers the maturation trend as the result of temperature and time, which is related to the thermal and burial history of the basin. Different kinetics were tested: Easy%Ro (Sweeney and Burnham, 1990); Easy%RoDl (Burnham (2016); and Basin%Ro (Nielsen et al., 2017). To calibrate the model, an iterative approach is applied, consisting of fitting the theoretical results to the paleothermal data measured. The variables mostly influencing the temperature in the basin, the basal heat flow and the erosion magnitude and timing are gradually changed up to obtain a satisfactory result. In order to test these values, more than 50 models were simulated. In this work, only the results of the most significant scenarios are presented (see Section 4).

### 3.5. Source rocks

In the Swiss Plateau three main source rocks have been identified (Leu and Gautschi, 2014; Misch et al., 2017; Schegg and Leu, 1998): (1) the Posidonia black-shale deposits (forming part of the Lias unit, Toarcian in age); (2) the Permian shale deposits and (3) coals and carbonaceous shales of the Carboniferous. None of these units was penetrated by the GT-1 well; thus there is a poor knowledge of the presence and properties of these source rocks in the St. Gallen area.

The Lias unit is poorly represented in the eastern sector of the NAFB (Bachmann et al., 1987; Moscariello et al., 2020b). In the 3D St. Gallen seismic, the Lias is not distinguishable, which is why it is grouped with the Dogger and Keuper units with a total thickness of less than 100 m (Fig. 3). Furthermore, there are not evidences that the Lias deposits contain high amount of organic matter. Therefore, the Posidonia shales are not considered as a potential source rock of the St. Gallen petroleum system.

In the Permo-Carboniferous grabens high impedance seismic facies are recognized, which can be interpreted as coal layers (Madritzich et al., 2018; Marchant et al., 2005). However, it is difficult to constrain their extension and thickness (Eruteya et al., 2019). Even more challenging is recognizing in seismic the potential Permian shale source rock units. Therefore, in order to assign properties for these potential source rocks in the model, their thickness and geochemical data were extrapolated from the only well that penetrated these units, located in the north-eastern sector of the NAFB (Weiach-1 well, northern Switzerland; Table 3). A mixed Type III and Type II kerogen was assigned to the Permian unit and a Type III kerogen was assigned to the Carboniferous coal unit (Table 3).

The geochemical parameters necessary to characterize the hydrocarbon potential of the source rocks (Espitalié and Bordenave, 1993) were provided by Rock-Eval 6 analysis (Espitalié et al., 1985a, 1985b; Espitalié et al., 1986; Lafargue et al., 1998), performed at the Institute of Earth Science, University of Lausanne (Switzerland). Ten samples were analysed, representative of the Lias, Permian and Carboniferous units. The average TOC (%) and HI (mgHC/gTOC) indices measured are shown in Table 3 (present-day TOC and HI indices). The original amount of organic matter contained in the source rocks before maturation, was estimated by the GeoChem module of the PetroMod suite, where the Peters’ method is applied (Peters et al., 2005). The results are shown in Table 3 (initial TOC and HI indices). Kinetic parameters were chosen considering the depositional environments where these deposits formed (Behar et al., 1997; Pepper and Corvi, 1995; Table 3).
S. Omodeo-Salé, et al.

The original geochemical properties used as input data are estimated by means of the Geochem module of Petrmod, applying the Peters (1993) method. In the maximum thickness column, (*) indicates the thickness assigned to the source rock in the scenario testing the effect of a greater source rock volume on the volume of hydrocarbons generated and accumulated.

Table 3

Properties of the source rocks identified in the analogue Weiach-1 well (measured Rock-Eval data in appendix A). The original geochemical properties used as input data are estimated by means of the Geochem module of Petrmod, applying the Peters (1993) method. In the maximum thickness column, (*) indicates the thickness assigned to the source rock in the scenario testing the effect of a greater source rock volume on the volume of hydrocarbons generated and accumulated.

<table>
<thead>
<tr>
<th>Source Rock</th>
<th>Maximum thickness (m)</th>
<th>Lithology and depositional environment</th>
<th>TOC (%) present day</th>
<th>HI (mgHC/gTOC) present-day</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>Initial TOC (%)</th>
<th>Initial HI (mgHC/gTOC)</th>
<th>Kinetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permian 1</td>
<td>75</td>
<td>Shales; Paralic, tidal delta, coastal wetland</td>
<td>2–3</td>
<td>124</td>
<td>430</td>
<td>3</td>
<td>150</td>
<td>Pepper and Corvi (1995) Type III (DE)</td>
</tr>
<tr>
<td></td>
<td>190*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permian 2</td>
<td>75</td>
<td>Shales; Coastal to shallow marine setting</td>
<td>3–6</td>
<td>330–350</td>
<td>440</td>
<td>7</td>
<td>500</td>
<td>Pepper and Corvi (1995) Type II (B)</td>
</tr>
<tr>
<td></td>
<td>190*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carboniferous</td>
<td>250</td>
<td>Coal and shales; Terrestrial setting</td>
<td>4–7</td>
<td>95–137</td>
<td>460</td>
<td>10</td>
<td>180</td>
<td>Behar et al. (1997) Type III coal</td>
</tr>
<tr>
<td></td>
<td>600*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Results

4.1. Geological modelling

The depth maps, obtained by seismic interpretation, were used to reconstruct the 3D geological model of the area. A depositional layer was generated for each stratigraphic unit, defining the related thickness and geometry. Erosion maps were added, in order to reconstruct the entire burial history. In order to simulate the infill evolution over time, ages were assigned to the depositional and erosion events (Table 1). Finally, lithologies were assigned to each layer. Thus, a consistent framework of the geological evolution of the area was provided (Fig. 4).

In the late Carboniferous the Variscan basement was structured in narrow and deep grabens, elongated in a SW-NE direction (2000–4000 m deep). These grabens were filled until the Early Permian by conglomerate and sandstone deposits interlayered with coal and organic matter-rich shales. These grabens are topped by the Mesozoic sequence composed of flat superimposed layers of nearly uniform thickness throughout the entire study area. The Triassic succession (100–200 m thick) is split into the Muschelkalk and Keuper units. The Jurassic succession (400–500 m thick) is split into the Lias, Dogger and Malm units. An unconformity, leaving no record until Oligocene time, tops the Jurassic sequence. For this time interval, two scenarios are simulated as discussed below: the first considers a depositional hiatus up to the Oligocene and the second the deposition of a Lower Cretaceous unit (up to 1000 m), composed of siliciclastic and marlstone deposits, which were subsequently eroded in the Late Cretaceous–Eocene interval.

In Oligocene to Miocene time, the thick Molasse siliciclastic succession was unconformably deposited on top of the Jurassic unit in the entire area. The Molasse succession is split into the following units: the Lower Freshwater Molasse (LFM), subdivided into a lower (ILFM, 1150 m thick) and an upper (uLFM, 1900 m thick) unit; the Upper Marine Molasse unit (UMM, 450 m thick) and the Upper Freshwater Molasse (UFM, thickness variable from 1000 m in the north of the study area to 2500 m in the south). In the Late Miocene to Pliocene (8–5 Ma) the triangle zone started to form and the southern border of the study area was gradually tilted and eroded. The entire NAFB was uplifted and eroded to create the present-day geometry.

4.2. Paleo-heat flow

The paleo-heat flow over time was estimated by the analysis of subsidence curves, which highlight the main tectonic events in the NAFB. The Weiach-1 well subsidence curve is reported here as an illustrative example (Marchant et al., 2005; Fig. 5), as it is one of the few wells crossing the entire stratigraphic sequence of the eastern sector of the NAFB, from the Molasse to the basement.

In the Swiss Foreland Basin, a first important subsidence acceleration is recorded in the Late Carboniferous-Early Permian time, followed by a slow decreasing subsidence trend from the Early Permian up to the Triassic (Fig. 5a). Important thermal anomalies, as a consequence of magmatic activity and thinning and delamination of the lithosphere, characterize the Stephanian-Early Permian period (Ziegler et al., 2004). Thus, an important thermal surge, up to 100–120 mW/m² is estimated in the Early Permian, coherently with what is estimated for a strike-slip geodynamic setting with deep lithospheric involvement (Allen and Allen, 2017).

Since the Triassic to the Late Jurassic - Early Cretaceous time, the Permian thermal subsidence was interrupted and partially overprinted by new subsidence acceleration phases, related to the rifting cycles associated to the opening of the Tethys Ocean and preceding the opening of the North Atlantic, Bay of Biscay and the Valais Through (Handy et al., 2010; Philippe et al., 1998; Stampfl, 1993; Pfiffner, 2014; Stampfl et al., 2002; Ziegler et al., 2002, 2004). Heat flow values of 70 mW/m² are assigned to these extensional pulses, in accordance with what is proposed in the literature for a rift to passive margin settings (Allen and Allen, 2017).

The lack of Cretaceous record in the eastern sector of the NAFB makes the interpretation of the subsidence trend at that time uncertain. Two end-member scenarios were considered: (Scenario 1) a continuous deceleration of the subsidence rate up to the Cenozoic, with a gradual heat flow decrease from the Jurassic peak to a constant value of 60 mW/m²; and (Scenario 1a) an acceleration of the subsidence rate in the Early Cretaceous associated with another extensional phase of the lithosphere and then to a new heat flow peak of 75 mW/m² in the Early Cretaceous (Fig. 5). The first case implies a depositional hiatus whereas the second case implies the deposition of Lower Cretaceous deposits, which were then uplifted and completely eroded between Late Cretaceous to Eocene time.

A last relevant subsidence acceleration is recorded in the Cenozoic when the Alpine foreland formed, as a consequence of the forming Alpine chain loading on the European plate (Allen et al., 1986). In the Weiach-1 well subsidence curve (Fig. 5a), this event is recorded by a low acceleration phase, due to the thin Molasse section preserved in the northern sector of the NAFB. However, greater thickness were deposited southward, toward the Alpine Chain, where the study area is located. A heat flow of 50–55 mW/m² is assigned to this period up to the Pliocene, as is generally proposed in the literature for a foreland basin (Allen and Allen, 2017). The present-day the heat flow (Q) was calculated applying the Eq. (1). A geothermal gradient of 29 °C/km, measured in in the St. Gallen GT-1 well (Naef and Schlanke, 2014) and an average thermal conductivity for the entire stratigraphic series of 2.5–2.7 W/m·k; a heat flow value of 72–78 mW/m² was calculated, which is in agreement with what was measured in most of the NAFB (Chelle-Michou et al., 2017; Rybach, 1992; Schegg, 1992; Vollmayr, 1983).

Taking into account the uncertainties of the paleo-heat flow trend reconstructed above, a second colder scenario (Scenario 2) was also tested, by uniformly shifting down the calculated heat flow trend to 20 mW/m² (Fig. 5).
Fig. 4. 3D geological evolution of the study area from the present-day to the infill of the Permo-Carboniferous grabens.
4.3. Paleothermal data

The thermal conditions of the stratigraphic series were mostly assessed by vitrinite reflectance data (Table 4). The samples contain few vitrinite particles of a small size. Therefore, to properly interpret the measured data frequency distribution analysis and petrographic observations were integrated. In the frequency distribution graphs re-sedimented and/or caved vitrinite populations were distinguished. In Fig. 6 the reflectance values of well-recognizable vitrinite particles are marked. By integrating these data, reliable mean, minimum and maximum values were assigned for each sample (Fig. 6 and Table 4). The mean vitrinite reflectance values gradually increase with depth, from 0.5%Ro at 140 m to 2.6%Ro at 4445 m, indicating an increasing temperature-versus-depth gradient with an error bar of 0.5/0.75%Ro (see the minimum and maximum values proposed).

Aromatic maturity parameters were used to assess/validate the

![Fig. 5](image)

**Fig. 5.** (a) Subsidence curve of the Weiach-1 well; (b) heat flow trends over the time used as boundary conditions for the thermal model.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Unit</th>
<th>Depth (m)</th>
<th>No. of %Ro measurements</th>
<th>%Ro min</th>
<th>%Ro max</th>
<th>Deviation standard</th>
<th>Estimated mean %Ro</th>
<th>%Ro equivalent from MPI-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG-140</td>
<td>UFM</td>
<td>140</td>
<td>24</td>
<td>0.45</td>
<td>1.35</td>
<td>0.30</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>SG-320</td>
<td>UMM</td>
<td>320</td>
<td>13</td>
<td>0.45</td>
<td>0.72</td>
<td>0.08</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>SG-470</td>
<td>UMM</td>
<td>470</td>
<td>104</td>
<td>0.40</td>
<td>0.65</td>
<td>0.08</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>SG-635</td>
<td>UMM</td>
<td>635</td>
<td>10</td>
<td>1.35</td>
<td>3.20</td>
<td>0.57</td>
<td>1.70</td>
<td></td>
</tr>
<tr>
<td>SG-2480</td>
<td>LFM</td>
<td>2480</td>
<td>5</td>
<td>1.60</td>
<td>1.75</td>
<td>0.07</td>
<td>1.67</td>
<td></td>
</tr>
<tr>
<td>SG-2530</td>
<td>Triangle Zone</td>
<td>2530</td>
<td>15</td>
<td>1.30</td>
<td>1.85</td>
<td>0.12</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>SG-3985</td>
<td>LMM</td>
<td>3985</td>
<td>19</td>
<td>1.80</td>
<td>2.70</td>
<td>0.33</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>SG-4422</td>
<td>Dogger</td>
<td>4422</td>
<td>35</td>
<td>1.70</td>
<td>2.70</td>
<td>0.21</td>
<td>2.15</td>
<td>2.36</td>
</tr>
<tr>
<td>SG-4430</td>
<td>Dogger</td>
<td>4430</td>
<td>27</td>
<td>2.10</td>
<td>2.75</td>
<td>0.18</td>
<td>2.30</td>
<td>2.40</td>
</tr>
<tr>
<td>SG-4445</td>
<td>Dogger</td>
<td>4445</td>
<td>15</td>
<td>1.80</td>
<td>3.70</td>
<td>0.51</td>
<td>2.60</td>
<td>2.44</td>
</tr>
</tbody>
</table>
Fig. 6. Statistical distribution and interpretation of the vitrinite reflectance measured data.
maturity of the three deepest samples. The aromatic parameters are based on the degree of alkylation of a given parent compound or shift in the isomer distribution towards thermally more stable isomers and can be applied to evaluate the reflectance values in the high maturity range (Radke, 1983, 1988; Radke et al., 1982). The studied samples are characterized by methylphenanthrene ratios (MPR) ranging from 4.06 to 4.49 and low values of 1-methylphenanthrene to phenanthrene ratios indicating high maturity levels of more than 2%Ro (Radke, 1988; Table 5). The calculated vitrinite reflectance (Rc) based on methylphenanthrene index (MPI-1) also indicates high maturity levels of 2.36–2.44%Ro for the samples (Table 4), in good agreement with the vitrinite reflectance data.

4.4. Thermal model calibration

Different vitrinite reflectance kinetics were tested (Fig. 7a). The Sweeney and Burnham (1990) kinetic leads to the best calibration results. The Burnham (2016) kinetic calculates too low a value in the middle of the stratigraphic section and slightly too high %Ro values in the deeper layers. The Nielsen et al. (2017) kinetic simulates too low value in the shallower layers.

Different heat flow and erosion scenarios were investigated by the construction of a series of thermal models where variables are tuned to fit the paleothermal data (Table 6). For the Pliocene-Quaternary erosional unconformity, a Molasse erosion of 1700, 2000 and 2500 m was tested for the heat flow scenarios 1 and 2. A further model was generated for the heat flow scenario 1a, which considers an additional heat flow peak in the Early Cretaceous and the deposition and the erosion of Lower Cretaceous deposits of between 500 and 1000 m. Based on the heat flow scenario 1a, additional models were constructed, where the onset of the Pliocene-Quaternary erosion was varied, at 10, 8 and 5 Ma (Scenarios 1a, 1b and 1c respectively; Table 6).

The heat flow scenario 1 leads to the best fit with the measured %Ro data (Fig. 7b). Indeed, in scenario 2, the thermal conditions calculated are too cold to validate the %Ro data (Fig. 7c). Also with a Molasse erosion of greater than 2500 m the geometry of the calibration curve would not fit the data. On the other hand, there are no relevant differences in the thermal conditions calculated by the scenarios 1 and 1a, aside from the Cretaceous erosion magnitude (Fig. 7b). This is because organic matter only registers the maximum thermal conditions attained by the rock, which in the St. Gallen area is reached with the deposition of the thick Molasse units in Oligo-Miocene time when the stratigraphic series reached the maximum burial depth (Fig. 8). Therefore, older and weaker thermal events are not detectable anymore from organic matter data which register the maximum temperature attained. Therefore, other geothermometers, able to register different thermal events such as low-temperature thermochronology, were implemented.

Apatite fission-track data reveal a high geothermal gradient in the Cretaceous in the north-eastern sector of the Swiss Plateau, which led to attaining at that time a temperature of 95–100 °C at the base of the Mesozoic (Mazurek et al., 2006). Our thermal model indicates that this temperature can be attained at this depth and at this time only by assuming a heat flow peak of 75 mW/m² in the Early Cretaceous (Fig. 5) and the deposition of 700 m of Lower Cretaceous deposits (Fig. 8 and Table 6). Supposing the temperature estimated in the northern Swiss Plateau border by apatite fission tracks can be extrapolated to the St. Gallen area, the scenario considering a heat flow peak in the Early Cretaceous with deposition and erosion of Lower Cretaceous deposits (scenario 1a) is most likely. However, to confirm this interpretation further low-temperature thermochronological studies will be necessary in this sector of the study area.

On the most likely heat flow scenario 1a, the effect of the timing of the uplift and erosion on the calibration results was also tested (Table 6). The thickness of the Molasse erosion changes as a function of the age assigned to the onset of the basin erosion, as the latter controls the interval of time during which the stratigraphic sequence is buried at the maximum depth. An erosion of 2000 m is estimated for the onset of the erosion at 10 Ma (scenario 1a, Fig. 7b) and 1800 m if the onset of the erosion is at either 8 and 5 Ma (scenario 1b and 1c respectively; Fig. 7d and e).

4.5. Petroleum system evolution

The most-likely calibrated model (scenario 1a) was used to simulate the hydrocarbon generation, migration and accumulation processes. The scenarios considering different ages of uplift and erosion of the basin (scenarios 1a, 1b and 1c) provide very similar results in terms of petroleum system evolution. Therefore, only the result of the scenario 1a is discussed in this chapter.

In order to analyse the hydrocarbon generation potential in the area, the thermal conditions attained by the entire stratigraphic record were first calculated (Fig. 9). Today the uppermost Molasse unit (UFM) is in the immature state, the UMM and LFM-2 are in the oil-window, and the LFM-1, the entire Mesozoic sequence and the Permo-Carboniferous grabens, where the hydrocarbon source rocks can be located, are in the gas-window. To visualize the maturation history of the source rocks, a burial versus time plot was extracted for the point where the Permain and Carboniferous deposits attain the maximum thickness (Fig. 10, see Fig. 9 for location of the virtual well V-1). The Carboniferous source rock entered the gas-window thermal conditions and the Permain source rock entered the oil-window in Cretaceous time (Fig. 10). Therefore, hydrocarbons started to be generated in the Early Cretaceous (Fig. 11a) and, in the Late Cretaceous, the kerogen of both source rocks was already 70% transformed (Fig. 10). Between 14 and 8 Ma the kerogen reached the maximum transformation rate (TR of 80–90%; Fig. 10). The hydrocarbons expelled by the source rocks migrated to the potential reservoirs, following the most permeable conduits formed by faults and permeable rocks. The major migration pathways simulated by the model are shown in a sequence of maps, representing the top of the most relevant stratigraphic units (Fig. 12).

Based on the slightly southward dipping of the foreland, most of the expelled hydrocarbons migrated N-NE, mainly throughout the Mesozoic units. In the Keuper unit a petroleum saturation over 20% is reached (Fig. 12). Few hydrocarbons migrated through the more impermeable micritic limestone Malm unit. Thus migration is considerably reduced in the uppermost Molasse units.

Hydrocarbons accumulated mostly from the Late Cretaceous to Oligocene times (Fig. 11a). Accumulations mostly formed along the graben borders in the Permo-Carboniferous coarse-grained sandstone intervals, just underneath the Mesozoic succession which behaves as a seal (Fig. 13). Migration occurred mostly along the faults bounding the graben. The maximum accumulation peak was reached in the Cretaceous (Fig. 11a). Most of the hydrocarbons were lost when the foreland basin started to be formed (Oligocene-Miocene time, Fig. 11a), most likely because of the bending of the plate southward, with a consequent northward migration of the hydrocarbons previously accumulated in the Mesozoic layers. The accumulated hydrocarbons are mostly the gas fractions due to the high temperature reached. Furthermore, the source rocks primarily consist of Type III kerogen, which is mostly gas-prone (Taylor et al., 1998; Tissot and Welte, 1984). The model simulates the formation of a gas accumulation just below the position of the St. Gallen

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>MPR</th>
<th>MPI-1</th>
<th>Rc, 1988</th>
<th>1MP/P</th>
<th>Measured Ro</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG-4422.5</td>
<td>4.43</td>
<td>0.39</td>
<td>2.36</td>
<td>0.03</td>
<td>2.15</td>
</tr>
<tr>
<td>SG-4430</td>
<td>4.49</td>
<td>0.33</td>
<td>2.40</td>
<td>0.02</td>
<td>2.30</td>
</tr>
<tr>
<td>SG-4445</td>
<td>4.06</td>
<td>0.26</td>
<td>2.44</td>
<td>0.02</td>
<td>2.60</td>
</tr>
</tbody>
</table>
GT-1 well (Fig. 13), with gas entering the well between 3990 and 4450 m.

4.6. Hydrocarbon volume estimates

An estimate of the volume of gas generated in the entire area is calculated by the software based on the total volume of the source rocks, their hydrocarbon potential, and their kinetic parameters (Peter’s equation, Peters et al., 2005). For the St. Gallen area, source rocks properties were mostly extrapolated from the Weiach-1 well (northern Switzerland) (Table 3), as there are not data available on the source rocks located in the Permo-Carboniferous graben. Therefore, these

Table 6

Scenarios tested in the thermal model to calibrate the %Ro data, where different heat flows, uplift ages and erosion magnitudes are proposed.

<table>
<thead>
<tr>
<th>Modelling Scenario</th>
<th>Heat Flow scenario</th>
<th>Uplift age (Ma)</th>
<th>Cretaceous erosion (m)</th>
<th>Molasse erosion (m)</th>
<th>Calibration results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>10</td>
<td>0</td>
<td>1700</td>
<td>Not calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2500</td>
<td>Not calibrated</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>1700</td>
<td>Not calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000</td>
<td>Not calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2500</td>
<td>Not calibrated</td>
</tr>
<tr>
<td>1a</td>
<td>1a</td>
<td>10</td>
<td>500</td>
<td>1700</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>700</td>
<td>2000</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>900</td>
<td>2500</td>
<td>Calibrated</td>
</tr>
<tr>
<td>1b</td>
<td>1a</td>
<td>8</td>
<td>700</td>
<td>1800</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000</td>
<td>Not calibrated</td>
</tr>
<tr>
<td>1c</td>
<td>1a</td>
<td>5</td>
<td>700</td>
<td>1800</td>
<td>Calibrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000</td>
<td>Not calibrated</td>
</tr>
</tbody>
</table>

Fig. 7. Calibration of thermal modelling for the St. Gallen GT-1 well considering different kinetic, heat flow, and erosion and uplift age scenarios (see Table 6 for the scenarios parameters).
Fig. 8. Burial-vs-time plot extracted from the St. Gallen GT-1 well showing the temperature variation over time in two scenarios: (a) scenario 1, which does not consider a heat flow peak and depositional event in the Cretaceous and (b) scenario 1a, which does consider a heat flow peak and depositional event in the Cretaceous. The latter validates the temperature reconstructed by apatite fission tracks data in the northern sector of the NAFB (Mazurek et al., 2006).

Fig. 9. Thermal conditions at the present day in the St. Gallen area. The location of the St. Gallen GT-1 well and of the virtual V-1 well (extraction in Fig. 10) is shown.
volume estimates have to be handled with care. Using these data the total volume of hydrocarbons generated is \( \sim 143 \text{ Bcm} \) (143,000 million cubic metres = 143 billion cubic metres). Based on the permeability of the stratigraphic units, their geometry, and the fault network the model calculates also the amount of hydrocarbon stored in potential traps and the volume lost by migration to the top surface or laterally from the model sides. These calculations indicate that nearly 80% of the hydrocarbons generated were lost, 20% are still trapped in the source rock, whereas only a very small proportion was accumulated in the reservoir (\( \sim 0.23\% \), 0.32 Bcm; Fig. 11a). This 0.32 Bcm estimate represents the volume of hydrocarbons accumulated in highly permeable units, i.e., proper reservoirs, simulated by the invasion-percolation migration method (see PetroMod simulation methods). Differently, the hydrocarbons stored in low permeable units is simulated by the Darcy Flow migration method, and results in a total of 15 Bcm of gas, mainly located in the fine-grained facies of the Permo-Carboniferous unit (13 Bcm) and secondarily in the marly Keuper unit (1.7 Bcm). Lower volumes (\( \sim 0.1 \text{ Bcm} \)) are accumulated in the Lias, Dogger and Malm units respectively. In the model output, low-permeable accumulations are shown by the petroleum saturation index (Figs. 12 and 13).

In the more detailed target area of the St. Gallen GT-1 well, several small gas accumulations are shown in the simulation (Fig. 13). The closest accumulation is located just below the lowest point of the St. Gallen GT-1 well, in the uppermost coarse-grained Permo-Carboniferous unit (Fig. 13). This accumulation, formed in a permeable unit, has a volume of 0.0024 Bcm, simulated by the invasion-percolation migration method. Very close to this point, in a gently folded structure, a larger volume of hydrocarbons is stored in the uppermost Keuper unit, with a volume of 0.094 Bcm of gas (Fig. 13). Because the Keuper unit has a lower permeability than the Permo-Carboniferous sandstone, the model simulates this volume by the Darcy Flow migration method. The model calculates a temperature of 175 °C and a pressure of 40.67 MPa for this gas accumulation. The volumes calculated herein can present large error bars, as the definition of the factors controlling the amount of hydrocarbon generated and accumulated is based on several assumptions (e.g., source rock thickness, amount of organic matter, stratigraphic geometry, faults, etc.). See details in the discussion section.

5. Discussion

5.1. Thermal and burial history

The results of the magnitude and timing of the relevant erosion processes can improve the understanding of the tectono-stratigraphic evolution of the eastern sector of the NAFB. The Miocene-Quaternary unconformity reflects a phase of uplift of the NAFB and of the related erosion of the uppermost foreland infill (Molasse deposits; Beck et al., 1998; Philippe et al., 1998; Schegg and Leu, 1998). The unconformity is diachronous throughout the basin, as the uppermost glacial Quaternary sediments lie unconformably on Molasse deposits, becoming older westward (Kuhlemann and Kempf, 2002). Significant erosion thickness variation has been estimated, from an average of 2250 m in the southwestern NAFB sector to 350 m in the eastern sector (Lemcke, 1974; Monnier, 1982; Schegg and Leu, 1998). In the north-eastern NAFB sector, Mazurek et al. (2006) estimated a pre-Quaternary erosion of nearly 1000 m (Herdern-1 Weiach-1 wells area). More recently, a similar eroded thickness of between 1 and 2 km and a simultaneous uplift age at 5 Ma has been estimated across the entire NAFB (Cederbom et al., 2004, 2011). This point to little spatial variation in magnitude of the uplift and erosion processes (Cederbom et al., 2011; Schlunegger and Mosar, 2011; Willett and Schlunegger, 2010). In the
St. Gallen area, our 3D thermal modelling results indicate a Molasse erosion thickness of between 1800 and 2000 m. These values are in good agreement with the erosion estimated in Cederbom et al. (2011) in the most equivalent tectonic position inside the NAFB, that is in front of the triangle zone back-thrust delimiting the Subalpine Molasse (Hünenberg-1 well). In this area apatite fission tracks data indicate an erosion of 1.4–2.1 km section.

The results provided by this work demonstrate that the magnitude of the erosion calculated by thermal modelling is also controlled by the period of time that the entire sedimentary pile remains buried at the maximum depth. This is determined by the age assigned to the end of the deposition of the youngest Molasse unit and to the onset of the erosion (Fig. 7d and e). Thus, these data might be considered when erosion values are interpreted by thermal modelling.

In the St. Gallen area, the age of the end of the Molasse deposition is hardly constrainable, as the top of the uppermost Molasse unit (UFM) has been eroded in most of the NAFB. In the western sector of the Swiss NAFB, the youngest age assigned to the Molasse deposits is late Serravalian (Burkhard and Sommaruga, 1998), whereas in the eastern sector is early Tortonian (Rahn and Selbekk, 2007). In the German and Austrian foreland basin, the termination of the deposition of the Molasse is dated at 5–6 Ma (Kuhlemann and Kempf, 2002). Different ages have been proposed for the uplift and erosion of the NAFB. In the western part, the uplift age has been estimated at 11–10 Ma, mostly related to the Jura mountain thrusting (Kuhlemann and Kempf, 2002; Ziegler and Fraefel, 2009). A similar age has been obtained by apatite fission tracks at the northeastern border of the NAFB where the uplift has been dated at 10 Ma (Mazurek et al., 2006). Considering 10 Ma as the age for the onset of the erosion, 2000 m of Molasse are necessary to calibrate our thermal modelling (Fig. 7b). If instead the end of

![Fig. 11. Balance of the hydrocarbons (HC) generated, accumulated and losses calculated for the entire 3D thermal model. In (a) the thickness of the source rocks is in the same order as what was measured in the Weiach-1 well. In (b) the thickness of the source rocks is 2.5 times greater. Volume indicated in the ordinate is expressed as indicated by the software, Mm$^3$ – millions of m$^3$.](image-url)
Fig. 12. Maps of the top of the main geological units showing the hydrocarbon migration paths. The petroleum saturation ratio calculated for each unit is also shown.
deposition is at 12–11 Ma (Serravalian-Tortonian) this scenario would require a very high sedimentation rate as it must accommodate 1–2 km of deposits in only 1–2 My before the basin was uplifted. By means of apatite fission track data, an exhumation age of 5 Ma, is uniformly found along the entire NAFB, occurring in a very short time-span (c. 2My) (Cederbom et al., 2004, 2011). This uniform uplift and erosion event has been related to the interplay among climatic, drainage reorganization and tectonic forces (Cederbom et al., 2011). By this scenario, a continued deposition of the Molasse deposits up to 5 Ma (when the basin is uplifted) can be assumed, which is more coherent with the sedimentation rate calculated for the UFM (0.3 mm/y; Kempf et al., 1999). To validate this scenario, lower erosions values (1800 m) are necessary than if the uplift age is assigned to 10 Ma (2000 m; Fig. 7e and Table 6) because the sedimentary section is buried for longer time. In the Subalpine Molasse, thrust activation, which could contribute to the erosion of the Subalpine Molasse, has been reconstructed at 10, 8 and 6–5 Ma, (Von Hagke et al., 2012). This tectonic activity has been related to the latest Adriatic and European plate convergence pulses and is also linked to folding of the Jura Mountains (Mazzoli and Helman, 1994). Therefore, it is plausible that in the areas proximal to the Subalpine Molasse (inner part of the NAFB where the study area is located) the uplift started before 5 Ma triggered by tectonic causes. Therefore, for the St. Gallen area, an onset of the erosion at 8 Ma can be assumed. The amount of Molasse erosion necessary to validate this scenario is 1800 m (Fig. 7d), similar to the previous 5 Ma model.

Summing up, this work posits that in the St. Gallen area the starting time of the uplift and erosion of this sector can be placed at 8 Ma, and is mostly related to the deformation of the southern Subalpine Molasse domain (Von Hagke et al., 2012). The erosion continued until 5-4 Ma, when most of the NAFB was uplifted (Cederbom et al., 2011). This scenario is validated by a Molasse erosion thickness of 1800 m.
5.2. The St. Gallen petroleum system: uncertainties

The 3D model reconstructs, for the entire area, the accumulation of a total volume of gas of 0.32 Bcm in the high permeability units (mostly represented by Permo-Carboniferous sandstones) and a total of 15 Bcm in the low permeability units (mostly represented by the Permo-Carboniferous and Triassic shale-dominant deposits). In the area close to the St. Gallen GT-1 well, the model estimates gas accumulations of 0.0024 Bcm (in the Permo-Carboniferous permeable sandstone layers) and an additional volume of 0.094 Bcm in the uppermost low permeability rocks of the Keuper unit (Fig. 13). The gas encountered during the well testing produced from the Malm and Dogger layers, could have flowed through both of these stratigraphically lower accumulations to uppermost layers via local fractures and/or localized lithological changes which could not be represented in the model. However, because of the several assumptions made in constructing the model a number of key uncertainties in the results must be accepted. The most uncertain variables controlling the volume estimates are listed below.

• The volume of the source rocks. The sedimentary infill of the Permo-Carboniferous grabens is poorly constrained. The 3D seismic interpretation of the lateral and bottom boundaries of the grabens are uncertain due to poor seismic images of deeper horizons and the uncertainty of the velocity model used for time to depth conversion (Eruteya et al., 2019). Different interpretation can, therefore, result in important variations in the total volume of the source rocks.

• The thickness of the layers rich in organic matter (shales and coal). The thickness of the source rocks defined in the model was extrapolated from the Weiach-1 well, which is the only well penetrating the entire Permo-Carboniferous sequence in the Swiss Foreland Basin. However this well is located on a structural high and it records a reduced section of the Permo-Carboniferous deposits, which reach only ca. 1000 m in thickness (Thury, 1989; Thury et al., 1994). The deepest parts of the closest graben reach an estimated thickness of ca. 4000 m (Madritsch et al., 2018) which is similar to what is interpreted for the St. Gallen area (Eruteya et al., 2019). The composition and age of the deepest part of the graben infill are unknown, as no wells reach this depth. The total thickness of source rocks could, therefore, be considerably greater than what is estimated in this work. As a consequence, larger amounts of hydrocarbons could be generated.

• The type of organic matter forming the Permo-Carboniferous source rocks and their original hydrocarbon potential. The data used in this work were also extrapolated from the Weiach-1 well because information on the properties of these deposits in the St. Gallen area is not available. Therefore, lower or higher values of TOC and HI are possible in the St Gallen GT-1 well. This would result in lower or higher amounts of hydrocarbon generated. The type and amount of organic matter can only be constrained by reentering the St. Gallen GT-1 well, in order to penetrate the infill of the Permo-Carboniferous graben and sampling the source rock intervals.

• Stratigraphic traps. Sedimentary facies were inferred from analysis of cuttings collected from the St. Gallen GT-1 well and literature data from the study area. The properties inferred were uniformly assigned throughout the entire model. Therefore, lateral sedimentary facies variations were not considered, with the result that no stratigraphic traps (i.e. fluvial channels within flood plain within the Permo-Carboniferous, Dogger and Molasse units) are included in the model. This may result in an overall underestimation of potential hydrocarbon accumulations.

• Porosity and permeability. Variation of the porosity and permeability of the stratigraphic units throughout the area is poorly constrained. The available data are mostly from the St. Gallen GT-1 well location, where a detailed description of the lithological properties of the subsurface deposits is available. Faults and fractures also play an important role in the permeability distribution. The low seismic image resolution at great depths has likely limited the ability to map small structural features controlling the hydrocarbon migration and accumulation processes. A higher seismic resolution could, therefore, improve the understanding of the spatial permeability variation in the area and therefore impact the result of the simulation of migration flow paths and hydrocarbons accumulations and losses.

• Hydrocarbon volume estimates. An intrinsic over-estimation of the hydrocarbon volumes calculated by the model may be present in the result. This is because the software considers optimal conditions (e.g. all pores are connected, regular intergranular space, etc.) and the size of the grid-model (100 × 120 m) used for this regional study is not optimal for calculating hydrocarbon volumes at a prospect level. The total volume of hydrocarbon accumulations estimated is considerably higher than what was estimated by the flow test performed after the gas kick (GIIP between 4 and 11 million of m³, corresponding to 0.004–0.011 Bcm) (Horne, 2015). This is important as the volume calculated by this short-term flow test only considers the volume of gas connected to the borehole whereas our thermal modelling calculation considers the entire volume of gas that may have accumulated in the area near the well in identified potential trapping structures.

The overall impact of all of the above-listed uncertainties could be considered by using a multivariable geo-statistical approach, which is not the aim of this paper. However, in order to quantify the effect of the possible variability of the Permo-Carboniferous source rock thickness, a further scenario was considered, where the Permian and Carboniferous source rock thickness was increased by 2.5 times (Table 3). The amount of hydrocarbons generated increases by a factor of two (337 Bcm), whereas the accumulation volumes in the entire 3D area (0.34 Bcm in the permeable unit and 17 Bcm in the low permeable units) have the same order of magnitude as the volumes calculated by the model with the original, thinner, source rock thickness (0.32 Bcm in the permeable unit and 15 Bcm in the low permeable units; Fig. 11b). Thus, an increase in the amount of generated hydrocarbon does not result necessarily in bigger hydrocarbon accumulations. This indicates that the maximum volume of the hydrocarbon accumulation simulated by the model is more controlled by the dimension of the geological traps rather than by the volume assigned to the source rocks. However, in the case of lower thickness and hydrocarbon potential of the source rock deposits than those in the Weiach-1 well would result in lower generated hydrocarbon volumes and hence the occurrence of empty or underfilled traps. This exercise pinpoints that the geological trapping features (structural and stratigraphic) and the thickness of the source rocks are key uncertainties that control the total volume of accumulated hydrocarbon in the subsurface. Further research, focused on delineating better the geometry and distribution of potential stratigraphic and structural traps, and on mapping the potential coal and shale organic-rich deposits, could, therefore, have an important impact on establishing the potential risks of hydrocarbon accumulations at depth.

6. Conclusions

This work provides an unbiased analysis of the petroleum system in the St. Gallen area. Furthermore, the results obtained herein provide new data on the thermal history of the eastern sector of the Northern Alpine Foreland (NAFB) and thus on its tectono-stratigraphic evolution by applying a thermal modelling approach.

The most relevant boundary conditions for thermal modelling are the heat flow trends over time which was estimated in this study by considering the main geodynamic evolution phases of the NAFB. A first heat flow peak was assigned to the Early Permian, associated with lithosphere thinning and high magmatic activity at the end of the Variscan orogeny. A second peak was assigned to the middle to Late Jurassic, related to lithosphere extension during the opening of the Tethys ocean. By considering literature data an additional thermal
surg can be added in the Early Cretaceous, and the deposition and subsequent complete erosion of lower Cretaceous deposits can be envisaged. Further data will be necessary to confirm this hypothesis. Organic paleothermal data allow estimation of the erosion of the Pliocene-Quaternary unconformity, resulting in an estimate of 1800 m of Molasse deposits eroded. The age of the onset of the erosion is most likely at 8 Ma, triggered by the tectonic activity of the adjacent Subalpine Molasse and continuing to 5 – 4 Ma when the entire NAFB was uplifted.

The thermal conditions reconstructed by modelling are favourable for the activation of a petroleum system in the area. The most likely source rocks are in the Permo-Carboniferous grabens and composed of coals and carbonaceous shales, present in the gas window. The volume of hydrocarbons generated is related to the thickness and richness of the source rocks assigned to the model, which was extrapolated from indirect data. Only a minimal proportion of the hydrocarbons generated were accumulated in reservoirs, mostly located in the Permo-Carboniferous sandstones and in the lowermost Mesozoic units. The volumes calculated for these accumulations mostly depend on the resolution of the stratigraphic and structural traps that can be reconstructed in the model. The volume calculations can be improved by further work aimed at increasing the resolution of the geological structures in the area.

In conclusion this work demonstrates that thermal modelling can predict gas accumulations in the St. Gallen area. Further research is needed to constrain the uncertainties controlling the volumes of hydrocarbons generated and accumulated. Based on the indications that the Swiss Foreland Basin is an active petroleum system, the scenario-based workflow approach adopted in this study should be incorporated into the feasibility and planning phase of future geothermal exploration campaigns. This will permit evaluation of the risks associated with the presence of hydrocarbons in the subsurface in deep geothermal drilling activities. The data obtained by drilling operations will permit, in a second phase, to evaluate the different scenarios proposed, in order to better estimate the volume of any potential hydrocarbon accumulations.

Appendix A. Rock-eval data of the Weiach-1 well

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unit</th>
<th>PC [%]</th>
<th>RC [%]</th>
<th>TOC [%]</th>
<th>MINC [%]</th>
<th>HI [mg HC/g TOC]</th>
<th>OI [mg CO2/g TOC]</th>
<th>Tmax [°C]</th>
<th>S1 [mg HC/g]</th>
<th>S2a [mg HC/g]</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEI-672.51</td>
<td>Toarcian</td>
<td>3.01</td>
<td>3.48</td>
<td>6.49</td>
<td>4.34</td>
<td>545</td>
<td></td>
<td>15</td>
<td>427</td>
<td>0.60</td>
<td>35.37</td>
</tr>
<tr>
<td>WEI-676.37</td>
<td>Toarcian</td>
<td>1.08</td>
<td>2.61</td>
<td>3.68</td>
<td>3.99</td>
<td>331</td>
<td></td>
<td>35</td>
<td>426</td>
<td>0.36</td>
<td>12.21</td>
</tr>
<tr>
<td>WEI-678.23</td>
<td>Toarcian</td>
<td>2.61</td>
<td>3.87</td>
<td>6.47</td>
<td>5.09</td>
<td>464</td>
<td></td>
<td>28</td>
<td>422</td>
<td>0.81</td>
<td>30.01</td>
</tr>
<tr>
<td>WEI-1310.58</td>
<td>Permian</td>
<td>0.35</td>
<td>2.76</td>
<td>3.11</td>
<td>1.04</td>
<td>124</td>
<td></td>
<td>16</td>
<td>433</td>
<td>0.25</td>
<td>3.87</td>
</tr>
<tr>
<td>WEI-1336.12</td>
<td>Permian</td>
<td>2.04</td>
<td>4.31</td>
<td>6.35</td>
<td>0.16</td>
<td>357</td>
<td></td>
<td>5</td>
<td>440</td>
<td>1.77</td>
<td>22.67</td>
</tr>
<tr>
<td>WEI-1350.95</td>
<td>Permian</td>
<td>0.86</td>
<td>2.36</td>
<td>3.22</td>
<td>3.08</td>
<td>304</td>
<td></td>
<td>20</td>
<td>440</td>
<td>0.33</td>
<td>0.65</td>
</tr>
<tr>
<td>WEI-1666.15</td>
<td>Carboniferous</td>
<td>0.10</td>
<td>1.00</td>
<td>1.11</td>
<td>0.07</td>
<td>94</td>
<td></td>
<td>19</td>
<td>469</td>
<td>0.11</td>
<td>1.04</td>
</tr>
<tr>
<td>WEI-1654.03</td>
<td>Carboniferous</td>
<td>0.48</td>
<td>6.08</td>
<td>6.95</td>
<td>0.28</td>
<td>137</td>
<td></td>
<td>4</td>
<td>459</td>
<td>0.91</td>
<td>9.55</td>
</tr>
<tr>
<td>WEI-1656.45</td>
<td>Carboniferous</td>
<td>0.38</td>
<td>3.74</td>
<td>4.12</td>
<td>0.27</td>
<td>97</td>
<td></td>
<td>7</td>
<td>458</td>
<td>0.45</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.geothermics.2020.101876.

Data availability

The authors do not have permission to share the research data used to realize this work. All inquiries for original data should be directed to the St. Galler Stadtwerke, City of St. Gallen.

CRediT authorship contribution statement

S. Omode-Salé: Project administration, Data curation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. O.E. Erutuya: Investigation, Data curation, Writing - review & editing. T. Cassola: Software, Methodology. A. Baniasad: Formal analysis. A. Moscariello: Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study has been funded by the Swiss Federal Office of Energy (SFOE) and by the Swiss Federal Geological Survey Office (Swisstopo), in the framework of the UNCONGEO project. Thomas Bloch (St. Galler Stadtwerke, City of St. Gallen) is thanked for providing us the entire package of the subsurface data of the St. Gallen geothermal well and for his warm technical support. We thank Prof. Ralf Littke and the Institute of Petroleum and Coal (RWTH) of the Aachen University for allowing the use of facilities to obtain thermal maturity data from petrographic and geochemical organic matter analysis. Schlumberger is acknowledged for granting academic licenses of Petrel and PetroMod to the University of Geneva. The reviewers are thanked for their constructive comments that enhanced the manuscript. We warmly thank Sam Carmalt for language revision.

References
