HotLime – Mapping and Assessment of Geothermal Plays in Deep Carbonate Rocks – summary of mapping and generic characteristics of eleven case studies

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Rationale

Despite its significant potential to provide low carbon and dispatchable energy, geothermal energy has remained underdeveloped compared to other renewable energies except in a few particularly suitable regions situated on top of magmatic hot spots. In 2017, it accounted for only 3.0 % of the EU total primary renewable energy production (EUROSTAT 2019). The main reason for the discrepancy between its potential and the lagging development of geothermal resources is the high up-front costs of drilling and risks related to geological uncertainties.

Considered on a worldwide scale, carbonate rocks are regarded as the most prevalent geothermal aquifers of low-enthalpy systems (GOLDSCHEIDER et al. 2010). However, such low-enthalpy hydrothermal systems harbor a particular exploitation risk as they require drilling to great depths to reach suitably elevated temperatures. Such depths can result in a decreased fluid flow due to the decreased primary porosity and permeability caused by mechanical compaction – deep carbonate bedrock commonly is perceived as 'tight'. Accordingly, apart from a few areas where viability of hydrothermal heat and power generation has been proved, most deep carbonate bedrock across Europe has received relatively little attention. In order to de-risk geothermal exploration in deep carbonate rocks it is crucial to improve our understanding of generic geological conditions that determine the distribution and technical recoverability of their potential resources, specifically the possible groundwater yield controlled by fracture conduits and karstification.

The objective of HotLime is to apply established methods for characterization and estimation to hydrothermal resources in different geological settings rather than to conduct cutting-edge research. The key challenge is to do so in case studies of disparate levels of knowledge, data coverage and available information and to apply uniform methods for comparison and prospect ranking. On one hand, this inevitably means generalizing and reducing methods of resource base assessments and comparison to the lowest common denominator. On the other hand, this serves the revision of methods and their range of applicability and helps to share knowledge and experience, thus complying with the spirit of transnational collaboration as fostered by the EU.

Objective and focus of mapping and characterization

The basic requirement for any successful geothermal development is the presence of a reservoir of sufficient thickness with an adequate reservoir quality.

The objective of HotLime's WP2 "Mapping and Characterization" for all areas under consideration was to collate, revise and harmonize all existing geological data, from downhole data and geophysical surveys, to fill the gaps in between pre-existing spatial information, to merge it into one holistic overall picture and (re-)model the geometry and structural inventory of the reservoir. These revised geometries serve as the input for parameterization with respect to facies and temperature distribution.

Actual mapping, characterization and comparison of geological situations, and the structural inventory of the deep carbonate hydrothermal plays was implemented in 11 different target areas across Europe from July 2018 to December 2019, aimed at identification of the generic structural controls of geothermal plays in deep carbonate rocks.

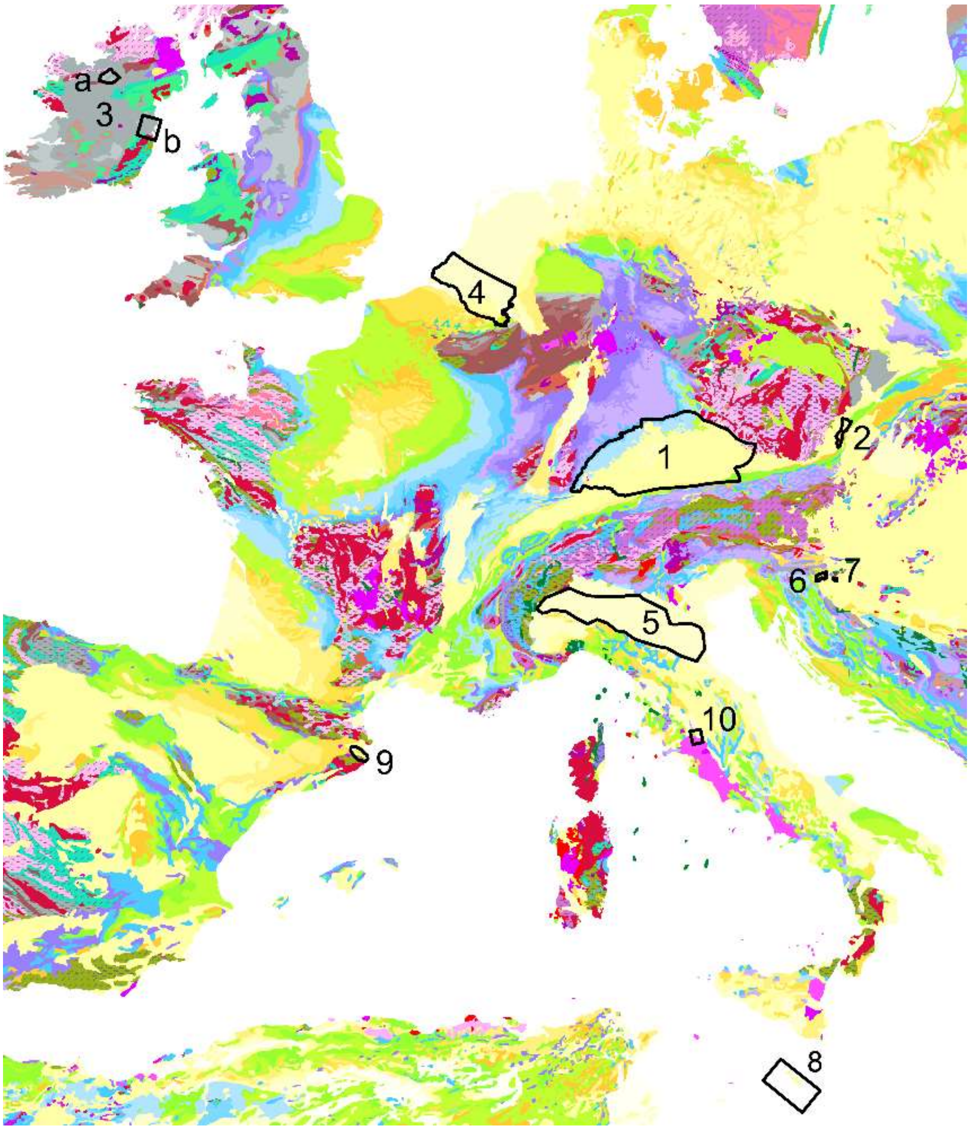


Figure 1: Location of HotLime's case study areas plotted on the 1:5m-scale International Geological Map of Europe – IGME5000 (Asch 2005). The map omits offshore geology for clearer territory contours. (From Diepolder et al. 2020, updated)
***#1**: Upper Jurassic and Middle Triassic carbonates in the central part of the North Alpine Molasse Basin (DE/AT)*
***#2**: Upper Jurassic carbonates in the Molasse Basin-Carpathian Foredeep transition zone (AT/CZ)*
***#3**: Carboniferous carbonates in (**a**) Lough Allen Basin and (**b**) Dublin Basin (IE)*
***#4**: Dinantian carbonates at the flanks of the London-Brabant Massif (NL/BE)*
***#5**: Upper Triassic to Lower Cretaceous carbonates of the Po Basin (IT)*
***#6**: Triassic carbonates of the Krško-Brežice sub-basin (SI)*
***#7**: Miocene and Triassic carbonates of Zagreb hydrothermal field (HR)*
***#8**: Triassic carbonates of the Pantelleria-Linosa-Malta rift complex (MT)*
***#9**: Eocene carbonates of the Empordà Basin (ES)*
***#10**: Triassic carbonates of Tuscan, Umbria and Marche nappes in the Umbria Trough (IT)*

The size of the case study areas varies from 54 km^2 to 47,700 km^2, and all encompass at least one hydro-thermal carbonate horizon of proven but not yet quantified geothermal potential. All plays under consideration – except #6, #7 and #10 – are blind systems with no hydrothermal manifestation or measurable anomaly at the surface. According to the play type concept (Moeck 2014) most case studies are Conduction Dominated Systems that can be assigned to the Orogenic Belt (CD-2) Play Type (# 1, 2, 5, 6, 7, 9, 10) or the Intracratonic Basin (CD-1) Play Type (# 3, 4), except for #8 which appears to be a Convection Dominated – Extensional Domain (CV-3) Play Type.

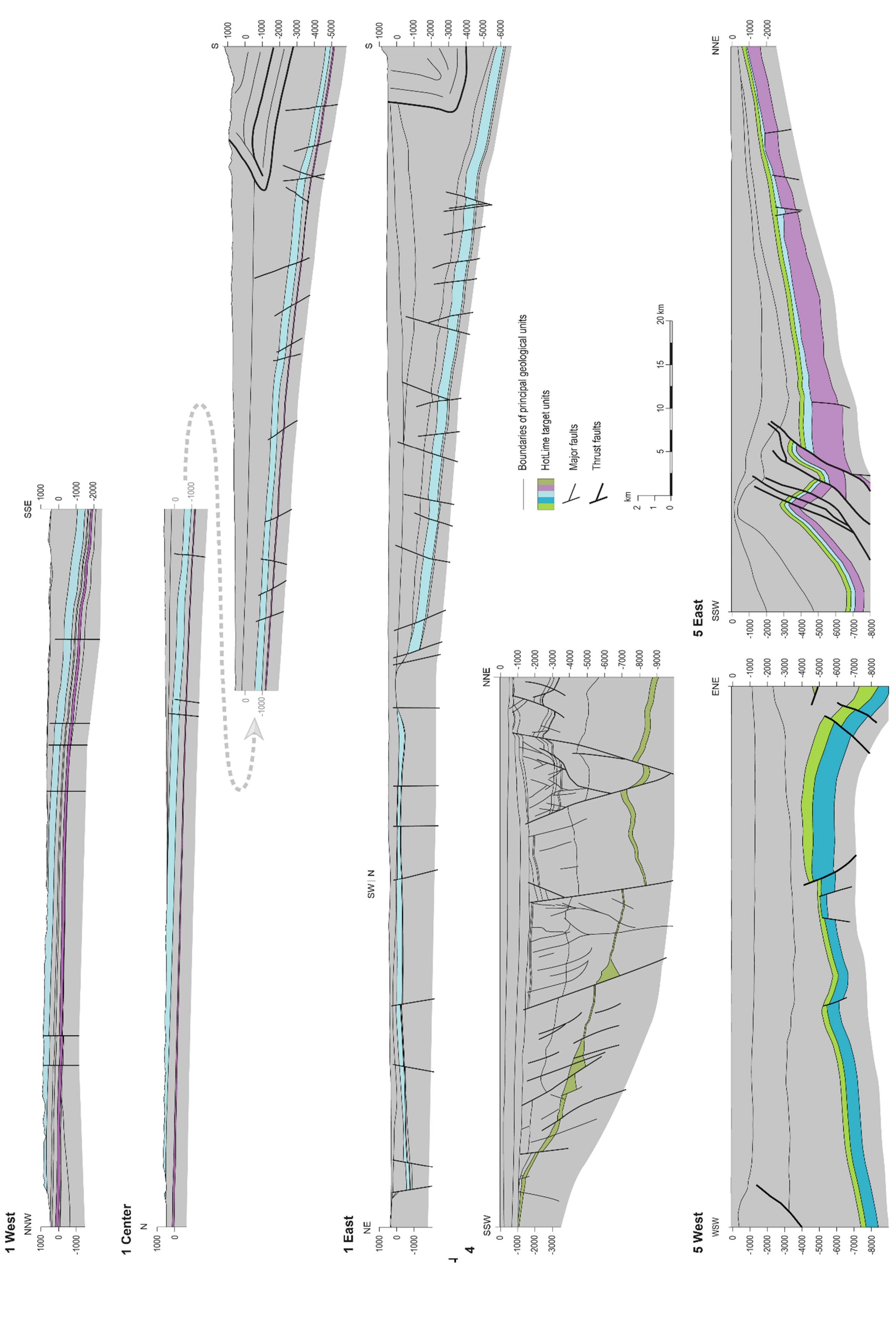
Upfront Geothermal resource assessment, as implemented in HotLime, faces the problem of high degrees of uncertainties for both subsurface geometries and petro-physical property data: A major challenge in mapping and characterization of rock formations at great depths is the availability of data with an adequate distribution and resolution to address the geological situation properly. Legal requirements on data privacy imposing data access restrictions on some of HotLime's partners exacerbate the problem of data paucity, as not all partners could make full use of mature databases from extensive hydrocarbon exploration campaigns. However, sharing of knowledge and exchange of experience among HotLime's 15 partners helped to mitigate the lack of hard data through comparison of the geological situation and its evolution, and conclusions by analogy conveyed to less thoroughly documented areas.

Mapping – capture of subsurface geometries

Recent simulations for geothermal reservoir assessment (e.g. WELLMANN et al. 2011) illustrate that small uncertainties in the geological structure can have significant impact on geothermal resource estimations. Accordingly, special emphasis in HotLime's capture of the subsurface structure was placed on the mapping of the reservoir geometries, the structural inventory and the geological framework of all case study areas, applying state of the art 3D geological modeling methods at most partners. Varying among the partners in abundance and significance, the baseline data for HotLime's case studies beyond conceptual models have comprised scattered and clustered downhole data, various geophysical surveys, specifically seismic sections, geological maps and, rarely, legacy 3D models of subareas. As many data sets required for mapping the deep subsurface are classified, access restrictions required that all mapping and model building had to be implemented at the jurisdictional regional or national GSO. Consequently, the capture of subsurface geometries was conducted with different pre-existing proprietary software packages. Data sets of derived and re-interpreted data, however, were shared among partners for cross-border harmonization in transnational study areas (#1, #2, #4). Even though an overarching general workflow for data preparation, (seismic) interpretation, time-depth conversion and the entire mapping and modelling cascade was set up, we learned that there is no universal best practice applicable to all geological regions or project settings. With scarce baseline data, mapping and modelling was driven by geological concepts and implicit knowledge guided by the modeler and the software's algorithms. In contrast, when baseline data are sufficiently available and expert knowledge is on hand, explicit modeling was the means of choice. In practice, both extremes and all facets in between could occur in the same investigation area. In all cases, the geologists' expertise focused and controlled the capture of subsurface geometries through the mapping and modelling. Mapping outcomes, in turn, fed back into the conceptual models of the geological evolution of the target area, incrementally improving the understanding of the geological setup and the reservoir formation in space and time.

Throughout the entire mapping procedure, from seismic interpretation through to model consistency checks, a special focus was the fault and fracture network intersecting the target horizons. Such discontinuities not only define the possible compartmentalization of reservoirs and seal integrity, first and foremost they represent damage zones usually of higher permeability, thus conduits for hydrothermal fluids, and hence are the prime target for hydrothermal exploration in deep carbonate rocks.

Spatial representations (in 2D or 3D), revealing the principal geological setup for subsequent geothermal base assessment, are the prime outcomes of mapping and characterization. Figure 2 provides a comparative overview of the reservoir geometries, the structural features and the geological setting of HotLime's target horizons highlighted in the standardised colors of the International Chronostratigraphic Chart.


1 West
1 Center
1 East
4
5 West
5 East
Boundaries of principal geological units
HotLime target units
Major faults
Thrust faults
km
20 km

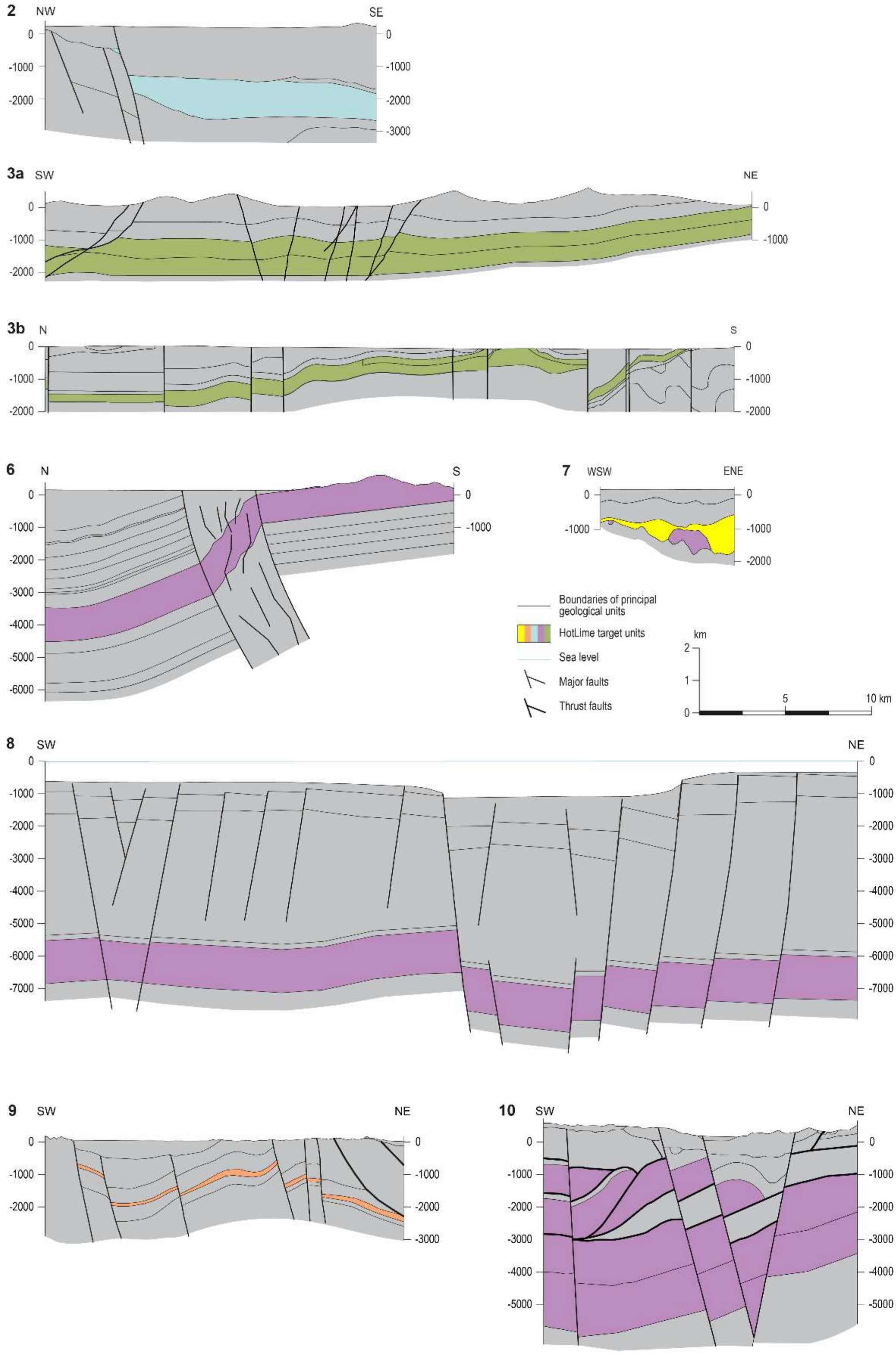


Figure 2 (cont'd from previous page): Comparison of HotLime's case study areas in geological sections. The investigated carbonate reservoirs are highlighted using the color codes of the ICS International Chronostratigraphic Chart (http://www.stratigraphy.org). Vertical exaggeration of all cross-sections is 2x, and, within the same plate, they are depicted at the same scale – but note the different scales of the plates. For section numberings refer to the map in figure 1, for the location of the cross-sections see the trace lines in figure 3.

Characterization – capture of petro-physical properties

Unlike systems in porous rocks, carbonate plays are highly heterogeneous and anisotropic with respect to rock properties. Their groundwater yield, a crucial factor for any hydrothermal development, depends only to a minor degree on the primary rock porosity (matrix permeability), but predominantly is controlled by fault, fracture and karst conduits. The quality of 'regular' carbonate reservoirs with respect to their hydrothermal potential, therefore, is governed by the fracture and fault network as well as the degree of dolomitization and karstification, which in turn are widely controlled by the facies type. Mapping these dominant factors at depth is particularly challenging because downhole data coverage increasingly dwindles with increasing depth of the aquifer. The only parameter that can be reliably assessed on a larger scale and at the forefront of exploration, before drillings are carried out, is fracture density. Due to the brittle characteristic of carbonates – dolostones more than limestones – the highest density of discontinuities generally is found in the core and damage zones along faults, which can be clearly identified in reflection seismic. For example, even at great depth beneath a thick overburden, DUSSEL et al. (2016) determined mechanically altered, permeable zones with a width of 50-150 m along main faults. BAUER et al. (2016) describe permeable zones of intensely fractured, uncemented rock up to hundreds of meters wide along faults in karstified carbonates. From this perspective, faults are the most reliable targets in geothermal prospectivity screening of the deep carbonate rocks. Many successful drillings for geothermal installations in carbonate reservoirs, specifically in the Molasse Basin, have proved this approach. However, recent failures of ultra-deep explorations (> 5,500 m) show that it is not inherently propitious at great depth where compaction by the high load of overburden seems to be a widespread process. Hence, faults and fault zones as mapped in HotLime's case study areas are considered indications rather than evidence for planar structures of higher groundwater yield and require verification through further investigations.

In contrast, facies and dolomitic domains – reef facies, reef debris and dolostones feature a higher secondary porosity than basin facies limestones – can be reliably detected only after drilling and seismic well log correlation (MOECK et al. 2015), or can be assessed from high-resolution 3D-seismics, usually available only for project size areas in advanced development stages. Consequently, these indicators for increased rock permeability, and thus higher groundwater potential, could be regionalized and mapped in very few (sub-)areas only, where distribution density of downhole information was deemed adequate. Extrapolation of subcrop facies distribution and paleo-geographic maps – usually available at large scales only – harbor an uncertainty that is too high for any scientifically sound statement. However, ongoing work in "Play and Prospect Evaluation" might reveal further generic controls that could help to tackle this issue.

Temperature Modelling

As with geological information for mapping and characterization, available temperature data for the HotLime case study areas are disparate with respect to distribution density and quality. Measurements collected for temperature modelling predominantly stem from downhole data of (legacy) hydrocarbon E&P campaigns, mostly taken as Bottom Hole Temperatures (BHT) and corrected using established weighting classifications (e.g. ZSCHOCKE 2005, RÜHAAK et al. 2010), or rarely from drill stem tests (DST). Only in the Molasse Basin (#1) are a significant number of temperature measurements from recent geothermal E&P available. The areal coverage of preexisting temperature models or temperature distribution maps for HotLime's target horizons in the different case study areas varies from full coverage to nil. Area-wide subsurface temperature information is available for #4 down to 6 km depth (BONTÉ et al. 2012) and for the top of the Upper Jurassic hydrothermal aquifer in #1 (AGEMAR & TRIBBENSEE 2014). The top of Middle Triassic of #1 (GeoMol TEAM 2015) is partially covered, and the top of the Upper Triassic to Lower Cretaceous sequence of the Po Basin (#5) has been extended and upgraded within HotLime. For most of the case study areas only few temperature measurements exist, in many cases too far apart for reliable interpolations.

As an area-wide temperature distribution is a crucial pre-requisite for all geothermal resource base assessments, regionalized geothermal gradients derived from downhole data (borehole logs) and literature values of heat flow density were used to fill the voids in areas where no reliable interpolation of measured values could be performed. To this end, isolated temperature gradient derivations, assumed to be representative for a certain area, have been used to extrapolate the temperature distribution depending on the depth of the top of the reservoir, applying the basic equation: $T_r = T_0 + gradT * Z$ (where T_0 is the mean annual surface temperature; gradT is the geothermal gradient and Z is the depth of the top surface of the target horizon). However, such generalization neglects the non-linearity of geothermal gradients and must be considered a first-order approximation only.

In some smaller case study areas lacking hard data, as in sub-areas of larger case studies, this approach of regionalization of geothermal gradients has been applied for the entire distribution of the reservoir top surface. Even so, some of the temperature distribution maps collated in figure 3 show “no data” sub-areas for realms where the data situation is considered inappropriate even for an educated guess pursuant to this approximation.

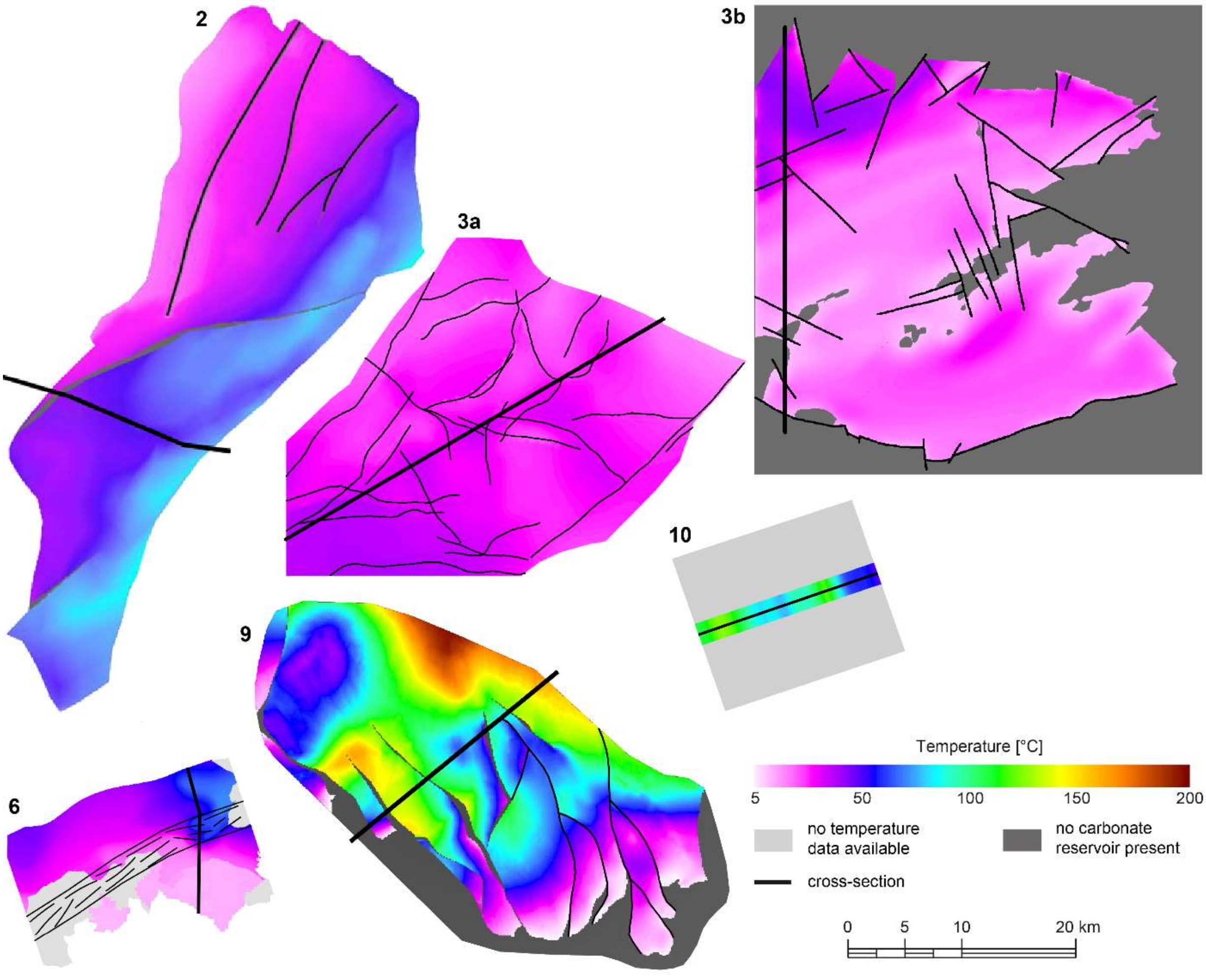
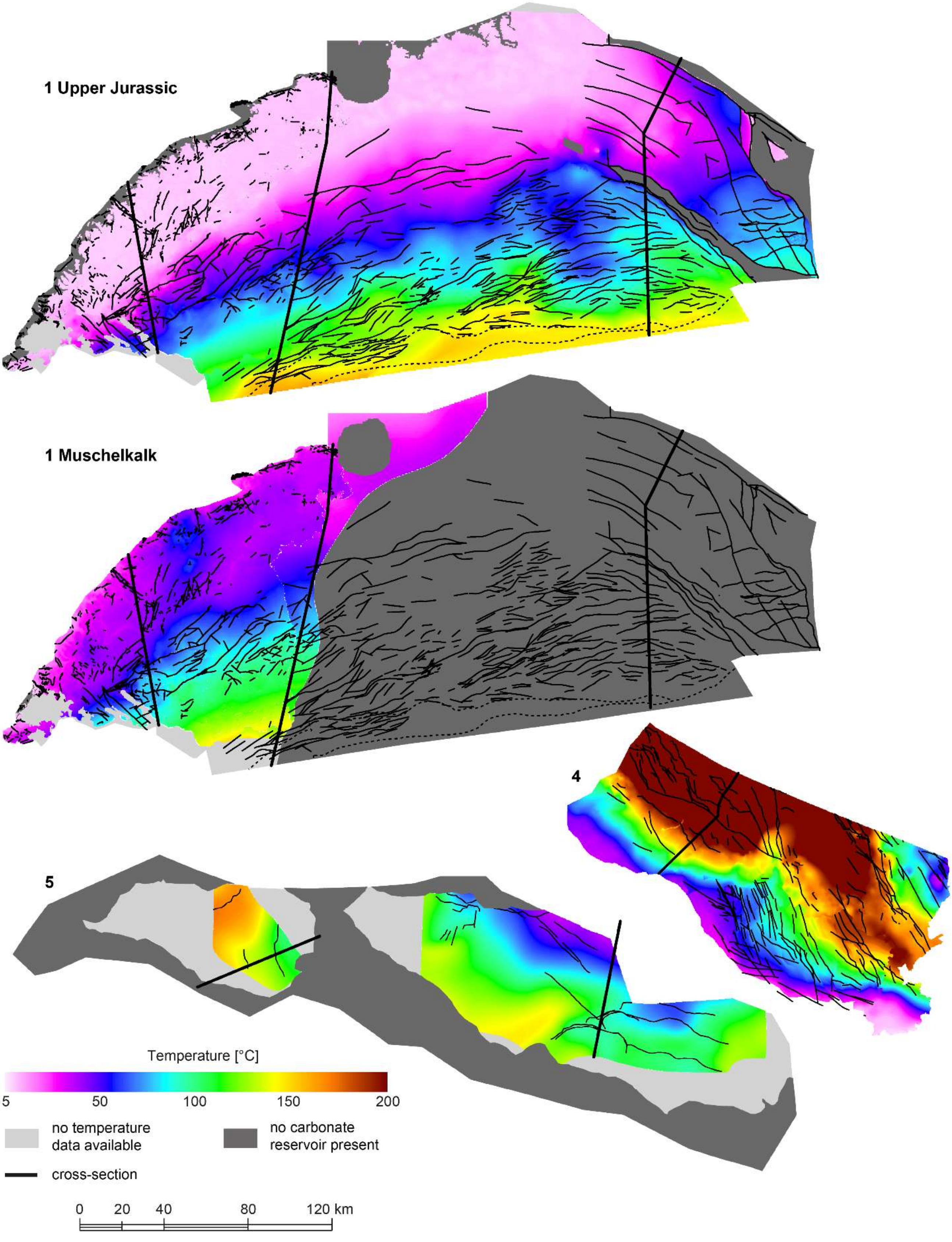


Figure 3 (cont’d next page): Case examples of temperature distribution calculated/assessed for the top of HotLime’s target carbonate reservoirs. Also showing no reservoir realms, narrow linear “no reservoir present” zones are mostly due to dip-slip offsets at faults. For area numberings refer to the map in figure 1. The trace lines of cross-sections correspond with the geological sections depicted in figure 2.


1 Upper Jurassic
1 Muschelkalk
4
5
Temperature [°C]
5
50
100
150
200
no temperature data available
no carbonate reservoir present
cross-section
0
20
40
80
120 km

Regionalized geothermal gradients are also used to estimate temperatures at the base of the considered reservoirs, usually far below the deepest BHT value measured. Particularly in reservoirs featuring a gross thickness of more than 200 m, the increase of temperature with depth within the target layers has a significant effect on the geothermal resource base assessment. Accordingly, such large-thickness reservoirs are dealt with as layered incremental intervals in the ongoing geothermal base assessment using the "Heat-in-Place" method of MUFFLER & CATALDI (1978) and applying both the deterministic as well as (optionally) the probabilistic approach of GARG & COMBS (2015), see DIEPOLDER et al. (2020) for details.

As demonstrated by some initial reliable tests, this present stage of the capture of the subsurface setup and temperature distribution gives good reasons to expect a sufficiently detailed knowledge of the reservoir geometries necessary for a sound geothermal resource base assessment, considering the volume of the reservoir, the temperature, the specific heat capacity of the rocks, and areas of increased porosity along the damage zone of faults.
For that purpose, additional parameterization, validation, and refinement within HotLime's "Play and Prospect Evaluation" presently is being carried out and modelling these parameters might reveal further generic controls of the geothermal prospectivity. Feedback thus may further improve knowledge about, and spatial products of, HotLime's case study areas until they are eventually uploaded to the GeoERA Information Platform (EGDI) in 2021, supplemented by LOD SKOS based controlled vocabularies (glossaries) on the displayed features and a knowledge base on the scientific background, methods and use limitations.

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