DELIVERABLE D5.1
REVIEW AND SELECTION OF OUTCROP-ANALOGUES OF THE FOUR VARISCAN RESERVOIR TYPES IN REGARD TO SAMPLE COLLECTION

WP5: VARISCAN GEOTHERMAL RESERVOIRS (GRANITIC AND METAMORPHIC ROCKS)

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CONTENT

1 EXECUTIVE SUMMARY

1.1 DESCRIPTION OF THE DELIVERABLE CONTENT AND PURPOSE

In the framework of WP5, based on literature research, own mapping data and field campaigns, we will present a selection of outcrops most representative for the four Variscan reservoir types to (a) allow sample collections for laboratory tests and (b) to characterize the petrological and tectonic settings in terms of geothermal reservoir potential. This basic work is relevant for D5.2, D5.5 to D5.9. There is no risk of failure to find adequate outcrops, it is just an issue on the quality level of the outcrops.

1.2 BRIEF DESCRIPTION OF THE STATE OF THE ART AND THE INNOVATION BREAKTHROUGHS

Most of the geothermal reservoirs are only accessible by deep drilling which on the one hand represented an expensive method and on the other hand limits the size and number of available rock samples. Thus, deep reservoirs correspond to hidden rocks lying at great depth. Therefore, surface studies on relevant outcrop analogues are very helpful, cheap by comparison to deep boreholes, low risk and very informative for collecting high quality datasets on larger areas. Therefore, structural, mineralogical and petrophysical analysis of relevant outcrops planned in the framework of MEET are relevant methods for characterising geothermal reservoirs. For structural analysis, several techniques can be carried out such as field work, photogrammetry, structural mapping at various scale (sample, scanline, mine, drone, aerial pictures). For mineralogical and petrophysical study, most of the investigations will be carried out at sample scale.

1.3 CORRECTIVE ACTION (IF RELEVANT)

NA

1.4 IPR ISSUES (IF RELEVANT)

NA

2 DELIVERABLE REPORT

2.1 SAMPLE STRATEGIES OF OUTCROP-ANALOGUES OF THE FOUR VARISCAN RESERVOIR TYPES

2.1.1 Variscan metasedimentary (and metavolcanic) successions overprinted by younger extensional tectonics (fault and graben systems)

2.1.1.1 Selection of the analogue site

Target horizons for developing enhanced deep geothermal systems to supply heat energy for the existing Göttingen Campus district heating system, are the Variscan metasedimentary and meta-volcanic successions at a depth of around 4000 m (e.g. Leiss et al 2011). Göttingen is situated in the tectonic North-South striking Leinetal Graben System, which developed in the Permian-Mesozoic sedimentary cover of around 1500 m thickness. These Mesozoic to Cenozoic extensional and inversion structures are also supposed to overprint the Variscan, low-grade metamorphic basement, which is expected to be composed of folded and thrusted slates, meta-greywackes, cherts, quartzites and diabase of Devonian to Carboniferous age. It cannot be excluded to also hit Devonian reef carbonates or late Variscan granites during drilling, but a seismic survey of 2015 gave no such indications (internal report). In the wider area of Göttingen, only a very few wells exist, some of them just reaching possible Variscan rocks. The only rock sample available derives from around 1500m depth, however, it is probably a volcanic rock of the Rotliegend. As Fig. 1 shows, the closest outcrop areas along the Variscan strike are the Rhenish massif in the Southwest and the Harz mountains in the Northeast of Göttingen. The correlation of the basis of the Gießen-Harz nappe complex illustrates that Göttingen is probably just located on the nappe boundary. Due to the shallow dip of the nappe boundary to the Southeast, we can expect to hit the nappe underlying sequences. Therefore, our investigations on the lithological and structural characterization of possible reservoir rocks focus on the units of the Western Harz for our analogue studies.

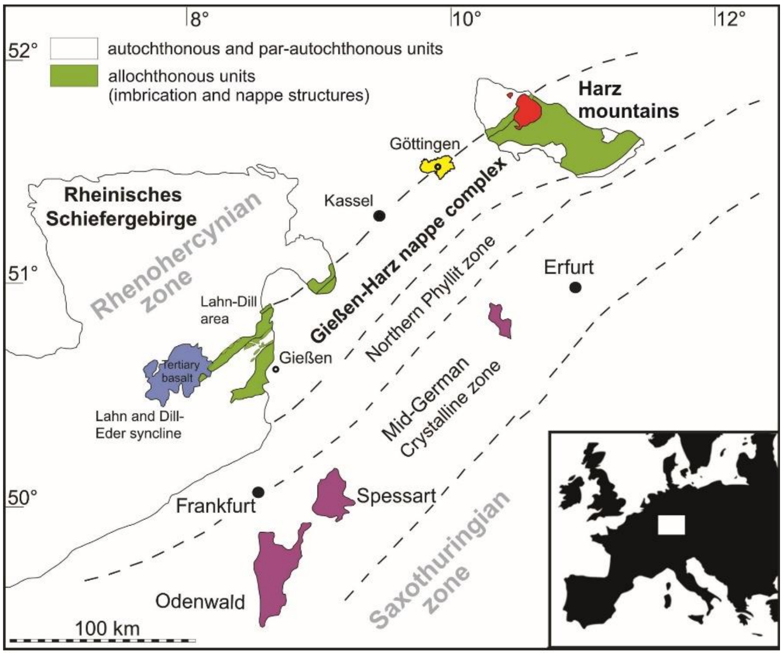

Figure 1*: Location of Göttingen in regard to the basis of the Gießen-Harz nappe complex (modified after Eckelmann et al. 2014)*

2.1.1.2 Geological setting of the analogue site (Western Harz Mountains)

The Western Harz Mountains comprise the Upper Harz Anticline composed of cherts, meta-limestone layers, slates (Wissenbach Schiefer), the Carboniferous Clausthal Culm Fold Zone mainly composed of slates, an intercalated slate/meta-greywacke succession and greywackes, the synsedimentary Carboniferous Diabase Range and the Carboniferous Acker-Bruchberg-Range consisting of quarzite. A Devonian reef-complex at km-scale is exposed within the Clausthal Culm Fold Zone. The NW-directed fold-and-thrust-system shows open to tight and upright to overturned folds at a scale range between cm and km. Thrust systems can also be developed at all scales but thrust zones at larger scales are extremely difficult to observe at surface because they are strongly weathered and covered by Quaternary soils. This is also true for a younger (Jurassic to Cretaceous), East-West striking fault system (Ruschelzones) which developed during the uplift of the Harz Mountains. Even though this system developed in another tectonic context than the faults of the Leinetal Graben system, they can serve as a fault analogue as long as possible different depths during development are considered. Such fault zones can be studied only underground, e.g. in the historical ore mines or drainage galleries.

2.1.1.3 Sampling approach (type of chosen rocks, geological significance)

The main target horizons for developing geothermal systems are the Devonian and Carboniferous slates and the Carboniferous greywacke-successions because these units can show thicknesses of up to several hundred metres. This means that these units provide rock volumes relevant at reservoir scale. Since we expect that these rock units are the most probable deep reservoir rocks we will encounter below Göttingen, in the first step, they get highest priority for our reservoir characterization.
Our general approach in developing a reservoir model of the Variscan meta-sedimentary succession, is to design a conceptual structural 3D-model based on field investigations. This model must be fed with structure-related petrophysical and rock mechanical data especially considering the anisotropic physical properties at lab scale.
Greywackes: During our fieldwork within MEET, we could identify a model area for folded and thrusted meta-greywackes in the valley of the river Innerste in the West of the town Clausthal-Zellerfeld. Relatively well exposed outcrops allow the characterization of the fold-and-thrust-structures ranging from the m to the km-scale. Oriented samples can be collected from the different meta-Greywacke lithologies, i.e. different grain sizes ranging from fine sand to cm-conglomerates. Samples will be collected from normal and overturned limbs as well as from hinge zones because these different tectonic settings show different stresses and might have resulted in different micro-fracture patterns which are thought to strongly influence the petrophysical properties.
Slates: Sampling of structure–related slates can be done very well in the well-exposed outcrops around the Okertal dam (e.g. Schulenberg-fold) for the Carboniferous slates and in the area around the Granetal dam south of Goslar for the Devonian slates. However, for our designed lab test program, it would be preferable to collect samples from the underground, where cleavage is not optically obvious. Only weathering, i.e. wet-dry cycles and cyclic temperature changes at the surface lead to the development of open cleavage planes. For most of the lab

tests, it would be clearly more suitable to collect samples from underground mines and drill cores. We have already been in historical mines (e.g. “Roter Bär”, St. Andreasberg), but are continuing to evaluate the access to additional mines as well as drill cores, which are archived and accessible by the “Federal Institute for Geosciences and Natural Resources”(BGR) in Hannover. Another option to get relatively “fresh” samples is drainage galleries or interconnection galleries between water reservoirs.

Veins: All rock units show syn- and post-deformative (related to Variscan tectonics) hydrofractures healed with quartz or calcite. Special attention is not only paid to these natural mechanical stimulation features to understand the structurally controlled fracture development, but also to the setting up of fluid inclusion studies to determine the pressure and temperature conditions during formation as well as the composition of the fluids.

Other rock units: Other lithologies show thicknesses probably not large enough to serve as a reservoir rock or are only of local occurrence, which makes it quite unlikely to hit them during the geothermal exploitation in Göttingen. However, since other lithologies are partly intercalated with the volume-dominating greywacke- and slate-units and since these units can be encountered at other locations, we are also going to characterize these rocks petrophysically depending on available time and lab resources. Structure-related sampling areas have been identified for the Lower Carboniferous cherts in outcrops in Lautenthal, for the strongly thrusted quartzites of the Acker-Bruchberg-zone in the area of the Hammersteinklippen or the Hans-Kühnenburg area (strong sampling restrictions are due to the National park regulations), the Devonian Diabase in the Huneberg-Quarry, reef carbonates in the Winterberg-Quarry and the Lower Devonian sandstones of the Kahleberg unit south of Goslar.

Wherever it is possible, we will take oriented samples, so all experimentally determined directional data can be correlated with the field data and anisotropies or heterogeneities are easily identified.

2.1.1.4 Intended sample investigations (thin sections, experimental deformation, geochemical analyses)

Besides the classical determination of physical and mechanical rock properties carried out mainly by TUDa (e.g. permeability, density, porosity, thermal conductivity, thermal diffusivity, heat capacity, compressive and shear wave velocity, Uniaxial compressive strength, Young’s modulus, Poisson ratio, cohesion, friction angle, tensile strength, shear strength etc.), the most crucial information is expected from the long-term experiments on fractured reservoir (analog) rocks planned by GFZ Potsdam. From these experiments, the mechanical, thermal and chemical effects on fracture propagation and long-term fracture closure & healing processes (stress corrosion, solution-precipitation) will be characterized. At the same time, such long-term experiments are limiting the number of samples, since experiments with different conditions (e.g. temperature, fluid composition) will be carried out on the same samples. Within the MEET-project, it is realistic to measure 10 to 20 samples. This limitation requires to focus on the greywackes and slates, since the number of samples quickly increase when considering different compositions and tectonic positions. Especially for the slates, it is crucial to experimentally consider the anisotropy caused by the bedding and the cleavage.

For all these samples and samples of the other units, routine microfabric characterizations (optical microscopy, Scanning electron microscopy for the slates) will be carried out.

The texture (crystallographic preferred orientations)-related anisotropy of physical properties of the slates will be quantitatively determined with Synchrotron diffraction at the ESRF in Grenoble.
A special focus goes to the complex vein development. Analyses by optical microscopy will be complemented by optical hot cathodoluminescence to distinguish different vein generations. Based on these results we will select locations in the samples for fluid inclusion analyses.

Acknowledgements: Concerning the Harz geology, we greatly appreciate support by Christine Hofmann, Hans-Joachim Franzke, Carl-Heinz Friedel and Wilfried Ließmann

References:
Eckelmann, K, Nesbor, H.-D., Königshof, P., Linnemann, U., Hofmann, M., Lange, J.-M. & Sagawe, A. (2014) Plate interactions of Laurussia and Gondwana during the formation of Pangaea – Constraints from U–Pb LA–SF–ICP–MS detrital zircon ages of Devonian and Early Carboniferous siliciclastics of the Rhenohercynian zone, Central European Variscides. Gondwana Research, 25: 1484-150

Leiss, B., Vollbrecht, A., Tanner, D., Wemmer, K. (2011): Tiefengeothermisches Potential in der Region Göttingen – geologische Rahmenbedingungen.- In: Leiss, B., Vollbrecht, A., Tanner, D., Arp, G.: Neue Untersuchungen zur Geologie der Leinetalgrabenstruktur - Bausteine zur Erkundung des geothermischen Nutzungspotentials in der Region Göttingen: 163 - 170, Universitätsdrucke Göttingen.

2.1.2 Variscan metasedimentary (and metavolcanic) successions overprinted by younger extensional tectonics (fault and graben systems)

2.1.2.1 Geological Setting

The former gas exploration borehole of Havelange was drilled in the Devonian (meta-) sedimentary formations of the Rhenohercynian fold-and-thrust belt in Belgium. This belt is the result of the inversion of Devonian-Carboniferous passive margin during the Variscan orogeny during Upper Carboniferous ([330-300 Ma]). This compressive event was followed by limited numbers of late orogenic events such as transversal faulting. Since then, the tectonic activity in the area is regarded as very limited.
At the regional level the Havelange borehole is located within the Dinant Synclinorium where Devonian and Carboniferous formations were folded and thrusted. The encountered formations during the Havelange drilling are restricted to rocks from Lower-Devonian to Famennian ages with a global ageing downward.
Two study areas for analog sampling were selected, namely a near-field representing the area within a 5 km distance from the borehole and a far-field zone located to the East and South to Havelange where Lower-Devonian to Famennian formations are outcropping.

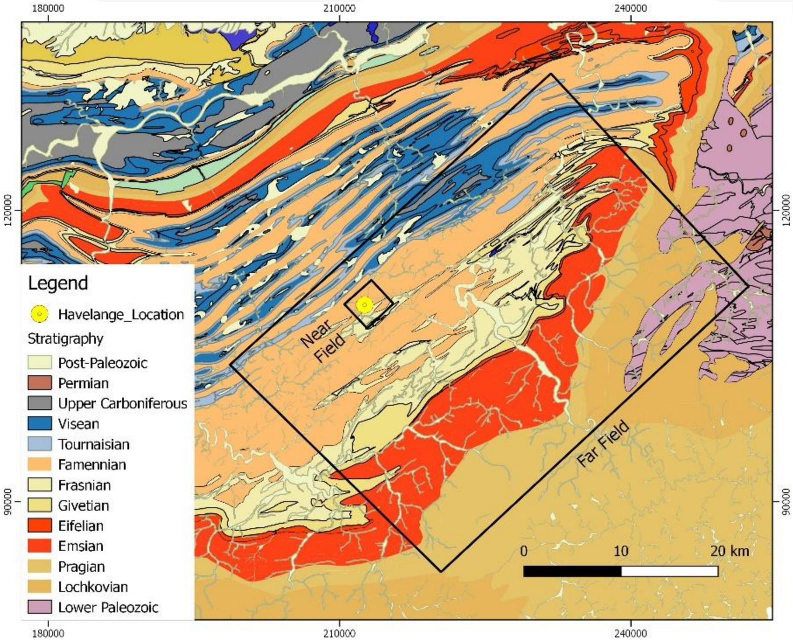

Figure 2: Map definition of the analog near and far fields around the Havelange borehole

2.1.2.2 Selection of the areas

The Havelange borehole reached a depth of 5648 m, but only some horizons were cored: at shallow depth the Upper Devonian shale units and at greater depth the Lower Devonian quartzite members. The other lithologies were explored through destructive drill methods for which only cuttings are available. The two selected analog fields represent areas for which different sampling targets will be conducted. Due to the geological structure the rocks outcropping in the near field area correspond to those observed at shallow depth in the borehole (Figure 3). For this part only Upper Frasnian and Lower Famennian shales were cored. The other lithologies (mainly carbonates and shales) will be sampled in the near field. By contrast, rocks observed at greater depth in the borehole do not outcrop in the near field, but are encountered in the far field. Since the main geothermal reservoir target for this study site are the Lower Devonian quartzite horizons a significant part of the sampling will be conducted on this target from both the borehole core collection and the analog far field. The Lower Devonian quartzites are also associated with sandstones and shales units from the Lower- and Middle Devonian. Those lithologies will be collected in the far field.

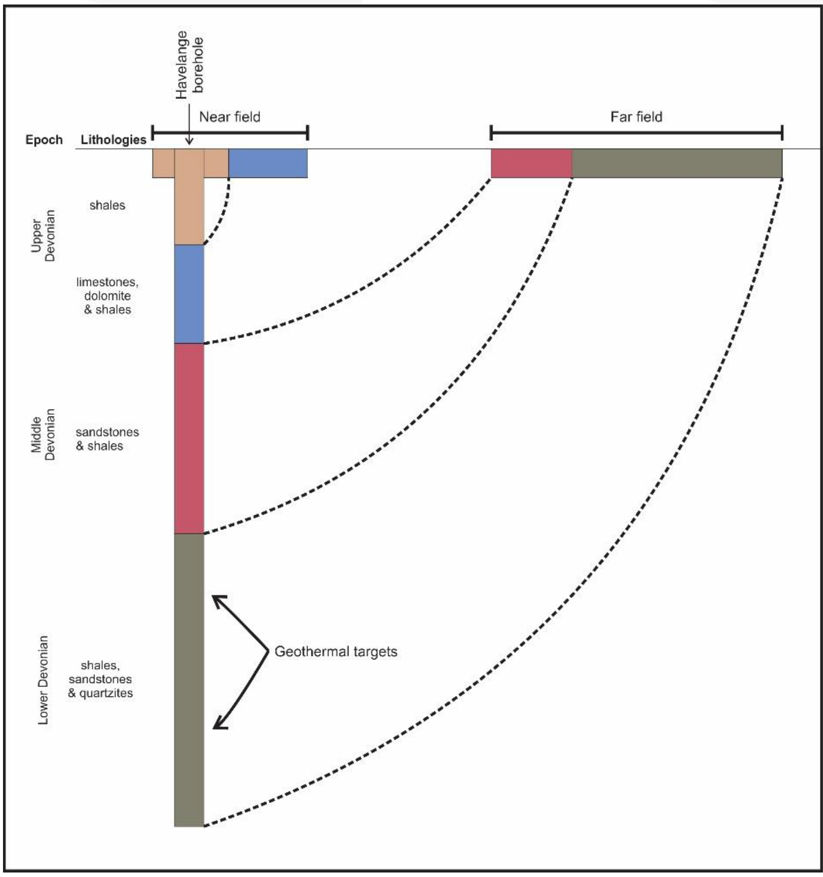

Figure 3: Diagram of near and far field definition and main lithologies of the study site (not to scale).

2.1.2.3 Sampling strategy (Havelange boreholes and outcropping analogs)

As core and cutting samples from the Havelange borehole are available for analysis, the sampling strategy will be based on the study of both Havelange borehole samples (considered as in-depth analogues) and outcropping analogue lithologies.

The main lithologies characterizing the study site subsurface are shales, sandstones, quartzites and carbonates of various ages. The sampling methodology will take into account the available cores and the existing lithologies as well as the planned experiments and required sample sizes, but the bulk of the effort will focus on the quartzite horizons, since they are representing the main target for the development of geothermal reservoirs in the study zone.

The sampling preparation will follow the requirement for the mechanical tests that are the preparation of rock cylinders. Rock cylinders will be produced from the Havelange borehole core samples (~30 cylinders foreseen) as well as from analogue outcrops (30-40 cylinders foreseen, see figure 4 for examples of outcrops). Given the outcrop quality, more suitable outcrops, e.g. active quarries, where effects due to weathering can be ruled out will also be included. Large outcrops of Devonian sandstones, quartzites and slates have been sampled in the far-field in the Hunsrück and Taunus mountains (e.g. Bär 2012, Bär et al. 2016).

Planned analyses will be conducted on the off-cut fragments resulting from the rock cylinder preparation, but also from the borehole cuttings (~80 cuttings samples foreseen).
More detailed samplings will also be conducted on cores and cuttings for target zones, where logging or drilling reports indicate the presence of water influx or fracture or faulted zones, especially the presence of altered zones.

Figure 4: examples of far field outcrops to be sampled (Lower Devonian shales -left and sandstones -right)

2.1.2.4 Planned analyses

Havelange boreholes and outcropping analog samples will be processed mostly by the same analytical protocols. On the rock cylinders produced from cored section of the borehole and analog rocks we will conduct first of all non-destructive analyses such as micro-CT scanning to evaluate the internal composition, texture and porosity. The core samples will then be sent to the project partners for non-destructive petrophysical and destructive mechanical tests (as described in section 2.1.1.4, e.g. TUDa and GFZ), this information will be later on combined with logging data available for the whole length of the borehole. The off-cut samples will be analyzed to have a full characterization in terms of mineralogy composition (XRD, Raman), geochemical composition (EDS, LIBS), thermal conductivity and diffusivity (TCS).

Table 1: Synthetic listing of planned analyses

Rock cylinders		**Rock fragments**	
Havelange borehole in-deph analogs	**Outcropping analogs**	**Havelange borehole in-depth analogs**	**Outcropping analogs**
microCT scanning, LIBS	microCT scanning, (LIBS)	Mineralogy (XRD, Raman)	
geomechanical and petrophysical test	geomechanical and petrophysical test	Geochemical composition (EDS, LIBS)	
-microCT & petrophysical tests	microCT & petrophysical tests	Thermal conductivity and diffusivity (TCS scanner)	

coupling -combination with borehole logging data	coupling	

References:
Bär, K. (2012): Untersuchung der tiefengeothermischen Potenziale von Hessen. Dissertation, XXVI und 265 pp, 111 fig., 28 Tab., 6 App., 1 DVD-ROM, Technische Universität Darmstadt
Bär, K., Hintze, M., Weinert, S., Sippel, J., Freymark, J., Scheck-Wenderoth, M., Sass, I. (2016): Das Verbundprojekt Hessen 3D 2.0. Geothermische Energie 85(3): 24-25.

2.1.3 Variscan crystalline basement overprinted by post-Variscan extensional faults. Target horizon: fractured granites below a post-Paleozoic sedimentary cover

Analogue field sites: Pfälzer Wald, northern Vosges, Odenwald, Black Forest, and another site suitable for upscaling of well/quarry scale to reservoir scale to be defined and the geothermal test site at Soultz-sous-Forêts, France.

2.1.3.1 Demonstration site geological context: the Upper Rhine Graben

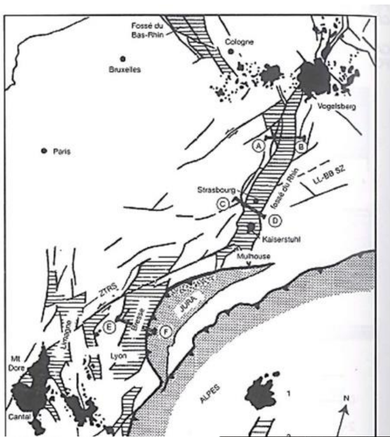

Figure 5: Structural scheme of the Western European rift system

The Western European Rift System is formed during an extensional phase affecting the European plate in Cenozoic times. In map trace, the rift has a length of about 1000 km and can be followed between the Mediterranean Sea and North Sea. Along strike, several graben type basins are encountered bordered by numerous transfer zones.

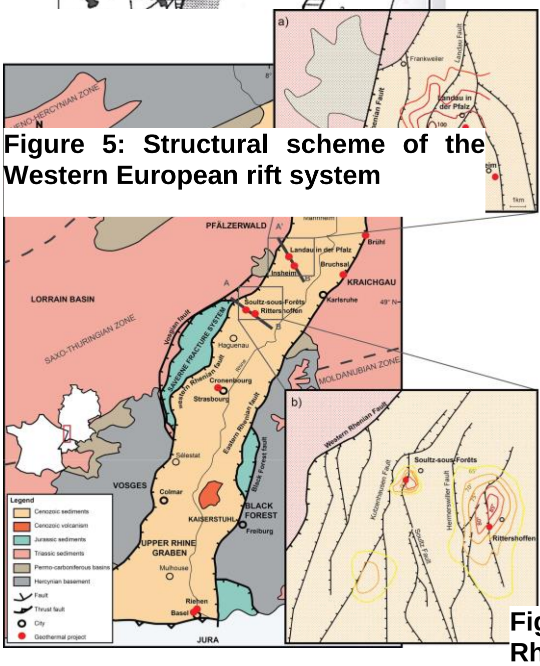

Figure 6: Structural Scheme of the Upper Rhine graben after Vidal and Genter (2018)

The Upper Rhine Graben (URG) is part of this rift system, with a length of about 300 km and a width of maximum 40 km. It is bordered by the dominantly Variscan crystalline units from the Vosges massif in the West (France) and the Black Forest and the Odenwald in the East (Germany). These outcrops on the Graben shoulders are representative outcrop analogues of the geothermal reservoir units at depth and can be sampled in various quarries both east and west of the Graben (e.g. Kushnir et al. 2018, Bär 2012, Hoffmann 2015). Both the Variscan basement as well as the Paleozoic to Mesozoic sediments

(primarily Permo-Triassic sandstones and volcanic rocks) were the targets for numerous deep geothermal projects.
Within the Graben the geothermal reservoirs are covered by thick sedimentary formations from Mesozoic to Cenozoic in age. Displacement estimates show horizontal extension amounts between 2.5 and 7 km. Estimates of sinistral displacement along the bordering faults are between one and 3 km.
The URG presents numerous thermal anomalies with geothermal gradients up to 100°C/km as a consequence of hot fluid circulation associated to intense basement and sedimentary pile faulting. Several power plants are present and use the geothermal energy for heating and electricity production with a total of 15 geothermal wells.

2.1.3.2 Analogue site for the geological context at reservoir scale: the Death Valley basin

Since all the outcrop analogues on the Graben shoulders of the Upper Rhine Graben are covered by dense vegetation and the rocks are only exposed in quarries, road or river cuts, it was decided to investigate an analogue site for the geological context at reservoir scale, which allows for the large-scale investigation of fault distribution and fracture network governing the geothermal reservoir behaviour.
Due to its excellent outcrop conditions, the chosen analogue lies at the southern termination of the Death Valley (DV) National Park in California, USA, where no vegetation cover hiding the geological structures, is present at all.

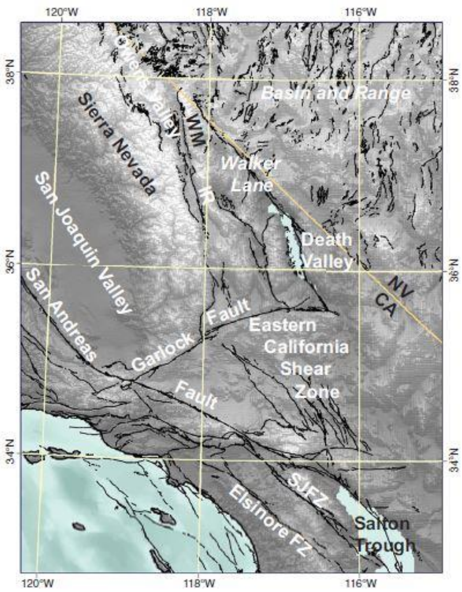

Figure 7: Regional topography of Western North America (Norton, 2011)

This part of the American territory includes the extensional province of the Basin and Range in the North, the collision front of the Sierra Nevada microplate and the San Andreas Fault zone and related Eastern California Shear zone marking the boundary with the North American plate in the East and Pacific plate in the West.

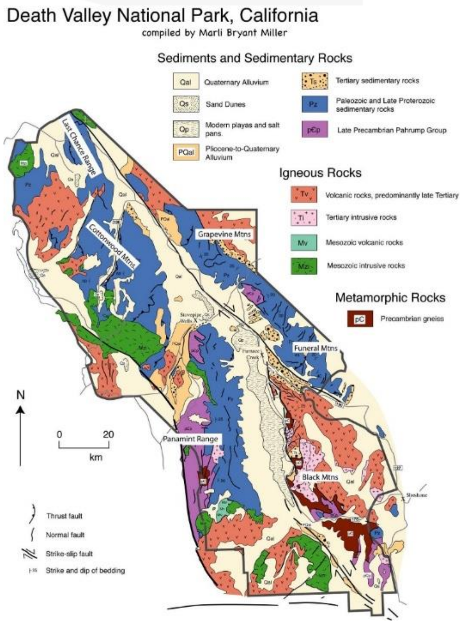

Figure 8: Death Valley geological map

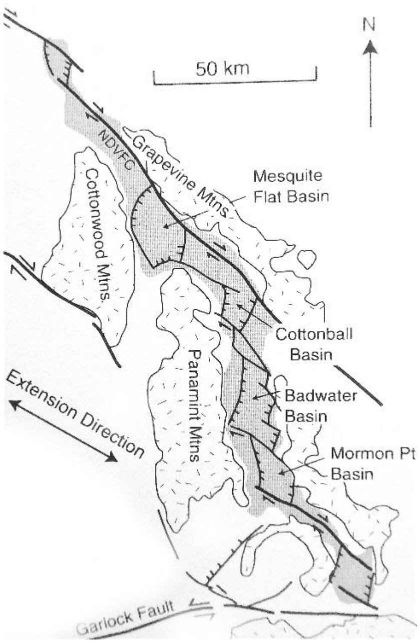

Figure 9: Structural scheme of DV after Miller and Wright 2007

The massifs bordering the Death Valley (Grapevine, Cottonwood and Panamints mountains) consist of Proterozoic basement and sedimentary cover affected by intense faulting (Death Valley Fault System). These massifs show numerous occurrences of Mesozoic magmatic intrusives all related to the Sierra Nevada magmatic arc activity.

The DVFS, classically divided in a Northern Death Valley Fault Zone and a Southern Death Valley Fault Zone, is the consequence of right lateral movements along the ECSZ at an average displacement of about 12 mm/year. The onset and amount of displacement along the DVFS is still a matter of debate in the literature, but a minimum of 25 to 30 km of displacement of late Tertiary and Quaternary age is generally accepted.

Extension within the Death Valley is at best described using a pull-apart model as a consequence of strike-slip motion transfers between the NDVFZ and SDVFZ. Cenozoic sedimentary deposits accumulated in several basins (Mesquite Flat, Cottonball, Badwater and Mormon Point basins) and mainly consist of detrital formations deposited in alluvial fans, ephemeral and perennial lakes and large amounts of evaporites.

Reasons for selecting the given analogue at Death Valley, California, USA

In addition to the abovementioned reason, we here detail the six main arguments in favour of a field campaign along the SDVFZ. We concentrate our efforts on the southern termination of the DVFZ along a previously described granitic pluton about 12 km in length and 2 km large.

1) The Rhine valley is densely populated and intensively used for agriculture and the Vosges, Black Forest and Odenwald massifs covered by forest. Given the poor outcropping conditions both in terms of geographical extend and weathering of samples, geological information like natural fracture or fractured zones is gained from exploration and exploitation boreholes (core, cuttings, borehole image, well-logging, Vertical Seismic Profile), few active quarries and geophysical campaigns. The desertic climate conditions at DV allow for virtually 100% outcrop exposure and limited rock weathering. Such conditions are ideal for large scale 3D models construction in the view of fracture analysis networks and sampling with a relatively intact rock original microfabric characteristics.
2) Both Rhine Graben and SDVFZ have a comparable tectonic setting consisting in a transtensional deformation with ancient basement rocks (variscan granite at Soultz sous Forêts demonstration site, Mesozoic granite in Southern DV) and sedimentary cover (Mesozoic and Tertiary sediments of the Rhine graben, Tertiary Sediments of the Noble Hills formation in the SDVFZ).
3) The SDVFZ is fairly recent and well documented in literature which can rule out any polyphase tectonic deformation and polyphase metamorphic overprint of the observed rock units.
4) It is expected that the presence of vast amounts of evaporites (gypsum and halite) at the base of the Noble Hills Tertiary sedimentary sequence will increase the salinity of the fluids circulating in the SDVFZ. This point is of particular importance regarding the analogy with the Soultz sous Forêts power plant where geothermal brines are characterized by a high salinity of about 100 g/l.
5) The size of the analogue at DV is directly comparable to the inferred reservoir size below the Soultz sous Forêts and Rittershoffen geothermal plants.
6) Massive geothermal energy is already exploited in this part of the ECSZ in fractured basement rocks, at the 170 MWe power plant of Coso. The Coso valley running parallel to the strike of Death Valley at a distance of less than 200 miles presents a geological setting similar to the Death Valley zone.

Methods of investigation

We are aiming at a combined conventional field mapping and digital photogrammetric survey at different scales (airborne, drone and ground photogrammetry) plus several sampling profiles across the deformed granitic pluton.

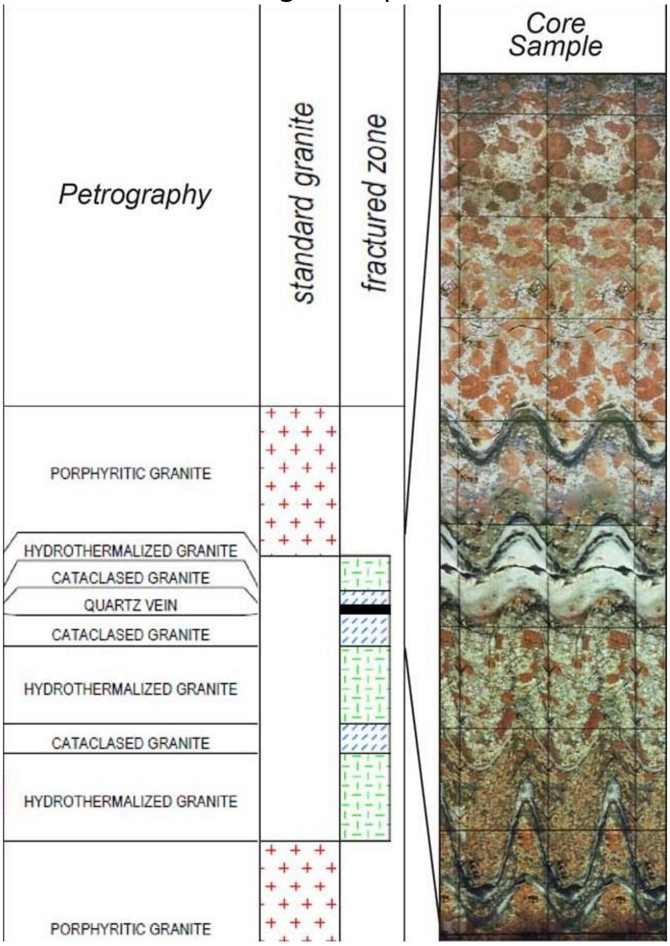

Figure 10: Core section of a fracture zone from a Soultz sous Forêts borehole (Vidal and Genter, 2018)

Inspection of the cores retrieved from a Soultz sous Forêts borehole (Figure 10) show that fractures present a clustered organization with low spacing fractures and associated hydrothermal alteration. Some of those clustered fractured and hydrothermally altered zones show evidences of paleo or present day permeability. It turns out that massive granite is intersected by fractures at different scales from individual tiny fractures to highly deformed brittle cataclastic facies: cataclastic granite, brecciated to micro-brecciated granite, ultracataclastic deformation bands and secondary quartz veins.

As already mentioned these data are restricted to borehole core and limited outcrop analysis at surface. No direct extrapolation of fracture organization or reconstruction of fluid circulation paths at larger scale of more than few 100 m can be proposed without a huge amount of hypothesis. Under such circumstances the validity of the obtained models remains questionable.

Our multiscale photogrammetric approach based on more than 6000 aerial pictures and 15 h drone flying using a high resolution 4K camera aims to fill this gap by first obtaining a precise 3D model down to decimeter scale of the whole reservoir and centimetric scale on selected profiles. This model, precisely calibrated in space using Differential GPS referencing combined to detailed mapping on key outcrops, will be used for an automated fracture network reconstruction with excellent statistics.

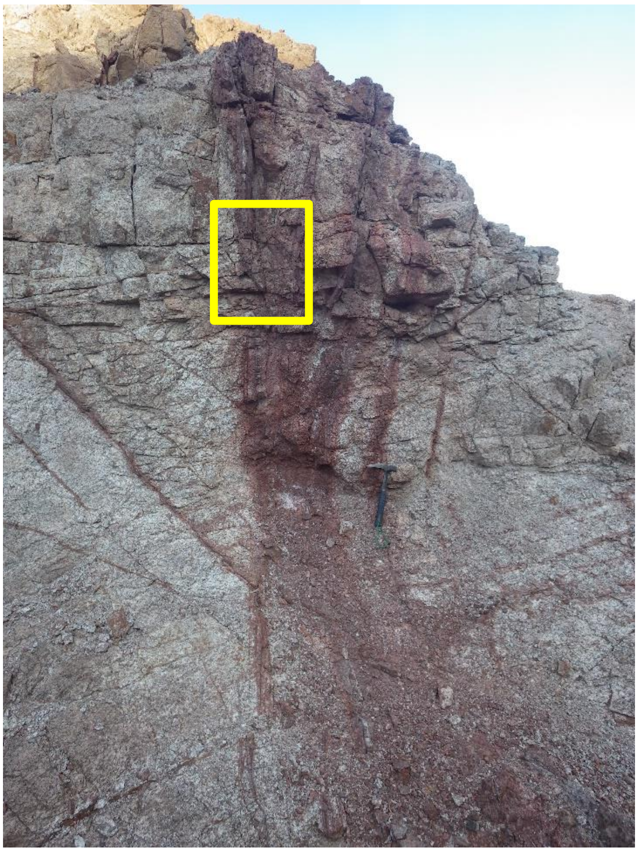

Figure 11: Typical fracture network encountered in granitic rocks affected by activity along the SDVFZ. Note the complicated fracture pattern and deposition of oxide minerals in the fracture planes.

Finally, we are in the process of achieving several sampling profiles across the deformed granitic units in order to outline the fluid rock interaction processes on fracture porosity and permeability through time and petrophysical properties of the rock matrix. These parameters are of primary importance regarding geothermal reservoir productivity through time. The chosen analogues show gradients of deformation in the granite and samples will be collected along these gradients.

The samples will be investigated in the laboratory by means of detailed thin section mapping from light and electron microscopy both in terms of microstructure (grain size and grain shape analysis) and mineral determination. EDS analysis is also planned in order to complete the details of the petrographic analysis.

XRD measurements will be used to outline the possible presence and nature of clay minerals within fault gauges. Fluid inclusions analysis on quartz veins will bring further insights on the fluid temperature having circulated in the fracture. This method will also outline possible multiple generation of quartz precipitates corresponding to different pulses of fluid flow in the fracture. Finally, if sufficient sample material can be obtained with a high enough sample stability analysis of petrophysical and mechanical properties is planned.

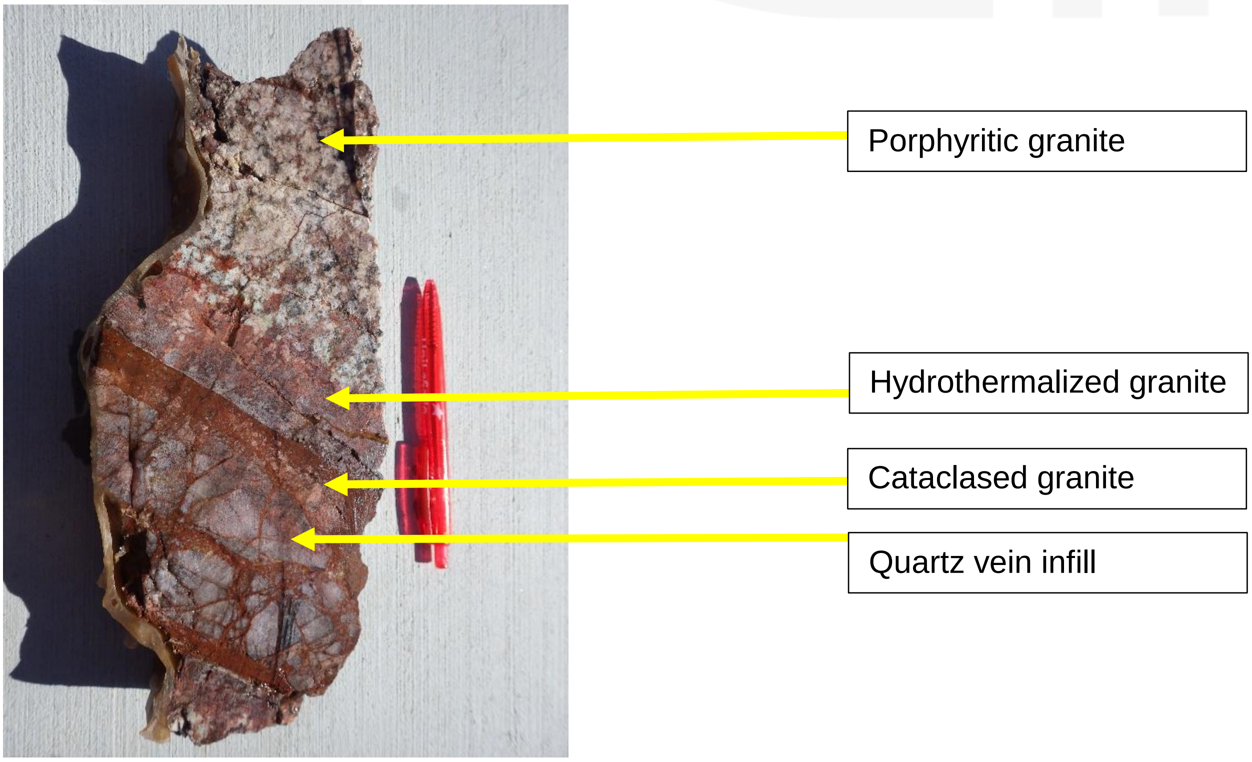

Figure 12: Detailed view of a hand specimen collected across the fracture depicted in the previous picture. Note the striking similarity with the core presented by Vidal and Genter (2018) with a distribution of quartz veins infill in fracture center and a succession of cataclased granite, hydrothermalized granite and porphyritic granite away from it.

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2.1.4 Variscan basement not overprinted by late extensional faults (Authors: K.Bär, J. Reinecker)

Target horizon: Carnmenellis granites outcropping in the quarries between Redruth and St. Austell.

Geothermal test site: United Downs Deep geothermal Power project (UDDGP) Redruth/Cornwall, Britain.

2.1.4.1 The UDDGP project

The United Downs Deep Geothermal Power project (UDDGP) located near Redruth in Cornwall/UK is being led by Geothermal Engineering Ltd. (GEL) and partly funded by the European Regional Development Fund, by the Cornwall Council and by private investors (https://www.uniteddownsgeothermal.co.uk/). Several European and national research projects (e.g. H2020: S4CE, CHPM2030, MEET) or research institutions (University of Plymouth, Camborne School of Mines, British Geological survey and many more) are directly connected to UDDGP focussing on different or even partly overlapping aspects associated to it.

In contrast to the earlier Rosemanowes Hot Dry Rock (HDR) project (Parker 1999) approximately 7 km south of United Downs, the UDDGP project aims to drill two deviated wells through a deep seated sub-vertical fault zone in the local Carnmenellis granite. The first one aims to penetrate the fault in about 2.5 km depth, the second in approx. 4.5 km. Cold water being injected in the first well is expected to infiltrate the fault zone by gravity, to heat up and to be produced through the second well. Drilling through a pre-existing, favourably aligned, but inactive fault zone is thought to capitalise on natural permeability within the fault zone. This should enable more flow to occur at lower injection pressures, improving the long-term economics of the project.

2.1.4.2 Regional Geology

Most of Cornwall's geology comprises units of Devonian metasediments ('Killas') and Early Permian granites (Figure 13). During the Devonian marine sediments (mainly black siltstones and mudstones) were deposited within large basins (Leveridge and Hartley 2006). Basic igneous rocks intercalate as sills or layer-parallel bodies. This succession has been intensely affected by the Variscan orogeny by faulting (thrusting), folding and low grade metamorphism resulting in a complex deformation of the Killas. By the end of active Variscan convergence in the Late Carboniferous orogenic collapse leads to regional extension, intense magmatism, and the emplacement of the Cornubian Batholith (Charoy 1986) in several stages. Associated hydrothermal mineralization during the main stage is hosted in ESE-WNW striking mineral 'lodes' and in NW-SE to N-S striking 'cross-course' structures (a traditional term in Cornish geology for mineralised faults that cut and displace the lodes of any given district at (or around) right-angles to their strike), many of which are reactivations of earlier strike-slip faults (LeBoutillier 2002).

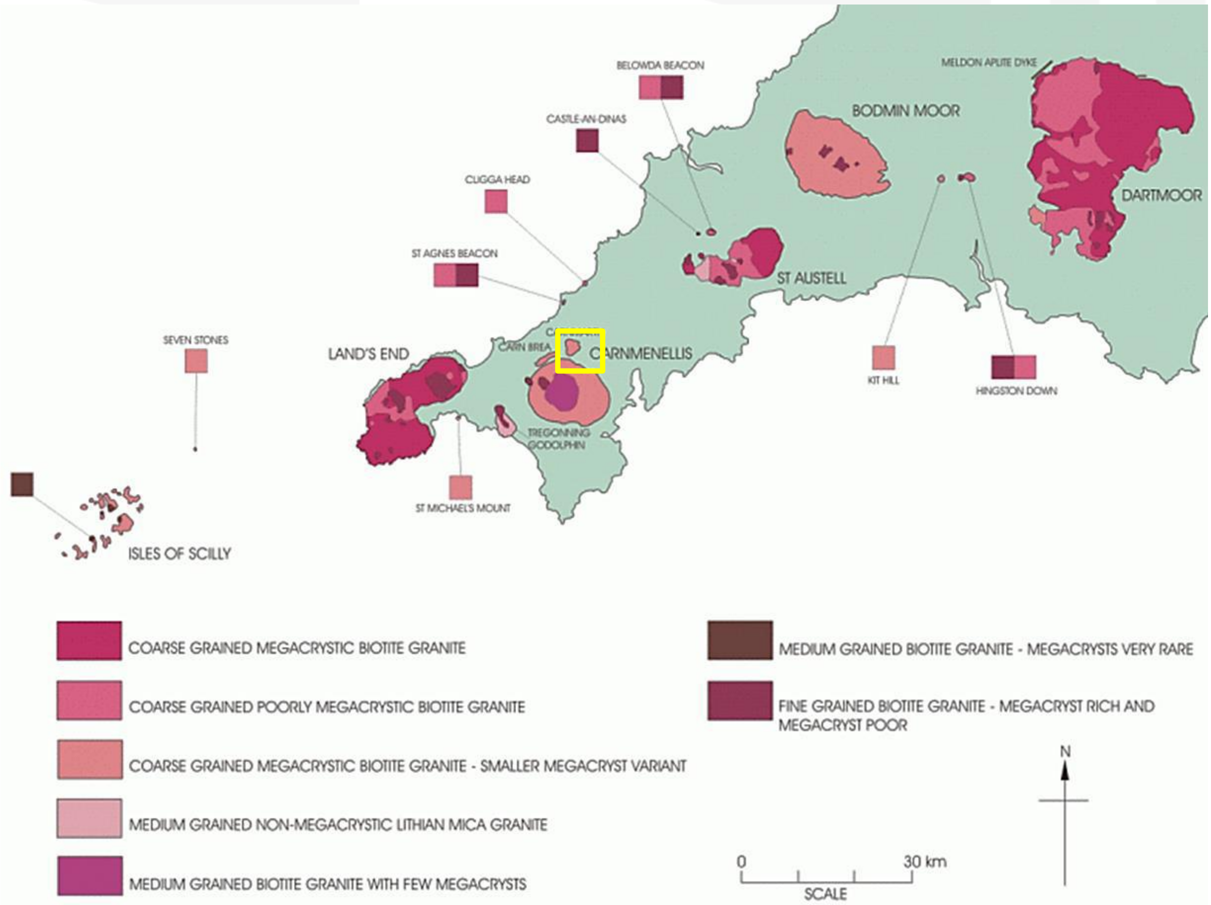

Figure 13: The distribution of granite varieties across the Cornubian Batholith (Hawkes et al., 1987); green: Devonian metasediments ('Killas'), yellow square: location of the UDDGP project

The Carnmenellis granite is a sub-circular composite intrusion and forms part of the Variscan Cornubian batholith. The medium to coarse-grained granite often shows abundant K-feldspar megacrysts >15 mm. Much of the rock has been affected by hydrothermal alteration (chloritisation of biotite, kaolinisation, and sericitisation of feldspars). Minor lithologies include dyke-like 'elvans' and narrow, steeply dipping pegmatitic veins. Intrusion of the Carnmenellis granite took place around 293.3 ± 1.2 Ma (Chen et al. 1996, Chesley et al. 1993) in multiple pulses with differing chemistry and texture (e.g. Charoy 1986) and during a phase of late- to post-orogenic collapse in an extensional regime (e.g. Alexander and Shail 1995). With depth there may be changes in grain size and mineral composition as indicated by surface mapping in the wider region which shows variations which probably reflect a multi-phase intrusion history. In addition, although the granite is expected to be the main rock type to depths >5 km the possibility of locally encountering inter-digitated Devonian metasediment units cannot be ruled out. The shape of the Cornubian batholith has been derived from gravity modelling (Willis-Richards and Jackson 1989, Willis-Richards 1990, Taylor 2007). In the north two satellite granite bodies are exposed, the Carn Brea in the west and the Carn Marth in the east, both in close relation to the Carnmenellis intrusion (see figures 13 and 14).

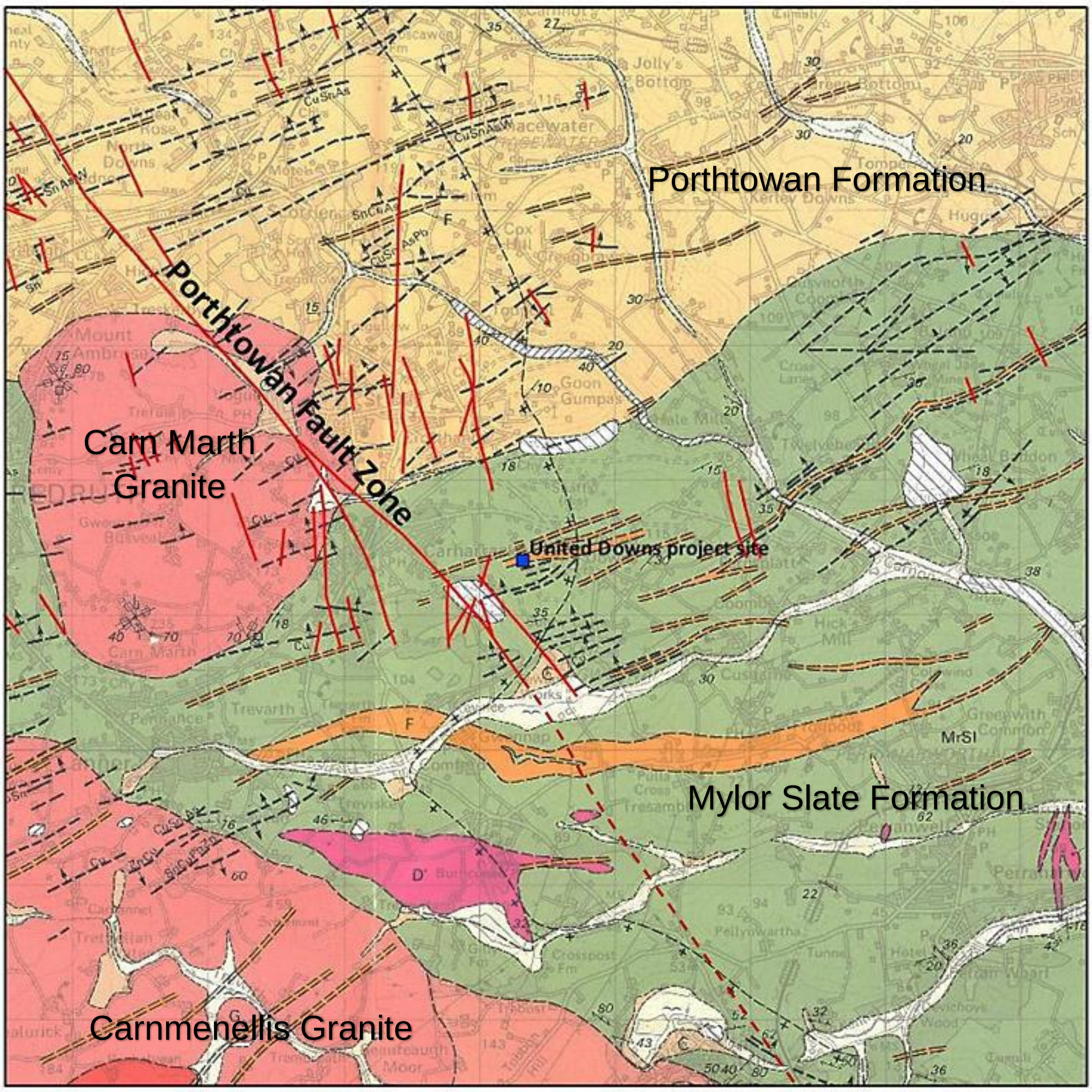

Figure 14: Geological map of the UDDGP site indicating the main formations and structures (Geology after BGS, sheet 352 Falmouth)

The development of 'cross-courses' was controlled by pre-granite tension joints and wrench faults (many of these fractures appear to have a movement history that is pre-, syn- and post-granite emplacement, only becoming mineralised during the final stages of the development of the orefield), oriented NNW-SSE to N-S. 'Cross-courses' typically reach a few metres in width (but may range from ~1 cm to >100 metres) and often have dextral throws from a few metres to tens of metres to over 100 m (LeBoutillier 2002). Information on vertical displacement along these 'cross-courses' has not been compiled within MEET and will be reviewed in more detail in the upcoming months.

The Porthtowan Fault Zone (PTF, figure 14) belongs to a family of cross-courses and similar NW-SE striking structures that transect SW England (BGS 1975) and are strike-slip fault zones which accommodated periods of extensional (Devonian, Permo-Triassic) and compressional (Variscan, Alpine) tectonics with dextral and sinistral movements respectively. The PTF is a sub-vertical (~050°/85°) structure penetrating both 'killas' and granite. Foliated and mylonitised granites give evidence for PTF being active during granite emplacement. Tertiary activity is possible due to its association with the Sticklepath Fault and other similar structures further east. Fault plane solutions from the Rosemanowes HDR project and present day in-situ stress field would even support a more recent activity of the PTF.

2.1.4.3 Outcrop analogue sites

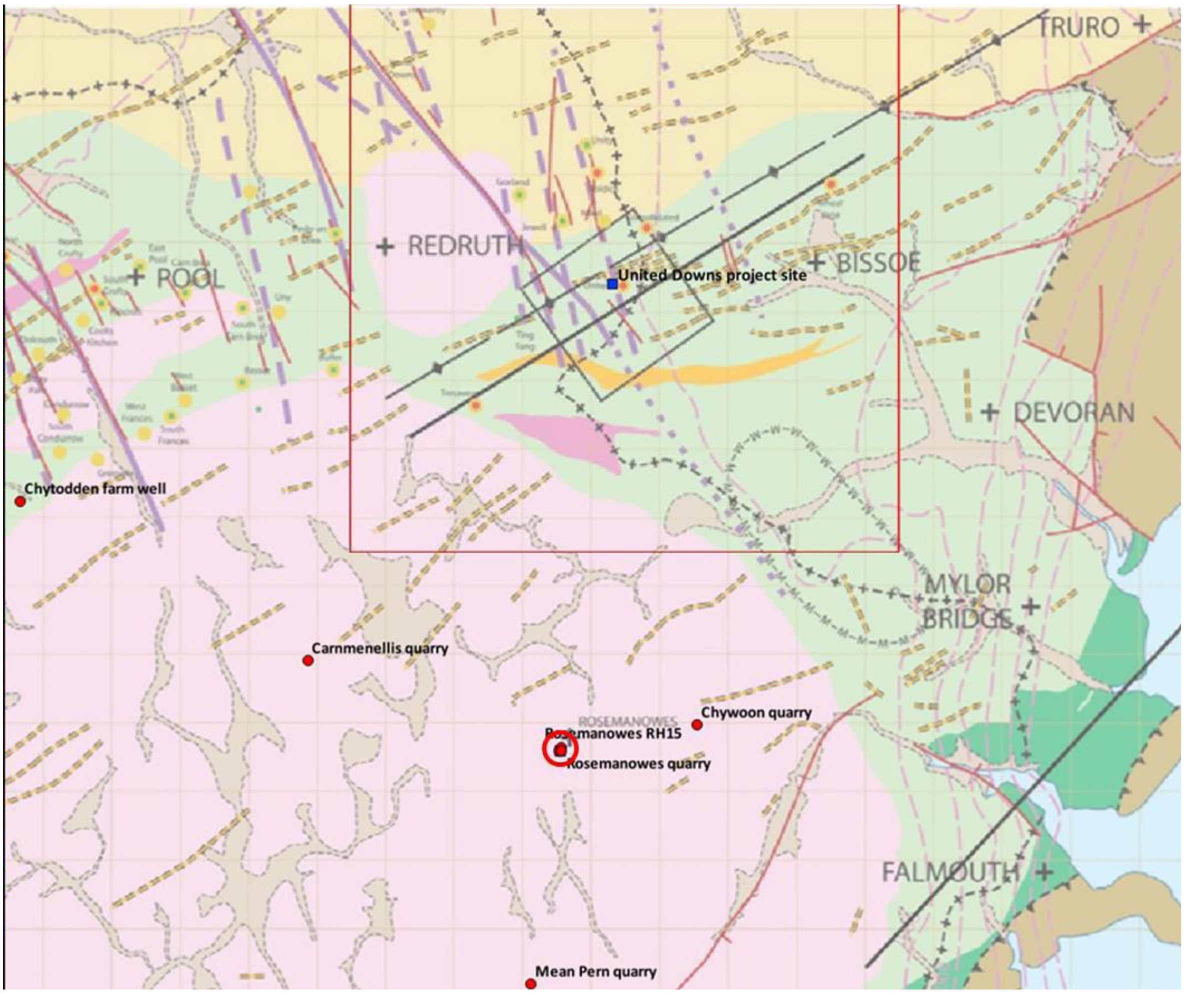

Figure 15: Local geological map of the UDDGP site including the locations of the former Rosemanowes EGS project test site and some quarries within the Carnmenellis granite.

Within the CHPM2030 project and its research associated to the UDDGP the BGS in cooperation with the Camborne School of Mines and the project leaders Geothermal Engineering Ltd. (GEL) developed a project related field guide, which is about to be published via the BGS online repository before the end of November 2018 (Deady et al. 2018 in prep). An additional field trip was conducted within the S4CE project in 2018. These field guides together with the older

reports and publications of the Rosemanowes project describes and rates the different outcrops of the Carnmenellis and associated granites and is the basis to the selection of suitable outcrop analogues for the lab investigations planned within MEET. The closest outcrops in active or recently closed open pit quarries are displayed in Figure 15 and will be the primary locations for sampling. Due to the multi-stage emplacement of the Carnmenellis and its associated granites it is not guaranteed, that all geochemical and textural variations of the granites are covered by these outcrops and it remains to be determined by the UDDGP drilling activities whether the granite at depth resembles the outcropping granites sufficiently and whether significant sections of meta-sediments ('killas') are present at larger depth, which also need to be considered.
Based on the results of the first well, it will be decided within the project consortium of MEET in close cooperation with the UDDGP consortium, whether sidewall coring within the first well is necessary to obtain representative sample material of both the host rocks and fracture zones including fracture mineralizations.
Secondary locations will be selected with a focus on fault zones or 'cross-courses' along the cliffs at the cost lines to sample fracture filling mineralizations and host rock affected by hydrothermal alterations along these fracture corridors. Since the Carnmenellis and directly associated granites are not outcropping along the coast, similar granites of the Cornubian Batholith will be sampled as analogues.
Sampling will be completed by cutting samples from the first UDGGP well, where GEL already agreed on providing sampling material as requested by MEET in September 2018. This will be complemented by access to the drilling reports, borehole geophysical logging and test results.

2.1.4.4 Planned analyses

Rock samples will be processed mostly by the same analytical protocols as described in the previous sections. On the rock samples we will conduct first of all non-destructive analyses such as thin section analysis, XRF and XRD for petrography to evaluate the internal composition, texture and porosity and geochemistry. The samples will then be used for non-destructive petrophysical and destructive mechanical tests. The results will later be combined with logging data available for the whole length of the first borehole.
The fracture mineralization samples together with the drilling report, borehole geophysical logs and well test results will be used for the design of the chemical stimulation approach. The cuttings and samples of outcropping mineralized fractures will be used for chemical dissolution experiments to determine, which chemical composition of a possible stimulation agent would be best suited.

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