

Arbeitsbericht NAB 20-09

**TBO Trüllikon-1-1:
Data Report**

**Dossier V
Structural Geology**

June 2021

**National Cooperative
for the Disposal of
Radioactive Waste**

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Keywords:

TRU1-1, Zürich Nordost, TBO, deep drilling campaign,
structural geology, goniometry, drill cores

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

This NAB aims at reporting drilling results at an early stage. Additional borehole-specific data will be published elsewhere.

In the event of inconsistencies between dossiers of this NAB, the dossier addressing the specific topic takes priority. In the event of discrepancies between Nagra reports, the chronologically later report is generally considered to be correct. Data sets and interpretations laid out in this NAB may be revised in subsequent reports. The reasoning leading to these revisions will be detailed there.

This Dossier was prepared by a project team consisting of:

- A. Ebert (writing and QC)
- S. Cioldi (core description, core photograph picking, core goniometry, writing)
- L. Gregorczyk (writing and QC)
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Editorial work: Geomecon and the graphics and editing teams at Nagra

The Dossier has greatly benefitted from technical discussions with, and reviews by, external and internal experts. Their input and work are very much appreciated.

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Note: In the digital version of this report the appendices can be found under the paper clip symbol.

1 Introduction

1.1 Context

To provide input for site selection and the safety case for deep geological repositories for radioactive waste, Nagra has drilled a series of deep boreholes in Northern Switzerland. The aim of the drilling campaign is to characterise the deep underground of the three remaining siting regions located at the edge of the Northern Alpine Molasse Basin (Fig. 1-1).

In this report, we present the results from the Trüllikon-1-1 borehole.

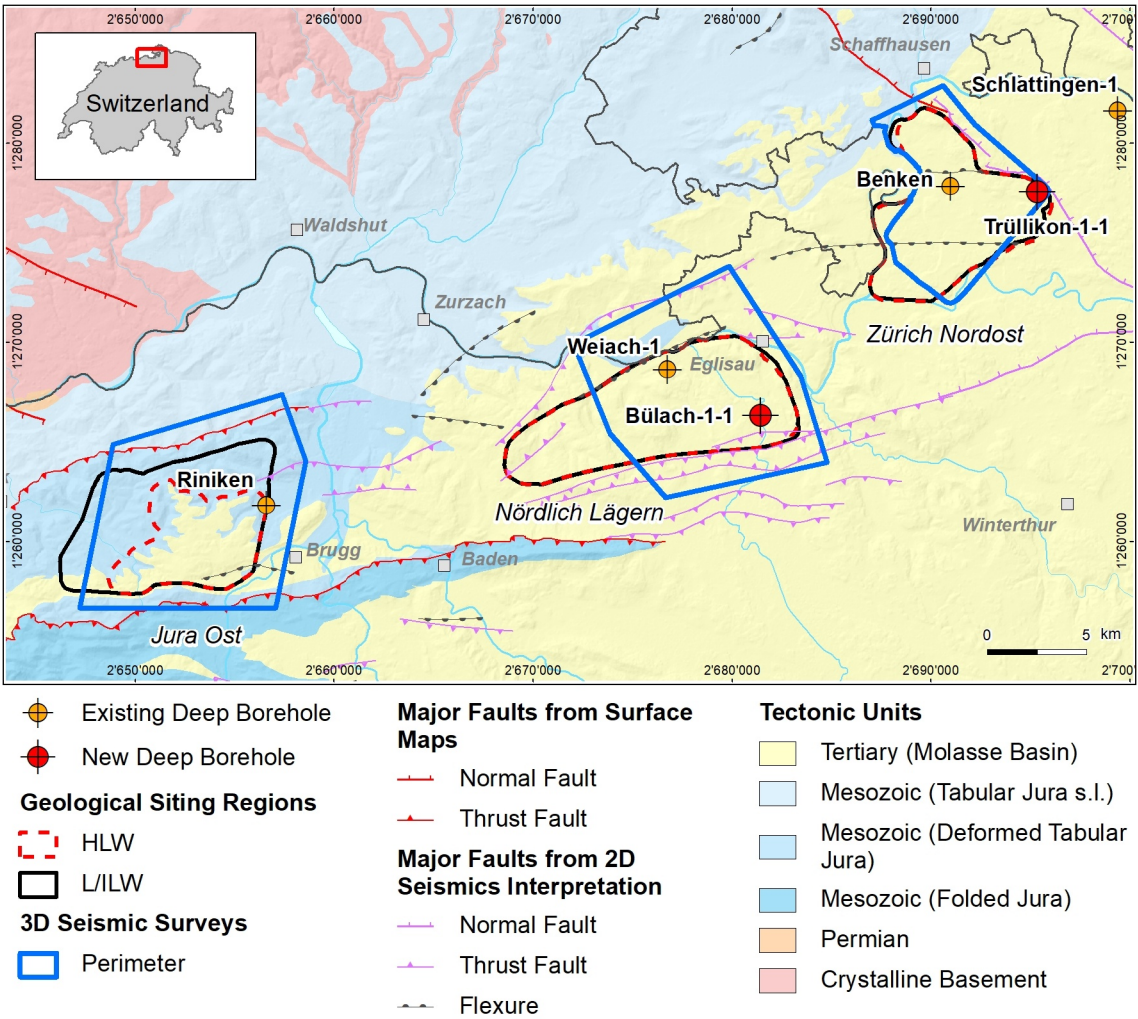


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Trüllikon-1-1 (TRU1-1) exploratory borehole is the second borehole drilled within the framework of the TBO project. The drill site is located in the eastern part of the Zürich Nordost siting region (Fig. 1-2). The vertical borehole reached a final depth of 1'310 m (MD)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the TRU1-1 borehole

Siting region	Zürich Nordost
Municipality	Trüllikon (Canton Zürich / ZH), Switzerland
Drill site	Trüllikon-1 (TRU1)
Borehole	Trüllikon-1-1 (TRU1-1)
Coordinates	LV95: 2'695'372.648 / 1'277'548.076
Elevation	Ground level = top of rig cellar: 475.07 m above sea level (asl)
Borehole depth	1'310.0 m measured depth (MD) below ground level (bgl)
Drilling period	15. August 2019 – 5. April 2020 (spud date to end of rig release)
Drilling company	PR Marriott Drilling Ltd.
Drilling rig	Rig-16 Drillemec HH102
Drilling fluid	Water-based mud with various amounts of different components such as ² : 46 – 712 m: Pure-Bore® 712 – 1'161 m: Potassium silicate 1'161 – 1'310 m: Sodium chloride & polymers

The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. The comparison of the core versus log depth³ of the main lithostratigraphic boundaries in the TRU1-1 borehole is shown in Tab. 1-2.

¹ Measured depth (MD) refers to the position along the borehole trajectory, starting at ground level, which for this borehole is the top of the rig cellar. For a perfectly vertical borehole, MD below ground level (bgl) and true vertical depth (TVD) are the same. In all Dossiers depth refers to MD unless stated otherwise.

² For detailed information see Dossier I.

³ Core depth refers to the depth marked on the drill cores. Log depth results from the depth observed during geophysical wireline logging. Note that the petrophysical logs have not been shifted to core depth, hence log depth differs from core depth.

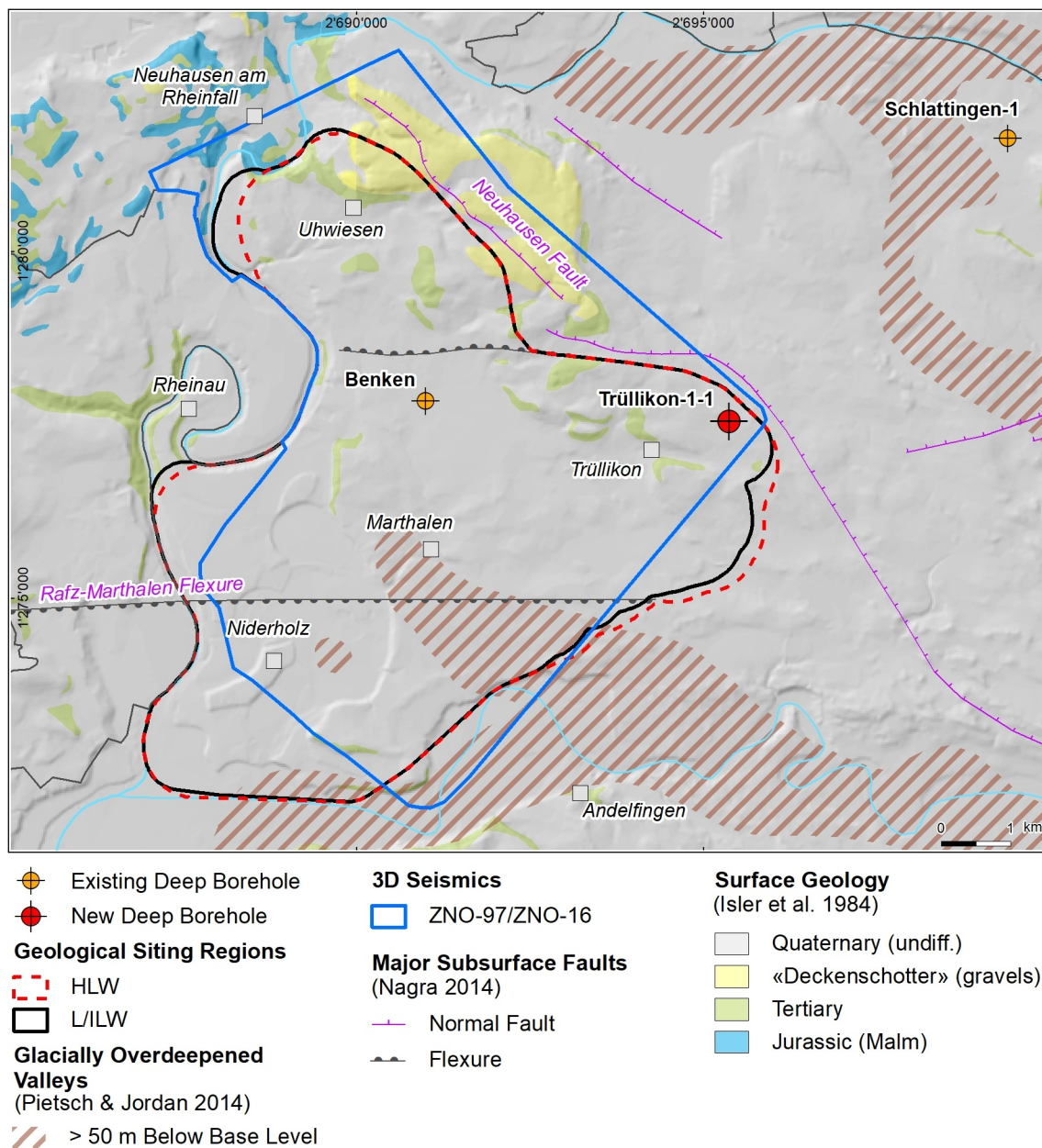
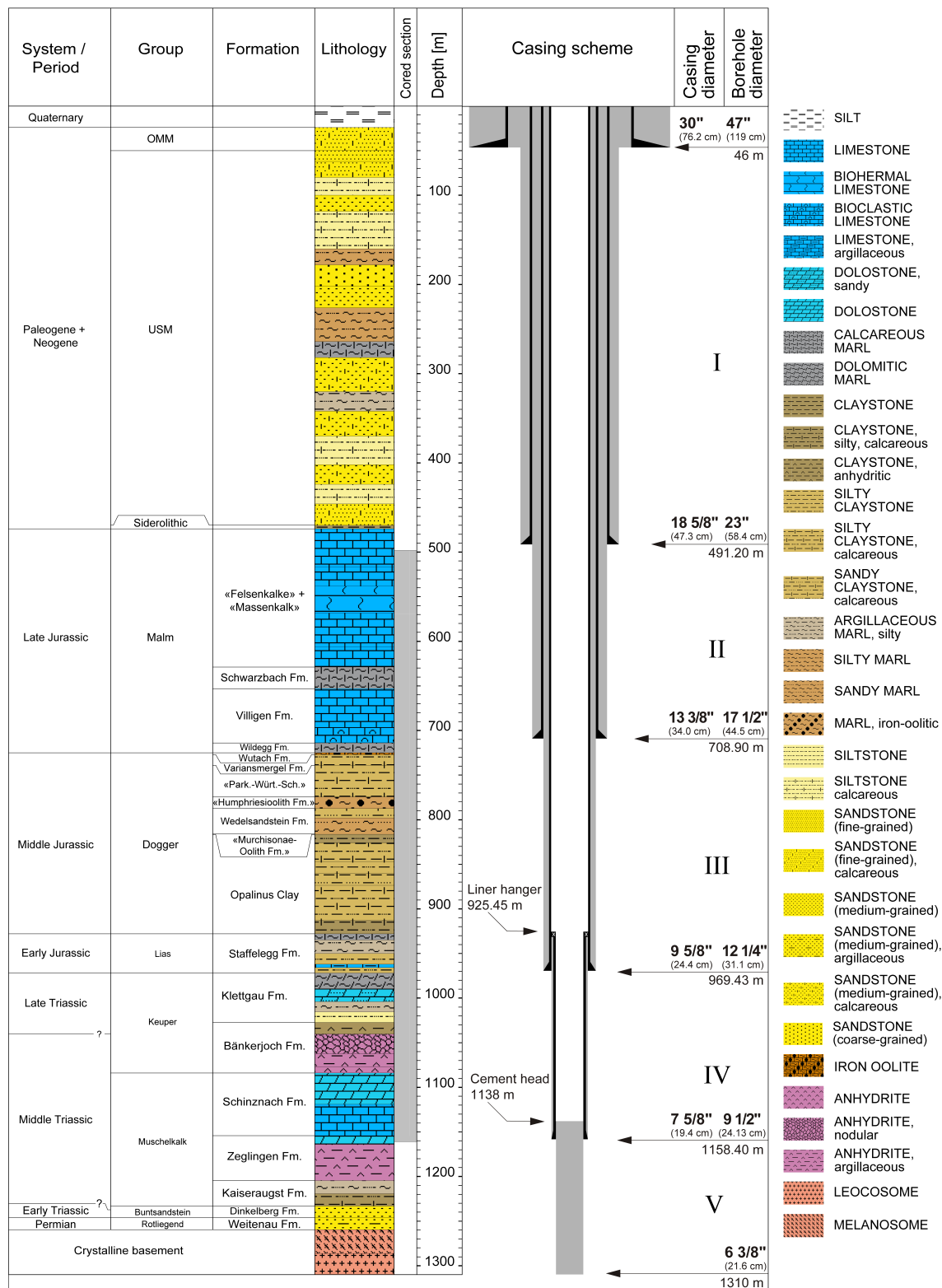


Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the TRU1-1 borehole in relation to the boreholes Benken and Schlattigen

Fig. 1-3: Lithostratigraphic profile and casing scheme for the TRU1-1 borehole⁴⁴ For detailed information see Dossier I and III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the TRU1-1 bore-hole⁵

System / Period	Group	Formation	Core depth in m (MD)	Log
Quaternary			24.0	—
Paleogene + Neogene	OMM		50.0	—
	USM		470.0	—
	Siderolithic		474.0	—
Jurassic	Malm	«Felsenkalke» + «Massenkalk»	628.87	628.75 —
		Schwarzbach Formation	653.29	653.15 —
		Villigen Formation	714.00	714.00 —
		Wildegge Formation	724.85	725.03 —
	Dogger	Wutach Formation	727.13	727.27 —
		Variansmergel Formation	738.97	739.06 —
		«Parkinsoni-Württembergica-Schichten»	774.55	774.66 —
		«Humphriesioolith Formation»	787.50	787.55 —
		Wedelsandstein Formation	815.51	815.50 —
		«Murchisonae-Oolith Formation»	816.42	816.43 —
		Opalinus Clay	927.91	927.87 —
		Lias	971.68	971.55 —
Triassic	Keuper	Klettgau Formation	1027.22	1027.44 —
		Bänkerjoch Formation	1084.01	1084.22 —
	Muschelkalk	Schinznach Formation	1154.25	1154.43 —
		Zeglingen Formation	1204.5	—
		Kaiseraugst Formation	1233.2	—
	Buntsandstein	Dinkelberg Formation	1246.1	—
Permian	Rotliegend	Weitenau Formation	1259.7	—
		Crystalline Basement	1310.0	final depth

⁵ For details regarding lithostratigraphic boundaries see Dossier III, for details about depth shifts (core goniometry) see Section 2.1.

1.3 Documentation structure for the TRU1-1 borehole

NAB 20-09 documents the majority of the investigations carried out in the TRU1-1 borehole, including laboratory investigations on core material. The NAB comprises a series of stand-alone dossiers addressing individual topics and a final dossier with a summary composite plot (Tab. 1-3).

This documentation aims at early publication of the data collected in the TRU1-1 borehole. It includes most of the data available approximately one year after completion of the borehole. Some analyses are still ongoing (e.g. diffusion experiments, analysis of veins, hydrochemical interpretation of water samples) and results will be published in separate reports.

The current borehole report will provide an important basis for the integration of datasets from different boreholes. The integration and interpretation of the results in the wider geological context will be documented later in separate geoscientific reports.

Tab. 1-3: List of dossiers included in NAB 20-09

Black indicates the dossier at hand.

Dossier	Title	Authors
I	TBO Trüllikon-1-1: Drilling	M. Ammen & P.-J. Palten
II	TBO Trüllikon-1-1: Core Photography	D. Kaehr & M. Gysi
III	TBO Trüllikon-1-1: Lithostratigraphy	M. Schwarz, P. Jordan, P. Schürch, H. Naef, T. Ibele, R. Felber & M. Gysi
IV	TBO Trüllikon-1-1: Microfacies, Bio- and Chemostratigraphic Analyses	S. Wohlwend, H.R. Bläsi, S. Feist-Burkhardt, B. Hostettler, U. Menkveld-Gfeller, V. Dietze & G. Deplazes
V	TBO Trüllikon-1-1: Structural Geology	A. Ebert, S. Cioldi, L. Gregorczyk, S. Rust, D. Böhni & M. Gysi
VI	TBO Trüllikon-1-1: Wireline Logging and Microhydraulic Fracturing	J. Gonus, E. Bailey, J. Desroches & R. Garrard
VII	TBO Trüllikon-1-1: Hydraulic Packer Testing	R. Schwarz, L. Schlickenrieder, H.R. Müller, S. Köhler, A. Pechstein & T. Vogt
VIII	TBO Trüllikon-1-1: Rock Properties, Porewater Characterisation and Natural Tracer Profiles	L. Aschwanden, L. Camesi, T. Gimmi, A. Jenni, M. Kiczka, U. Mäder, M. Mazurek, D. Rufer, H. N. Waber, P. Wersin, C. Zwahlen & D. Traber
IX	TBO Trüllikon-1-1: Rock-mechanical and Geomechanical Laboratory Testing	E. Crisci, L. Laloui & S. Giger
X	TBO Trüllikon-1-1: Petrophysical Log Analysis	S. Marnat & J.K. Becker
	TBO Trüllikon-1-1: Summary Plot	Nagra

1.4 Scope and objectives of this dossier

The dossier at hand (Dossier V) documents the work of the structural geology experts. The objectives of the report are:

- core goniometry to reset drill cores to the correct depth and original orientation based on high resolution borehole images and high resolution 360° core photographs (Appendices E-1 and E-2)
- structural discontinuities identification on high resolution 360° core photographs and drill cores
- true dip and dip azimuth analysis of structures and bedding planes on high resolution 360° photographs in TerraStation II and/or manual measurements with a geological compass on drill cores
- documentation of recorded structures and their relevant parameters
- visualisation of structural geology data as profiles and overview plots:
 - profile 1:1'000: Appendix B
 - profile 1:100: Appendices C-1 to C-3
 - overview plot of stereograms and rose diagrams: Appendices D-1 and D-2

The level of detail in this dossier is limited by the data availability at data cut-off two months after the end of drilling operations. The lithostratigraphic subdivision used in this report is in line with the finding in Dossier III.

1.5 Petrophysical logs and preliminary log analysis available

The petrophysical logs and preliminary log analysis listed below were available at the data-freeze and considered as a supplementary source of information for this report (for more details, see Dossier VI):

- total natural gamma ray borehole and potassium corrected (GR)
- caliper / radius (RD1 to RD6)
- near / array corrected limestone porosity (APLC)
- high resolution formation density (RHO8)
- high resolution formation photoelectric factor (PEF8)
- array laterolog apparent resistivity from computed focusing mode 0 to 5 (RLA1 to RLA5)
- formation micro imager (FMI)
- ultrasonic borehole image (UBI)
- borehole breakouts and centreline fractures analysis based on FMI and UBI images

1.6 Borehole deviation

Within the cored section, the borehole TRU1-1 is almost vertical with a slight deviation towards the northwest. The maximum borehole deviation is 2.7° at 1'150 m MD log depth. This leads to a maximum deviation of 18 m to the northwest at TD (total depth; see Fig. 1-4).

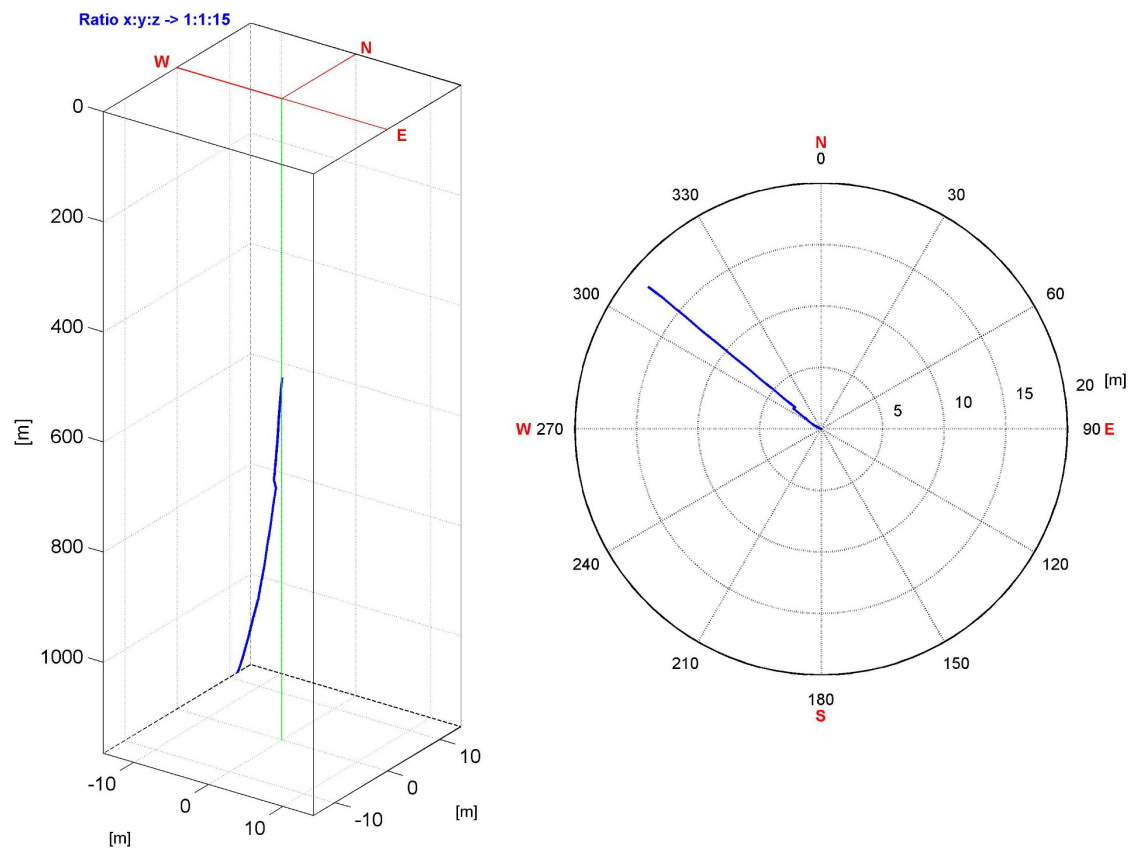


Fig. 1-4: Borehole deviation within the cored section

The left image visualises the borehole path in 3D with a compressed z-axis. The borehole azimuth is shown on the right.

2 Methodology

2.1 Core goniometry

2.1.1 Introduction

A structural analysis was performed on drill cores along with circumferential and planar drill core photographs. Using the reference line on the core surface, positioned at an azimuth of 0° during core photography, most drill cores could be oriented using borehole image logs.

For this study, high-resolution 360° and planar photographs were available for most of the cored interval from 498.00 to 1'161.03 m MD log depth. The data were delivered as 1'110 circumferential and 1'175 planar photographs in TIF format. The original photographs with a resolution of 10 pixels/mm, however, were too big to be handled within TerraStation II (TERRASCIENCES Inc.). Therefore, the original photographs were compressed by 25 % and exported with a resolution of 300 dpi. In addition, FMI and UBI logs were available. Both datasets were of good to excellent quality. Further relevant data included auxiliary borehole data, core orientation line and core section listings, lithostratigraphic tops and petrophysical logs.

2.1.2 Workflow

This section describes the methodology used for extracting the directional information from 360° core photographs. The following steps were tailored for efficient core goniometry using the TerraStation II software.

1. Quality control of core photographs:

Prior to loading the data, it was ensured that the core orientation line (red) on the 360° core photographs was set to 0°.

Note: The core orientation line (COL) represents a continuous reference line set to an azimuth of 0° to fix the relative orientation of drill cores. The COL was drawn on the core surface immediately after core retrieval at the drill site. The line lengths vary widely from a few centimetres up to several metres and therefore sometimes continue over several core sections. It depends on whether each individual core section could be fitted together along the core edges or not. If core sections could not be merged, a new COL was determined. The coherent COL was then used to orient the drill core using borehole image logs.

2. Data loading:

All 360° core photographs were loaded as mirror images in order to simulate the borehole image log. A constant value of 95 mm (3.74") was added as image diameter.

The processed FMI and UBI logs as well as the auxiliary petrophysical logs were imported into TerraStation II. It was checked that the depth of the petrophysical logs, especially the first GR run, matched the depth of the FMI data.

3. Depth shifting:

The 360° core photographs were shifted to FMI logs using distinct, correlated planar and/or non-planar features. For the purpose of simplicity and consistency, only one shift value was applied for each individual core section (generally 3 m per section). This resulted in minor data gaps and/or overlaps at core section boundaries of a few centimetres maximum. In total, 241 distinct depth shift values were applied for the core sections of the entire cored borehole; these varied from 0 to ± 1.58 m. The defined values are listed in Appendix E-1.

4. Core orientation:

The core was oriented using correlated geological features (e.g. faults / fractures, inclined / deformed bedding, nodules etc.) which were matched with the orientation on the FMI by rotating the 360° core photographs clockwise around the borehole axis.

The obtained angle of rotation was then applied to the entire core section with a continuous COL. Simultaneously, the validity across other geological features was checked. Note that the length of a linked COL segment was highly variable and could continue across several core sections. All COLs and the applied angles of rotation of the individual COLs are listed in Appendix E-2. To highlight the uncertainties related to core orientation, an uncertainty assessment was carried out and visualised in three confidence classes.

5. Quality control of core goniometry:

Prior to the structural recording of the drill cores, the depth shifts, the core correlation with the FMI / UBI combination and the core orientations were reviewed.

The following steps do not belong to classical core goniometry. However, they played a key role in the coherent workflow of the structural core analysis and are thus mentioned here:

6. Dip picking on oriented 360° core photographs:

Bedding-related planes were picked manually for a structural dip evaluation. Structural elements on drill cores were picked manually and characterised in detail with respect to relevant parameters.

7. Recording of kinematic features:

Kinematic indicators along fault surfaces such as slickensides, striations, shear sense indicators and (fault) offsets were identified and measured on the cores. To determine the lineation azimuth and plunge and/or planes not visible in the photographs, a goniometer constructed by Geo Explorers was used. The drill core was placed in the goniometer facing up-hole and rotated around the vertical axis by the angle of rotation determined from the core orientation line. Subsequently, the azimuth and plunge of the striation were measured using a geological compass (see Fig. 2-1).

8. Examination of angular differences:

Using the TectonicsFP software, the angular differences between the striation azimuths / plunges and the orientation of associated fault planes were checked. In cases where the angular offset exceeded 15°, the fault plane and lineation were remeasured.

9. Quality control:

A final quality control was performed with the main focus on consistency (between TerraStation, primary records of the structural core analysis and the structural inventory metadata), completeness of records and the accurate characterisation of the recorded tectonic features.

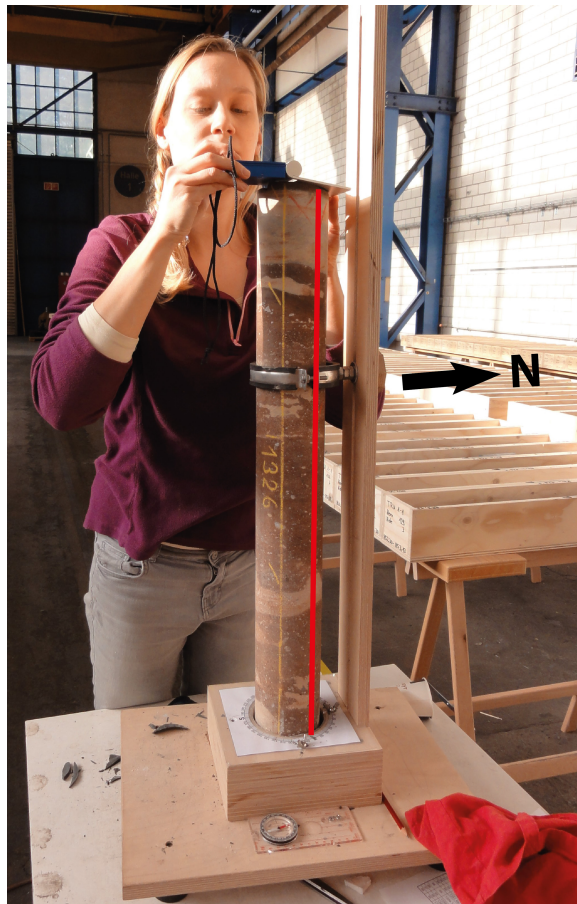


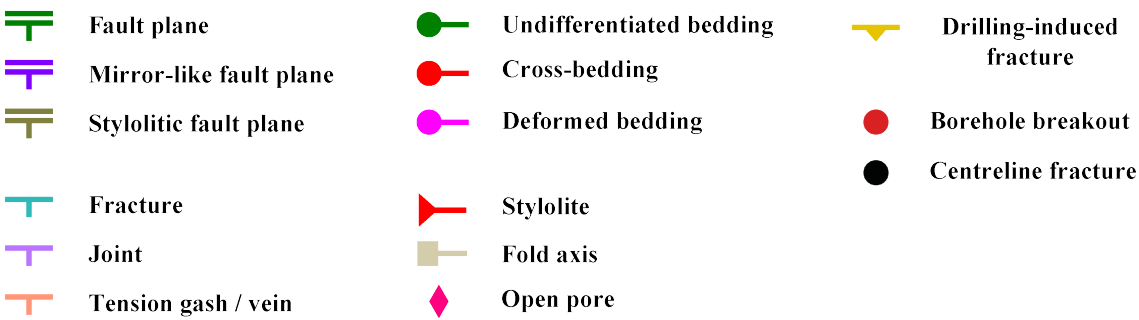
Fig. 2-1: Using a goniometer to determine kinematic indicators along faults
Note the red core orientation line defining the position of the drill core in the goniometer.

2.1.3 Dip picking and dip type classification

Due to higher accuracy and reliability compared to automated methods, a manual sinusoid method and a point-to-point method were used to pick all relevant features on the 360° core photographs. In a cylindrical borehole, a perfect plane will appear as a sine wave on the circumferential core scan and its amplitude reflects the dip relative to the borehole axis.

Different dip classes were defined for the different structure types. For this study, a total of 15 different dip types was defined in TerraStation (see Fig. 2-2).

Dip Types

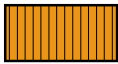


Fracture density classes

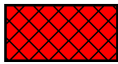
FDC2: 20 to 60 m²/m³



FDC3: 60 to 200 m²/m³

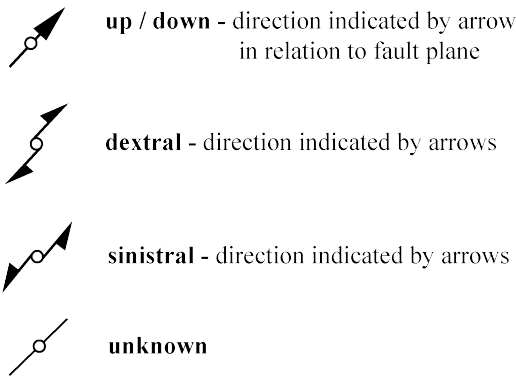


FDC4: > 200 m²/m³



TectonicsFP symbols

Shear sense:



Shear sense quality:

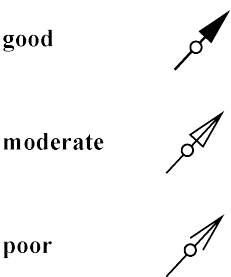


Fig. 2-2: Symbols for dip types, fracture density classes and kinematic data used for this study

Some structures were only visible on planes not outcropping at the rim of the core and were not visible on the 360° core photographs. The orientation of these structures was obtained with a geological compass and the data were subsequently imported into the digital dip dataset. Consequently, the associated dip sine waves did not fit with any visible traces and/or were simply not visible at this depth level, as exemplified in Fig. 2-3.

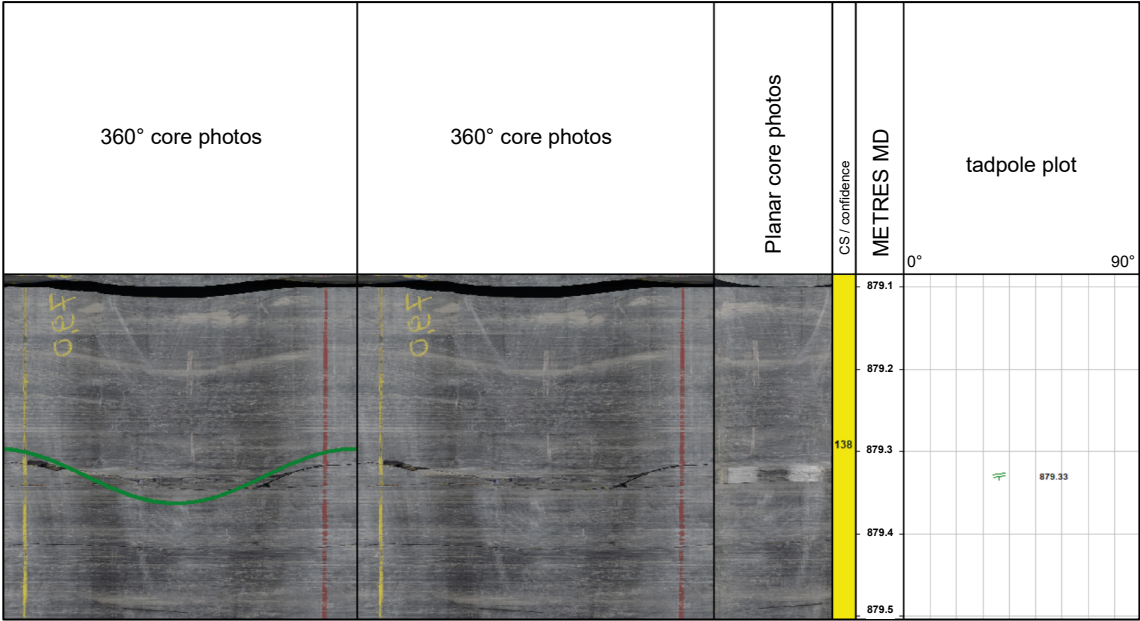


Fig. 2-3: Fault plane at 879.33 m MD log depth (Opalinus Clay)

From left to right: Shifted and oriented 360° core photograph with (left) and without (right) picked sine waves, followed by depth-shifted planar core photographs, core section numbering in the coloured bar displaying the goniometry confidence ranking, depth track showing the position and length of the currently displayed window, tadpole plot. Note that the displayed sine wave does not fit well with the visible (dark) fault trace and was implemented from the core analysis and the orientation obtained from compass measurement.

2.1.4 Dip data for non-oriented and missing cores

Due to a lack of correlated features and/or poor data quality, 102 m of the available drill cores remained non-oriented. 25 bedding planes and 466 tectonic / drilling-induced discontinuities could be observed and picked within these non-oriented drill cores. The structural planes were nevertheless manually measured with a geological compass and included into TerraStation II or digitally picked on 360° core photographs. In case of non-oriented drill cores and core photographs, the red core orientation line was set to 0°. As the dip measurement of these features are correct but the dip azimuth measurements are affected by the lack of orientation, the non-oriented dataset can only be used for fracture density calculations.

To highlight that the dip azimuth measurements of these features are incorrect, a quality indicator of 0 was assigned and hollow tadpoles used for visualisation (Fig. 2-4). A quality indicator of 1 was assigned to all correctly oriented features.

For intervals where 360° core photographs were missing, short drill core sections could still be oriented using the coherent core orientation line, which sometimes continued across several cores. The depth and orientation of the structures were then measured on the core and the dip data were subsequently imported into the digital database TerraStation (Fig. 2-5).

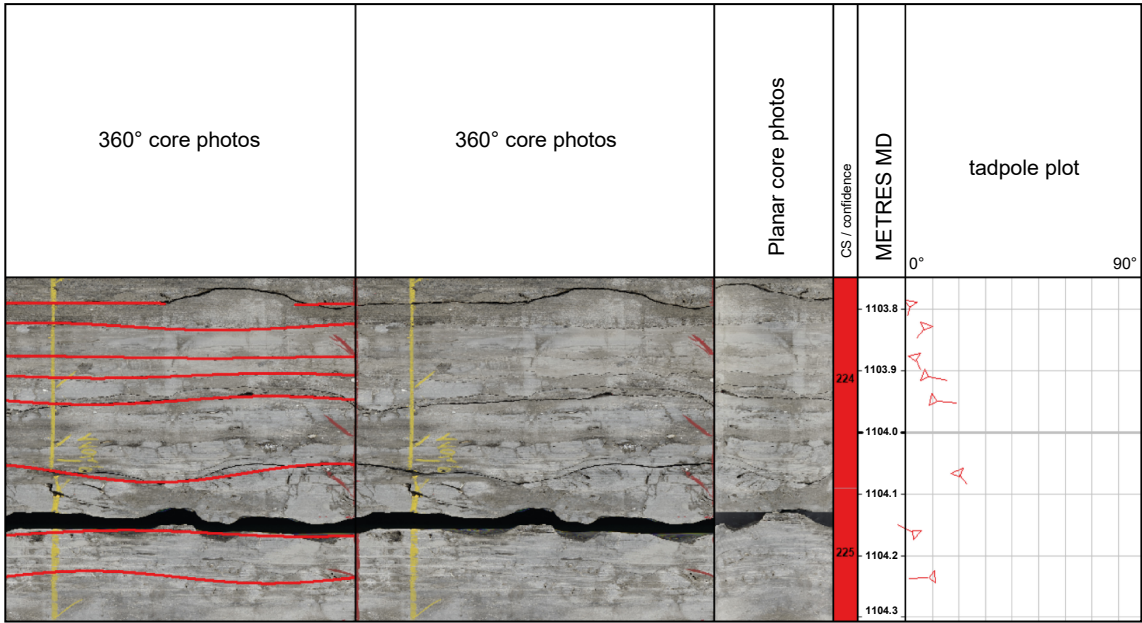


Fig. 2-4: Dip data in a non-oriented core section displayed with hollow tadpoles
The goniometry confidence is set to "core not oriented" (red). Example from the Schinznach Formation at around 1'104 m MD log depth.

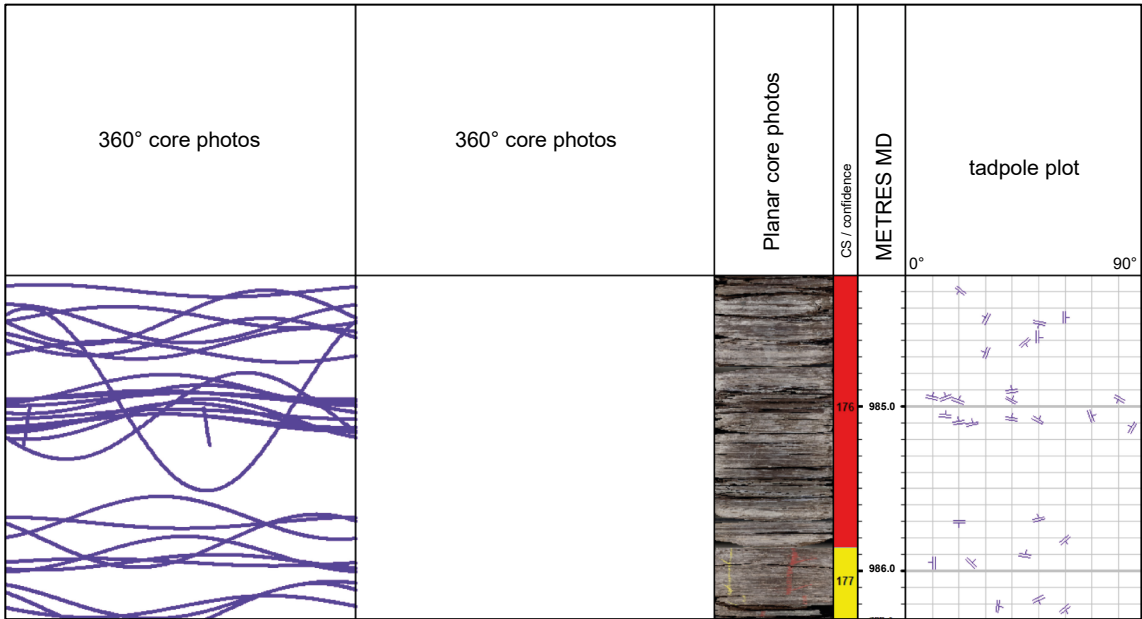


Fig. 2-5: Interval without 360° core photographs at around 985.00 m MD log depth (Klettgau Formation)

In this example, the core goniometry and structural analysis were performed directly on the drill core and the orientation data were determined with a geological compass and subsequently imported into the digital dip database of TerraStation II. The goniometry confidence is set to not oriented (core section 176; red) and moderate (core section 177; yellow).

2.1.5 Goniometry confidence assessment and uncertainties

Goniometry confidence ranking

To visualise the uncertainties related to the core goniometry, the reliability of the core orientation was classified using a confidence ranking scheme. The assessment was carried out for each connected core orientation line and depended particularly on the number of reliably correlated features within these intervals. Features with a moderate to steep ($> 15^\circ$) dip generally provided a higher confidence and resulted in lower angular uncertainties than e.g. shallow structures ($< 15^\circ$). Examples of the correlated features between the FMI and the core are presented in Figs. 2-6, 2-7 and 2-8.

There are three confidence levels for the goniometry illustrated as coloured fields in the structural composite plots (Appendix B and C). The level depends on the number of evident structures found within each coherent core orientation line:

- **high** is defined by three or more distinct, preferably moderately inclined to steep ($> 15^\circ$) planar and/or non-planar features (Fig. 2-6) resulting in a high angular accuracy
- **moderate** is associated with one or two correlated (non-)planar structures with shallow to moderate dip angles ($< 15^\circ$; Figs. 2-7 and 2-8). Thus, the core orientation bears some uncertainty and is less accurate
- **not oriented** is characterised by a lack of obvious indicators for the core orientation. These cores are not oriented

Tab. 2-1 presents an overview of the core goniometry confidence assessment. The procedure described in Section 2.1.2 resulted in a successful orientation of 546 m out of the total 648 m of drill cores (84 %).

Tab. 2-1: Core goniometry confidence assessment

Interval			Goniometry confidence								
Top	Bottom	Core length	High			Moderate			Not oriented		
[m]			[m]	[%]	N of COLs	[m]	[%]	N of COLs	[m]	[%]	N of COLs
498.00	1'161.03	648	184	28	30	362	56	81	102	16	66

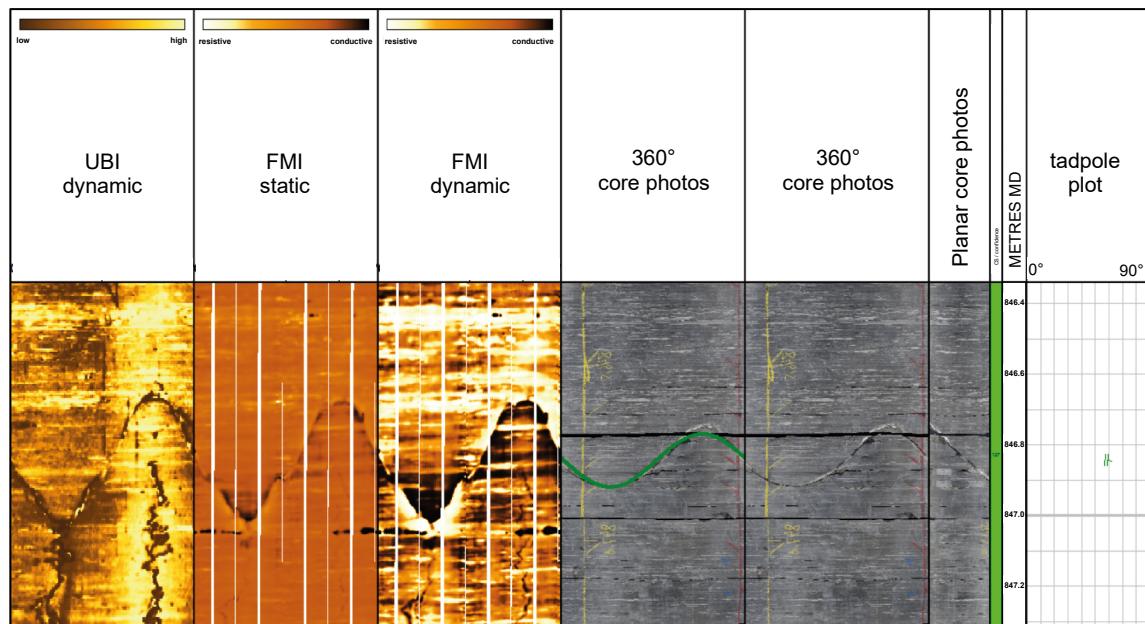


Fig. 2-6: Core – FMI / UBI correlation for a fault at 846.85 m MD log depth (Opalinus Clay)

This prominent 59° SE-dipping fault was unequivocally correlated across the UBI / FMI log and the core photograph and therefore represents a high-confidence indicator for the core orientation. From left to right: UBI dynamic, FMI static and dynamic, shifted and oriented 360° core photographs with (left) and without (right) sine waves, followed by shifted planar core photographs. The core section numbering is shown in the coloured bar displaying the goniometry confidence ranking (high – green, moderate – yellow, red – not oriented). The depth track shows the position and length of the currently displayed window. A tadpole plot with true orientation of manually picked features is also displayed.

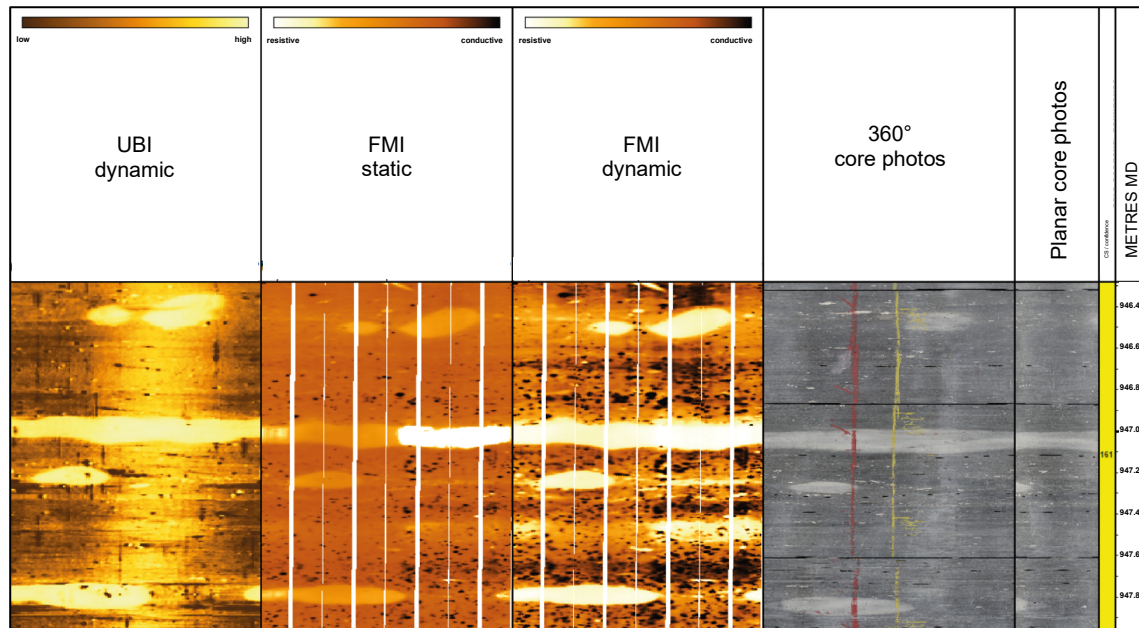


Fig. 2-7: Core – FMI / UBI correlation in the Staffelegg Formation at 947.00 m MD log depth

These unique structures represent elongated nodules appearing bright (high amplitude) on the UBI and resistive on the FMI. They were used to orientate the core section 161. Due to their heterogeneous nature they are considered as limited indicators for the core goniometry and assigned to the moderate confidence level (yellow). The FMI – core photograph depth match for the nodule at 946.47 m MD log depth fits well, whereas there is a slight depth offset (around 4 cm) for the features below 947.00 m MD log depth. This may relate to the dynamic depth shift of the borehole images or could indicate the irregular topography of the nodule.

Project-specific uncertainties

A number of unavoidable limitations and uncertainties were associated with the work performed and may have affected the accuracy of the results. These factors are evaluated below:

- angular uncertainty is associated with the core goniometry and is reflected by the confidence scheme. It particularly implies an angular error for the azimuth
- errors related to geological compass measurements on drill cores: to explore the measurement-related error, multiple measurements of the same structure were performed by different users. The reproducibility was 5° for the dip magnitudes and 5 – 10° for the dip azimuths. Considering that most geological compasses have an error margin within 2° for dip azimuth and magnitude, it can be concluded that the above-mentioned goniometer has an acceptable error margin and can safely be used for accurate structural core analysis

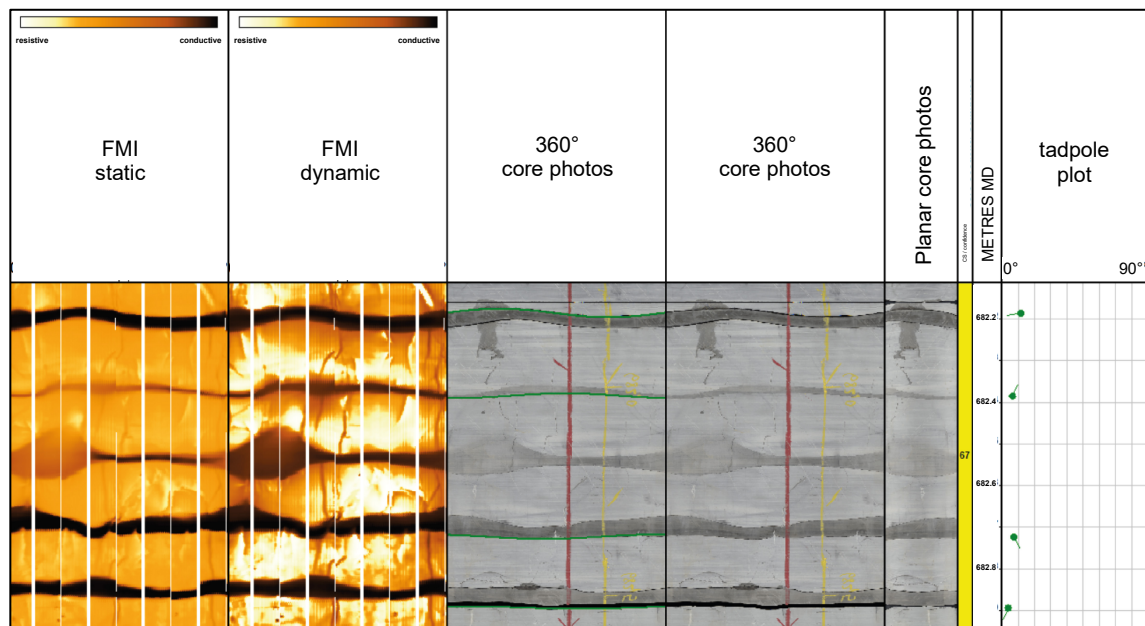


Fig. 2-8: Core – FMI correlation in the case of sub-horizontal to shallow bedding

The FMI and the core photograph match within the well-bedded strata in the Villigen Formation at 682.50 m MD log depth. Although the bedding planes are clearly visible on FMI and cores, the relatively low dip angles ($< 15^\circ$) imply some angular uncertainty and are therefore considered as moderate indicators for core goniometry (yellow).

- Dip picking on 360° photographs: the pixel resolution of the screen defines the angular uncertainty of the dip picks in 3D space and is 1 to 2° for the dip angle and 2 to 4° for the dip azimuth
 - core photographs: although the derived 360° core photographs covered almost the entire studied interval (498.00 – 1'161.03 m MD log depth), some data gaps occurred, e.g. at 678 m, from 712 to 720 m, 973 to 978 m, 983 to 994 m, at 1'005 m, at 1'130 m and at 1'146 m MD core depth. These gaps are mainly related to disintegrated drill cores which were not suitable for circumferential photography or to gaps between drilling sections
 - In some core intervals the core orientation line was discontinuous. This was mainly related to uncertainties in the assemblage of individual core pieces / sections at the drill site. In such cases the non-coherent core sections were treated separately
 - Due to the presence of steel in Nagra's core storage facility in Würenlingen, a site-specific magnetic field disturbance was recognised. Consequently, the goniometer needed to be carefully aligned towards relative north to obtain the correct orientations of the geological features (mainly lineations) measured with a compass. This always had to be kept in mind when moving the equipment across the core store

2.2 Structural work

This section describes (A) how the structural recording and characterisation of drill cores was carried out, (B) which structure types were distinguished, and (C) which structure parameters were defined. Details with regard to the structural core analysis are given in the structural analysis manual and enclosed factsheets and templates (Ebert & Decker 2019).

- A) After the core goniometry was finalised, all deformation structures were recorded on the drill cores.

The overall core quality was excellent. Only cores from clay-rich lithologies (especially Dogger) were affected by progressive discing but were still suitable for structural analysis. Due to approximately 350 samples with lengths of up to 50 cm being taken at the drill site (e.g. for porewater or geomechanical analyses), there were gaps within the core sections. Samplers were strictly advised not to sample core intervals containing tectonic structures. The completeness of structural record is therefore not biased or limited by sampling. Furthermore, it can be assumed that the complete structural inventory was recorded because high-resolution core photographs were taken from all cores, including the sampled core sections.

Most of the structural work was performed by two people. A structural geology expert defined all visible structure types along with their relevant parameters for each core section, which was usually 3 m long. At the same time the other colleague manually picked the structure in question on the 360° core photographs in TerraStation II. The structures and their parameters such as mineralisation, thickness or shear sense were documented on a DIN A3 template with content previously defined in Ebert & Decker (2019). The log depth was determined in metres MD along with the true orientation of the structures on oriented 360° core photographs. The difference in depth between the core and log depth mostly varied by only a few centimetres and depended on the dynamic depth shift of the core photos with regard to the FMI used as the main depth reference data. Striations on slickensides recognised on surfaces of broken cores were measured with a geological compass (Fig. 2-1). As soon as a core section was completely analysed, all entries from the DIN A3 template were digitised and data QC was carried out.

- B) Depending on rock rheology and the type and degree of deformation, different types of structural discontinuities may develop. Based on this, the structures were subdivided into five main groups of structural discontinuities (Fig. 2-9). In total, 11 types of structures were distinguished in this study (Tab. 2-2) and are illustrated with numerous examples in Chapter 3. Detailed definitions and information on the origin of the structures can be found in the structural manual of Ebert & Decker (2019).
- C) Additionally, parameters such as mineralisation, shear sense and thickness listed in Tab. 2-3 were determined and documented for each individual structure on the DIN A3 template (Fig. 2-10). In addition, each structure was sketched and labelled with a consecutive number on the designed grid with a scale of 1:10.

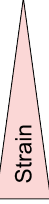
Mohr-Coulomb type brittle failure			Viscous (ductile) deformation	
Fractures			Without cohesion loss	
Drilling-induced	Extensional	Shear	Carbonate solution	Ductile shear
 Centrelines fracture Petal fracture Core discing	 Joint Vein (Tension gash)	 Fault plane Fault zone	Stylolite / Dissolution seam Stylobreccia	 Shear band Mylonite

Fig. 2-9: The five main groups of structural discontinuities

Tab. 2-2: Types of structural discontinuities identified in this study

For more details see Ebert & Decker 2019

Discontinuity group	Structure type	Characteristics
Brittle structures with shear indications	Fault plane	Planes of shear failure, i.e. planes along which there has been movement parallel to the plane (Peacock et al. 2016). Single, thin, planar and sharp structural discontinuities with shear indications (e.g. striation or slickenfibres).
	Mirror-like fault plane	A fault plane with a smoothed, polished or shiny slip surface.
	Stylolitic fault plane	A fault plane with dissolution seams and stylolite-bearing columns which are oblique or parallel to the plane (modified from Hancock 1985).
	Fault zone	A fault zone is defined as a zone with a volume which includes interacting and linked fault segments, densely fractured rock and/or fault rocks; zones are typically bounded by sub-parallel margins or fault planes (modified from Peacock et al. 2016).
Brittle structures without shear or slip indications	Joint	A barren, closed fracture on which there is no measurable slip or dilation at the scale of observation. If any mineral fill, including crystal growth fibres, is visible, the structure is better called a vein (Hancock 1985).
	Vein	Extensional fracture filled by secondary mineral crystallisation.
	Tension gash	Vein formed by dilation; tension gashes may be fully cemented (vein), partly cemented (partly open) or open (Passchier & Trouw 1996).
Structure without preserved evidence for the mode of fracturing	Fracture	General term for a structure without preserved evidence for the mode of fracturing, i.e. it is applicable to structures formed by extension or shear; fractures can include close-to-planar discontinuities such as dykes, faults, joints and veins. (Peacock et al. 2016).
Structures caused by dissolution	Stylolites	Stylolites are irregular seams of insoluble residues with dark, "mountainous" rough teeth formed by pressure solution (Passchier & Trouw 1996).
	Open pores	Isolated open volumes in the rock mass, resulting e.g. from incomplete cementation of veins, dissolution, or preserved cavities in fossils.
	Karst	Open networks resulting from dissolution of carbonates. These cm to m wide cavities may have been refilled later.

Tab. 2-2: continued

Discontinuity group	Structure type	Characteristics
Fabrics without cohesion loss, e.g. caused by ductile deformation	Shear bands	Minor planar shear zones in which the progressive deformation is non-coaxial (Passchier & Trouw 1996).
	Mylonites	Strongly deformed rock from a ductile shear zone with a planar foliation and usually with a stretching lineation (Passchier & Trouw 1996).
	Schistosity	Secondary foliation defined by preferred orientation of equant fabric elements in a medium- to coarse-grained rock. Individual foliation-defining elements (e.g. micas) are visible with the naked eye (Passchier & Trouw 1996).
	Dynamic recrystallisation	Dynamically recrystallised, smaller and elongated crystals.
Drilling-induced fractures (DIF)	Drilling-induced fractures	Collective term for fractures created by forces associated with drilling and coring procedures. Depending on load on drill bit, mud weight and rock properties, drilling-induced fractures develop during drilling or shortly thereafter. Based on the aperture, fracture surface and geometric relationships, drilling-induced fractures can be distinguished from natural fractures. Drilling-induced fractures are always open and never mineralised.
	Petal fracture	Drilling-induced fracture with convex-up geometry cutting a core downwards starting from its perimeter. Petal fractures form immediately ahead of the drill bit as a result of excessive bit weight during coring. They propagate downhole.
	Centreline fracture	Drilling-induced fracture that typically splits a core approximately in half.
	Core discing	The formation of discs of relatively uniform thickness which fracture on surfaces approximately normal to the axis of the core.

Tab. 2-2: continued

Discontinuity group	Structure type	Characteristics
Additional features / dip types	Undifferentiated bedding	Planar surface representing either the boundary between two different lithological units or internal bedding. Thought to reflect original horizontal and planar surfaces.
	Deformed bedding	Bedding planes occurring in narrow zones in any lithology with moderate to steep dip angles ($> 15^\circ$) which differ from the general structural dip. They have been subject to deformation due to faulting and/or folding.
	Cross-bedding	Inclined foreset surfaces in sandstone occurring in sets and bounded by set boundaries. These sedimentary features may be used as paleocurrent indicators. Upper truncation by the next set is diagnostic.
	Fold (axis)	One or a stack of originally flat and planar surfaces, such as sedimentary rocks, that are bent or curved due to applied external stress. Folds appear in various scales and shapes.
	Fracture density	Numerical value that reflects a quantitative measure of the abundance of fractures in rock mass (e.g. fractures per metre, fracture area per rock volume).

Tab. 2-3: Systematically recorded parameters for the investigated structures

Parameter	Definition of parameters and procedure for defining parameters
Depth	All types of structures are recorded quantitatively along the scanline of the core axis. The depth of the structure is measured at the point where it cuts the core axis. For steeply dipping planes, depth should be determined half-way between the top and the base of the intersection ellipse of the structure. If a zone is recorded (e.g. fault zone, shear band, fracture density class), the top (Top MD) and the base (Bottom MD) of the zone are specified in the corresponding columns.
Core orientation line number	After the extraction of the core from the inner tube, the core pieces are juxtaposed whenever possible. Continuous sections without drilling breaks, demarcated by grinding, crushed or core loss zones, are marked with a core orientation line and denoted with a consecutive number. This number enables linking of the recorded structure with the key structure of this orientation line section that was identified on the borehole image.
Depth shift between core and FMI	The depth shift is defined using correlated structures visible on both the FMI and core.
Correlation with log	Assessment whether each individual structure can be clearly identified on FMI / UBI and core. "yes" indicates that the structure can be correlated with the image log, and "no" indicates structures which cannot be correlated or which are not shown by the image log. In addition, a correlation quality ranking is carried out (1 – good, 2 – moderate, 3 – no correlation).
Dip direction and dip	Measured dip direction and dip of the structure.
Structure type	The abbreviations of structure types according to Fig. 2-10 are entered into the paper template.
Length of structure	The length of the long axis of the intersection ellipse should be measured for structures which cut the core axis at acute angles (dipping with more than about 70°) and structures which do not cut through the entire core diameter. The measured length will be used for the calculation of fracture density P32. Measurements are required to reduce the inaccuracy resulting from calculating fracture areas solely from the angle between the structure and the core axis.
Azimuth and plunge of lineations	Measured dip azimuth and plunge of the lineation observed on the measured plane.
Shear sense and quality	Shear sense of fault planes and shear bands using up (reverse fault), down (normal fault), dex (dextral strike slip) or sin (sinistral strike slip), and reliability indicators (good, fair, poor) of the shear sense observation.
Mineralisation / fault rock type	Any type of filling, mineralisation or fault rock associated with the structure (e.g. CC for calcite of a vein filling, synCC for mineralisation of slickenfibres).

Tab. 2-3: continued

Parameter	Definition of parameters and procedure for defining parameters
Open / closed and width / length of open structures	Information on whether a tension gash / vein is open (displaying a continuous aperture), partly open (displaying a discontinuous aperture) or closed at the observation scale (i.e. the naked eye), including the width of the aperture and the observed lengths of open streaks for partly open structures.
Roughness	Roughness classification of a structure using the joint roughness coefficient (JRC). The JRC gives a picture of the classification of fracture smoothness and waviness (planarity) along 10 cm length of the fracture (Barton 1976, Barton & Choubey 1977). The scale of the JRC is from 0 (very smooth and planar) to 20 (very rough and wavy).
Fracture condition	Specifies whether the core is broken naturally or artificially at the structure under consideration or intact. If it cannot be specified whether the break occurred naturally or artificially, broken should be used.
Fracture density class (FDC)	In cases where cores or parts of a core are heavily disintegrated and order cannot be restored, the density of natural fractures cannot be calculated accurately. Fracture density should be estimated using the classification scheme of Bauer et al. (2016): fracture density class 2 (spacing of fractures = 5 – 10 cm), fracture density class 3 (spacing of fractures = 1 – 5 cm) or fracture density class 4 (spacing of fractures < 1 cm).
Additional remarks	Offsets or displacements as well as crosscutting relations are documented under "remarks". Further remarks are e.g. karstification, the shape and length of the teeth of stylolites, alterations, recrystallisation phenomena or whether a structure is of synsedimentary origin.

[illegible]

Fig. 2-10: Completed DIN A3 sheet of primary record of the structural core analysis

2.3 Geo-statistical evaluation

For the geo-statistical evaluation presented in Chapter 4, different structural tools and techniques were applied to analyse the available dip dataset. Most of the work was performed with TerraStation II. This provides several advanced modules for the import, processing, visualisation and analysis of all types of available borehole data such as petrophysical logs, borehole images, core data and stratigraphic information.

For the structural evaluation of the different lithostratigraphic units and the different types of structural discontinuities, a series of figures was compiled:

- stereograms (Schmidt projection, lower hemisphere):
 - poles of the planes were displayed to examine the spatial orientation of bedding and structural planes
 - azimuth rose diagrams were compiled for planar features (bedding and fractures). The diagrams show the dip azimuth of the planes under consideration. The rose diagram is a circular histogram summarising orientation measurements. The radius of each segment of a rose diagram is proportional to the number of observations that occur within the angular range of that segment. Azimuth rose diagrams are displayed with cumulative petals resulting in "staked petals" for different dip categories. For the directional statistics a minimum threshold of ten structures was set for the rose diagrams
- dip histograms visualise the dip angle distribution and clustering for a given dip dataset
- vector means for representative clusters of the different structure types were calculated in stereograms
- the vector azimuth plot (dip walkout plot) reflects the along-borehole dip variations and was compiled for bedding-related dips only (deformed dips and cross-bedding were excluded). Here, the azimuth of a plane was plotted in a nose-to-tail fashion pointing in the direction of dip. The length of an interval is related to the number of dips and not to the thickness of lithostratigraphic units
- fracture density (P32 curves) reflects the fracture area per unit of rock volume (m^2/m^3). The algorithm computes the area of each fracture and creates a sum of the areas across the defined window of 1 m core length and steps of 0.1524 m. The lengths of sub-vertical fractures are incorporated whereas truncated parts of fractures are discarded. The computation of the area accounts for borehole ellipticity. The total area of fractures is then divided by the borehole volume (or volume of the rock mass) of the selected window. See Ebert & Decker (2019) and the literature therein for a more detailed discussion on P32 fracture density calculation. For this study, P32 fracture densities were calculated for all structural discontinuities as well as for each individual group:
 - fault planes, mirror-like fault planes and stylolitic fault plane
 - fractures, joints and tension gashes / veins
 - stylolites

The recorded kinematic indicators were analysed using TectonicsFP software. The available fault and kinematic data were plotted in stereographic Angelier projection where the symbols and colours reflect the different shear senses (up, down, sinistral or dextral) and the observed shear sense reliability (good, moderate, poor). Please be aware that all Angelier plots in this report show corrected datasets, where the data points of the lineations are projected on the great circle of the corresponding fault plane, even though they may have an angular offset $< 15^\circ$.

3 Inventory of structure types

The different structure types identified in the drill cores from TRU1-1 and their relevant characteristics were described in Section 2.2. In this Chapter, these structures are visualised with examples. The diameter of the cores in the following figures (Figs. 3-1 – 3-19) is 95 mm. The depth of the structures is given as the depth along core axis in metres MD core depth.

3.1 Examples of fault planes

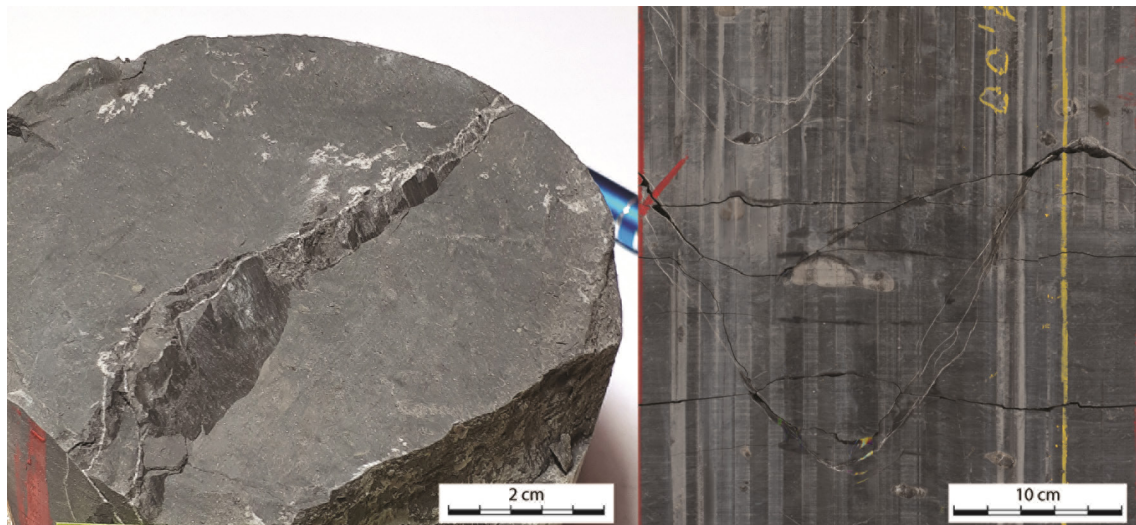


Fig. 3-1: Fault plane

Characteristics: (*Left*) Example of a fault plane with striation and mm-thick synkinematic calcite fibres. Shear sense is top down (normal fault). (*Right*) 360° core photograph view of the same structure with a high amplitude of the sine wave indicating a relatively steep dip angle.

Formation: Wedelsandstein Formation, Depth: 791.18 m MD core depth



Fig. 3-2: Fault plane

Characteristics: A discrete fault plane. The striation shows sub-horizontal slip with syn-kinematic calcite suggesting a sinistral shear sense.

Formation: Opalinus Clay, Depth: 846.78 m MD core depth

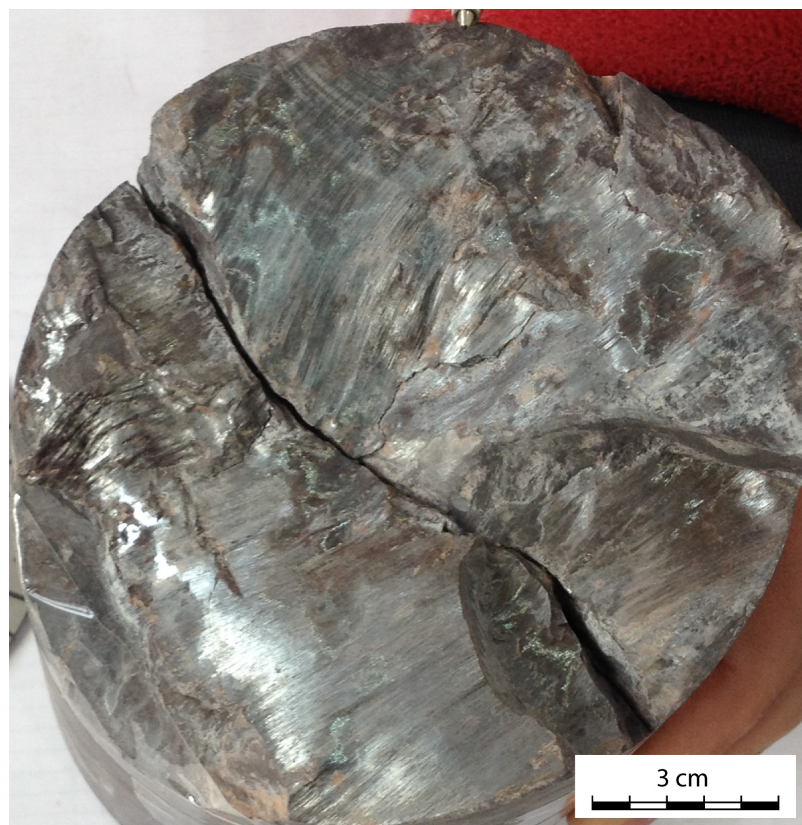


Fig. 3-3: Mirror-like fault plane

Characteristics: Shallow and irregular fault plane with a polished, mirror-like slip surface and striation.

Formation: Klettgau Formation, Depth: 1'016.62 m MD core depth



Fig. 3-4: Mirror-like fault plane

Characteristics: Example of a steeply dipping fault plane with a smooth and irregular mirror-like slip surface.

Formation: Bänkerjoch Formation, Depth: 1'030.63 m MD core depth

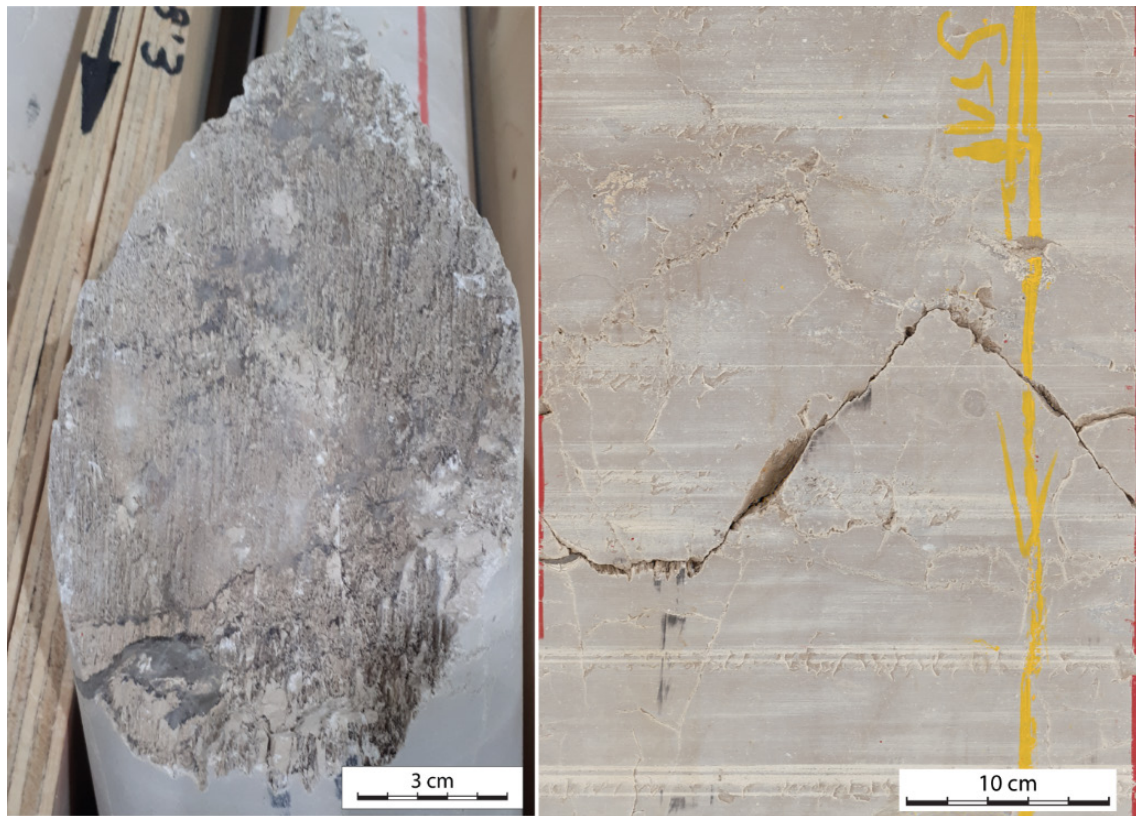


Fig. 3-5: Stylolitic fault plan

Characteristics: (Left) Example of a steeply dipping stylolitic fault plane with sub-vertical striation generated by stylolitic dissolution and displacement sub-parallel to the plane. Sense of shear is top down (normal faulting). (Right) Same stylolitic fault plane seen in the 360° core photograph.

Formation: «Felsenkalke» + «Massenkalk», Depth: 551.16 m MD core depth

3.2 Examples of fault zones

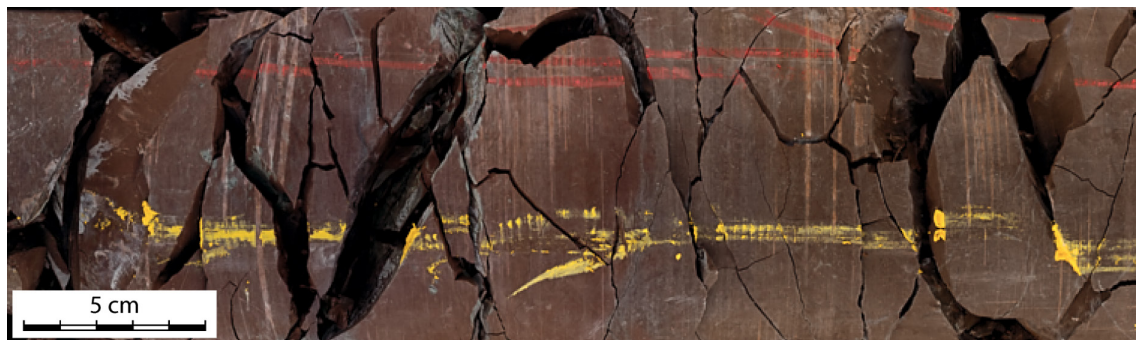


Fig. 3-6: Fault zone with FDC 3

Characteristics: Example of a fault zone with numerous individual and intersecting mirror-like fault planes. The core disintegration level corresponds to fracture density class 3.

Formation: Klettgau Formation, Depth: 1'004.50 – 1'004.75 m MD core depth

3.3 Examples of joints



Fig. 3-7: Joint

Characteristics: A 45 cm long, sub-vertical joint characterised by the absence of opening and slip indications.

Formation: Schinznach Formation, Depth: 1'118.05 m MD core depth

3.4 Examples of veins / tension gashes



Fig. 3-8: Vein / tension gash

Characteristics: Example of a 2 mm thick, sub-vertical calcite-filled vein (total length 65 cm).

Formation: Wedelsandstein Formation, Depth: 814.29 m MD core depth



Fig. 3-9: Vein / tension gash

Characteristics: 360° core photographs: (Left) Example of an irregular network of mostly curved non-planar anhydrite veins. (Right) Thick, sub-vertical anhydrite veins with blocky anhydrite.

Formation: Left: Bänkerjoch Formation, Depth: 1'060.50 m MD core depth
Right: Bänkerjoch Formation, Depth: 1'052.60 m MD core depth



Fig. 3-10: Vein / tension gash

Characteristics: Example of a sub-vertical calcite vein delimited by two sub-horizontal stylolites.

Formation: Villigen Formation, Depth: 664.38 m MD core depth

3.5 Examples of stylolites

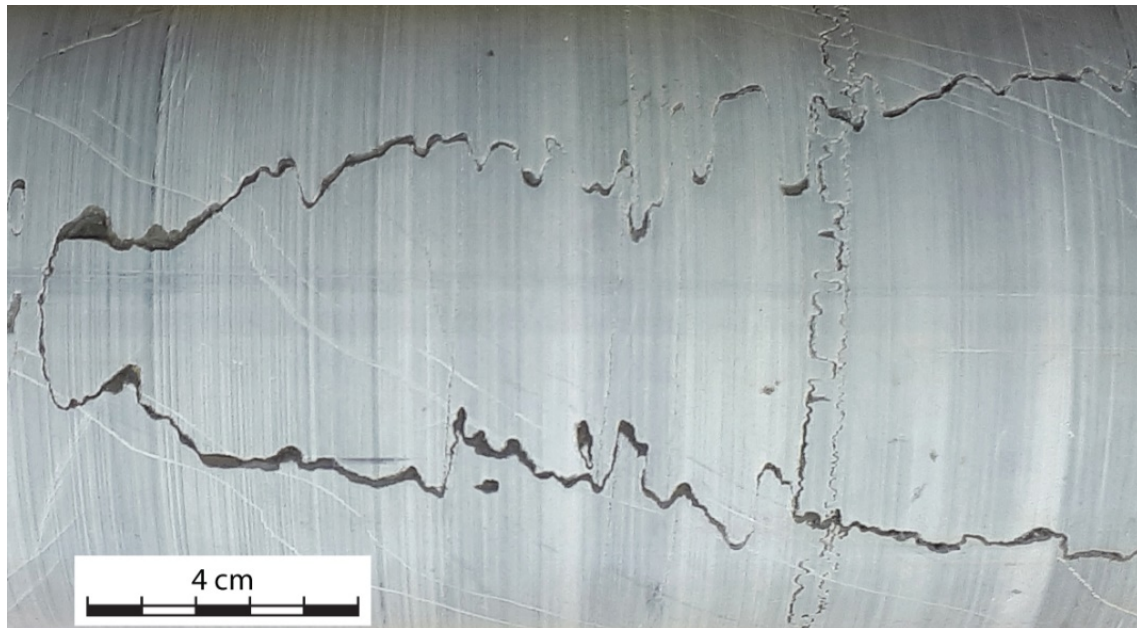


Fig. 3-11: Stylolites

Characteristics: Example of a 20 cm long sub-vertical stylolite with cm-long sub-horizontal teeth.

Formation: Villigen Formation, Depth: 661.45 m MD core depth

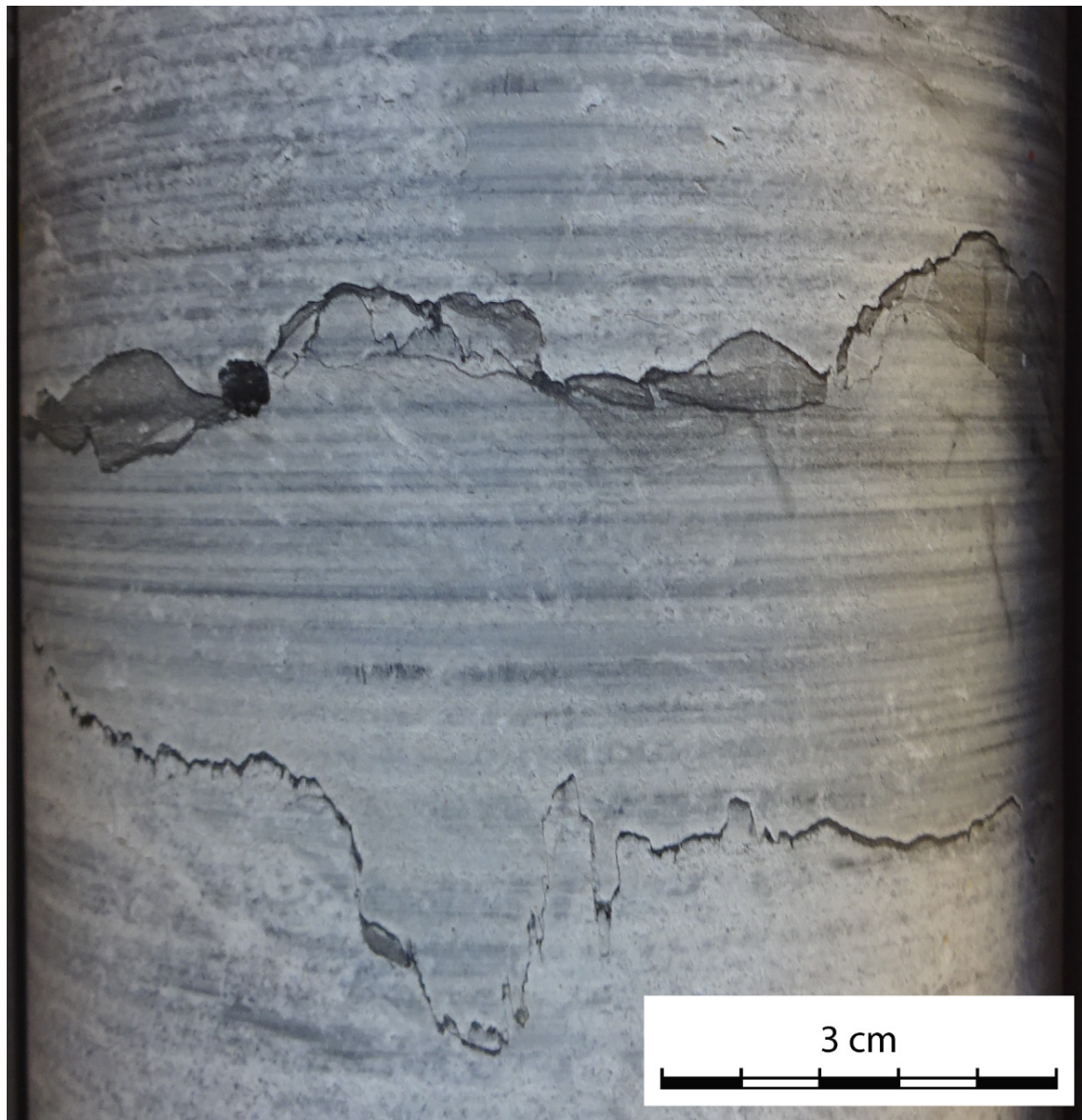


Fig. 3-12: Stylolites

Characteristics: Example of a sub-horizontal stylolite with up to cm-long sub-vertical teeth.

Formation: Schinznach Formation, Depth: 1'140.51 m MD core depth

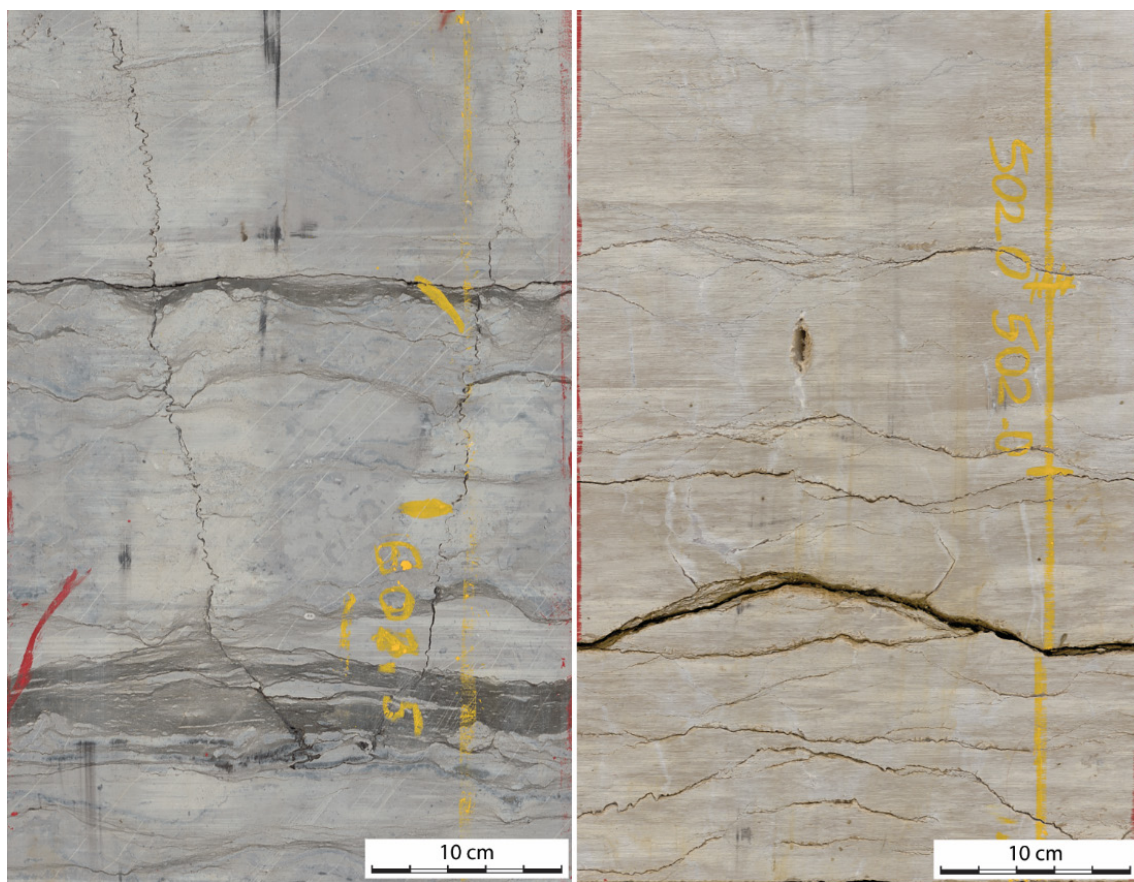


Fig. 3-13: Stylolites

Characteristics: 360° core photographs: (Left) Sub-vertical stylolite with sub-horizontal teeth. (Right) Sub-horizontal stylolites with small vertical teeth.

Formation: Left: «Felsenkalke» + «Massenkalk», Depth: 602.42 m MD core depth
Right: «Felsenkalke» + «Massenkalk», Depth: 502.00 m MD core depth

3.6 Examples of open pores

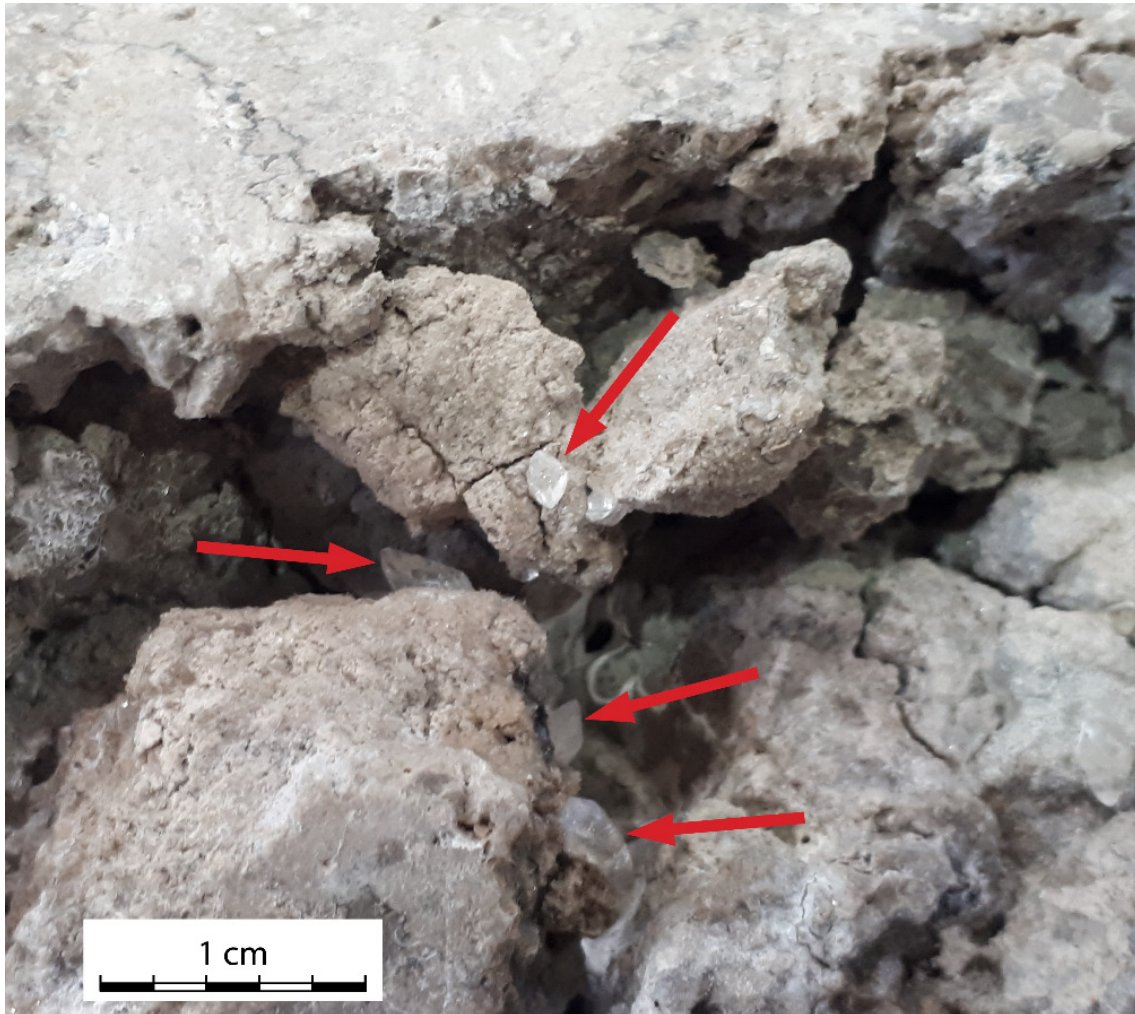


Fig. 3-14: Open pore

Characteristics: Example of large open pores with idiomorphic calcite crystals.

Formation: Klettgau Formation, Depth: 996.74 m MD core depth

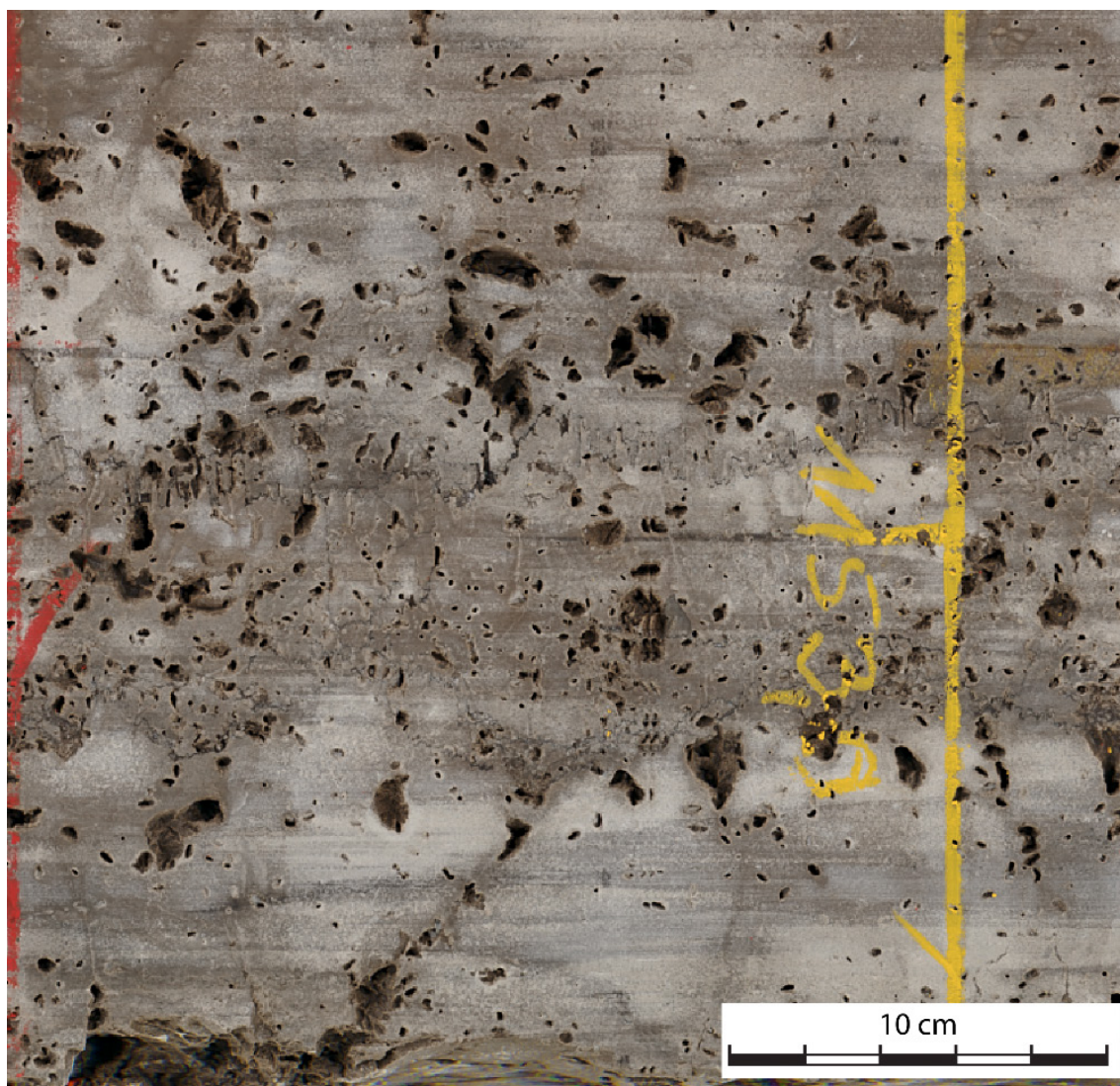


Fig. 3-15: Open pores

Characteristics: 360° core photograph: Example of small-sized open pores. Typical layer found in the Schinznach Formation with a dense network of mm-sized pores without mineralisation.

Formation: Schinznach Formation, Depth: 1'153.0 m MD core depth

3.7 Drilling-induced fractures

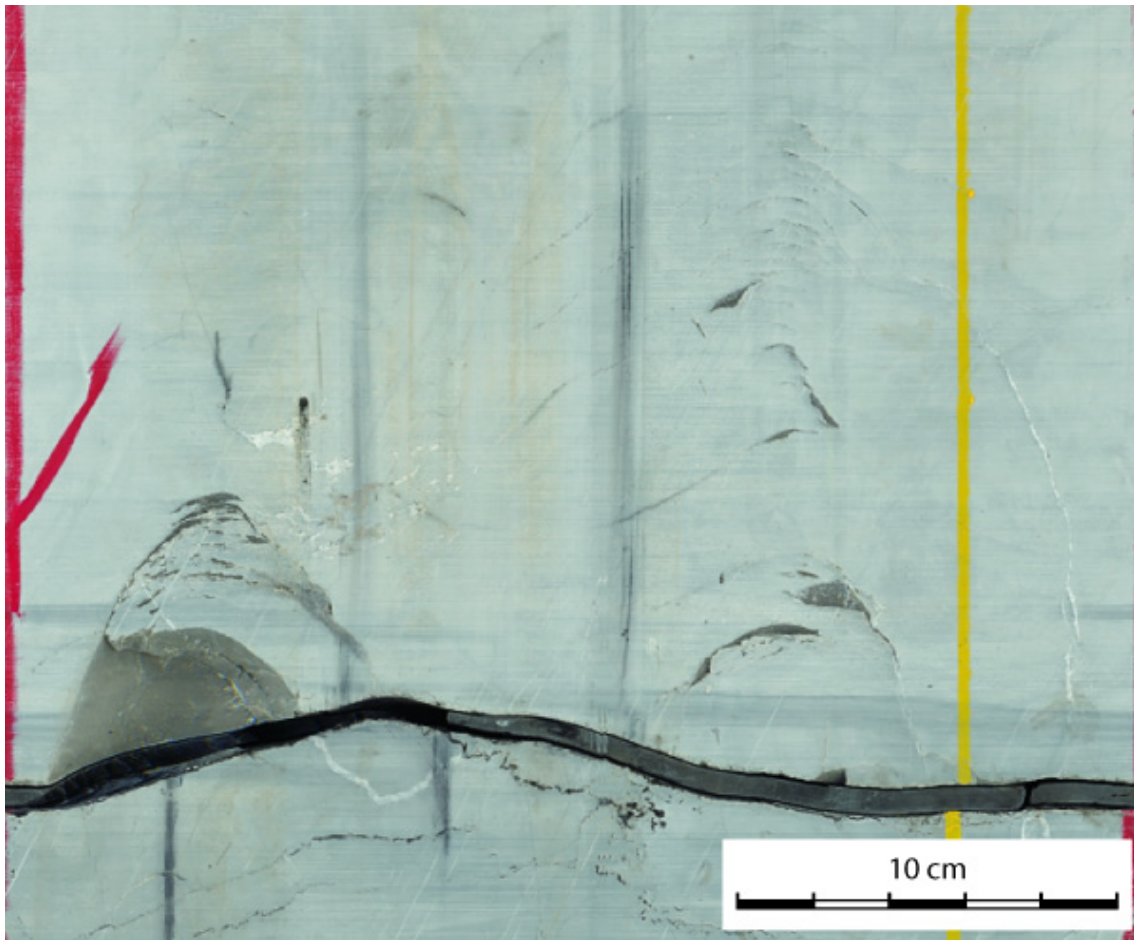


Fig. 3-16: Petal fractures

Characteristics: 360° core photograph: Pairs of petal fractures visible as two opposite facing, parallel sets of small, curved and broken core pieces. The strike of both sets was NNW-SSE and the mean dip directions were around 80° and 260°.

Formation: Villigen Formation, Depth: 673.36 m MD core depth

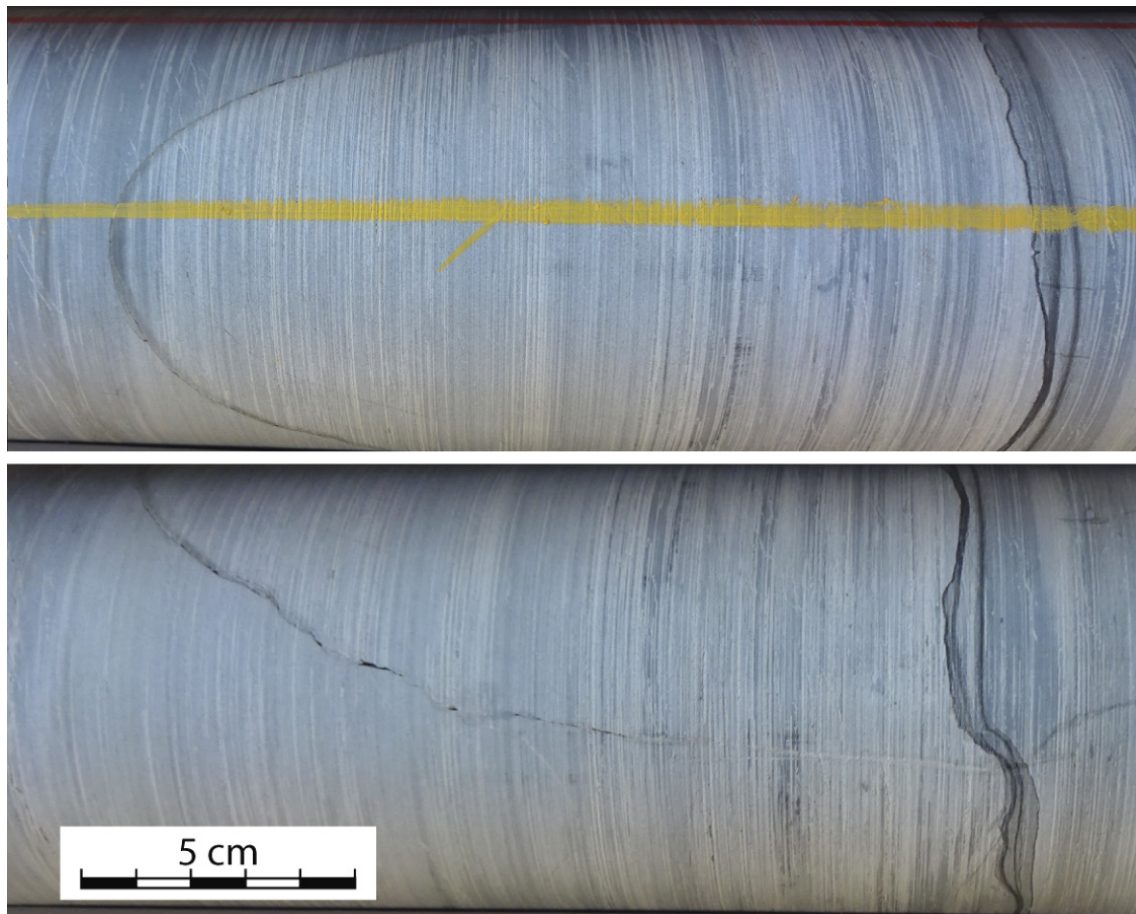


Fig. 3-17: Centreline fractures

Characteristics: A petal fracture (P-DIF) growing down-core into a centreline fracture (C-DIF, lower photo).

Formation: Schinznach Formation, Depth: 1'121.69 m MD core depth



Fig. 3-18: Discing

Characteristics: Example of discing in claystone splitting the core into several discs with typical parallel fractures. Discs were perpendicular to the core axis and (sub-)parallel to the bedding.

Formation: Opalinus Clay, Depth: 915.5 m MD core depth

3.8 Folding

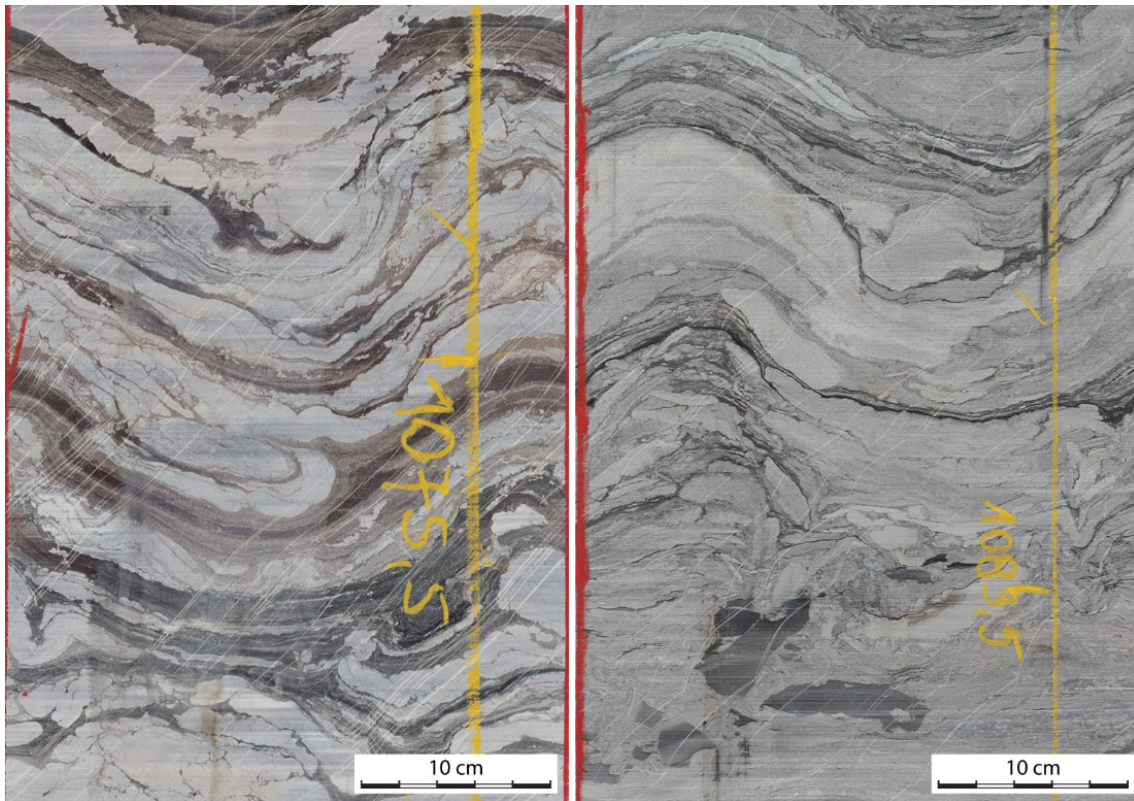


Fig. 3-19: Folding

Characteristics: Examples of folded anhydrite layers, most likely of synsedimentary origin.

Formation: Left: Bänkerjoch Formation, Depth: 1'075.57 m MD core depth

Right: Bänkerjoch Formation, Depth: 1'083.47 m MD core depth

4 Geo-statistical evaluation: Results

This Chapter focuses on the statistical evaluation of the obtained structural data. First, the entire borehole section is evaluated (Figs. 4-1 – 4-16); second, the data for the 11 lithostratigraphic units defined by Nagra are presented in detail in Sections 4.2 – 4.6. Each dataset is presented in a stereogram (Schmidt, lower hemisphere projection) and rose diagram.

Vector mean orientation values (dip direction and dip angle) of bedding planes and planar structural discontinuities were calculated for different data clusters in a stereogram projection (Tab. 4-1). **Note, bedding dips and structural discontinuities recorded in non-oriented cores (n = 492) were excluded from the following stereographic evaluation unless otherwise specified. However, they were included in the fracture density calculations (P32 curves) presented in Section 4.1.3.**

Tab. 4-1: Vector mean orientation values for bedding planes and structural discontinuities

	Cluster 1 (Main)			Cluster 2 (Subordinate)			Cluster 3 (Subordinate)		
	Azim	Dip	No.	Azim	Dip	No.	Azim	Dip	No.
Bedding	150	04	538						
Fault planes, mirror-like fault planes, stylolitic fault planes	161	05	219						
Tension gashes, joints, fractures	336	46	60	146	18	44			
Stylolites	162	07	563	339	82	34			

4.1 Cored borehole section (498.00 – 1'161.03 m MD log depth)

2'983 individual planar and non-planar features were identified during the core analysis and manual dip picking of the 648 m of drill core (498.00 – 1'161.03 m MD log depth; missing core intervals due to core losses or cutting intervals below casing). The structural results are described in the following section.

4.1.1 Basic structural dip evaluation

Bedding dips, particularly in lithologies of a plane-parallel nature such as in claystone, marl and siltstone sequences, are the best indicators for structural dip and its variation with depth. The dip variations along the current borehole are well reflected in the stereograms of Figs. 4-1, 4-2 and in the vector azimuth plot in Fig. 4-3.

The interpreted borehole interval from 498.00 to 1'161.03 m MD log depth (Malm to Muschelkalk) shows a sub-horizontal to shallow (1 – 10°) SSE to SE structural dip that is consistent throughout. The overall mean is 150/04 [dip direction / dip angle] (n = 538; see Tab. 4-1). However, there were a number of evident and abrupt dip changes associated with faults / fault zones from 830.90 to 830.94 m, 842.00 to 842.50 m, at 850 m, 881.58 m, 911.59 m, from 983.20

to 987.57 m, 1'040 to 1'050 m, 1'059.80 to 1'059.85 m, 1'084 to 1'086 m and at 1'155.29 m MD log depth. These dip changes are reflected by the vector azimuth plot (Fig. 4-3). Consequently, faulting may be considered as the main deformation mechanism in the current borehole controlling the structural dip.

Further local dip disturbances were observed within the lowermost Bänkerjoch Formation from 1'074 to 1'085 m MD log depth. The latter is characterised by inclined to steep (10 – 60°) SSW-dipping beds governed most likely by folding. In addition, there were several dip breaks along the studied borehole interval (e.g. at 867 m, 936 m and 942 m MD log depth). Some of these dip changes are indicated with question marks in Fig. 4-3 as their origin could not be elaborated with the available dataset.

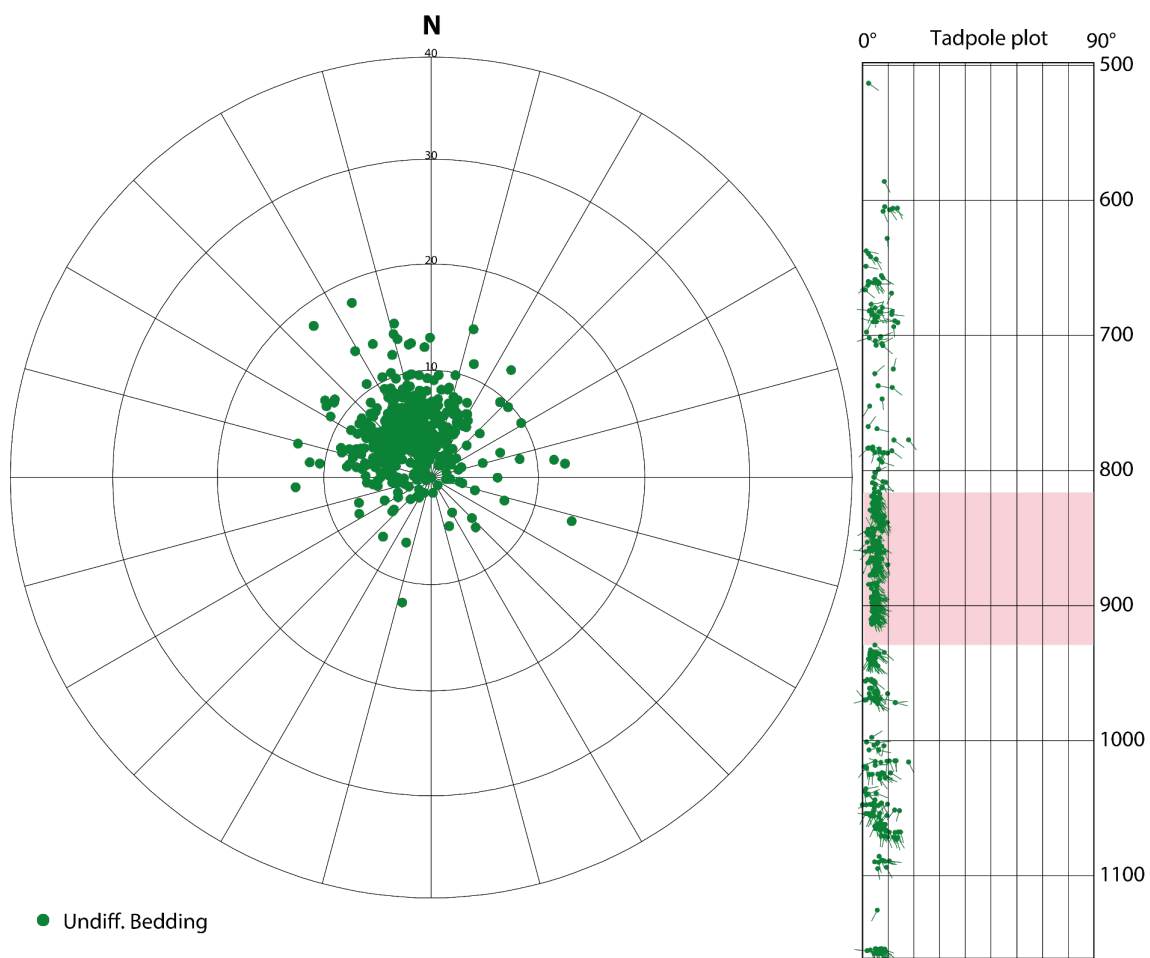


Fig. 4-1: Stereogram and depth plot for bedding planes ($n = 554$) for the entire cored borehole section

Note the predominance of 0 – 10° SSE and SE dips with an overall mean of 150/04 ($n = 538$). The rim of the stereogram is restricted to 40°. Depth range is from 498.00 to 1'161.03 m MD log depth. In the tadpole plot, the Opalinus Clay interval is shaded in red.

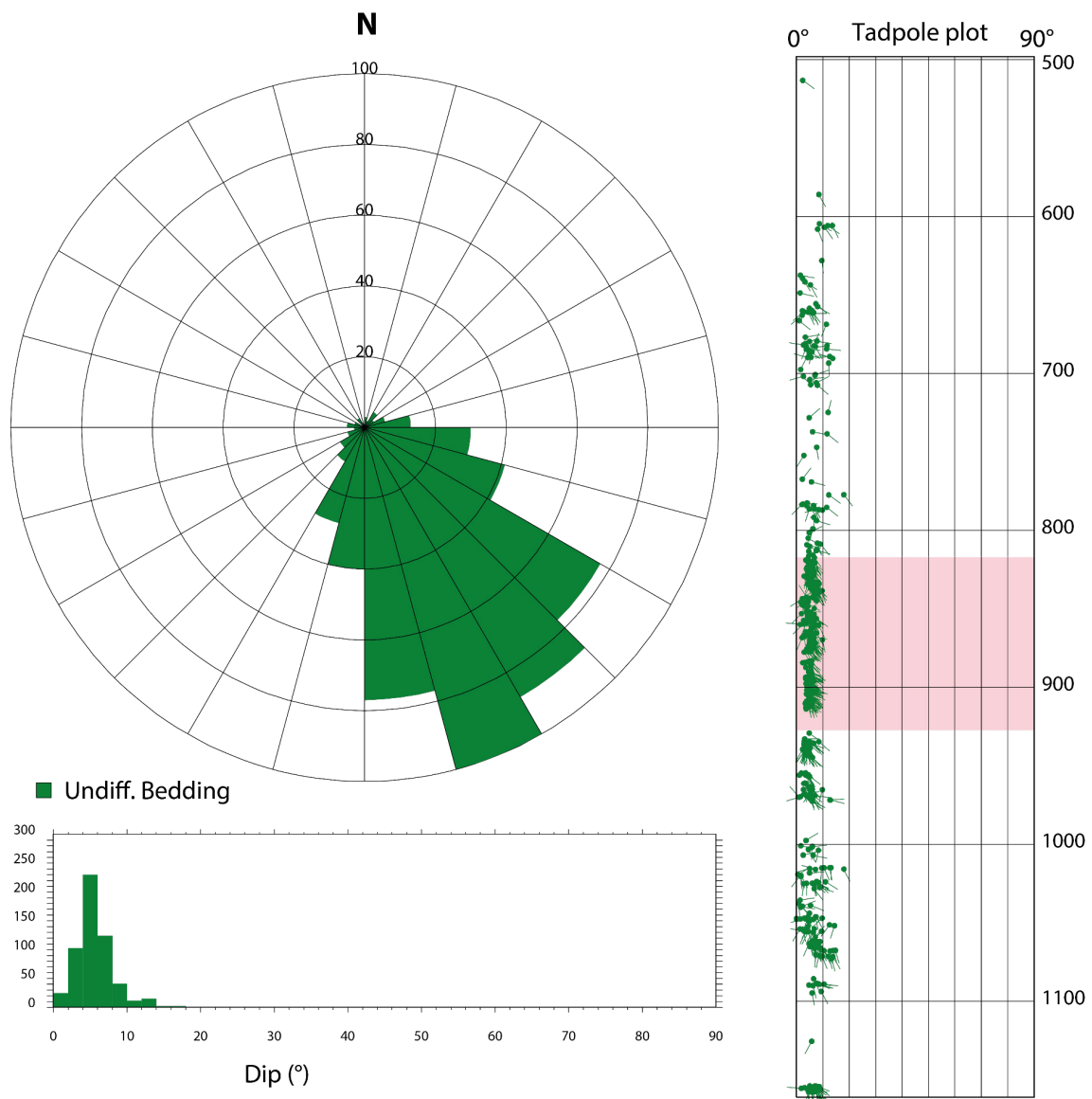


Fig. 4-2: Azimuth rose diagram, dip histogram and depth plot for bedding planes ($n = 554$) for the entire cored borehole section

Note the predominance of dip directions towards the SSE and SE. Depth range is from 498.00 to 1'161.03 m MD log depth. In the tadpole plot, the Opalinus Clay interval is shaded in red.

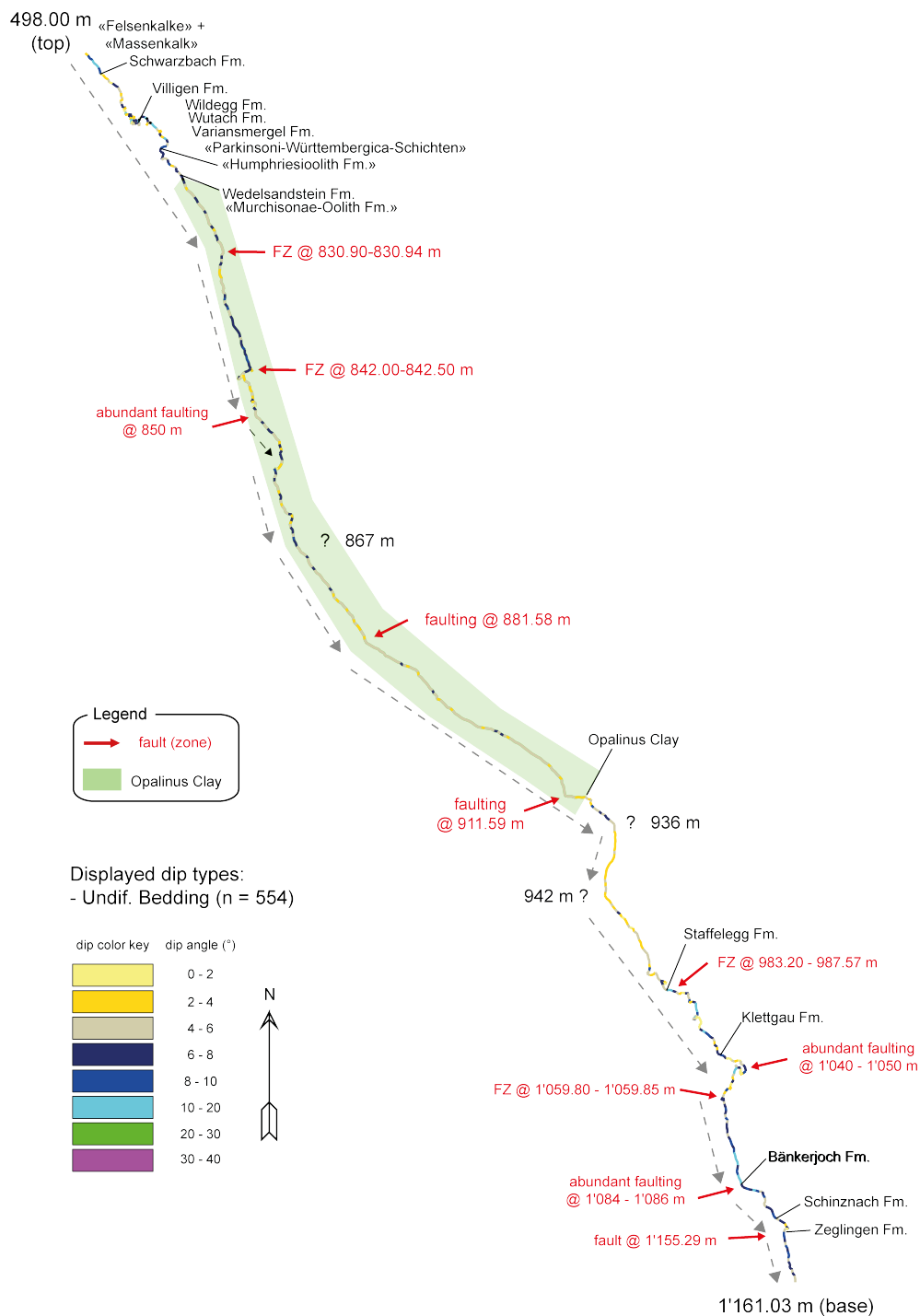


Fig. 4-3: Vector azimuth (or walkout) plot for bedding planes (n = 554) of the picks of bedding planes

The colour coding reflects the dip magnitude, while question marks indicate prominent dip changes. The horizontal distance has no meaning and represents only the number of bedding planes in the corresponding section. Grey arrows point in the direction of the overall dip direction. The bottom of lithostratigraphic formation boundaries are indicated as well as faulting / fault zones (red arrows) and the Opalinus Clay interval (shaded green). Note that commonly steeper, deformed bedding planes and those from non-oriented cores are excluded from this plot. Depth range is from 498.00 to 1'161.03 m MD log depth.

4.1.2 Natural structural discontinuities

Fault planes

In total, 657 individual faults were recorded in the TRU1-1 borehole. Faults are planes of shear failure, i.e. planes with plane-parallel movement. Depending on their appearance in the core, three types were distinguished: fault planes ($n = 25$), mirror-like fault planes ($n = 528$) and stylolitic fault planes ($n = 104$). Out of all recorded faults, 555 (85 %) were detected in oriented cores and are included in this evaluation.

Several structurally complex intervals along the borehole were categorised as fault zones. They are commonly associated with intense fracturing and high fracture densities. The latter correspond to the different fracture density classes (FDC) defined by Ebert & Decker 2019. A total of 22 individual fault zones were defined for the entire cored interval along with their FDC for each zone (Tab. 4-2).

Faults are unevenly distributed along the borehole as shown in Fig. 4-2 and are discussed in more detail in Section 4.1.4. At certain depths, faults are absent, whereas at other depths they occur as countless swarms causing heavily fractured and disintegrated rock (fault zones and core intervals described by fracture density classes).

The orientations of all recorded faults are displayed in the stereograms of Figs. 4-5 and 4-6. Faults show some orientation scatter with variable dip directions and dip angles ranging from sub-horizontal to sub-vertical ($1 - 85^\circ$). However, there was a slight predominance of the SSE-dipping cluster with an overall mean of 161/05 ($n = 219$, mean of selected cluster). Striations could be measured on 531 fault planes and are further evaluated in Section 4.1.4.

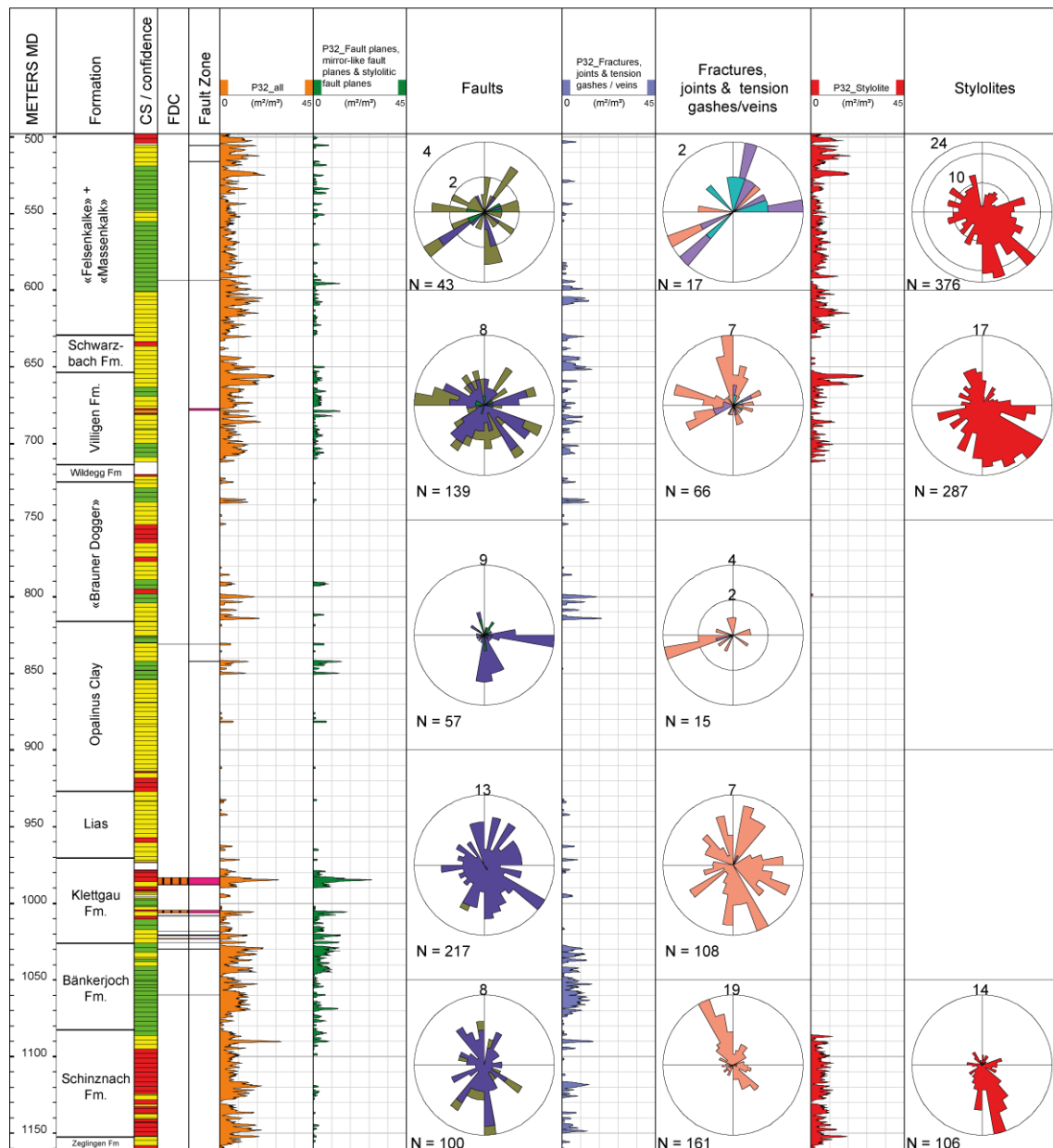


Fig. 4-4: Overview plot showing P32 fracture densities along TRU1-1

In addition, lithostratigraphic subdivision, core sections and goniometry confidence as well as fault zones associated with intense fracturing are shown. Note that the stereograms with the respective number of planes are displayed for 150 m intervals.

Tab. 4-2: List of interpreted fault zones, mirror-like fault plane (MirFP) zones and associated FDC (fracture density class)

Fault zones				FDC
Top [m MD log depth]	Bottom [m MD log depth]	Thickness [m]	Type	Type
505.38	505.62	0.24	Fault zone	
516.07	516.28	0.21	Fault zone	
593.34	593.45	0.11	Fault zone	FDC 3
677.05	678.35	1.30	Fault zone	
830.92	830.96	0.04	Fault zone	FDC 3
842.00	842.50	0.50	Fault zone	
983.20	985.86	2.66	Fault zone	FDC 3
986.17	986.37	0.20	Fault zone	FDC 4
986.63	986.75	0.12	Fault zone	FDC 4
987.39	987.57	0.18	Fault zone	FDC 3
988.00	988.20	0.20	Fault zone	FDC 3
1'004.62	1'005.37	0.75	Fault zone	FDC 3
1'005.31	1'006.12	0.81	Fault zone	FDC 2
1'007.92	1'008.22	0.30	Fault zone	FDC 3
1'018.03	1'018.07	0.04	Fault zone	FDC 4
1'020.40	1'020.65	0.25	Fault zone	FDC 2
1'020.85	1'021.07	0.22	Fault zone	FDC 2
1'022.79	1'022.97	0.18	Fault zone	FDC 2
1'025.60	1'025.8	0.20	Fault zone	FDC 2
1'029.75	1'029.89	0.14	Fault zone	FDC 2
1'035.73	1'035.88	0.15	MirFP zone	
1'059.80	1'059.85	0.05	Fault zone	FDC 3

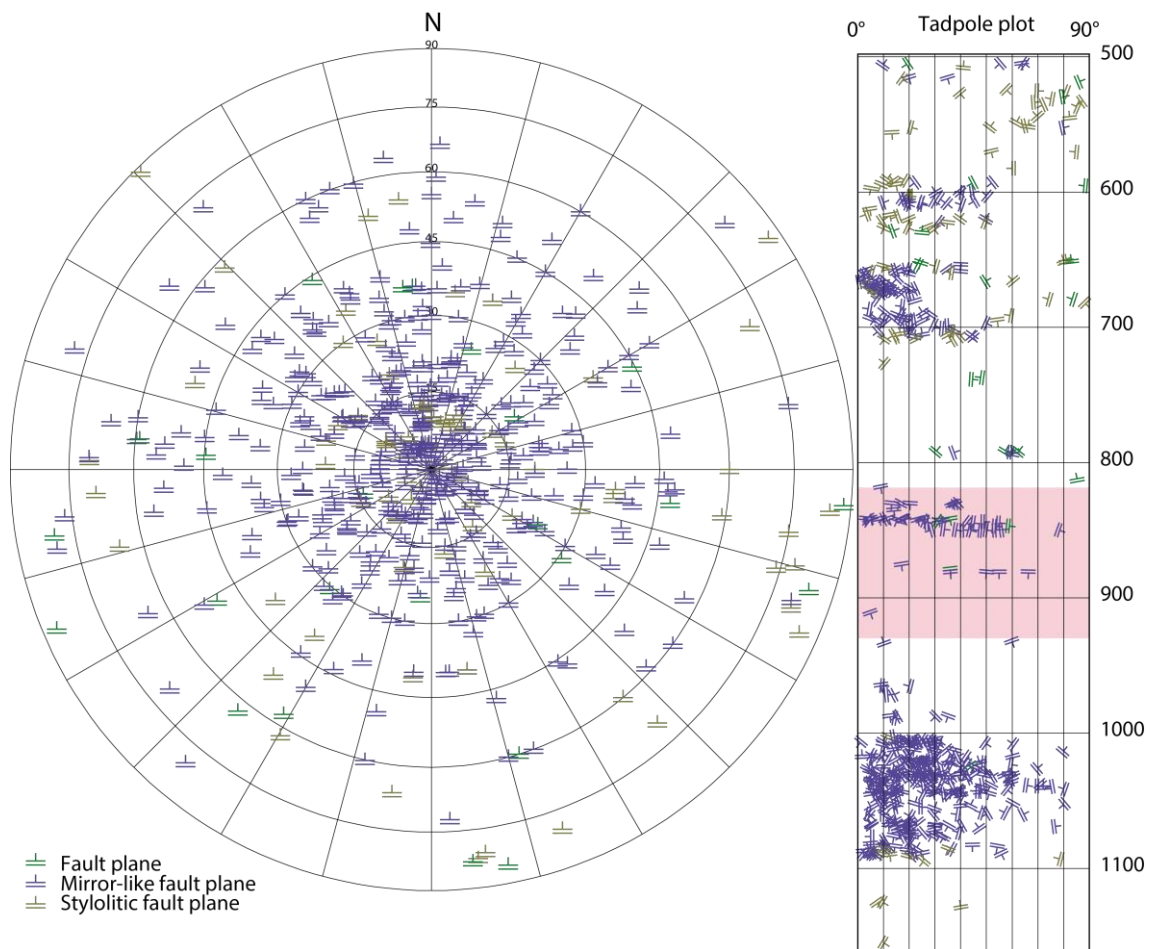


Fig. 4-5: Stereogram and depth plot of fault planes for the entire cored interval

A total of 555 fault planes in oriented cores are plotted: fault planes ($n = 24$), mirror-like fault planes ($n = 450$) and stylolitic fault planes ($n = 81$). Depth range is 498.00 – 1'161.03 m MD log depth. In the tadpole plot, the Opalinus Clay interval is shaded in red.

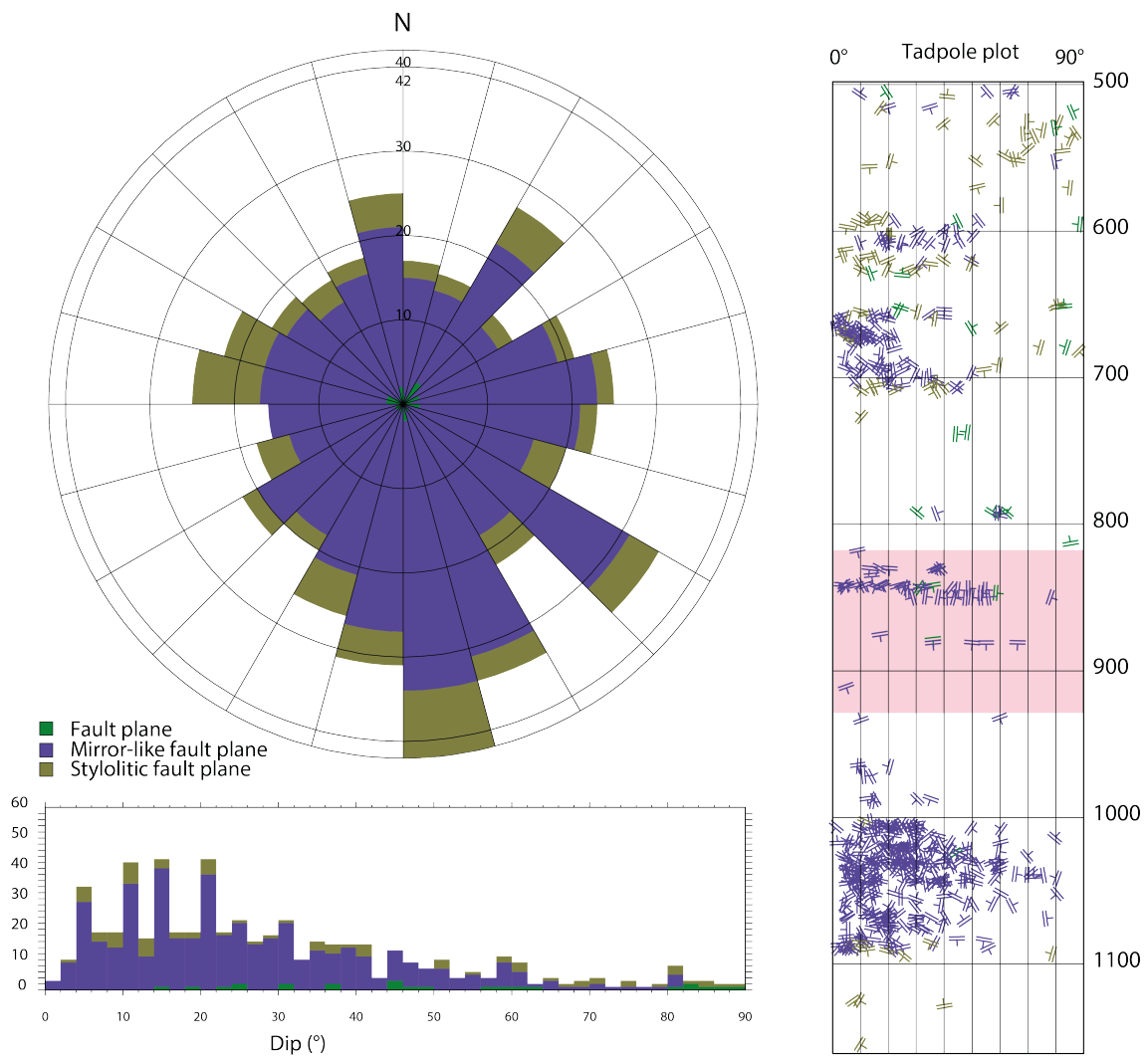


Fig. 4-6: Azimuth rose diagram, dip histogram and depth plot for fault planes in the entire cored interval

A total of 555 fault planes is displayed: fault plane ($n = 24$), mirror-like fault plane ($n = 450$) and stylolitic fault plane ($n = 81$). Depth range is 498.00 – 1161.03 m MD log depth. In the tadpole plot, the Opalinus Clay interval is shaded in red.

Tension gashes / veins, joints and unassigned fractures

This group of structures represents features without shear indicators and comprises tension gashes / veins ($n = 347$) and joints ($n = 33$). Also included are fractures ($n = 11$) which could not be assigned to a specific class of structure. With a total of 391 individual structures, they represent the smallest group of structural discontinuities. Out of these 391 structures, 366 (94 %) planes were recorded in oriented cores.

The spatial distribution of tension gashes / veins, joints and unassigned fractures along the TRU1-1 borehole is presented in Fig. 4-4 and discussed in Section 4.1.4. Compared to faults, they reveal an even larger orientation scatter as shown in Figs. 4-7 and 4-8. However, two weakly defined orientation clusters can be distinguished (Tab. 4-1): (1) a main steeply NNW-dipping cluster with an overall mean of $336/46$ ($n = 60$) and (2) a subordinate cluster with shallow SSE-dipping structures (overall mean of $146/18$; $n = 44$).

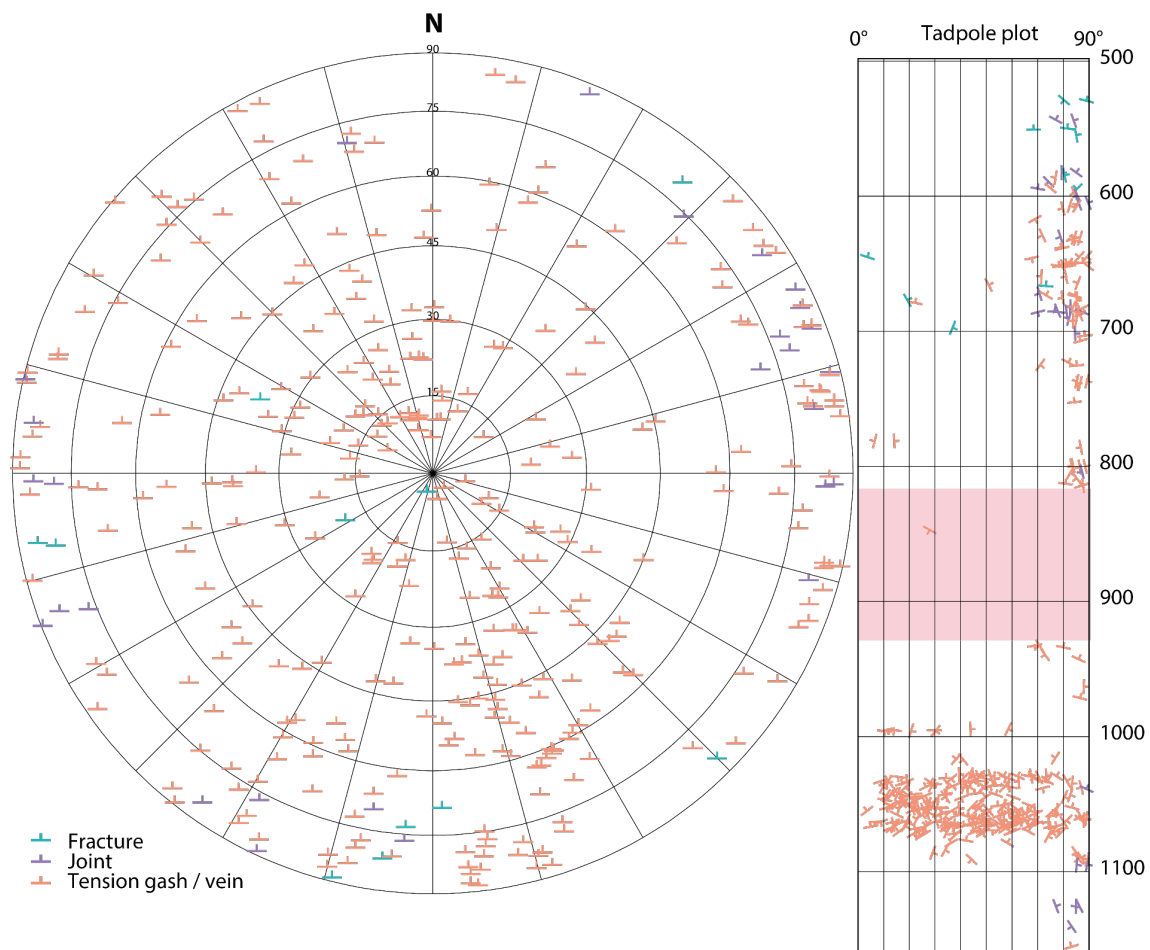


Fig. 4-7: Stereogram and depth plot for tension gashes / veins, unassigned fractures and joints in the entire cored interval

A total of 366 structures is displayed: tension gashes / veins ($n = 328$), joints ($n = 27$) and unassigned fractures ($n = 11$). Depth range is 498.00 – 1'161.03 m MD log depth. In the tadpole plot, the Opalinus Clay interval is shaded in red.

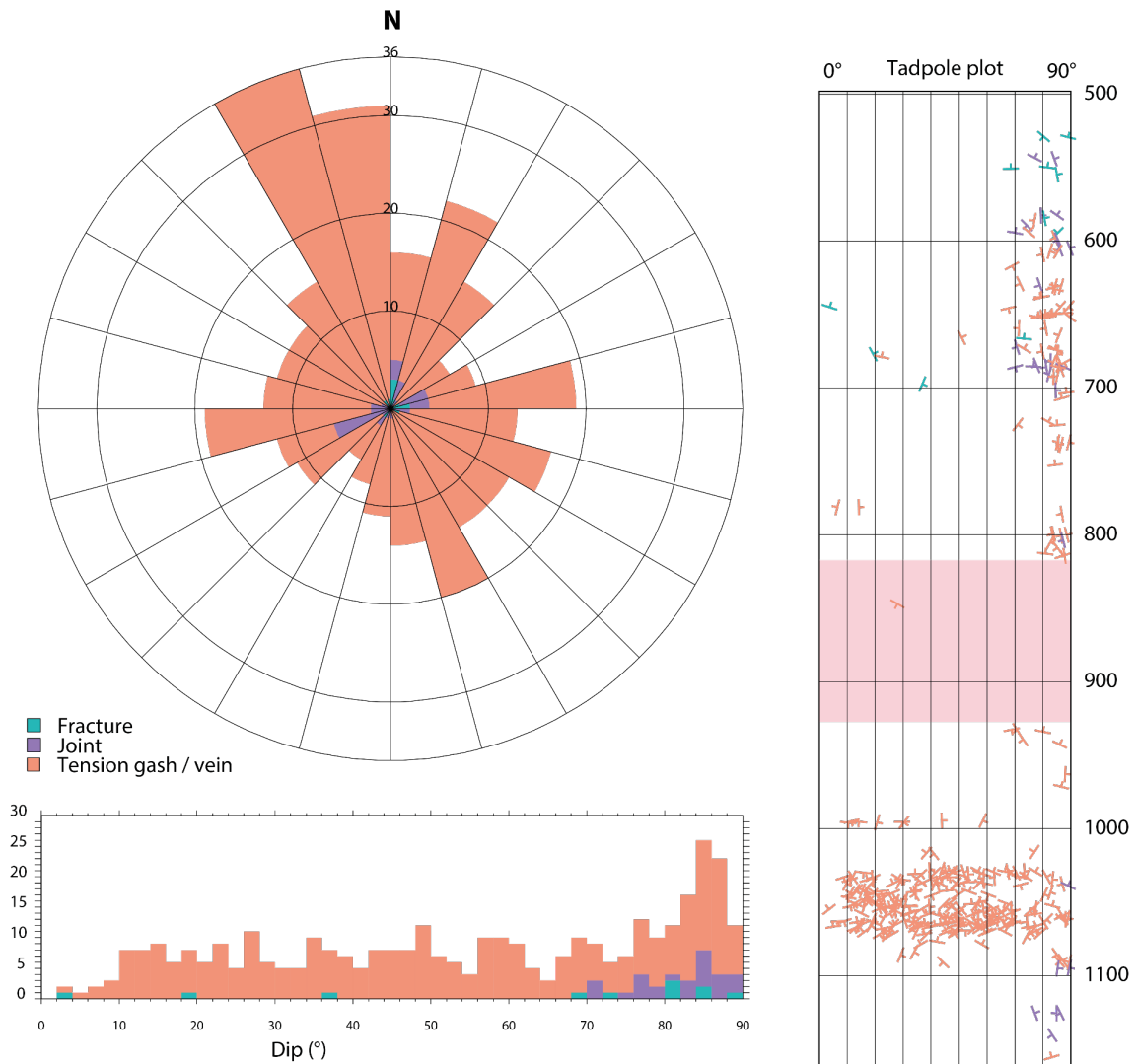


Fig. 4-8: Azimuth rose diagram of tension gashes / veins, unassigned fractures and joints in the entire cored interval

A total of 366 structures is displayed: tension gashes / veins ($n = 328$), joints ($n = 27$) and unassigned fractures ($n = 11$). Depth range is 498.00 – 1'161.03 m MD log depth. In the tadpole plot, the Opalinus Clay interval is shaded in red.

Stylolites

The majority of the identified structures in TRU1-1 are stylolites ($n = 1'086$). Out of this, 769 (71 %) were recorded in oriented cores. In stylolite-rich intervals such as the Malm and the Muschelkalk, not all individual stylolites could be picked or documented and only the dominant stylolites which could be clearly observed in core photographs have been documented and categorised. Intervals with high densities of stylolites have been defined as stylolitic zones.

Stylolites depict two well-developed orientation clusters (Figs. 4-9, 4-10 and Tab. 4-1): A main sub-horizontal to gently inclined ($1 - 20^\circ$) SSE- to S-dipping cluster (overall mean of $162/07$; $n = 563$) and a subordinate steep to sub-vertical ($60 - 90^\circ$) cluster striking roughly WSW-ENE (overall mean of $339/82$; $n = 34$).

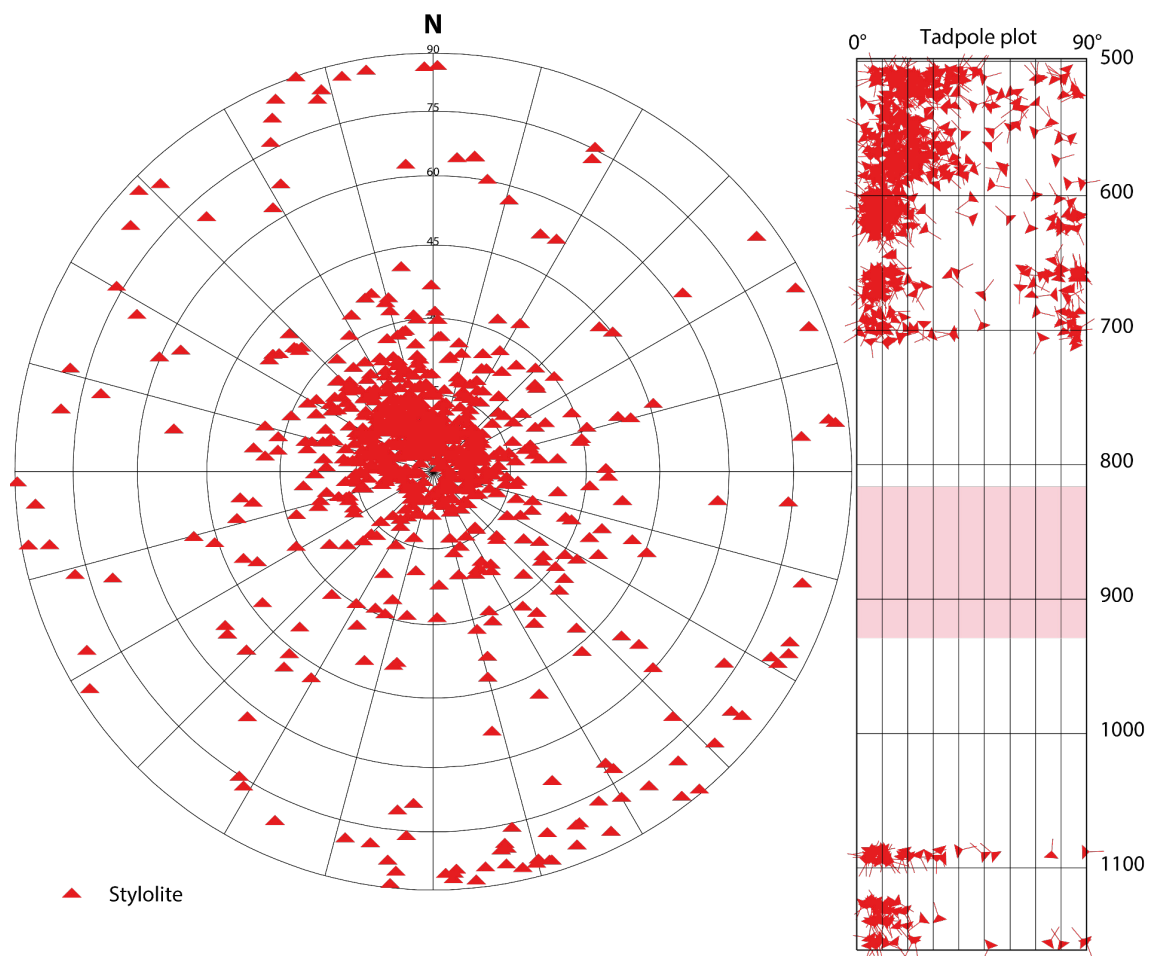


Fig. 4-9: Stereogram and depth plot for stylolites ($n = 769$) along the cored TRU1-1 borehole. Depth range is 498.00 – 1'161.03 m MD log depth. In the tadpole plot, the Opalinus Clay interval is shaded in red.

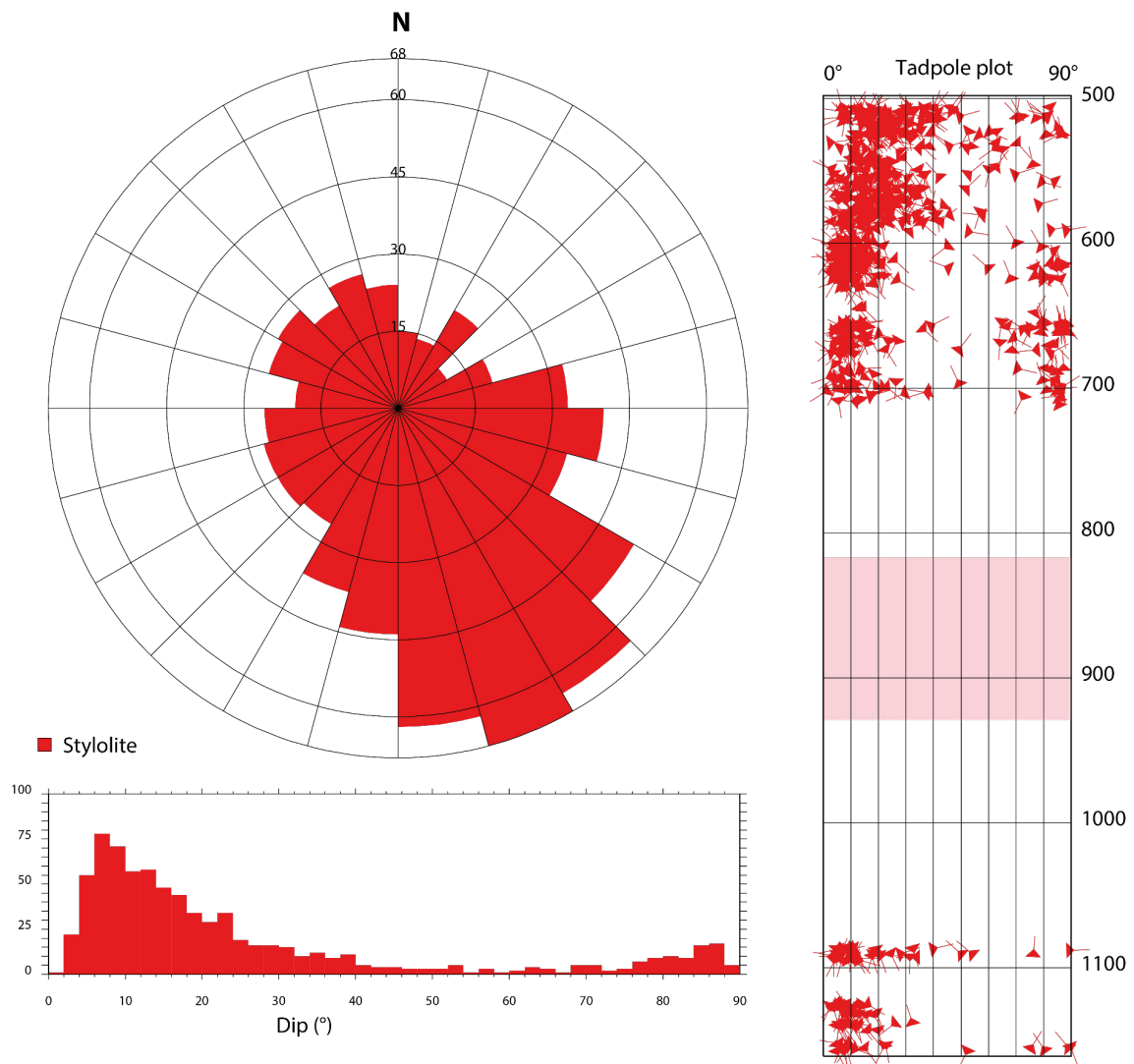


Fig. 4-10: Azimuth rose diagram and depth plot for stylolites in the entire cored interval
 Depth range is 498.00 – 1'161.03 m MD log depth, $n = 769$. In the tadpole plot, the Opalinus Clay interval is shaded in red.

4.1.3 Fracture density (P32) and distribution

Density histograms were prepared in order to evaluate the spatial fracture distribution (Fig. 4-4). As mentioned above, structures recorded in non-oriented cores ($n = 657$) were considered in the fracture density calculations.

Fault planes are unevenly distributed along the cored interval. They are abundant in the Malm from 590 to 629 m and from 653 to 710 m MD log depth, in the Opalinus Clay from 842 to 850 m MD log depth and in the Klettgau Formation from 979 to 990 m MD log depth and also from 1'005 to 1'091 m MD log depth, including the Bänkerjoch and the uppermost Schinznach Formations. The highest densities of fault planes with up to 28/m were observed within the fault zones from 983.20 to 987.57 m and from 1'004.67 to 1'006.15 m MD log depth within the Klettgau Formation, forming prominent fault zones and associated intensely fractured rock (Tab. 4-2 and Fig. 4-4). However, the average density of fault planes for the entire cored borehole section was about 1.1/m.

Tension gashes / veins are particularly abundant within the Bänkerjoch Formation from 1'028 to 1'079 m MD log depth as well as in the interval from 600 to 815 m MD log depth within the Malm and «Brauner Dogger». In contrast, fractures and joints were found within the Malm at 600 m and 687 m MD log depth and in the Schinznach Formation at 1'123 m MD log depth. The highest density of tension gashes / veins with up to 19/m was encountered from 799 to 814 m MD log depth and is related to sub-vertical, roughly NNW-SSE striking planes. However, the average density was about 1.3/m.

Stylolites revealed an uneven along-borehole distribution and occurred almost exclusively within the carbonate-rich lithologies of the Malm (from 498 to 709 m MD log depth) and Muschelkalk (from 1'086 to 1'161 m MD log depth). The highest density with up to 25 stylolites per metre occurred within the Villigen Formation from 655 to 662 m MD log depth. However, the average density for the whole borehole section was 2.1/m.

4.1.4 Kinematic indicators

Striations could be measured on 531 fault planes. In total, 85 % of the striations ($n = 454$) were collected in oriented cores. They are shown in the stereograms below. The orientations of the striations are given in Figs. 4-11 – 4-16. There is a slight predominance of south- and north-dipping striations. The vast majority has sub-horizontal to inclined ($0 - 50^\circ$) dip magnitudes.

Three groups of shear sense were distinguished on the analysed drill cores:

- up = thrusting / reverse faulting
- down = normal faulting
- dextral / sinistral = strike-slip faulting

A total of 72 shear indicators were identified as thrusts / reverse faults (Fig. 4-13). In contrast, most identified shear senses correspond to normal faults ($n = 119$; Fig. 4-14) and strike-slip faults ($n = 9$; Fig. 4-15). However, the shear sense of most fault planes ($n = 331$) was uncertain (Fig. 4-16).

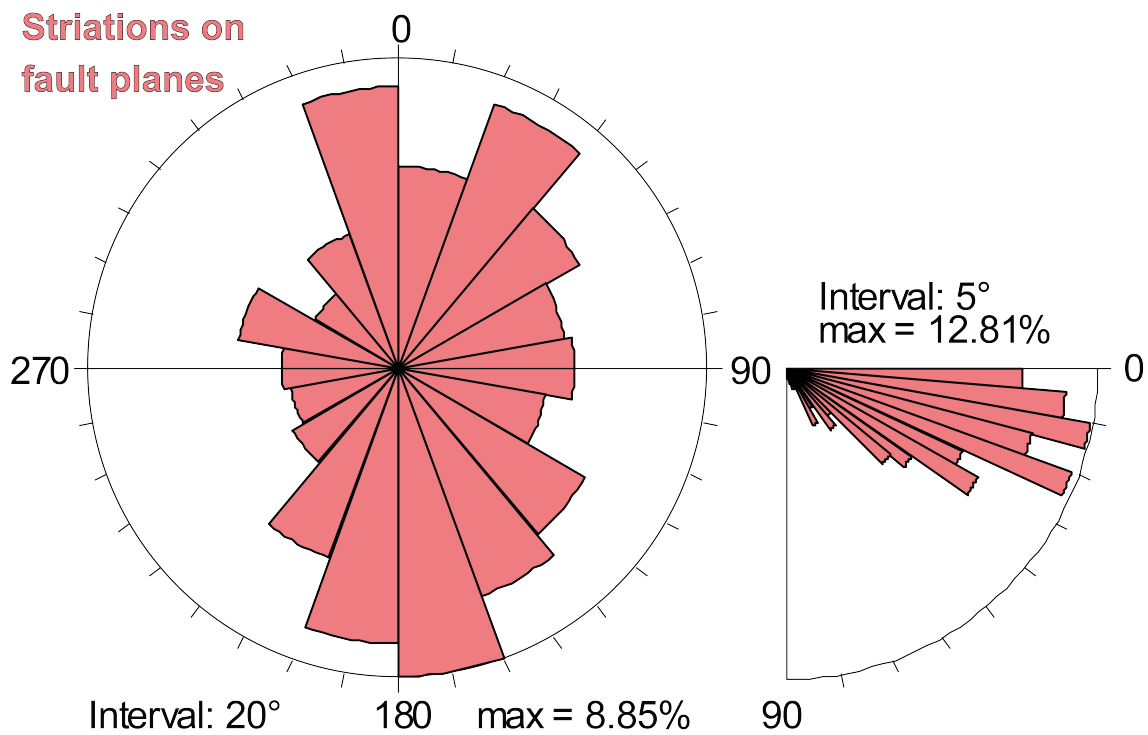


Fig. 4-11: Dip direction of striations along fault planes in the entire cored interval

The striations ($n = 454$) from oriented cores of the entire core interval from Malm to Muschelkalk are presented. Left: azimuth rose diagram, right: dip histogram. Depth range is 498.00 – 1'161.03 m MD log depth.

Tab. 4-3: List of all kinematic indicators in oriented and non-oriented cores

Shear sense	Number
Up	72
Down	119
Sinistral	6
Dextral	3
Unknown	331
In oriented cores	454
In non-oriented cores	77
Total measured lineations	531

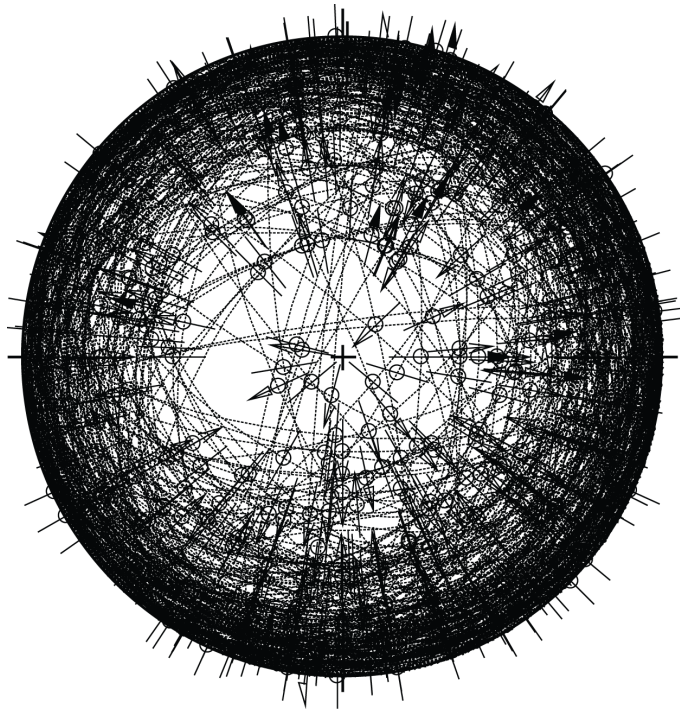


Fig. 4-12: Stereogram with all fault planes and associated kinematic data, including multiple lineations on a single fault plane

Up (n = 72), down (n = 119), dextral (n = 3), sinistral (n = 6) and unknown (n = 331). Depth range is 498.00 – 1'161.03 m MD log depth.

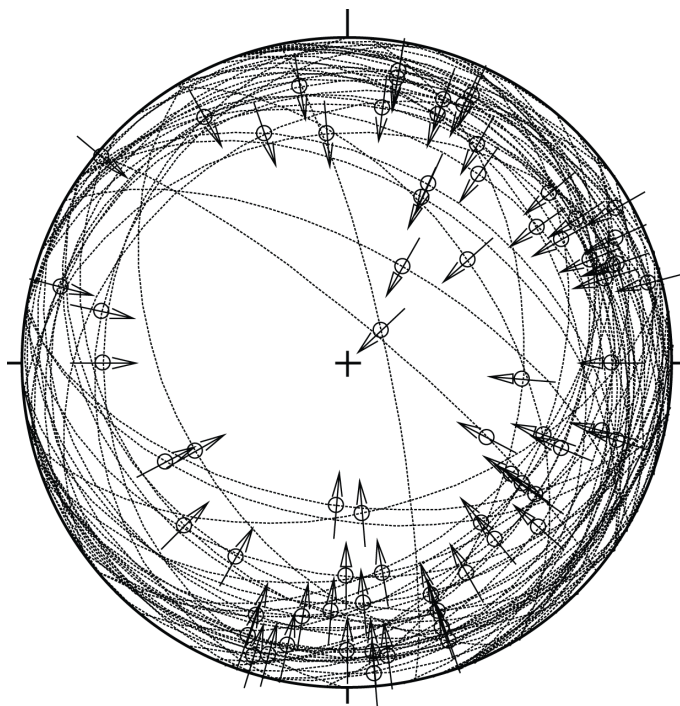


Fig. 4-13: Stereogram with all striations of thrust / reverse fault planes and associated kinematic data, including multiple lineations on a single fault plane

Up (n = 72). Depth range is 498.00 – 1'161.03 m MD log depth.

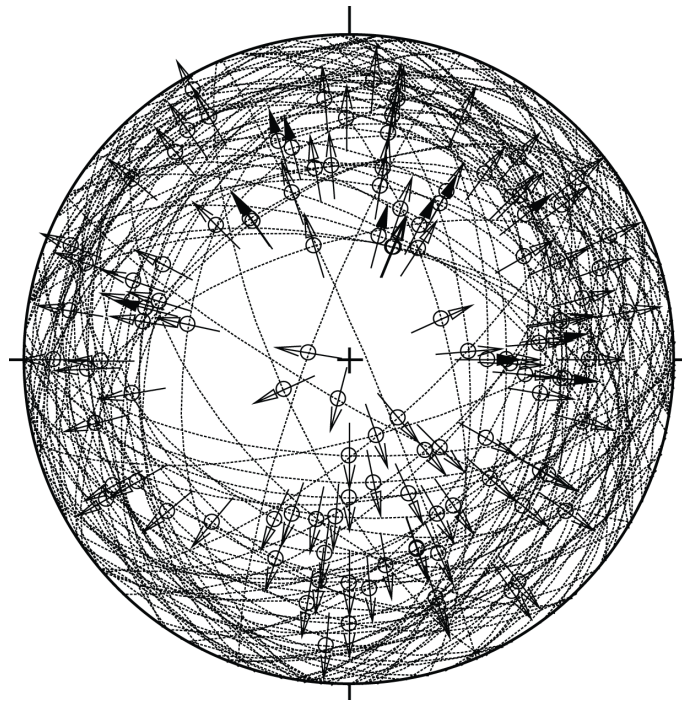


Fig. 4-14: Stereogram with all normal fault planes and associated striations, including multiple lineations on a single fault plane

Down ($n = 119$). Depth range is 498.00 – 1'161.03 m MD log depth.

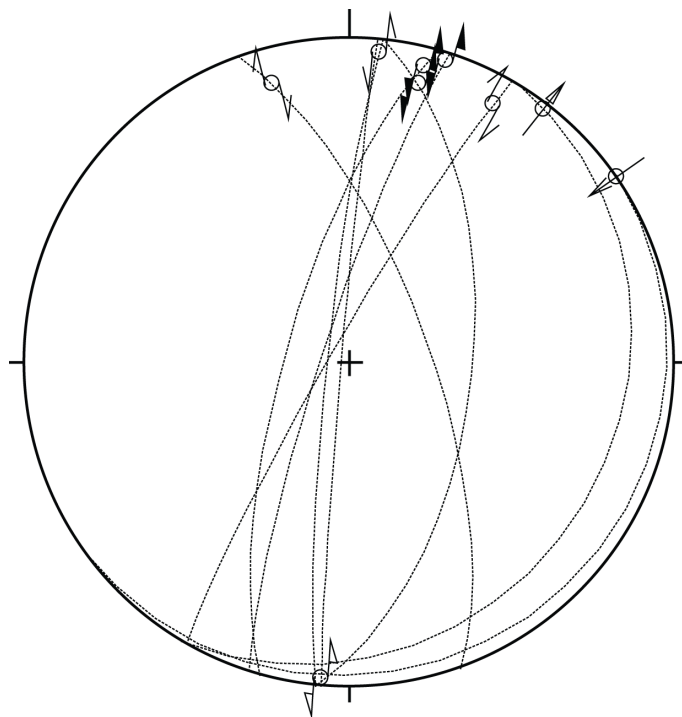


Fig. 4-15: Stereogram with all strike-slip fault planes and associated striations

Dextral ($n = 3$), sinistral ($n = 6$). Depth range is 498.00 – 1'161.03 m MD log depth.

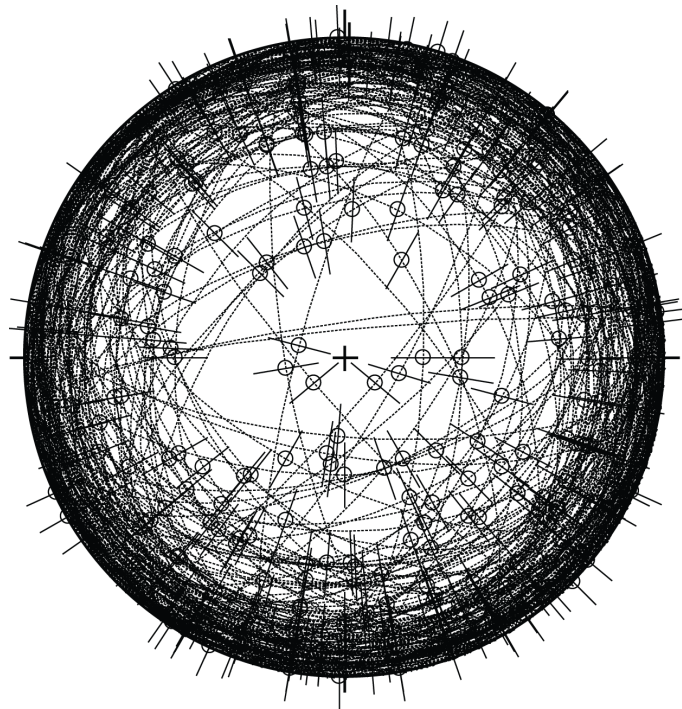


Fig. 4-16: Stereogram for all fault planes with unknown shear sense, including multiple lineations on a single fault plane

Unknown ($n = 331$). Depth range is 498.00 – 1'161.03 m MD log depth.

4.2 Malm

The cored Malm interval (498.00 – 725.03 m MD log depth) showed abundant stylolites and a significant number of fault planes. The average fracture density was 1.2 fractures per metre.

For the detailed stereographic evaluation, four lithostratigraphic units were defined within the Malm interval. Only the data for oriented cores are presented.

4.2.1 «Felsenkalke» + «Massenkalk»

The orientation and spatial distribution of structural discontinuities and lineations recorded within the cored interval of the «Felsenkalke» + «Massenkalk» (498.00 – 628.75 m MD log depth) are visualised below.

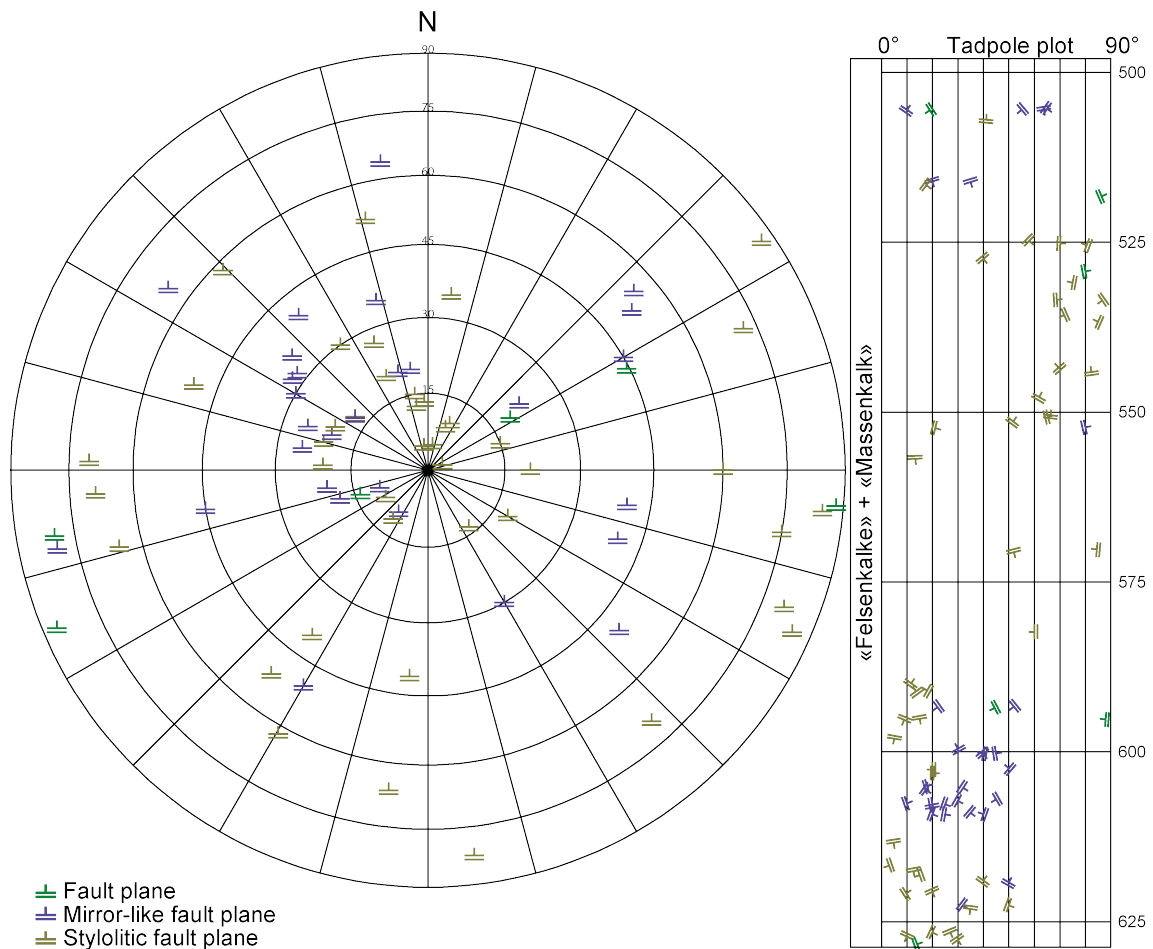


Fig. 4-17: Stereogram and depth plot of fault planes («Felsenkalke» + «Massenkalk»)

Fault planes (n = 6), mirror-like fault planes (n = 29) and stylolitic fault planes (n = 43).

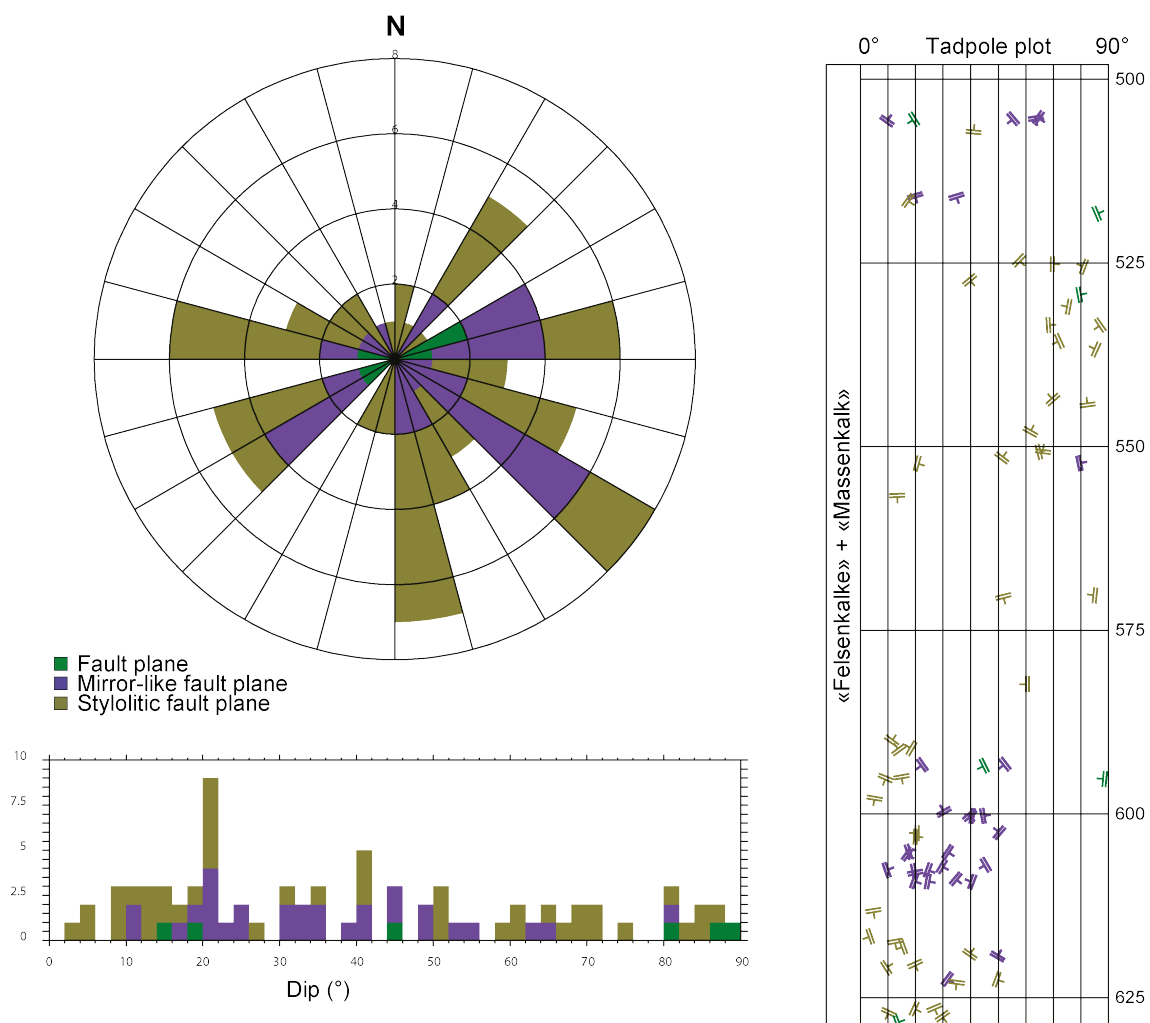


Fig. 4-18: Azimuth rose diagram, dip histogram and depth plot of fault planes («Felsenkalk» + «Massenkalk»)

Fault planes (n = 6), mirror-like fault planes (n = 29) and stylolitic fault planes (n = 43).

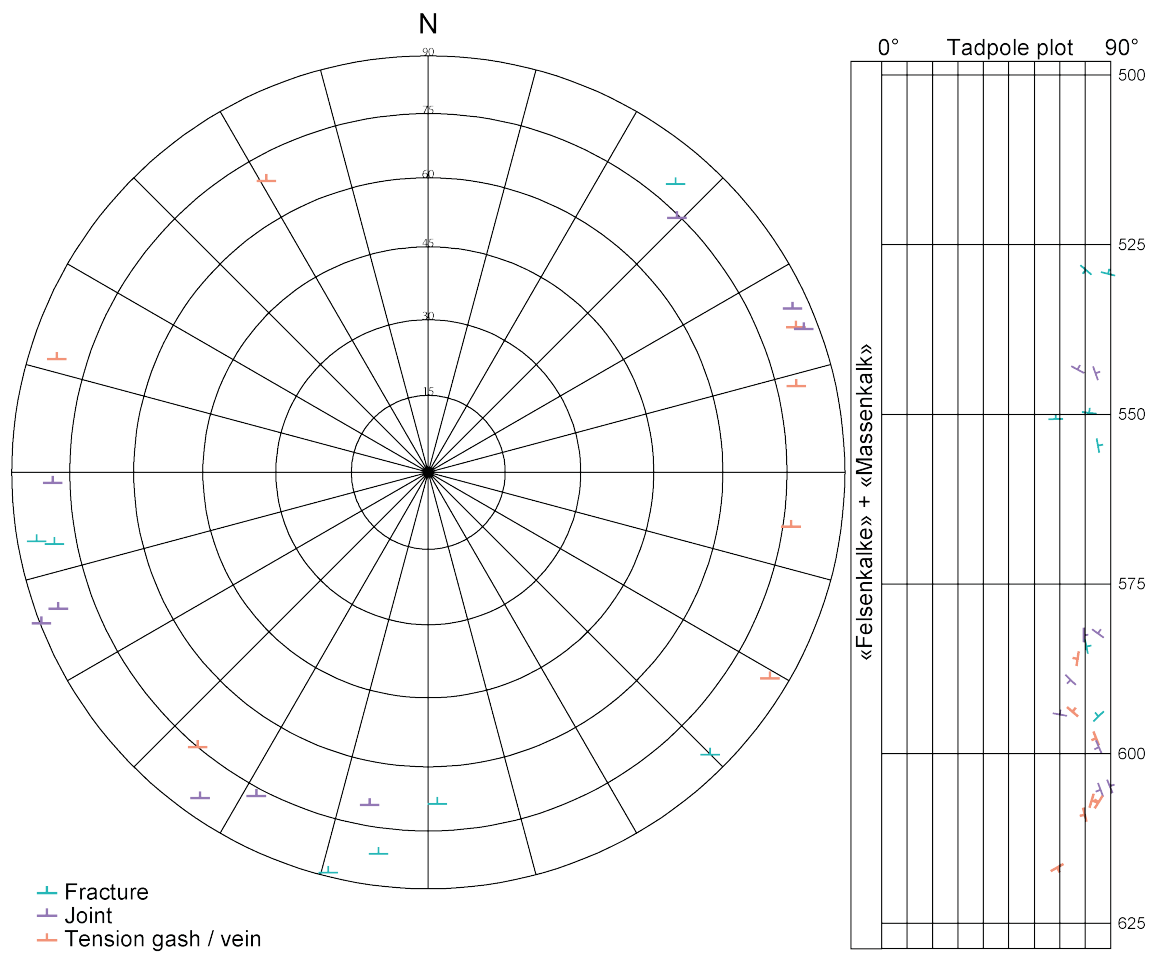


Fig. 4-19: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures («Felsenkalk» + «Massenkalk»)

Fractures (n = 7), joints (n = 9) and tension gashes / veins (n = 7).

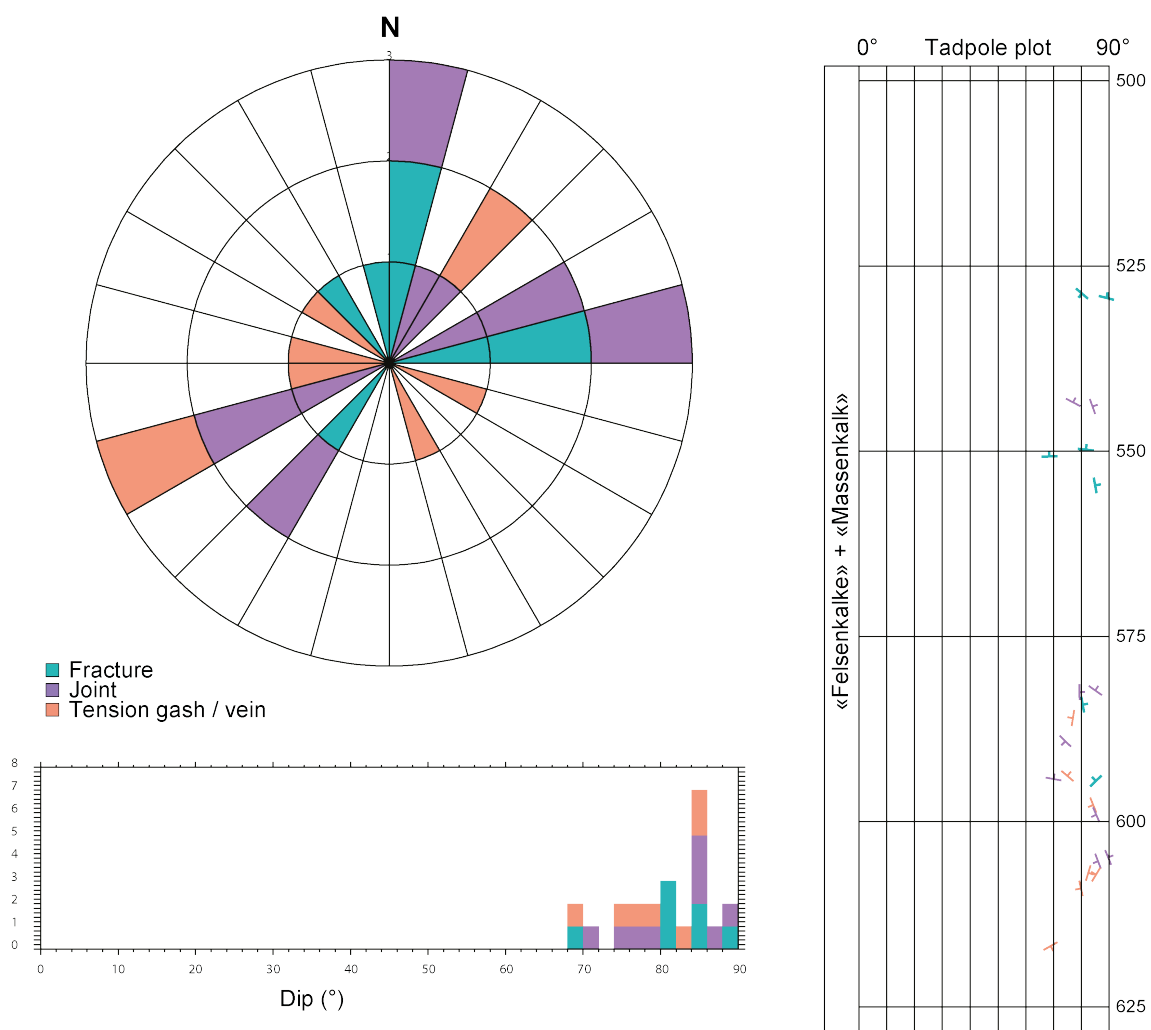


Fig. 4-20: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures («Felsenkalke» + «Massenkalk»)

Fractures (n = 7), joints (n = 9) and tension gashes / veins (n = 7).

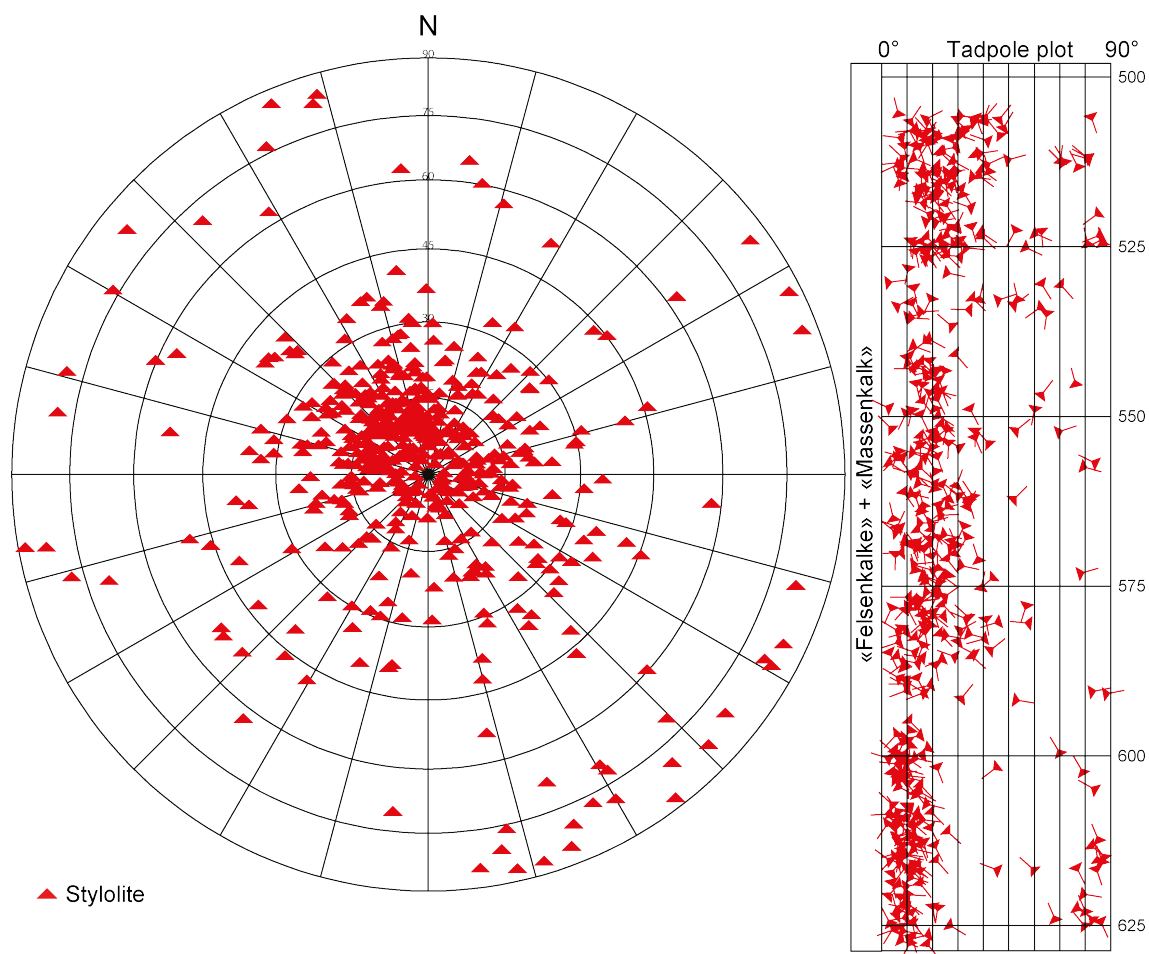


Fig. 4-21: Stereogram and depth plot of stylolites («Felsenkalke» + «Massenkalk», $n = 504$)

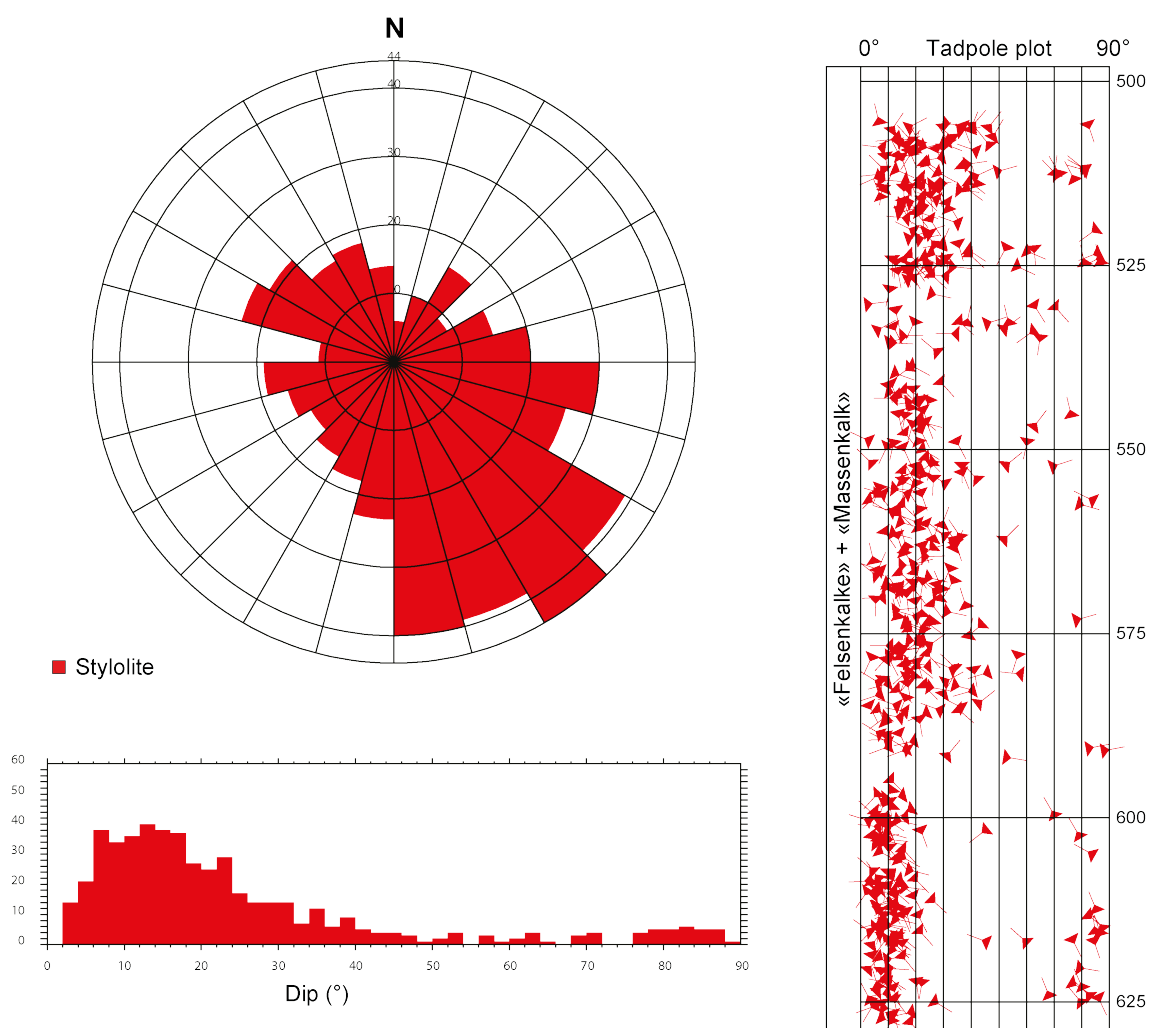


Fig. 4-22: Azimuth rose diagram, dip histogram and depth plot of stylolites («Felsenkalke» + «Massenkalk», n = 504)

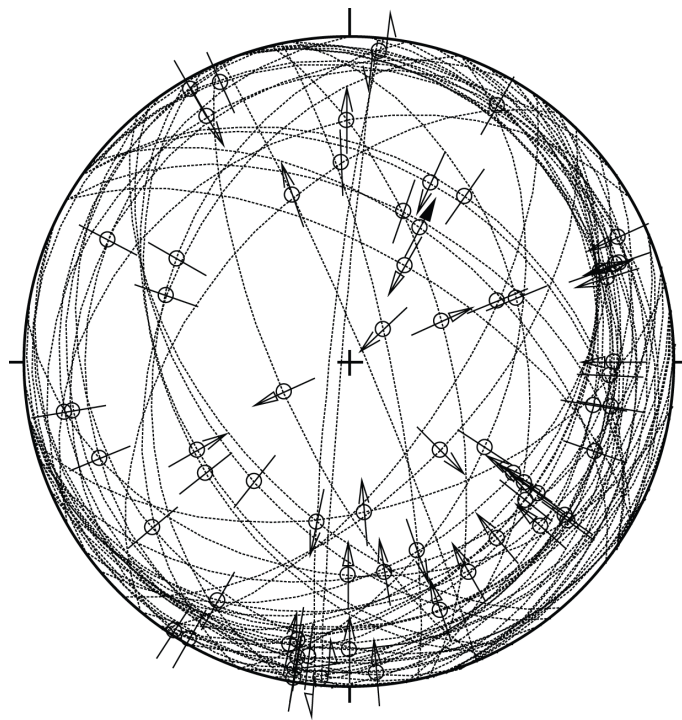


Fig. 4-23: Stereogram of fault planes with striations, including multiple lineations on a single fault plane («Felsenkalke» + «Massenkalk», $n = 69$)

4.2.2 Schwarzbach Formation

The structural data for the Schwarzbach Formation (628.75 – 653.15 m MD log depth) are presented below. Due to the low number of faults and stylolites ($n = 5$ respectively 9), rose diagram statistics were not calculated.

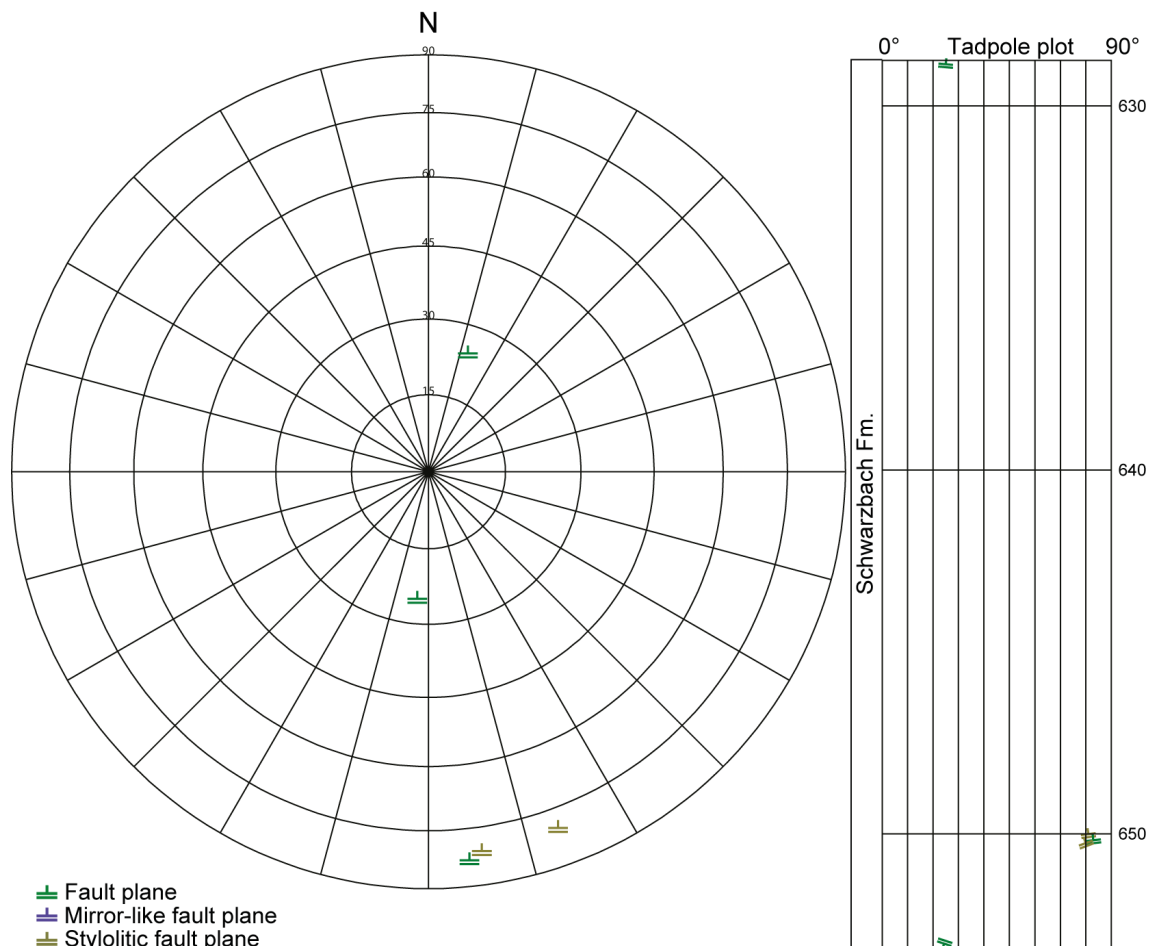


Fig. 4-24: Stereogram and depth plot of fault planes (Schwarzbach Formation)

Fault planes ($n = 3$), mirror-like fault planes ($n = 0$) and stylolitic fault planes ($n = 2$).

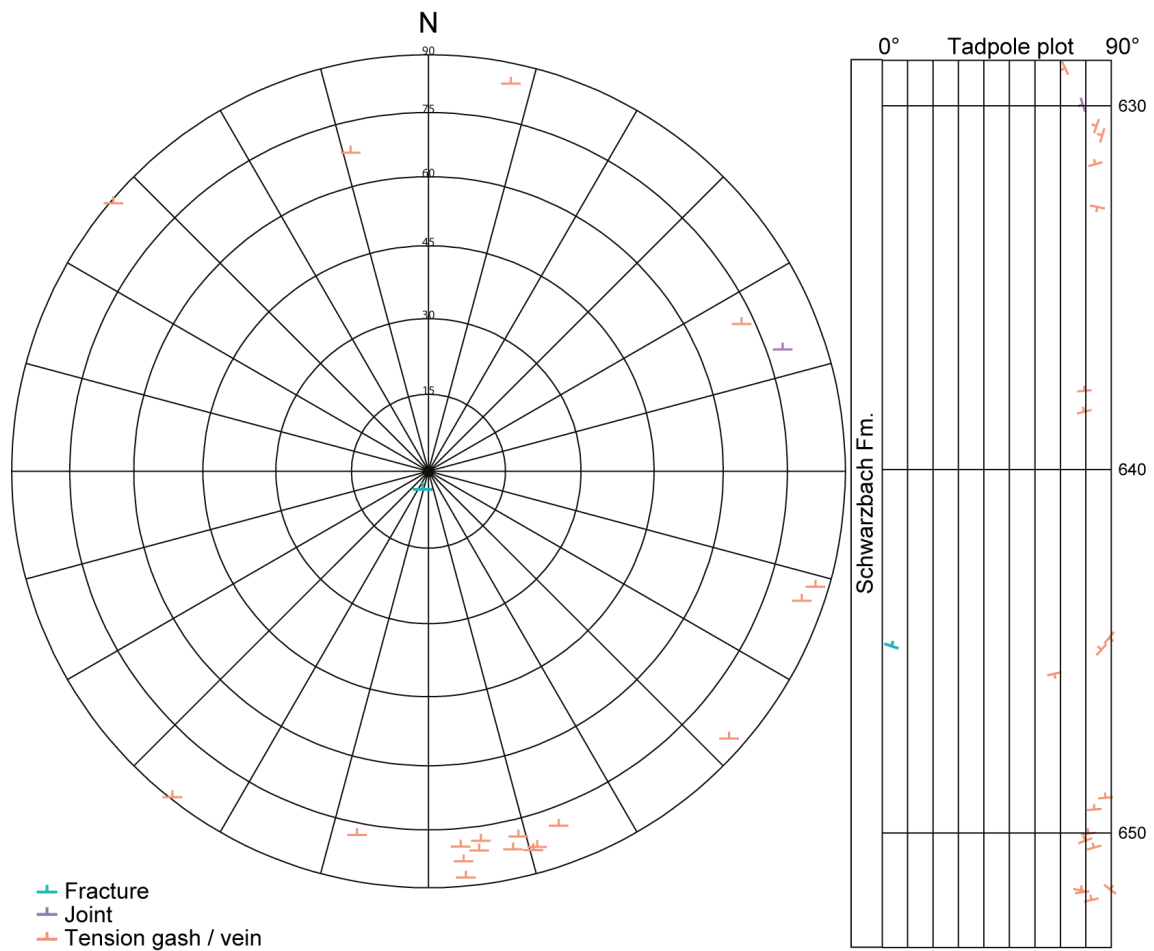


Fig. 4-25: Stereogram and depth plot for tension gashes / veins, joints and unassigned fractures (Schwarzbach Formation)

Fractures (n = 1), joints (n = 1) and tension gashes / veins (n = 19).

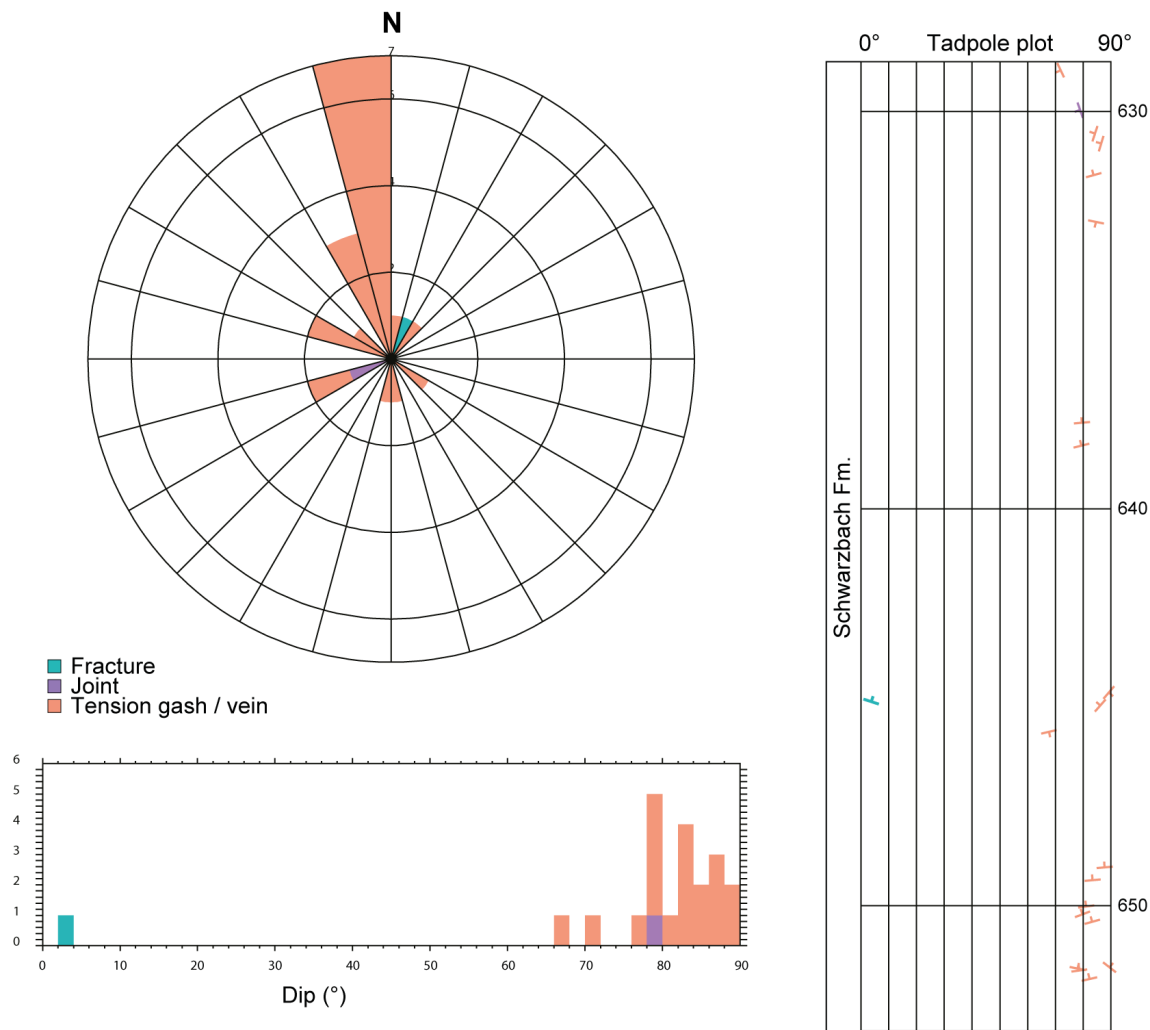


Fig. 4-26: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Schwarzbach Formation)
Fractures (n = 1), joints (n = 1) and tension gashes / veins (n = 19).

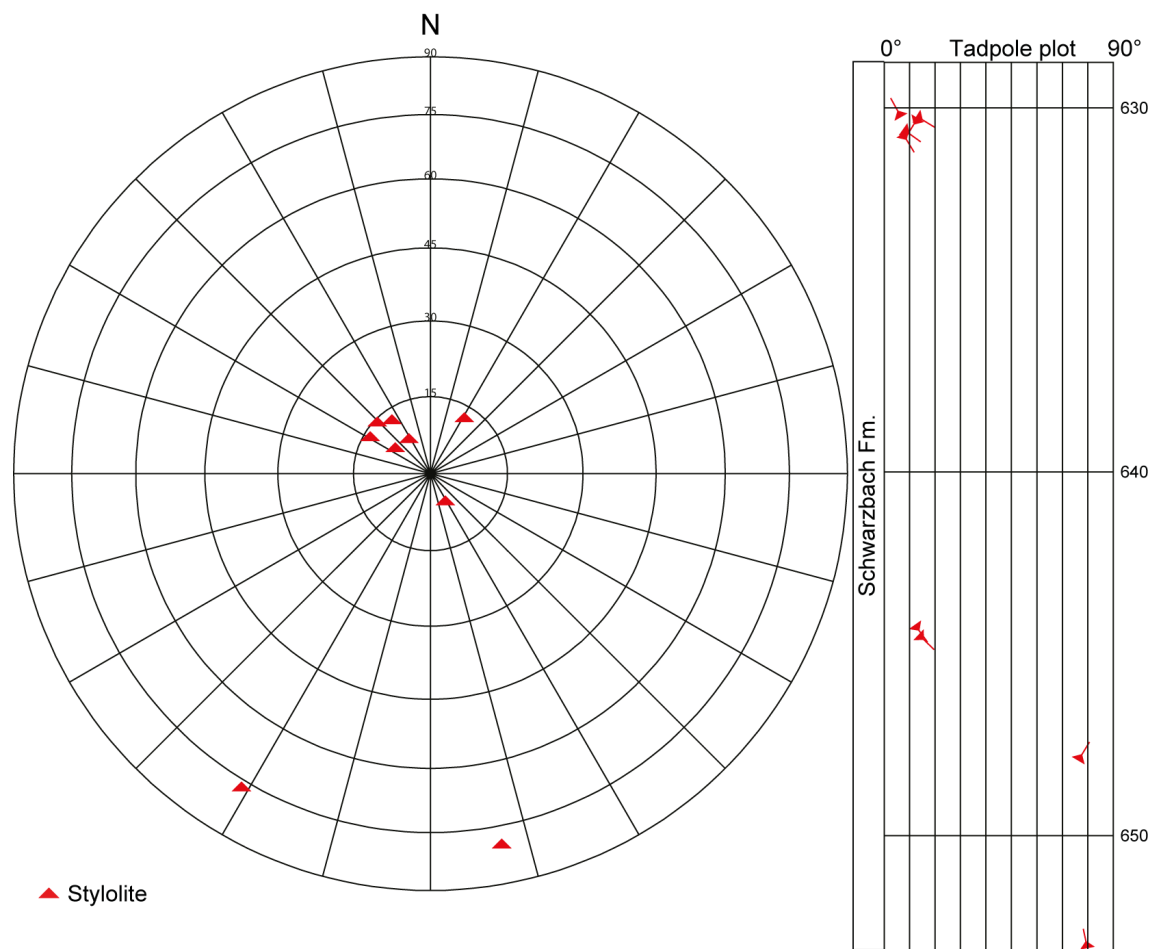


Fig. 4-27: Stereogram and depth plot of stylolites (Schwarzbach Formation, n = 9)

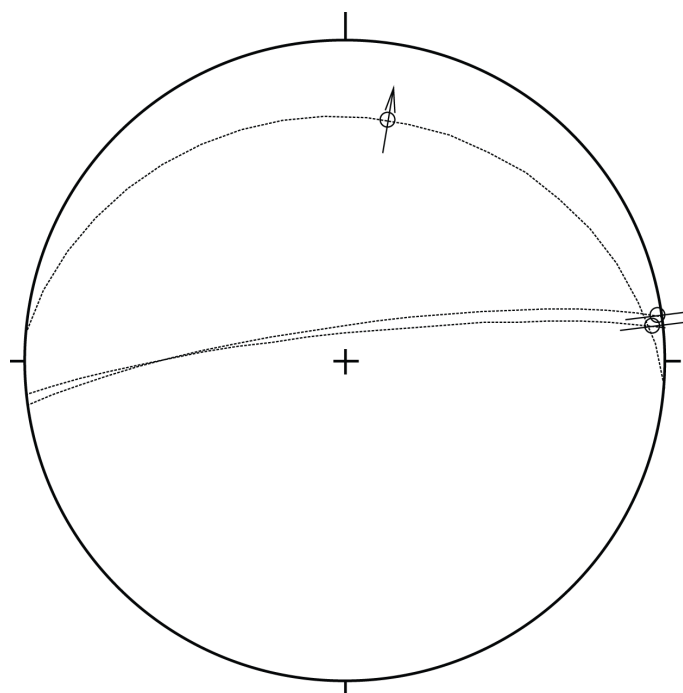


Fig. 4-28: Stereogram of fault planes and striations (Schwarzbach Formation, $n = 3$)

4.2.3 Villigen Formation

The orientation and spatial distribution of structural data in the Villigen Formation (653.15 – 714.00 m MD log depth) are visualised below.

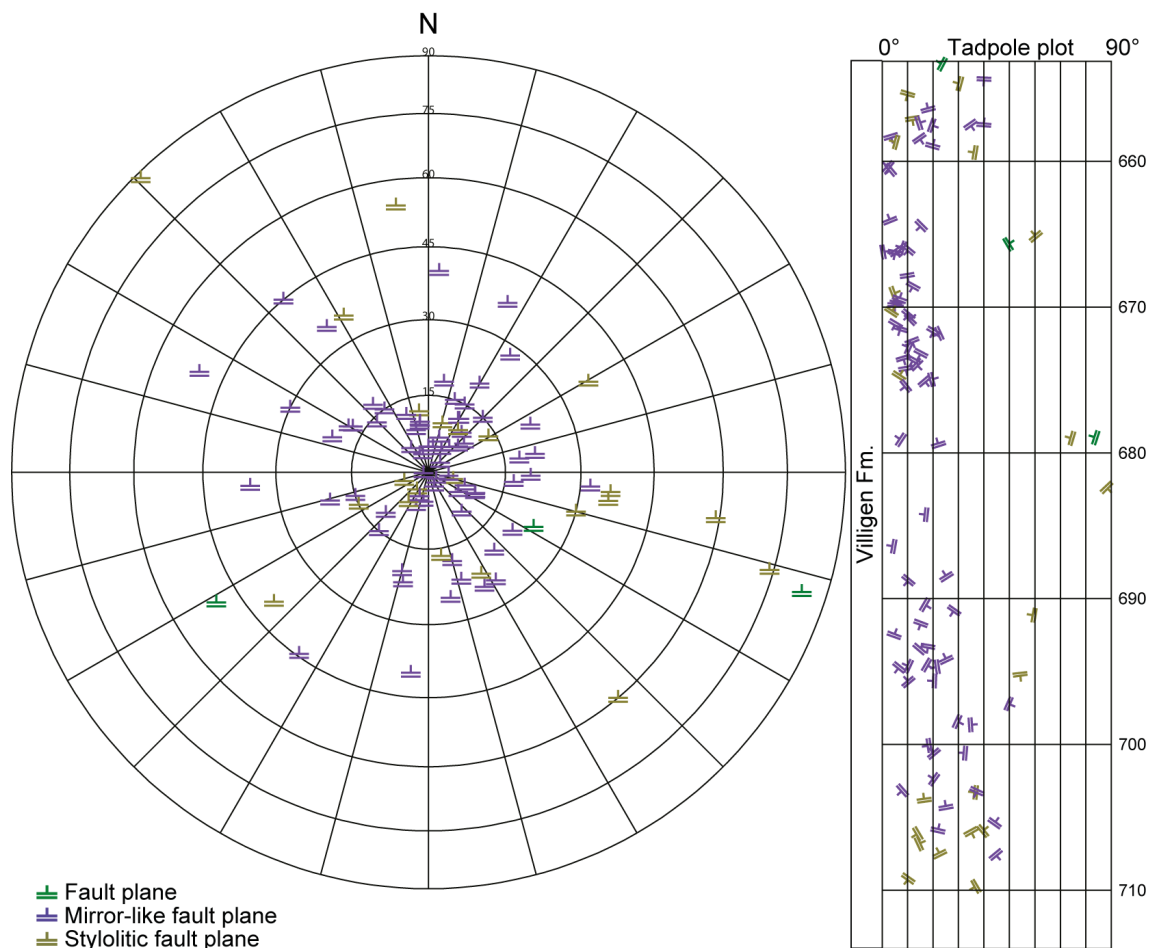


Fig. 4-29: Stereogram and depth plot of fault planes (Villigen Formation)

Fault planes (n = 3), mirror-like fault planes (n = 71) and stylolitic fault planes (n = 22).

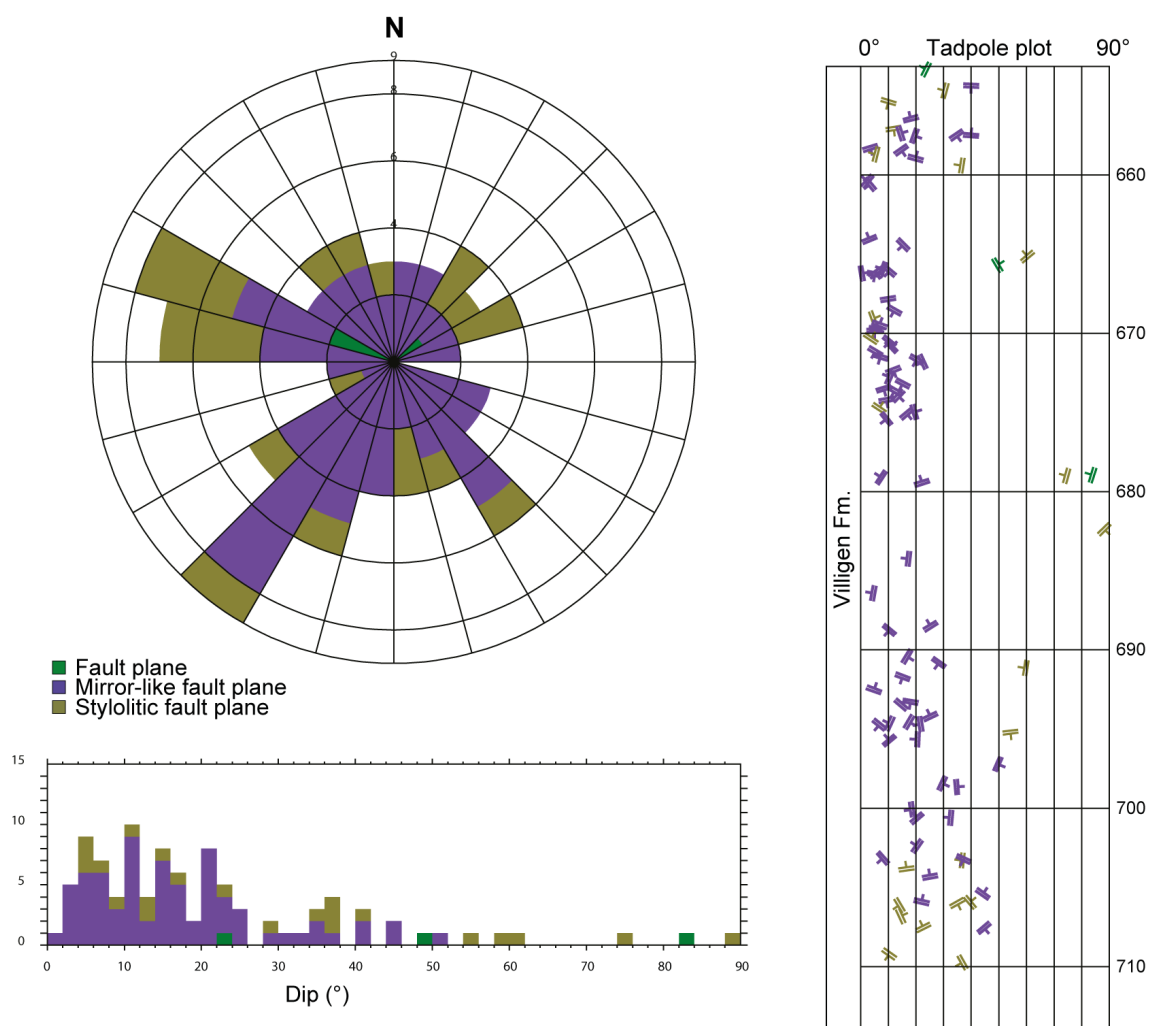


Fig. 4-30: Azimuth rose diagram, dip histogram and depth plot of fault planes (Villigen Formation)

Fault planes ($n = 3$), mirror-like fault planes ($n = 71$) and stylolitic fault planes ($n = 22$).

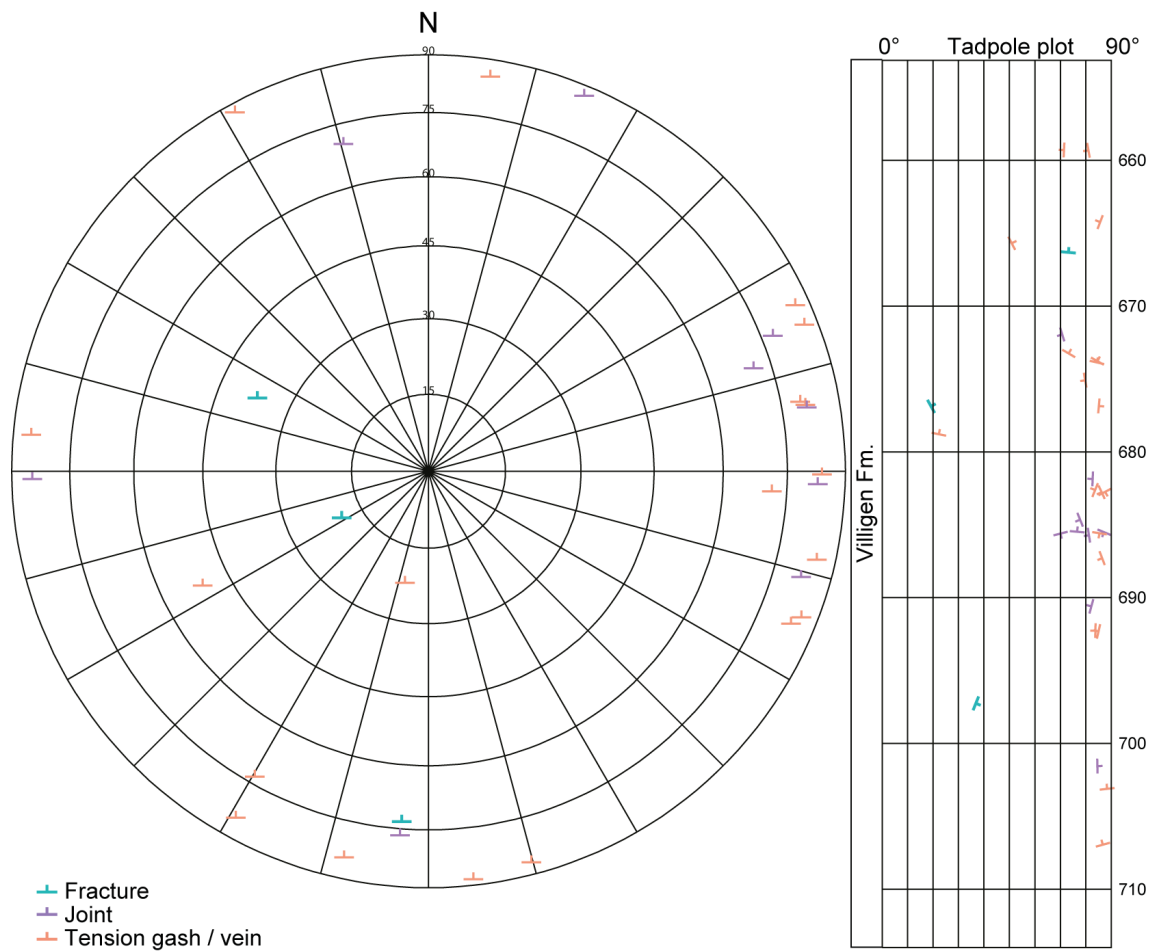


Fig. 4-31: Stereogram and depth plot of tension gashes / veins, and unassigned fractures (Villigen Formation)

Fractures (n = 3), joints (n = 9) and tension gashes / veins (n = 19).

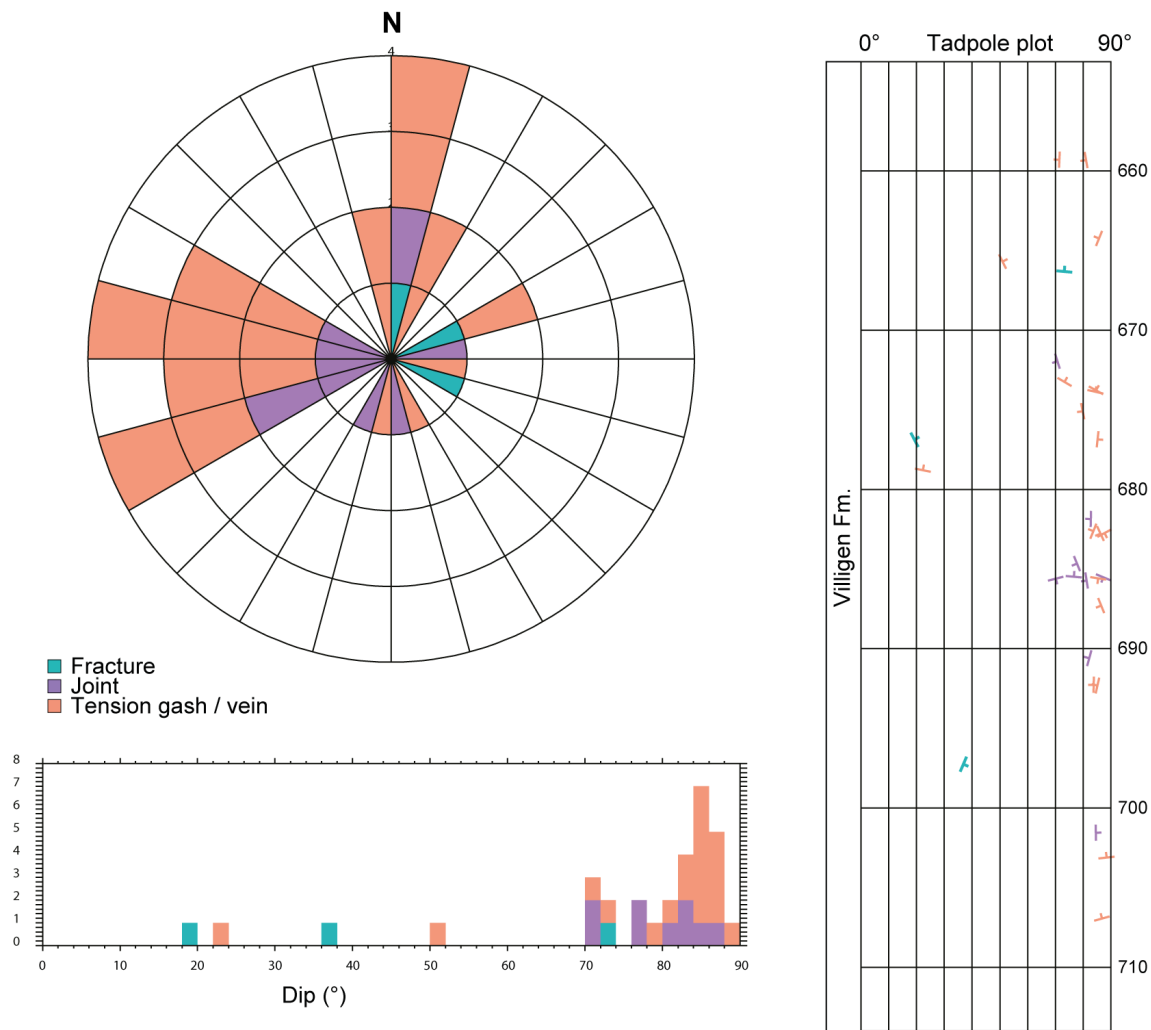


Fig. 4-32: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Villigen Formation)
Fractures (n = 3), joints (n = 9) and tension gashes / veins (n = 19).

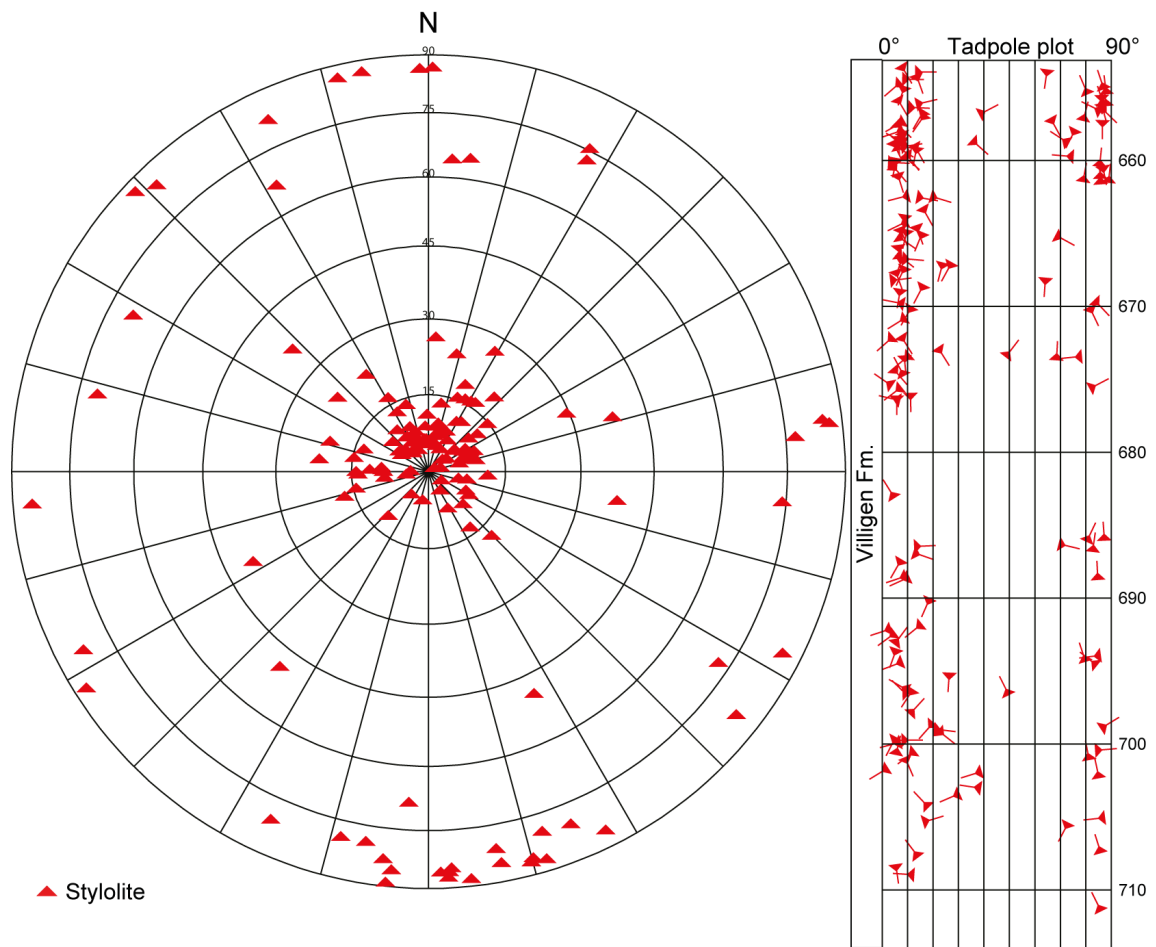


Fig. 4-33: Stereogram and depth plot of stylolites (Villigen Formation, n = 150)

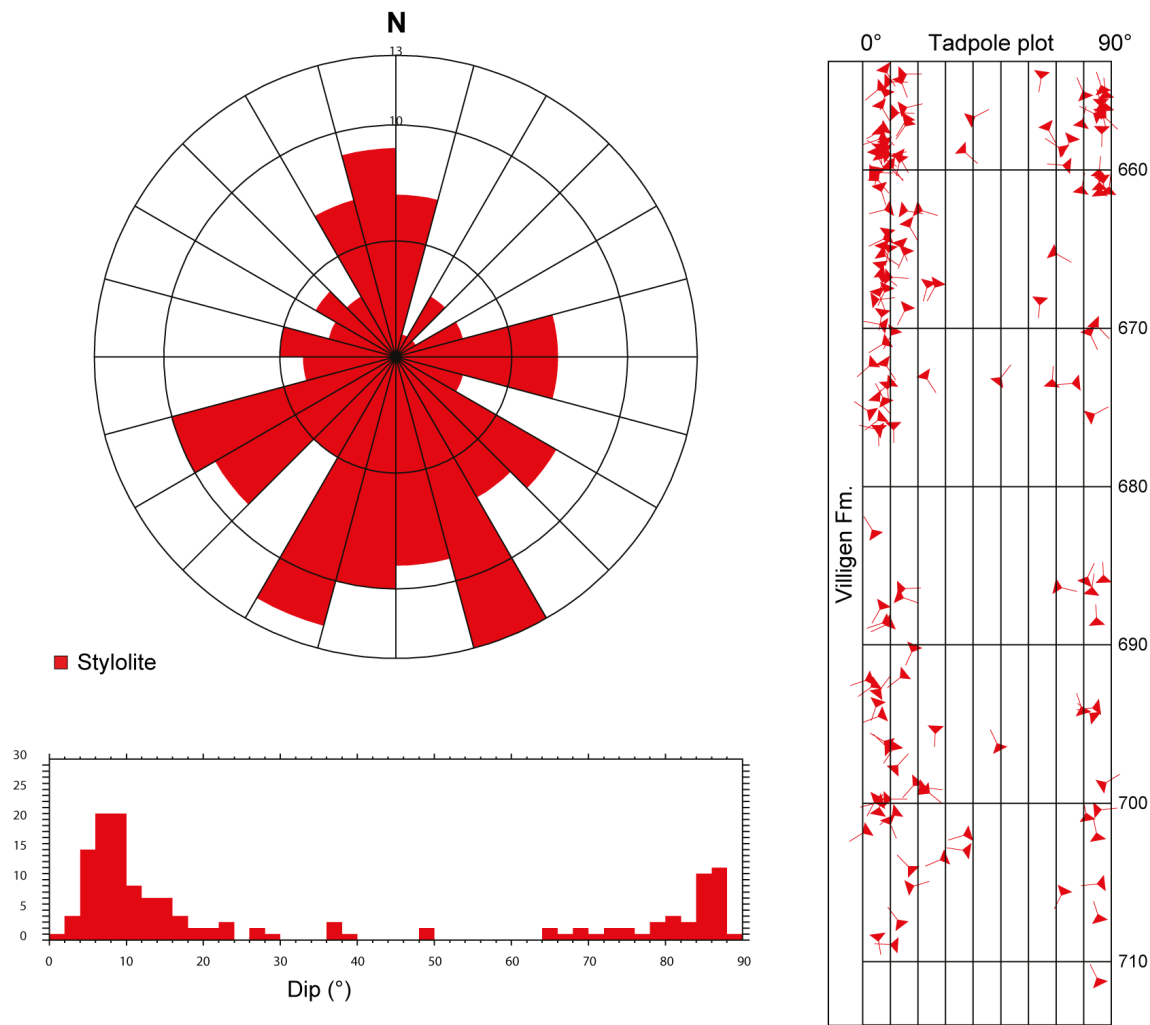


Fig. 4-34: Azimuth rose diagram, dip histogram and depth plot of stylolites (Villigen Formation, n = 150)

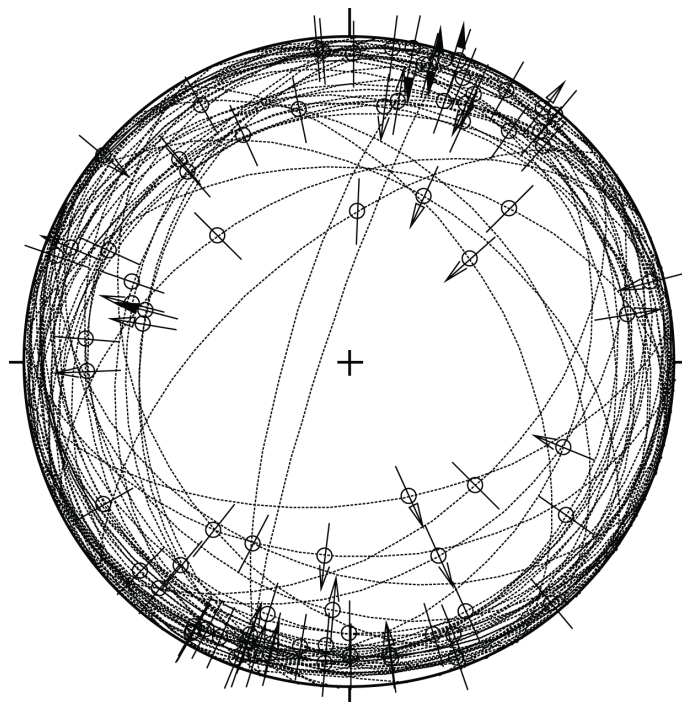


Fig. 4-35: Stereogram of fault planes with striations, including multiple lineations on a single fault plane (Villigen Formation, $n = 82$)

4.2.4 Wildegg Formation

The orientation and spatial depth distribution of recorded structures in the Wildegg Formation (714.00 – 725.03 m MD log depth) are shown below. Only a few veins could be identified along this borehole interval.

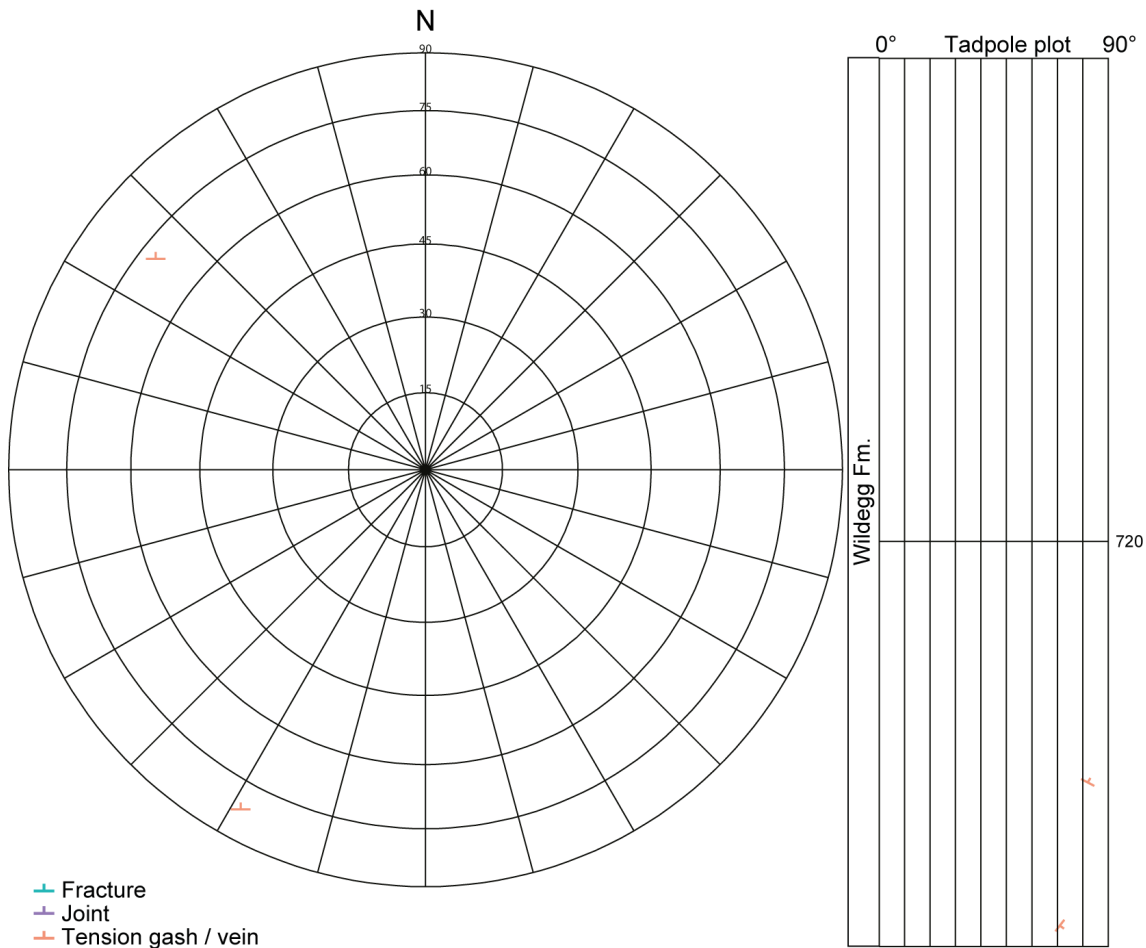


Fig. 4-36: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Wildegg Formation)

Fractures (n = 0), joints (n = 0) and tension gashes / veins (n = 2).

4.3 Dogger

For the stereographic evaluation, the Dogger was subdivided into two units: The «Brauner Dogger» and the Opalinus Clay. The orientation and spatial distribution of structural discontinuities within the «Brauner Dogger» are visualised below. Only the data from oriented cores are presented.

4.3.1 «Brauner Dogger» (Wutach Formation – «Murchisonae-Oolith Formation»)

The «Brauner Dogger» (725.03 – 816.43 m MD log depth) showed a low density of fault planes (n = 11), joints and tension gashes / veins (n = 19). Stylolites were not observed along this depth interval.

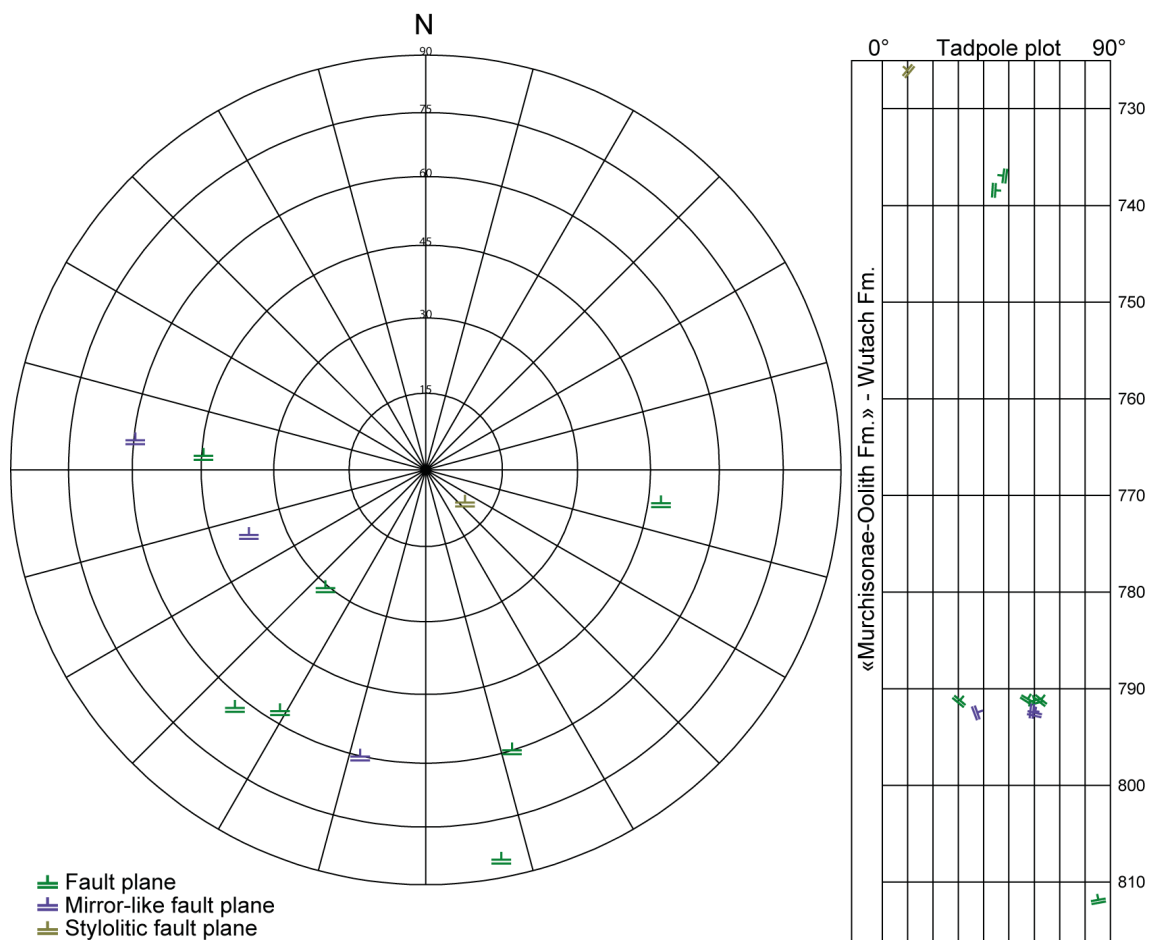


Fig. 4-37: Stereogram and depth plot of fault planes («Brauner Dogger»)

Fault planes (n = 7), mirror-like fault planes (n = 3) and stylolitic fault planes (n = 1).

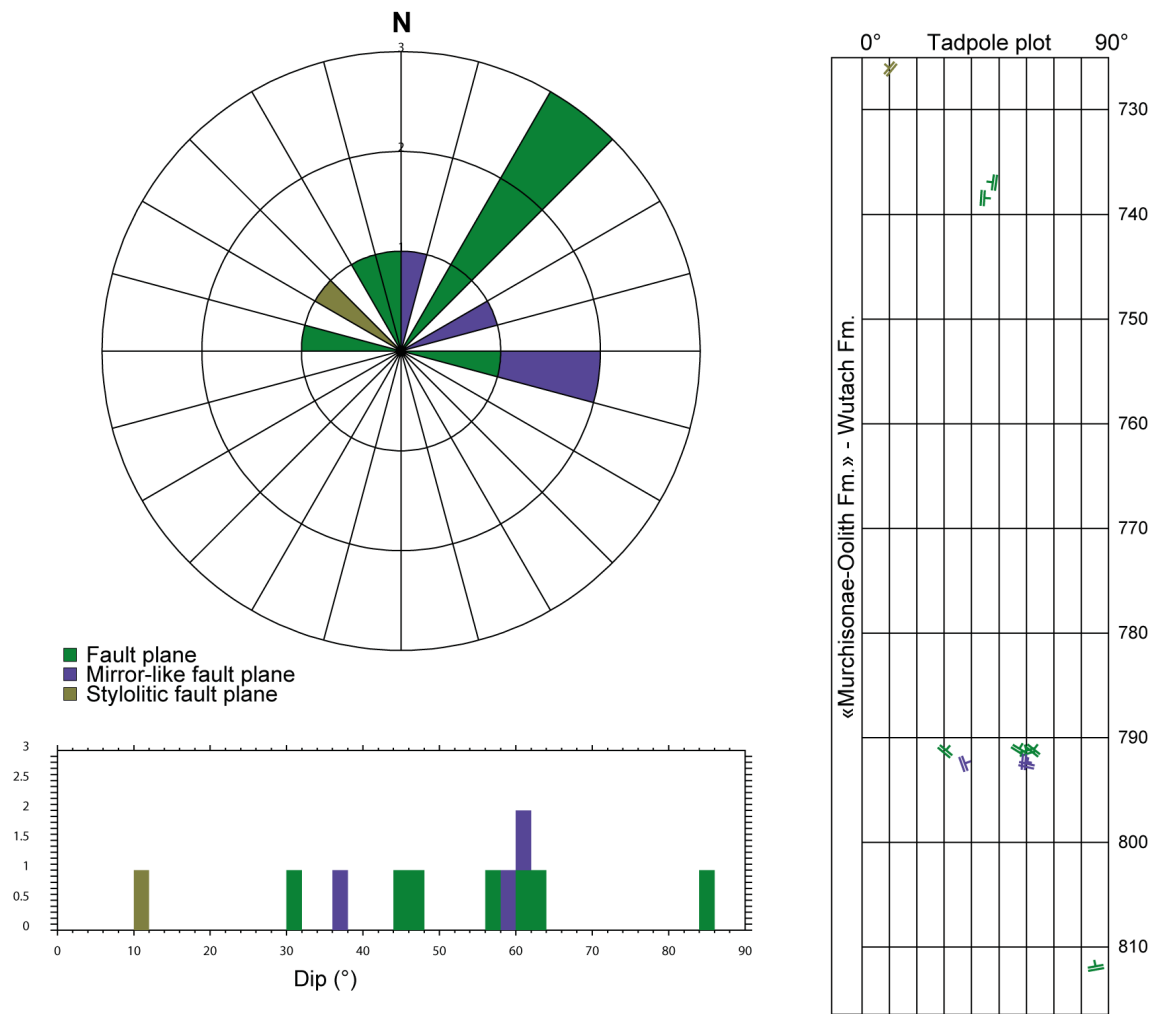


Fig. 4-38: Azimuth rose diagram, dip histogram and depth plot of fault planes («Brauner Dogger»)

Fault planes (n = 7), mirror-like fault planes (n = 3) and stylolitic fault planes (n = 1).

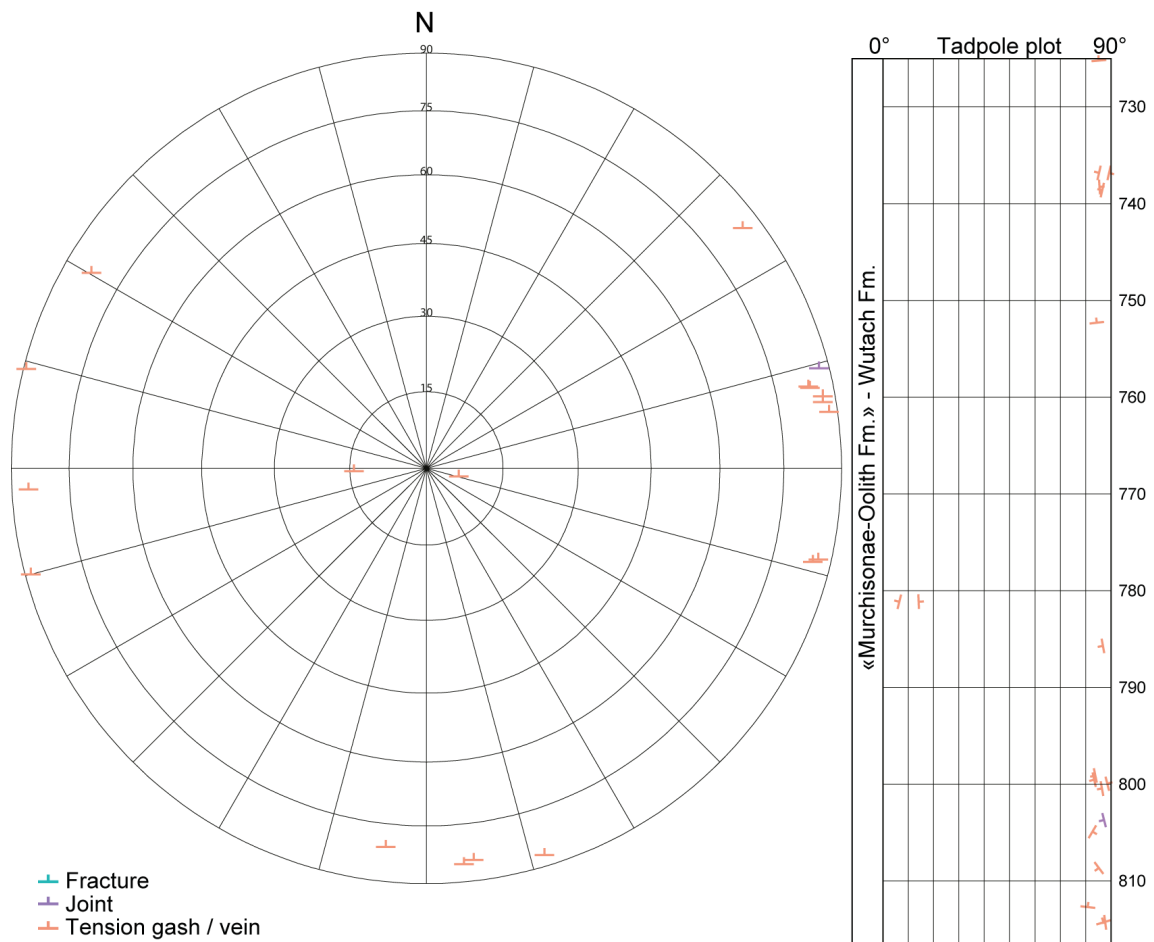


Fig. 4-39: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures («Brauner Dogger»)

Fractures (n = 0), joints (n = 1) and tension gashes / veins (n = 18).

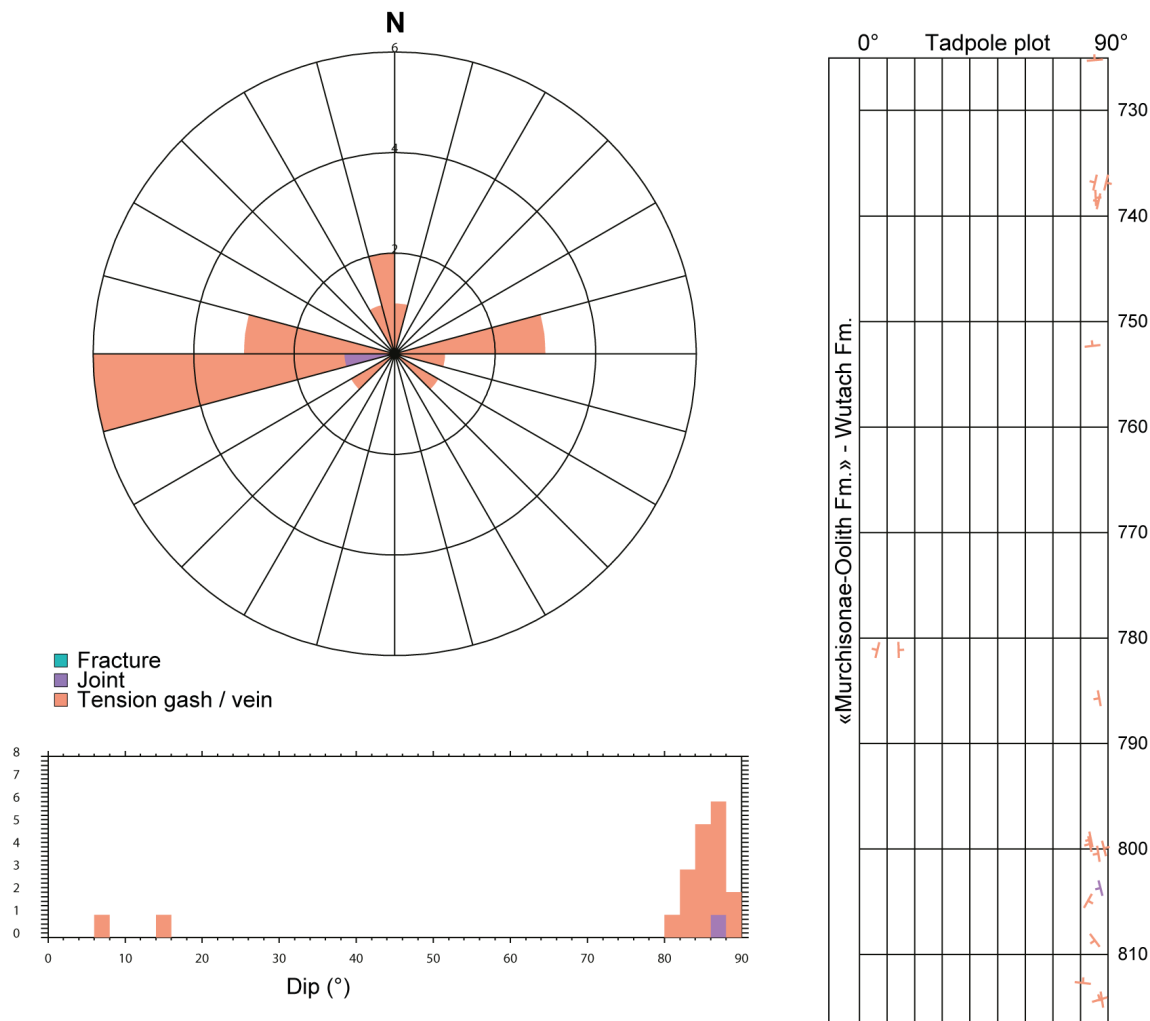


Fig. 4-40: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures («Brauner Dogger»)
Fractures (n = 0), joints (n = 1) and tension gashes / veins (n = 18).

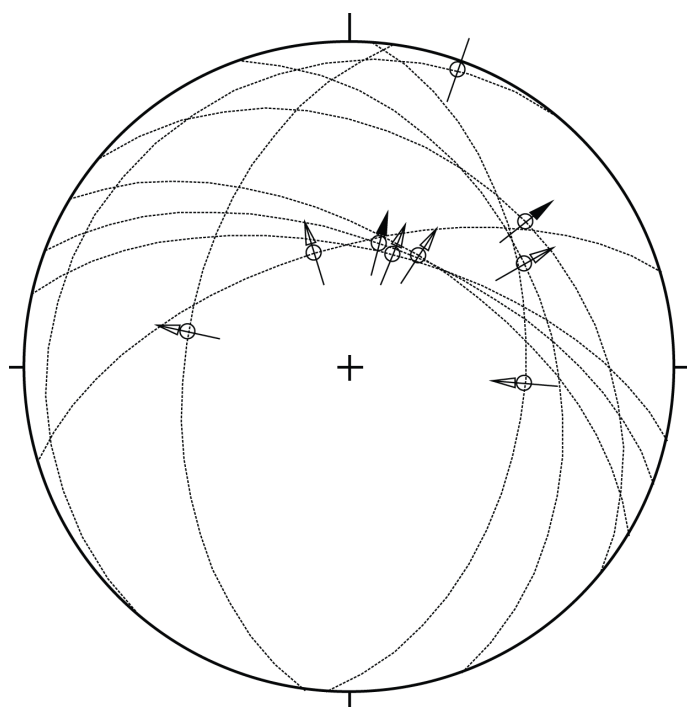


Fig. 4-41: Stereogram of fault planes with striations («Brauner Dogger», n = 9)

4.3.2 Opalinus Clay

The Opalinus Clay (816.43 – 927.87 m MD log depth) revealed an overall sub-horizontal to shallow SSE to SE bedding. With a total of 4 fault planes, 45 mirror-like fault planes and one vein, it showed a low average natural fracture density (0.4 per metre). However, distinct faults / fault zones cause prominent and abrupt dip changes within the Opalinus Clay. The fault planes are concentrated in four narrow zones and form two distinct fault zones at 830.92 – 830.96 m MD and 842.00 – 842.50 m MD log depth. They dip mainly to the east and south and have variable dip angles ranging from 0° to 60°.

The structural inventory for the Opalinus Clay is presented below. Stylolites were not observed in this depth interval. Due to the low number of fractures, joints and veins ($n = 1$), rose diagram statistics were not calculated.

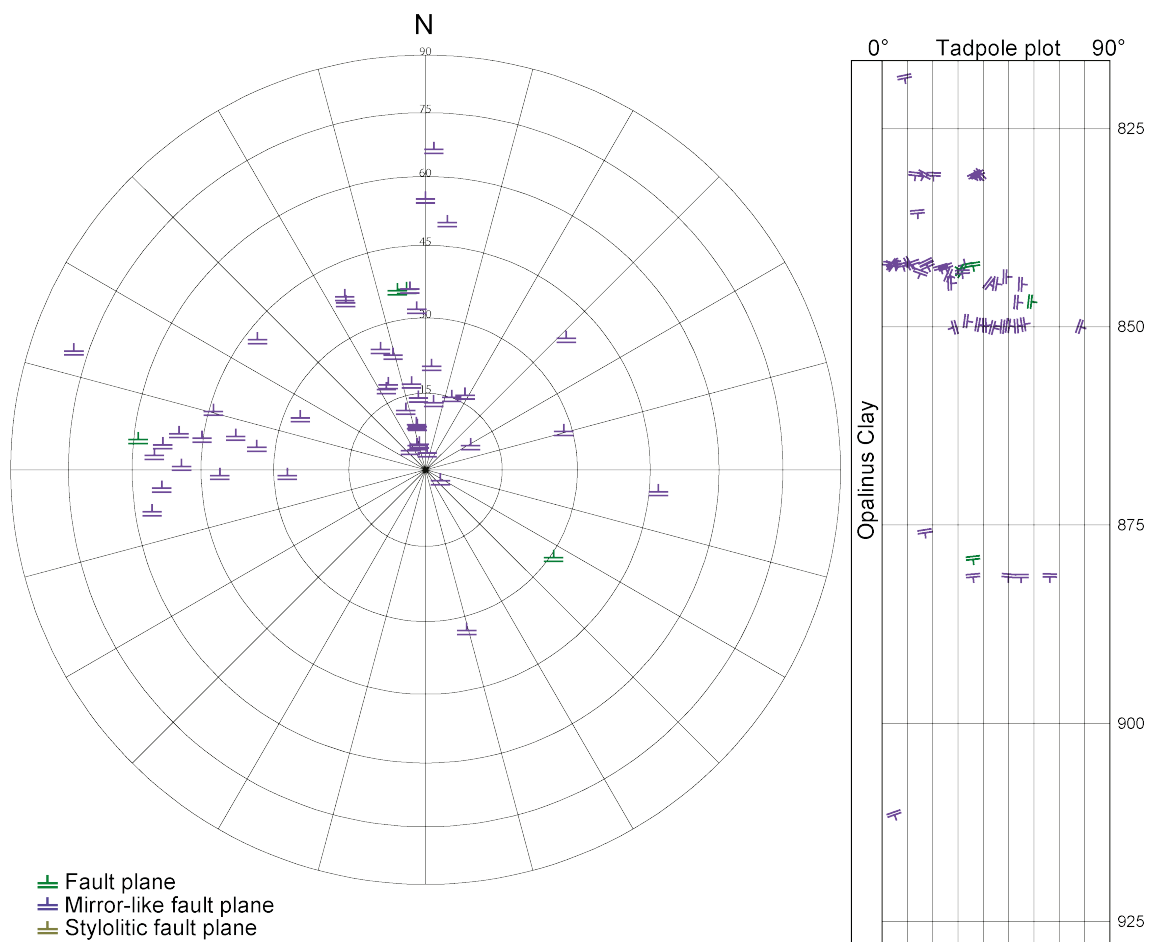


Fig. 4-42: Stereogram and depth plot of fault planes (Opalinus Clay)

Fault planes ($n = 4$), mirror-like fault planes ($n = 45$) and stylolitic fault planes ($n = 0$).

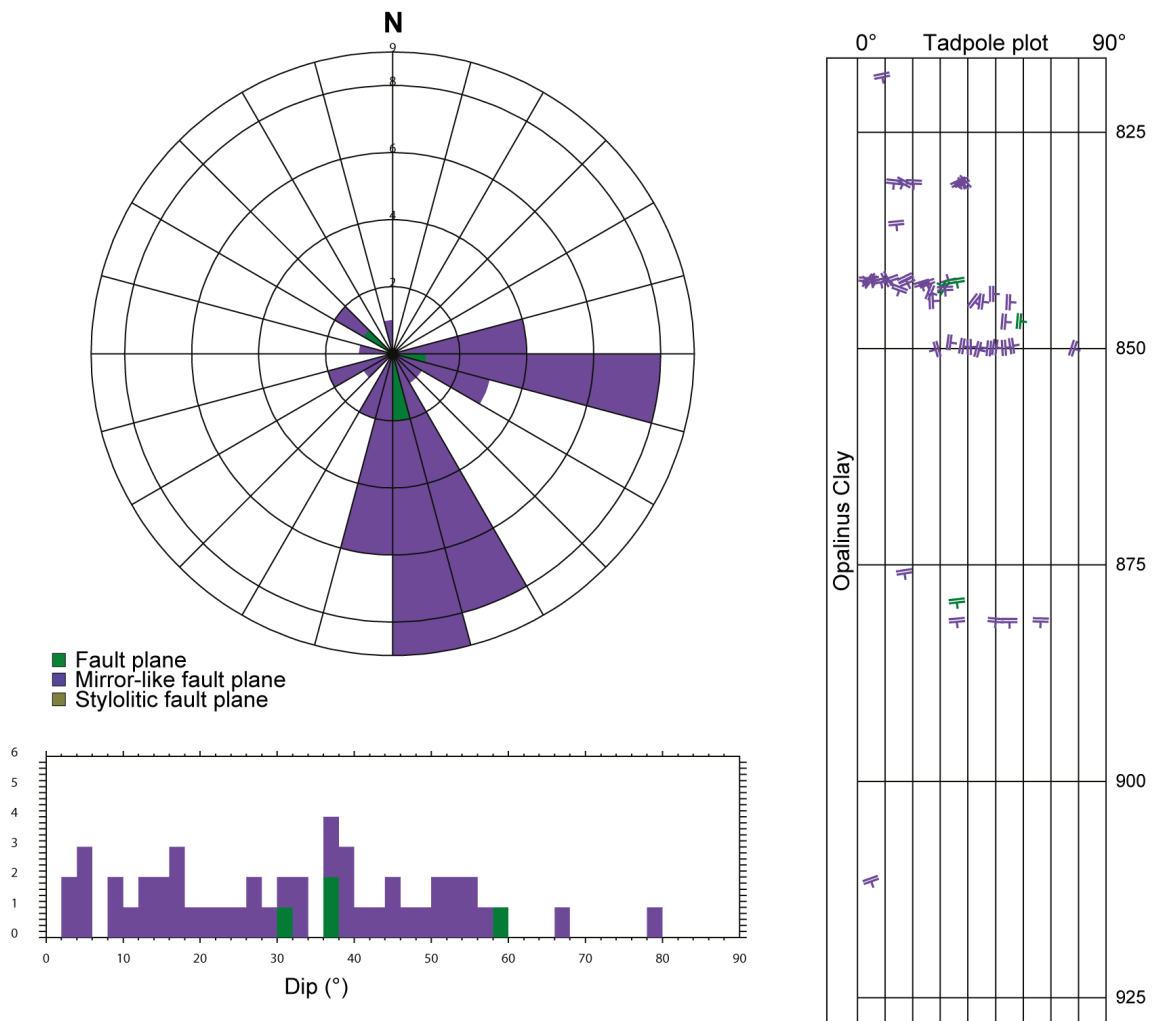


Fig. 4-43: Azimuth rose diagram, dip histogram and depth plot of fault planes (Opalinus Clay)
 Fault planes (n = 4), mirror-like fault planes (n = 45) and stylolitic fault planes (n = 0).

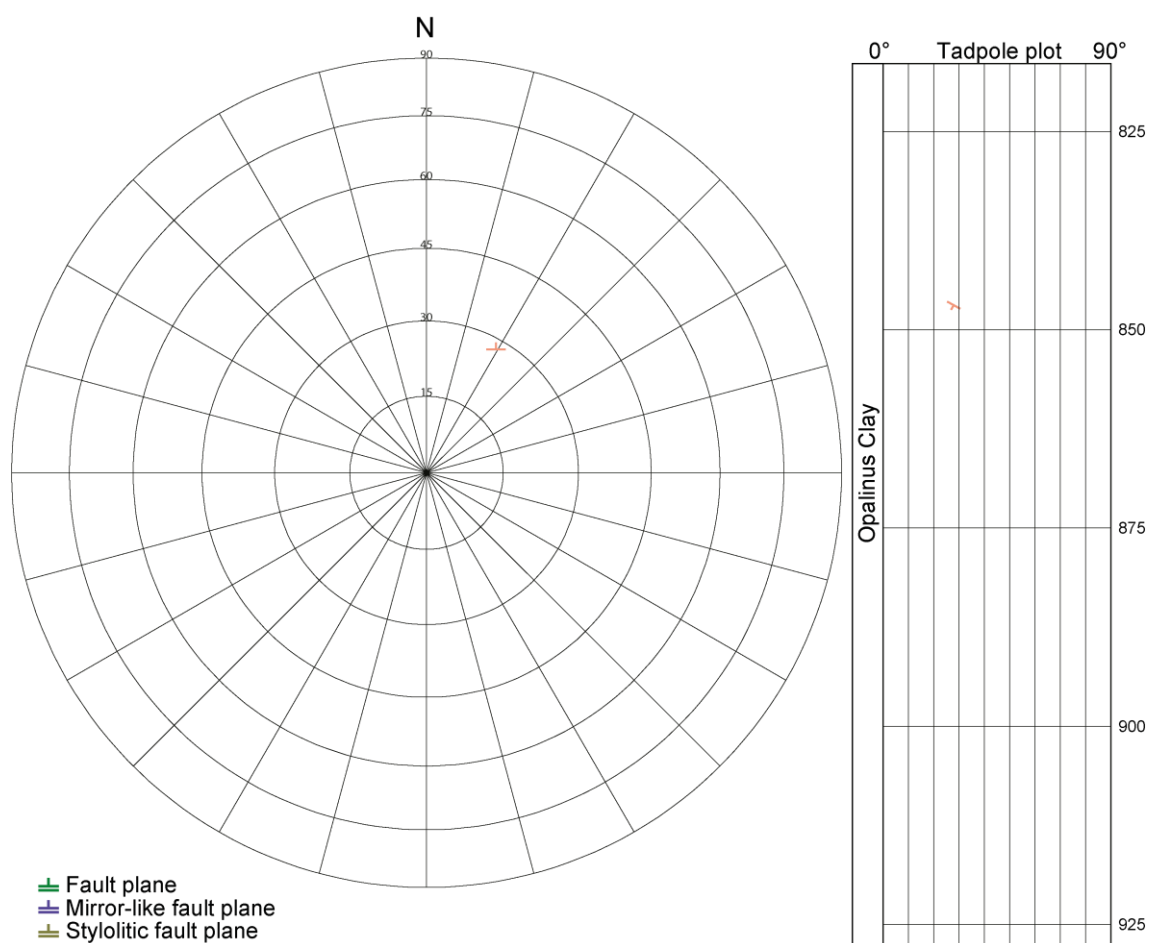


Fig. 4-44: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Opalinus Clay)

Fractures ($n = 0$), joints ($n = 0$) and tension gashes / veins ($n = 1$).

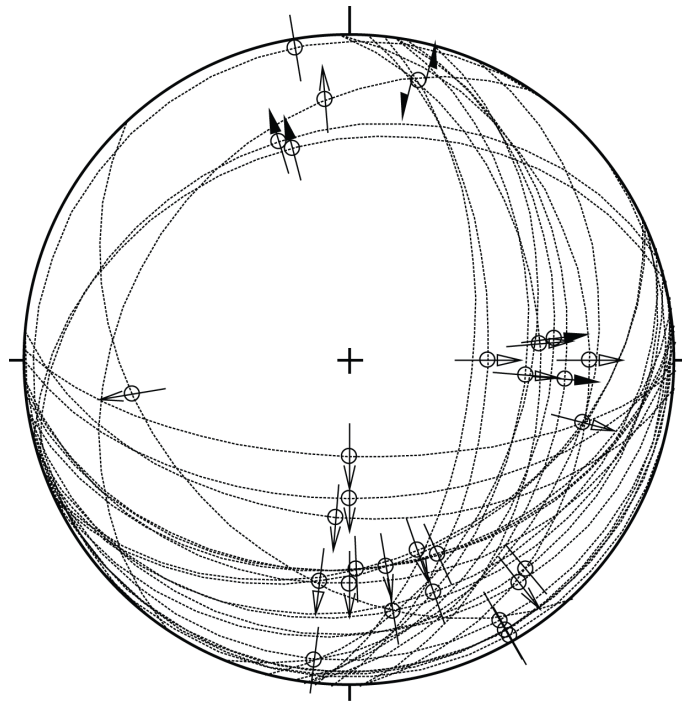


Fig. 4-45: Stereogram of fault planes with striations, including multiple lineations on a single fault plane (Opalinus Clay, $n = 32$)

4.4 Lias (Staffelegg Formation)

As presented below, the Lias (927.87 – 971.55 m MD log depth) showed a very low number of structural discontinuities. Only the data for oriented cores are presented. Due to the low number of faults ($n = 5$), fractures, joints and tension gashes / veins ($n = 7$) and stylolites ($n = 0$), rose diagram statistics were not calculated.

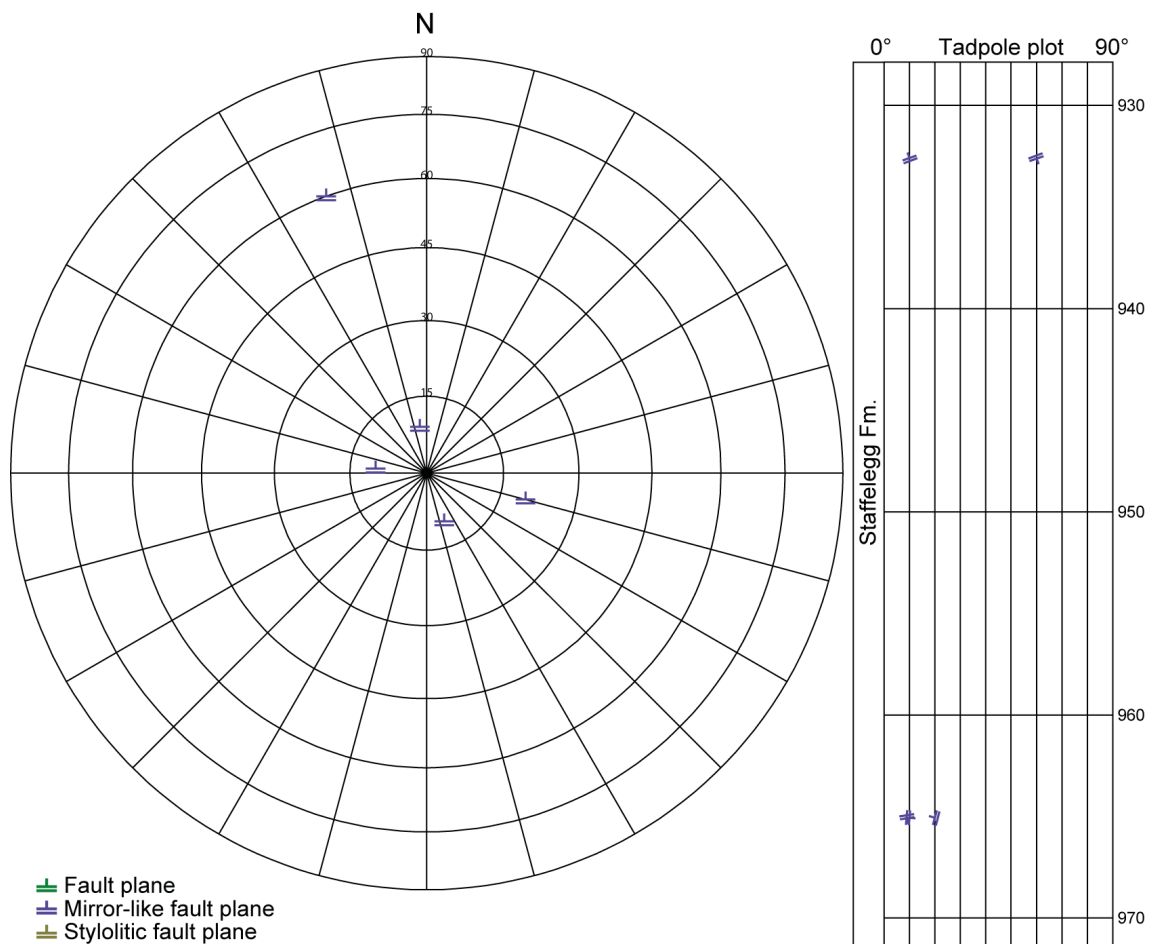


Fig. 4-46: Stereogram and depth plot of fault planes (Lias)

Fault planes ($n = 0$), mirror-like fault planes ($n = 5$) and stylolitic fault planes ($n = 0$).

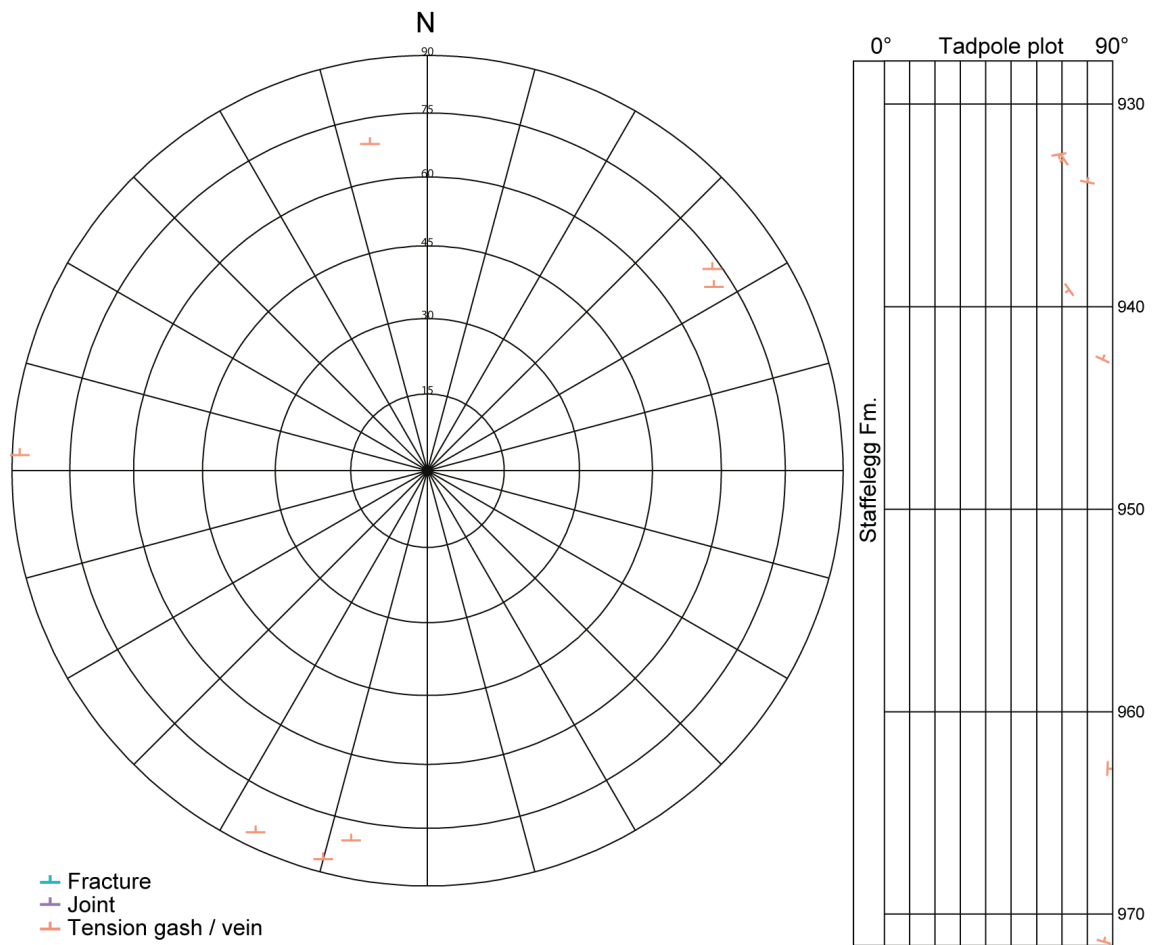


Fig. 4-47: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Lias)

Fractures ($n = 0$), joints ($n = 0$) and tension gashes / veins ($n = 7$).

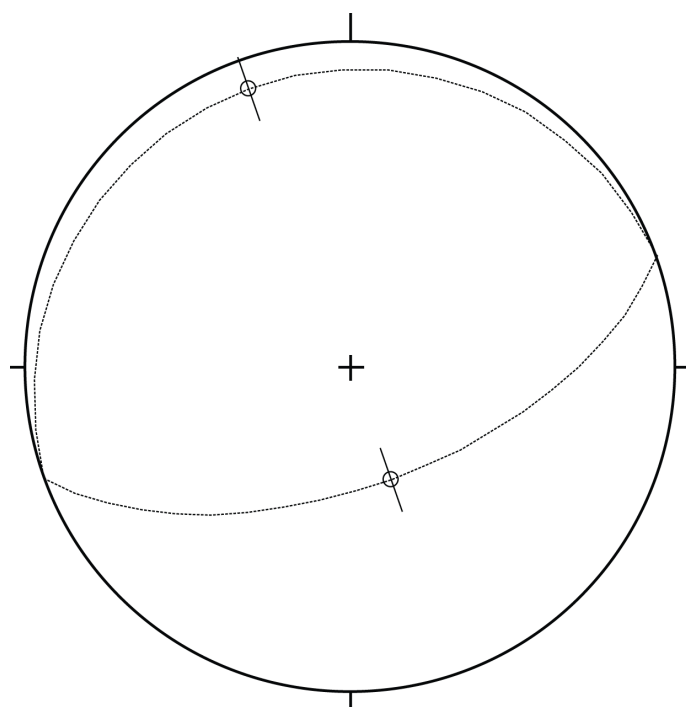


Fig. 4-48: Stereogram of fault planes with striations (Lias, $n = 2$)

4.5 Keuper

The Keuper (971.55 – 1'084.22 m MD log depth) is the structurally richest zone and revealed the highest average fracture density of 5.4 fractures per metre. Mirror-like fault planes and tension gashes / veins prevailed. The latter were mainly found within the Bänkerjoch Formation. Only the data for oriented cores are presented.

4.5.1 Klettgau Formation

The orientation and spatial distribution of structural discontinuities within the Klettgau Formation (971.55 – 1'027.44 m MD log depth) are visualised below. Stylolites were not observed along this depth interval.

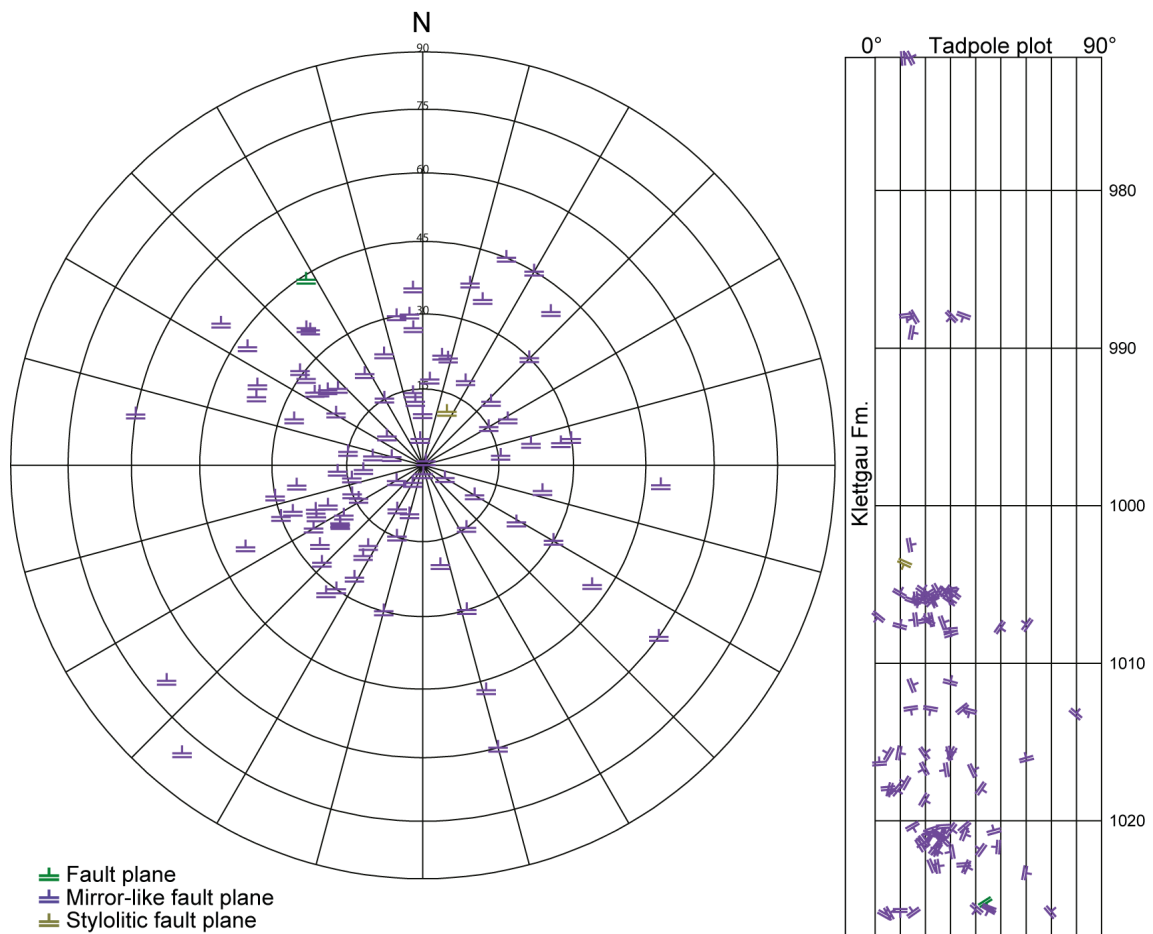


Fig. 4-49: Stereogram and depth plot of faults (Klettgau Formation)

Fault planes (n = 1), mirror-like fault planes (n = 95) and stylolitic fault planes (n = 1).

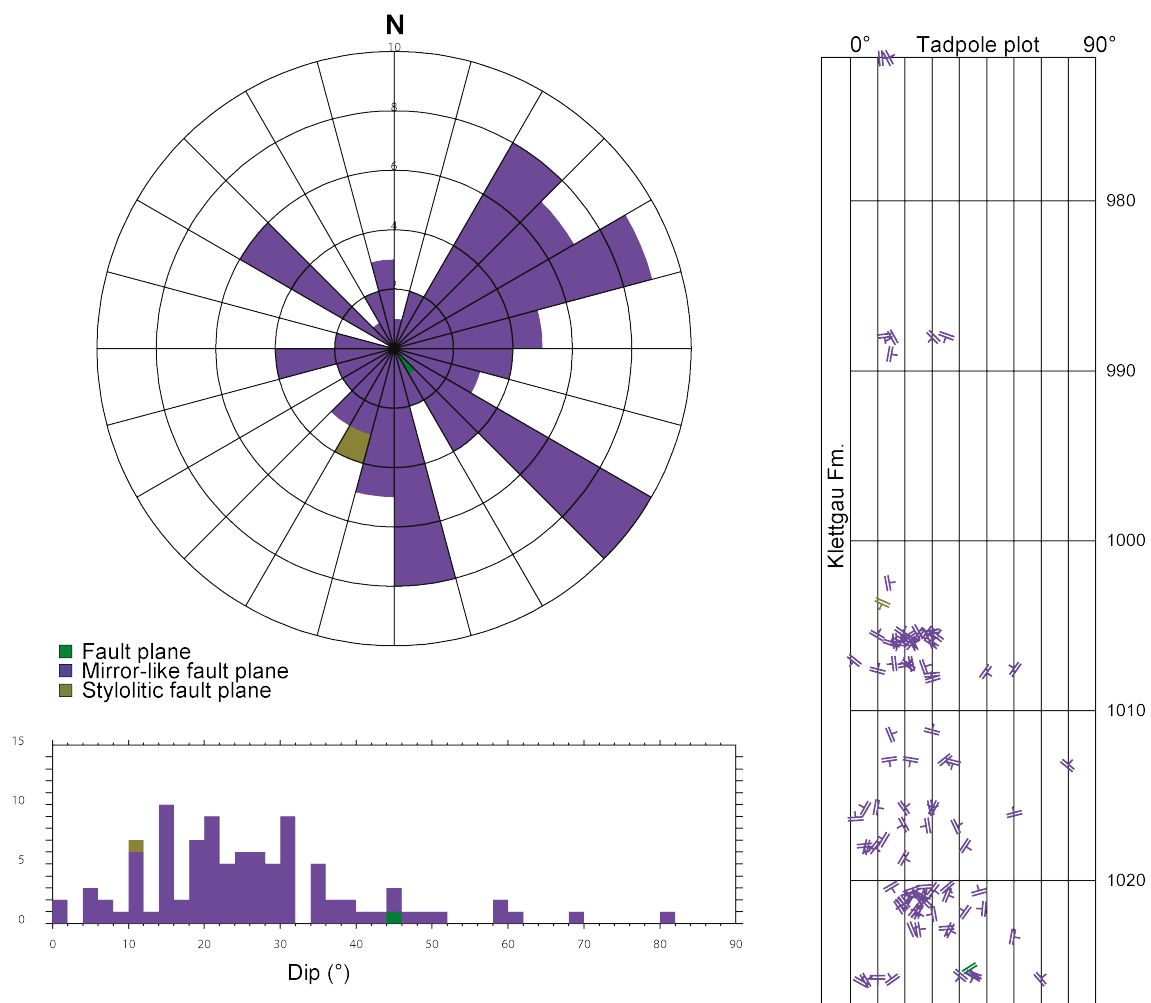


Fig. 4-50: Azimuth rose diagram, dip histogram and depth plot of faults (Klettgau Formation)
 Fault planes (n = 1), mirror-like fault planes (n = 95) and stylolitic fault planes (n = 1).

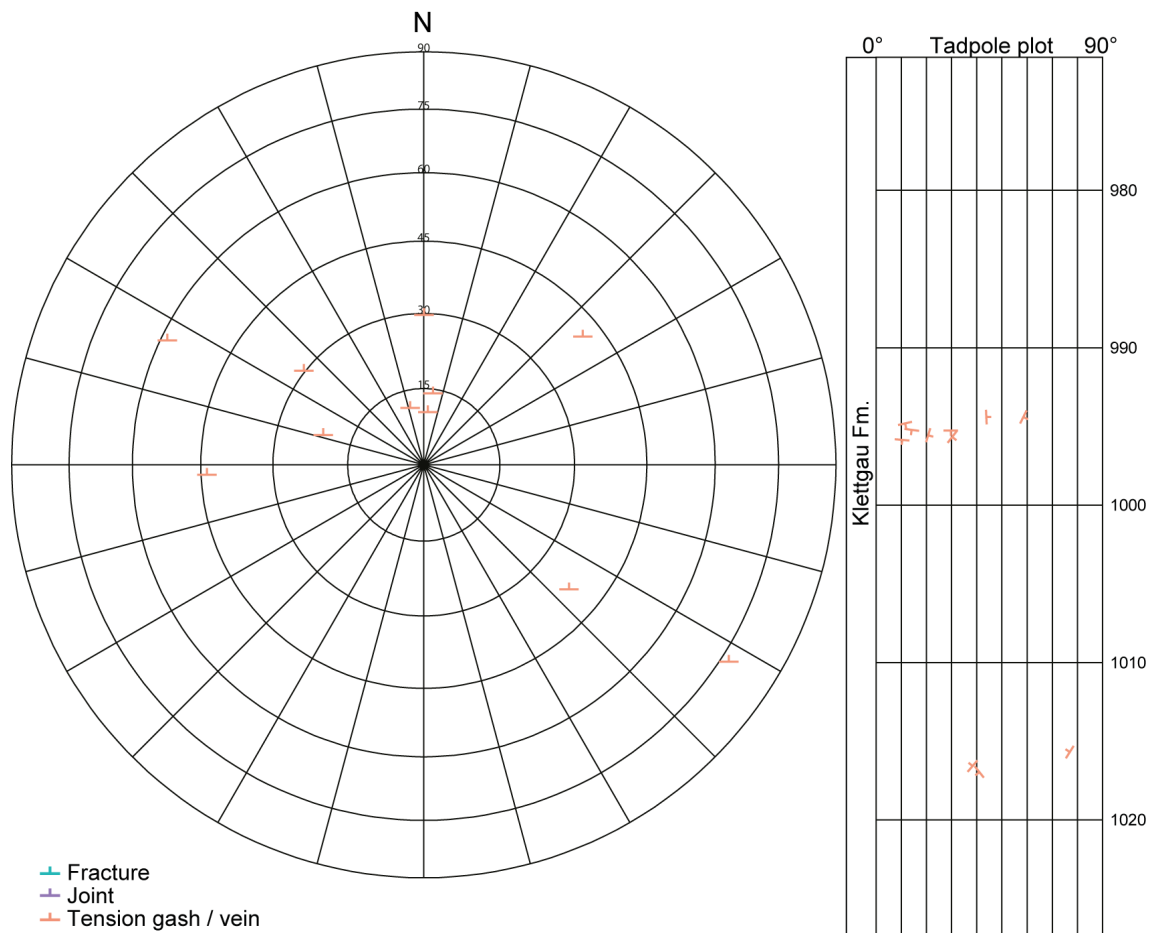


Fig. 4-51: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Klettgau Formation)

Fractures ($n = 0$), joints ($n = 0$) and tension gashes / veins ($n = 11$).

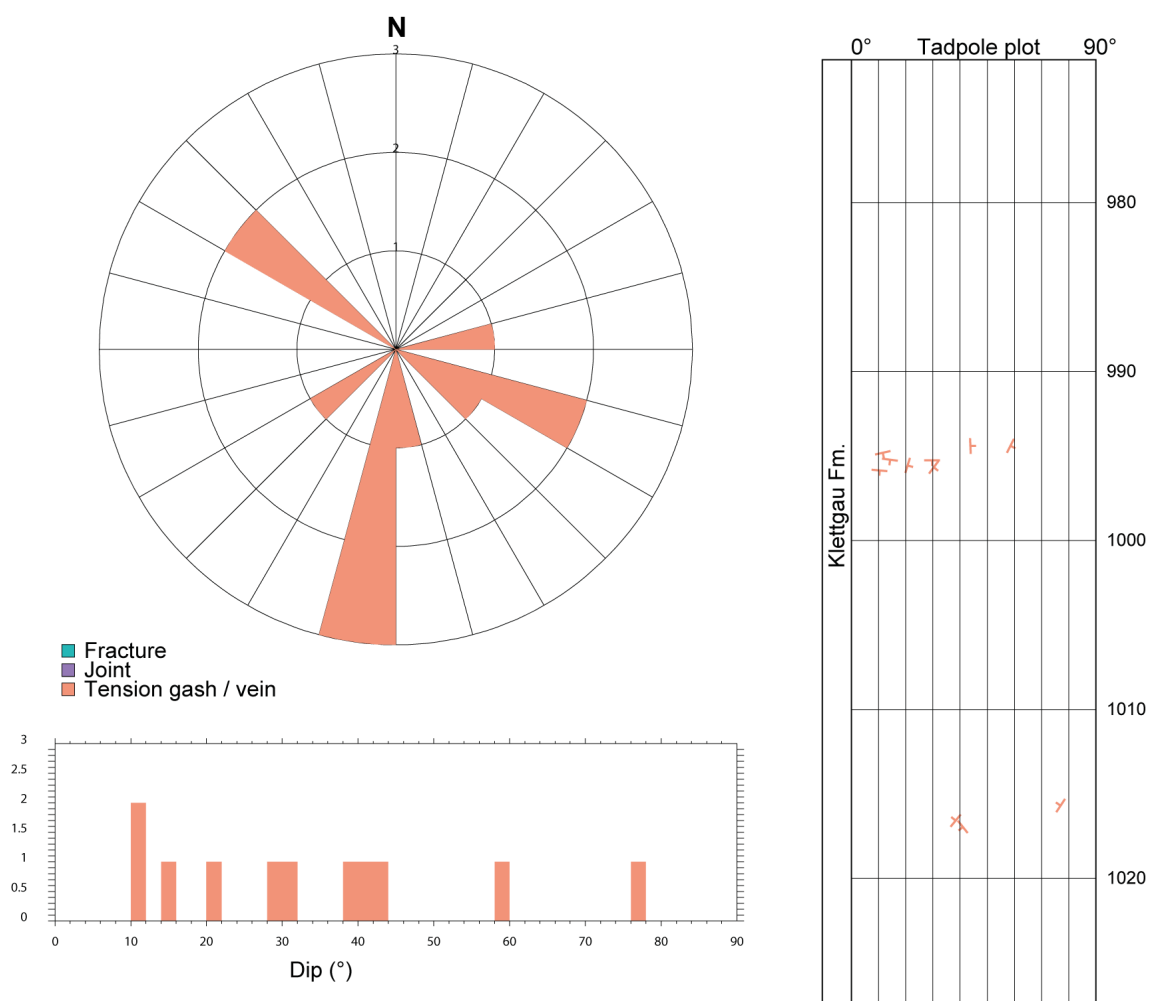


Fig. 4-52: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Klettgau Formation)

Fractures (n = 0), joints (n = 0) and tension gashes / veins (n = 11).

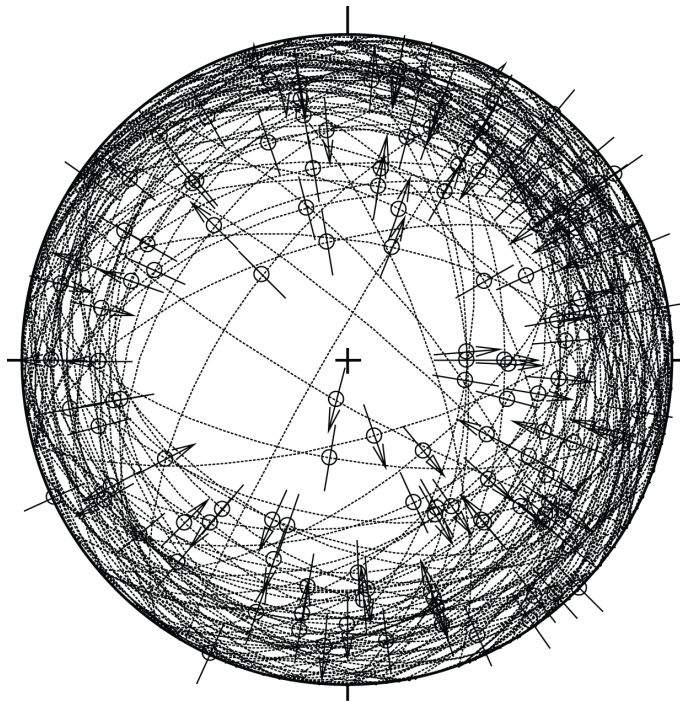


Fig. 4-53: Stereogram of fault planes with striations, including multiple lineations on a single fault plane (Klettgau Formation, $n = 149$)

4.5.2 Bänkerjoch Formation

The orientation and spatial distribution of the structural inventory of the Bänkerjoch Formation (1'027.44 – 1'084.22 m MD log depth) are shown below. Stylolites were absent in this borehole interval.

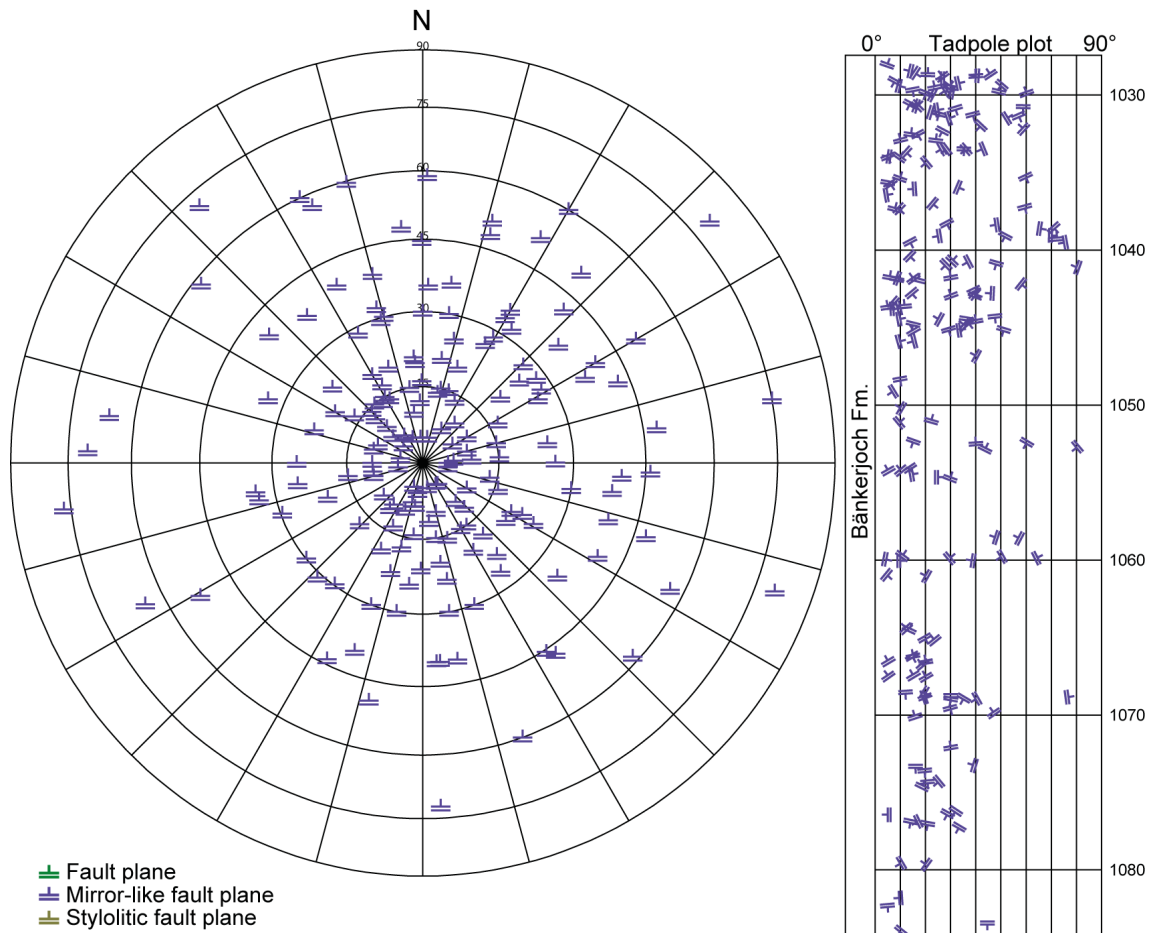


Fig. 4-54: Stereogram and depth plot of faults (Bänkerjoch Formation)

Fault planes (n = 0), mirror-like fault planes (n = 184) and stylolitic fault planes (n = 0).

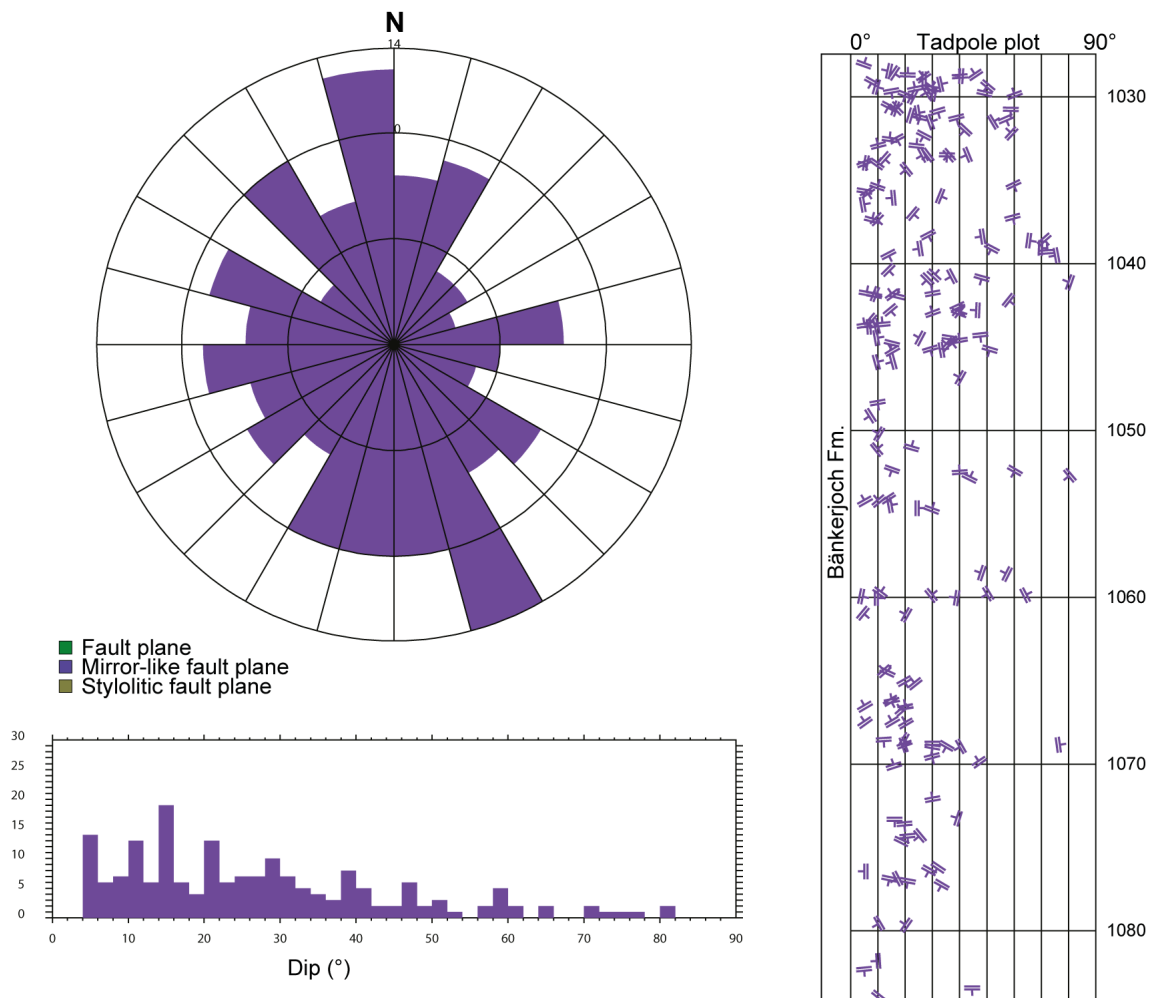


Fig. 4-55: Azimuth rose diagram, dip histogram and depth plot of faults (Bänkerjoch Formation)

Fault planes ($n = 0$), mirror-like fault planes ($n = 184$) and stylolitic fault planes ($n = 0$).

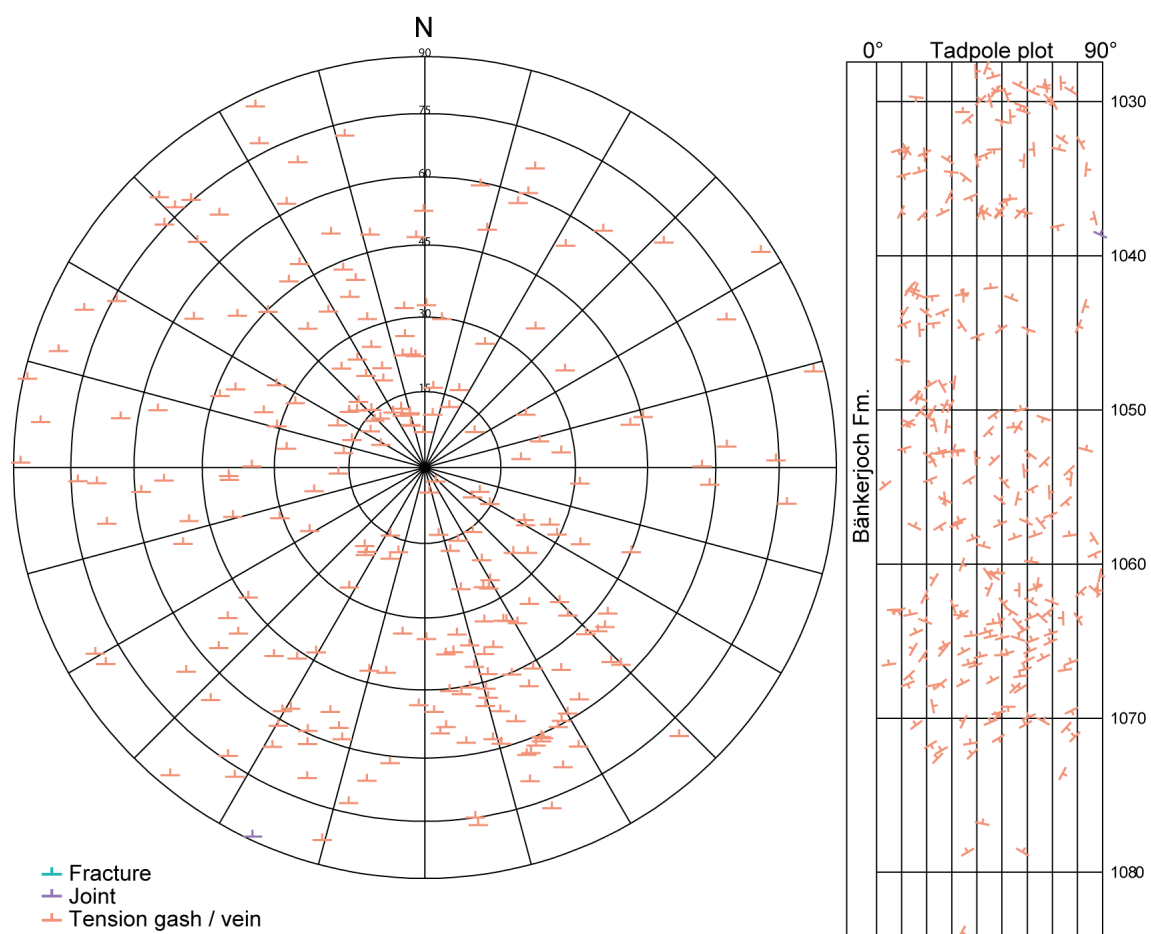


Fig. 4-56: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Bänkerjoch Formation)

Fractures ($n = 0$), joints ($n = 1$) and tension gashes / veins ($n = 237$).

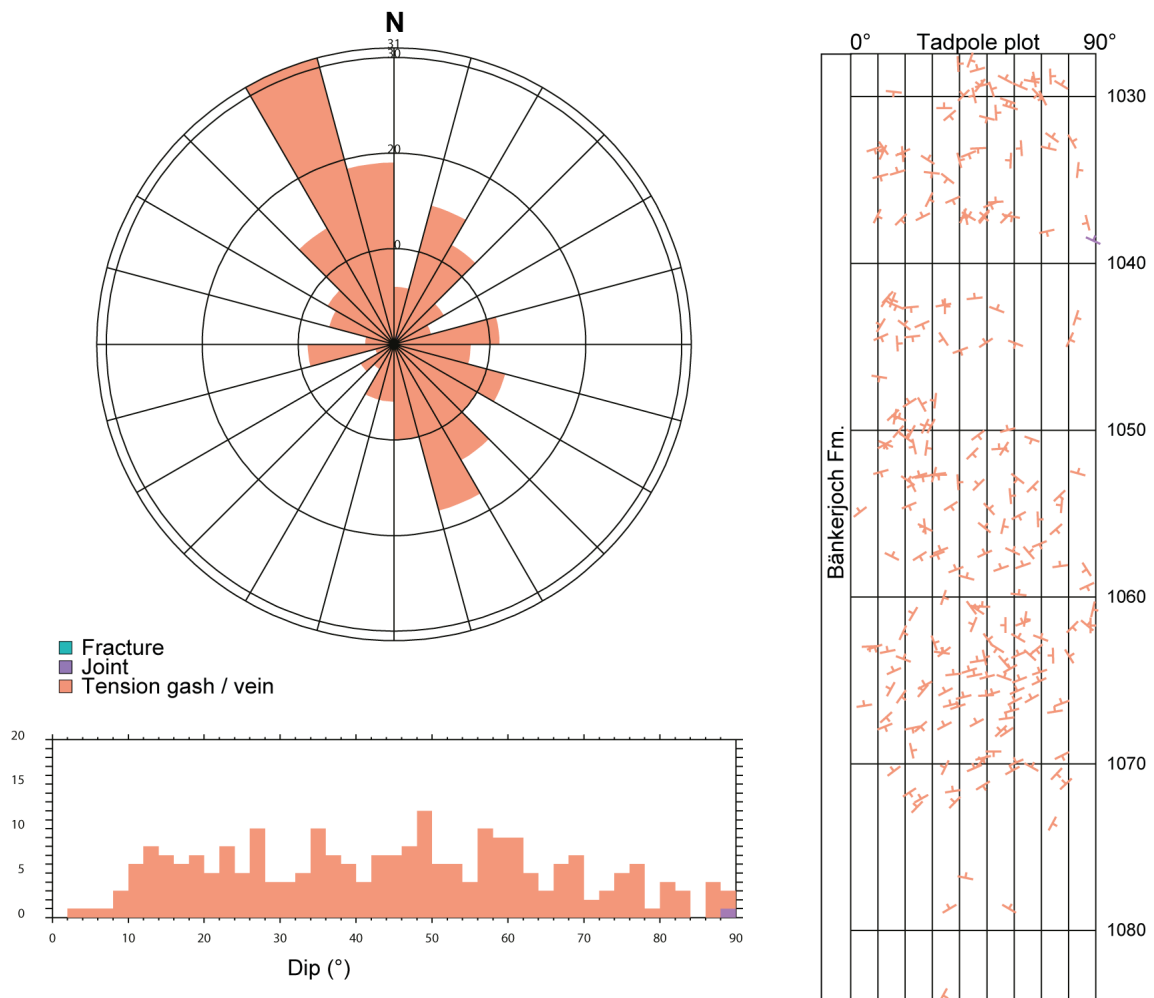


Fig. 4-57: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Bänkerjoch Formation)

Fractures (n = 0), joints (n = 1) and tension gashes / veins (n = 237).

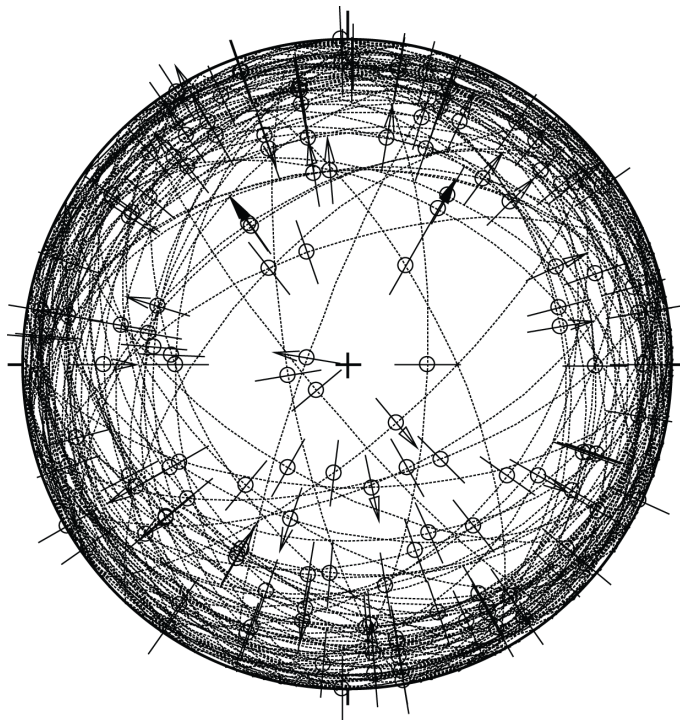


Fig. 4-58: Stereogram of fault planes with striations, including multiple lineations on a single fault plane (Bänkerjoch Formation, $n = 149$)

4.6 Muschelkalk

The dominant structures within the Muschelkalk (1'084.22 – 1'161.03 m MD log depth) were stylolites followed by mirror-like fault planes. In addition, abundant mm- to cm-sized open pores (vugs) were observed particularly within the Schinznach Formation.

Cores were available and analysed only for the Schinznach Formation and the top Zeglingen Formation. Note that only the data for oriented cores are presented.

4.6.1 Schinznach Formation

The orientation and spatial distribution of structural observations within the Schinznach Formation (1'084.22 – 1'154.43 m MD log depth) are shown below.

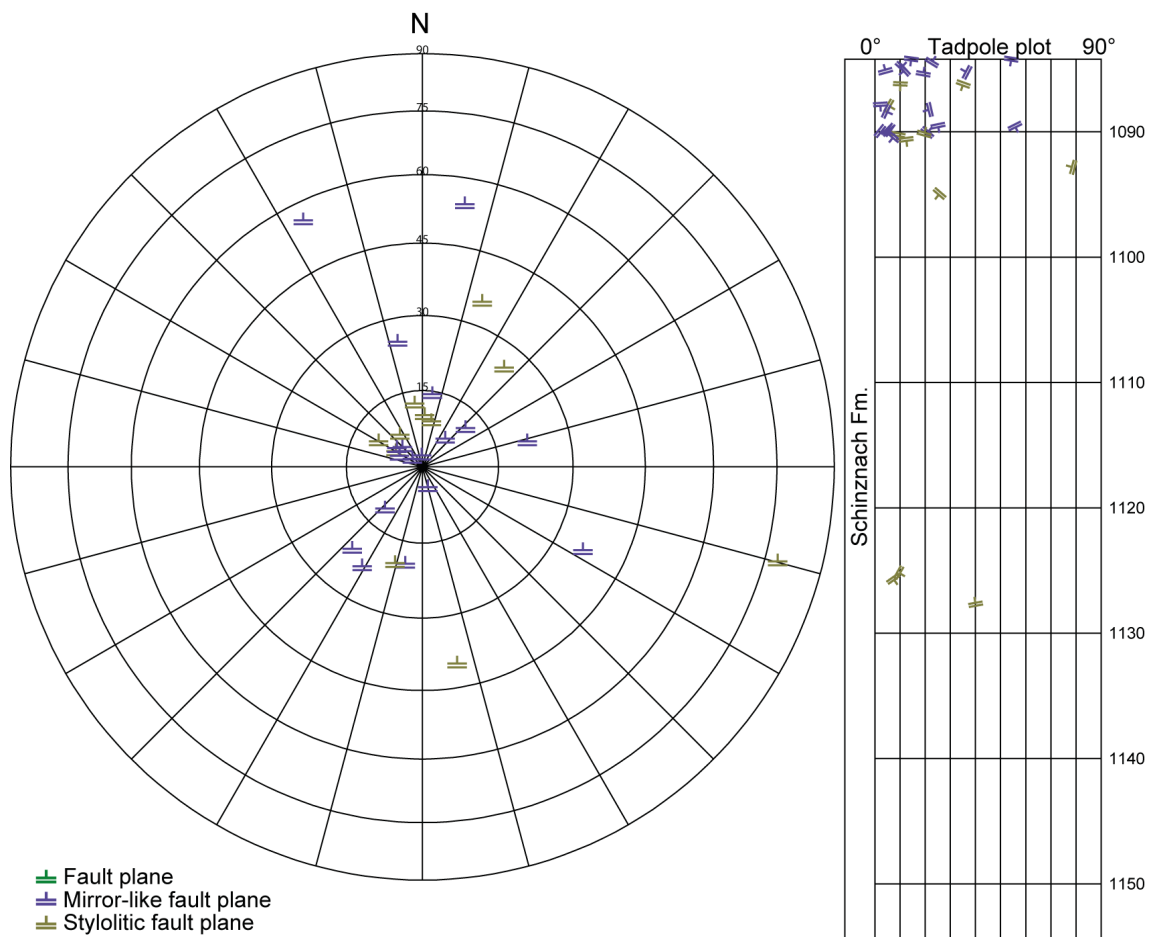


Fig. 4-59: Stereogram and depth plot of fault planes (Schinznach Formation)

Fault planes ($n = 0$), mirror-like fault planes ($n = 18$) and stylolitic fault planes ($n = 11$).

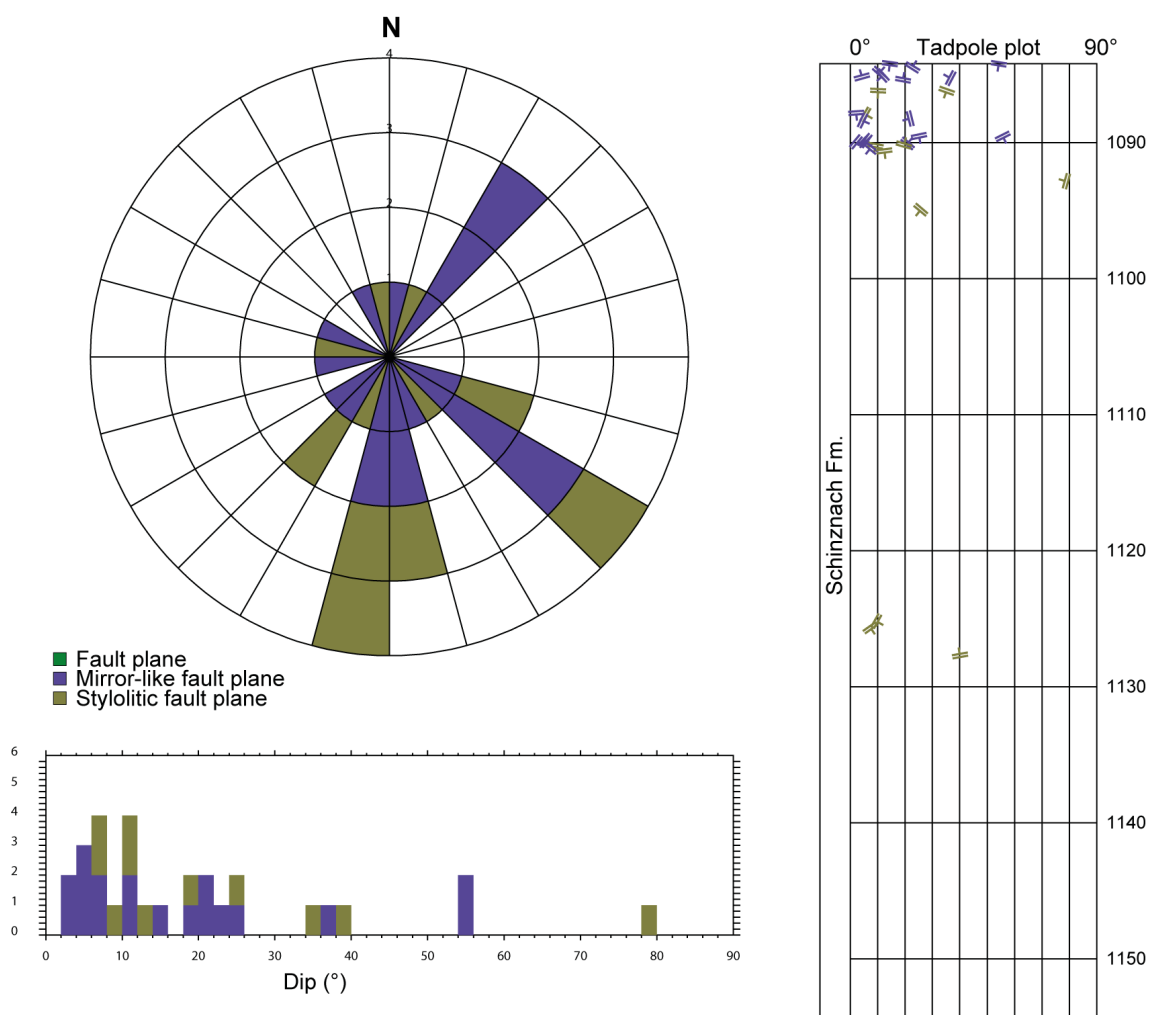


Fig. 5-60: Azimuth rose diagram, dip histogram and depth plot of fault planes (Schinznach Formation)

Fault planes ($n = 0$), mirror-like fault planes ($n = 18$) and stylolitic fault planes ($n = 11$).

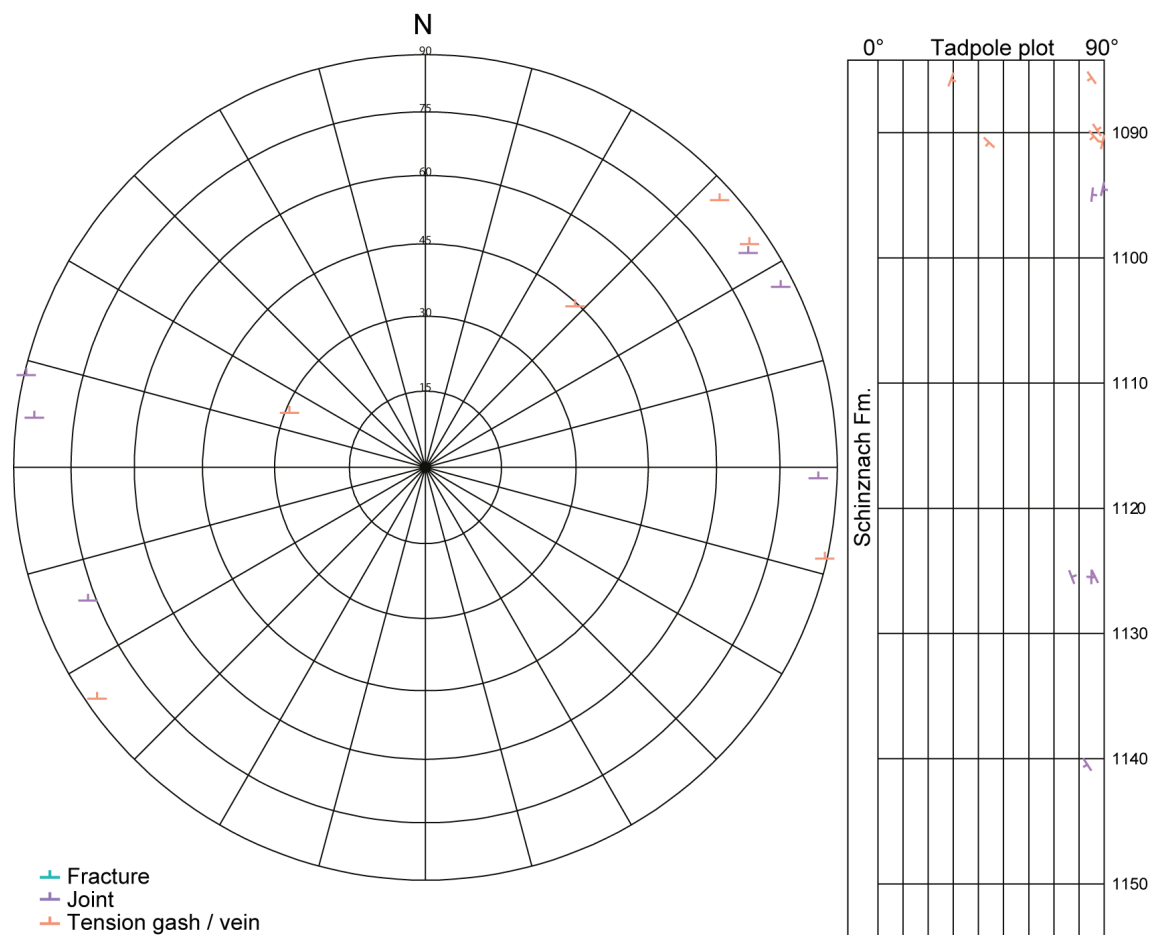


Fig. 4-61: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Schinznach Formation)

Fractures (n = 0), joints (n = 6) and tension gashes / veins (n = 6).

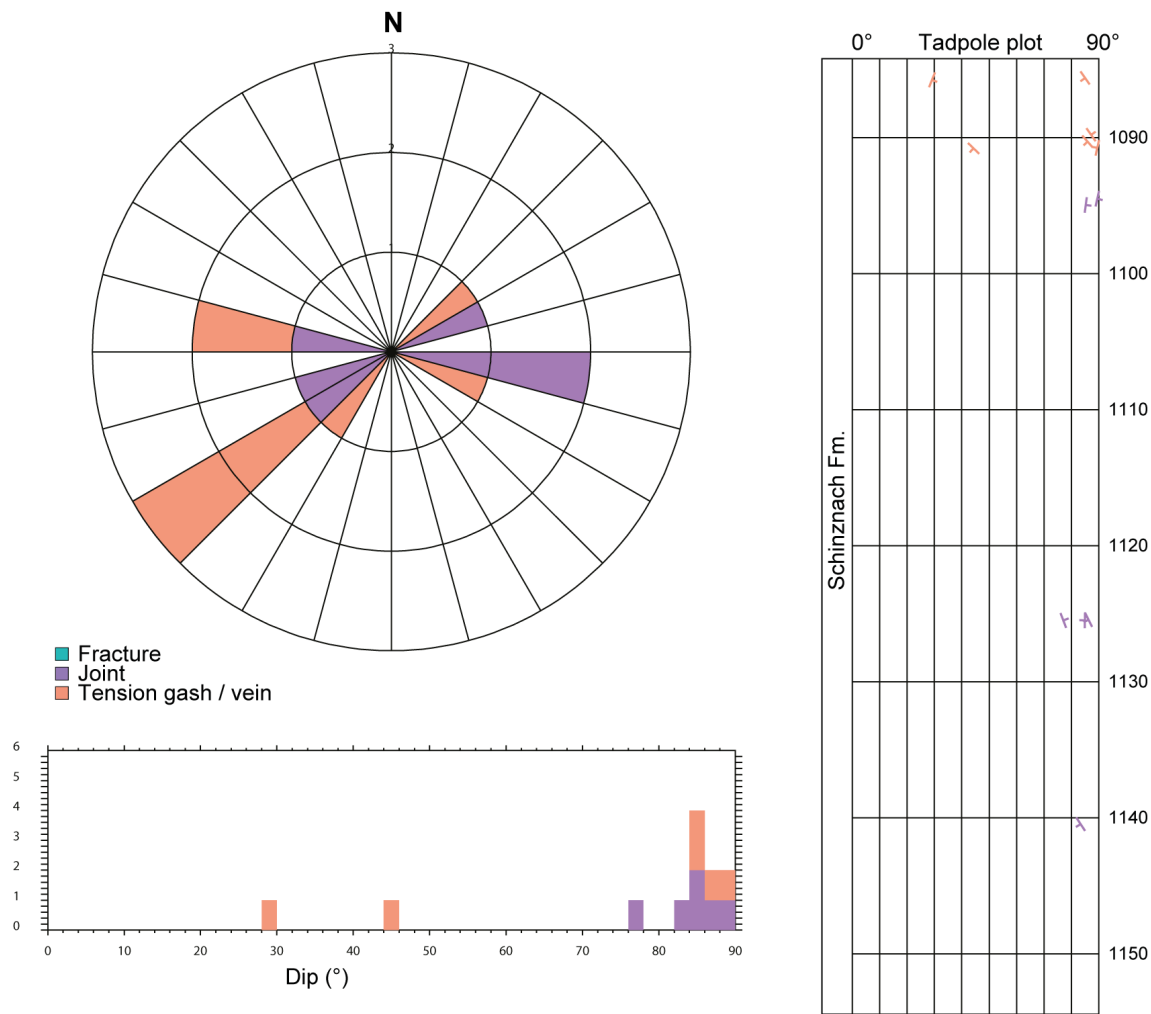


Fig. 4-62: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Schinznach Formation)

Fractures (n = 0), joints (n = 6) and tension gashes / veins (n = 6).

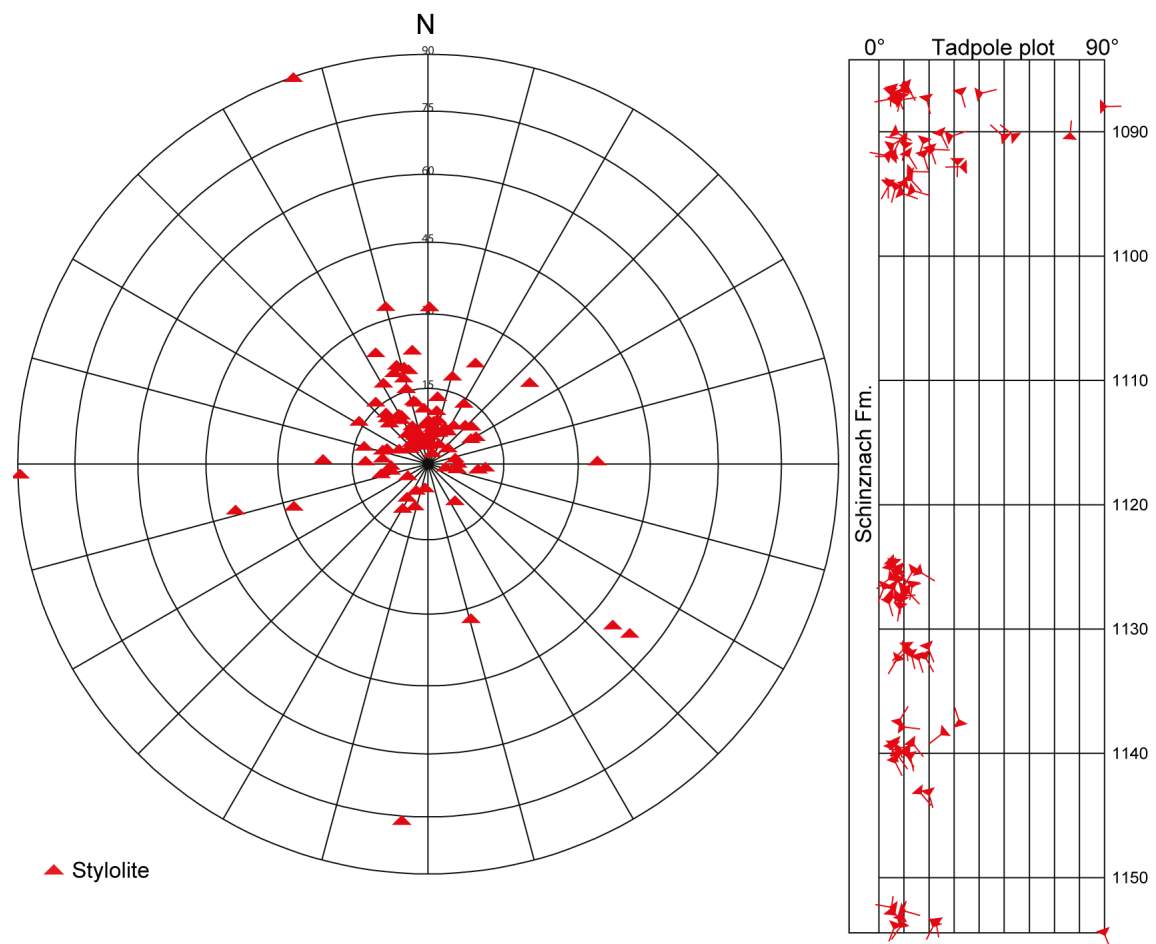


Fig. 4-63: Stereogram and depth plot of stylolites (Schinznach Formation, n = 96)

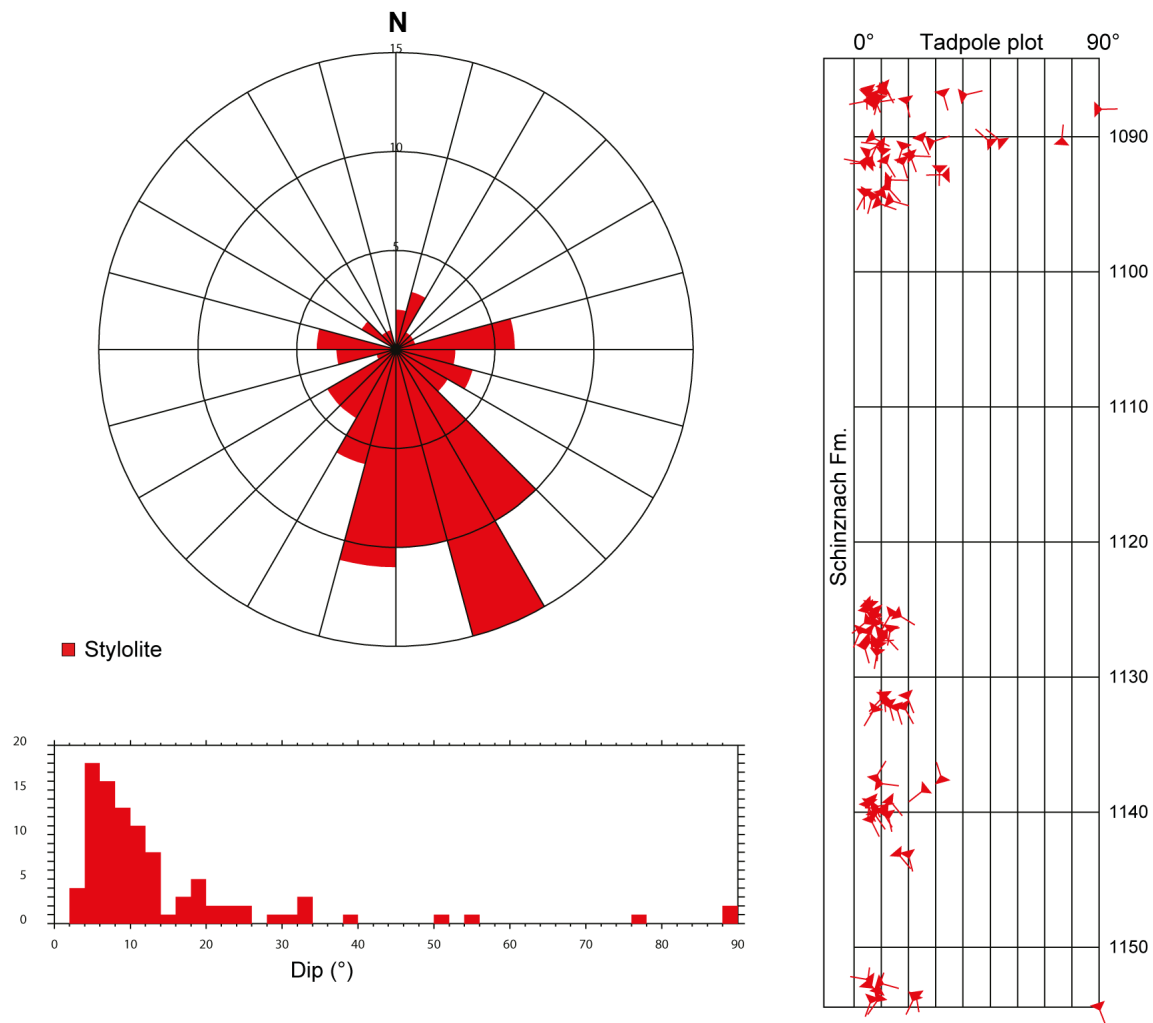


Fig. 4-64: Azimuth rose diagram, dip histogram and depth plot of stylolites (Schinznach Formation, n = 96)

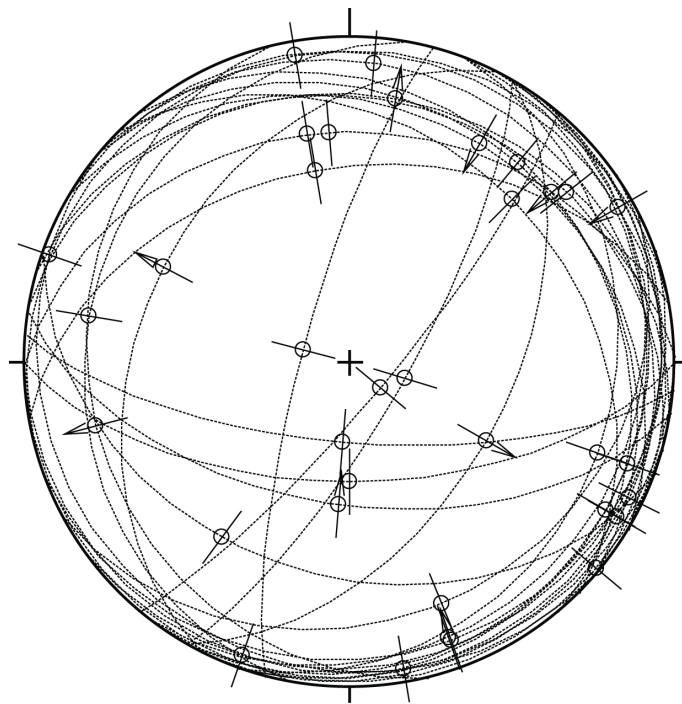


Fig. 4-65: Stereogram of fault planes with striations, including multiple lineations on a single fault plane (Schinznach Formation, $n = 35$)

4.6.2 Upper part of Zeglingen Formation («Dolomitzone»)

The orientation and spatial distribution of the structures observed in the «Dolomitzone» (1'154.43 – 1'161.03 m MD log depth) are shown below. Due to the low number of faults ($n = 1$), fractures, joints and tension gashes / veins ($n = 1$), rose diagram statistics were not calculated for those structures.

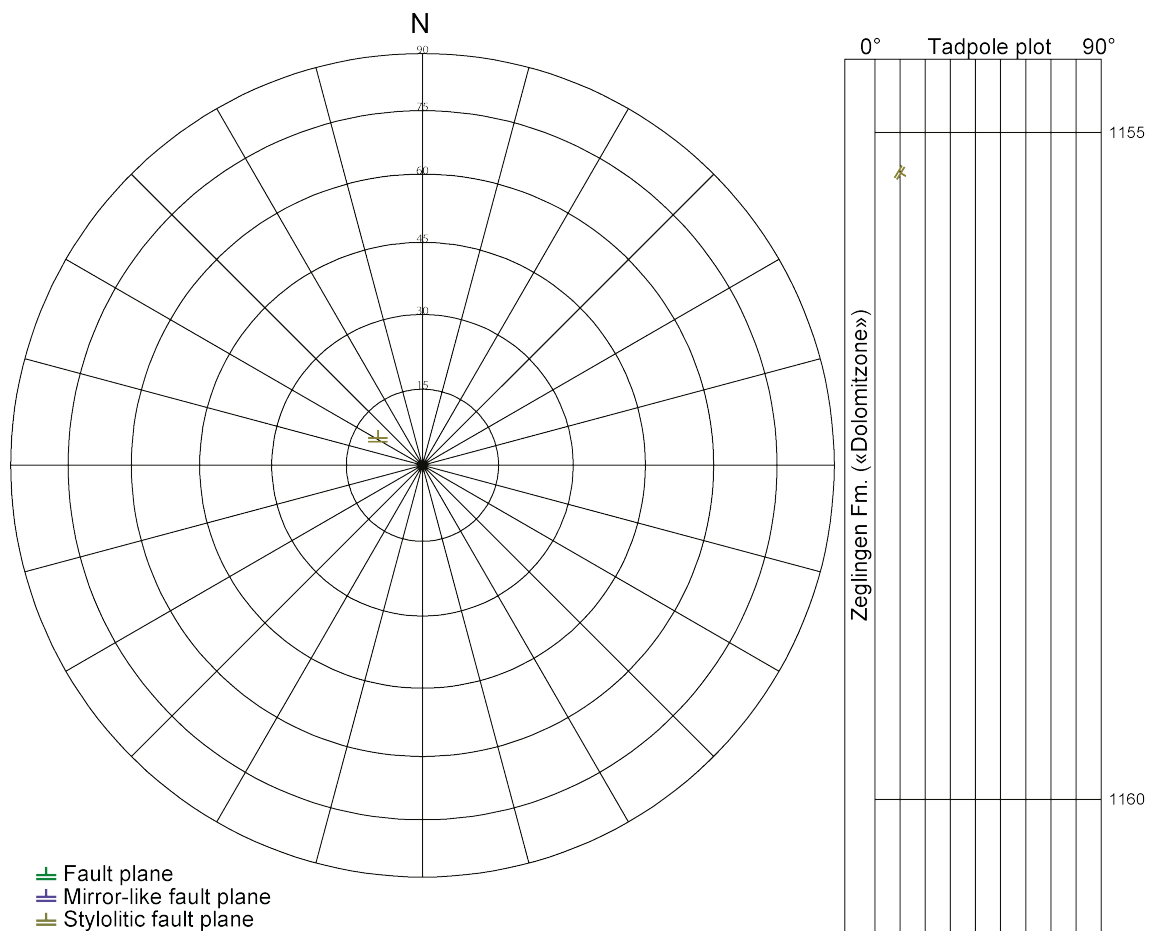


Fig. 4-66: Stereogram and depth plot of fault planes («Dolomitzone»)

Fault planes ($n = 0$), mirror-like fault planes ($n = 0$) and stylolitic fault planes ($n = 1$).

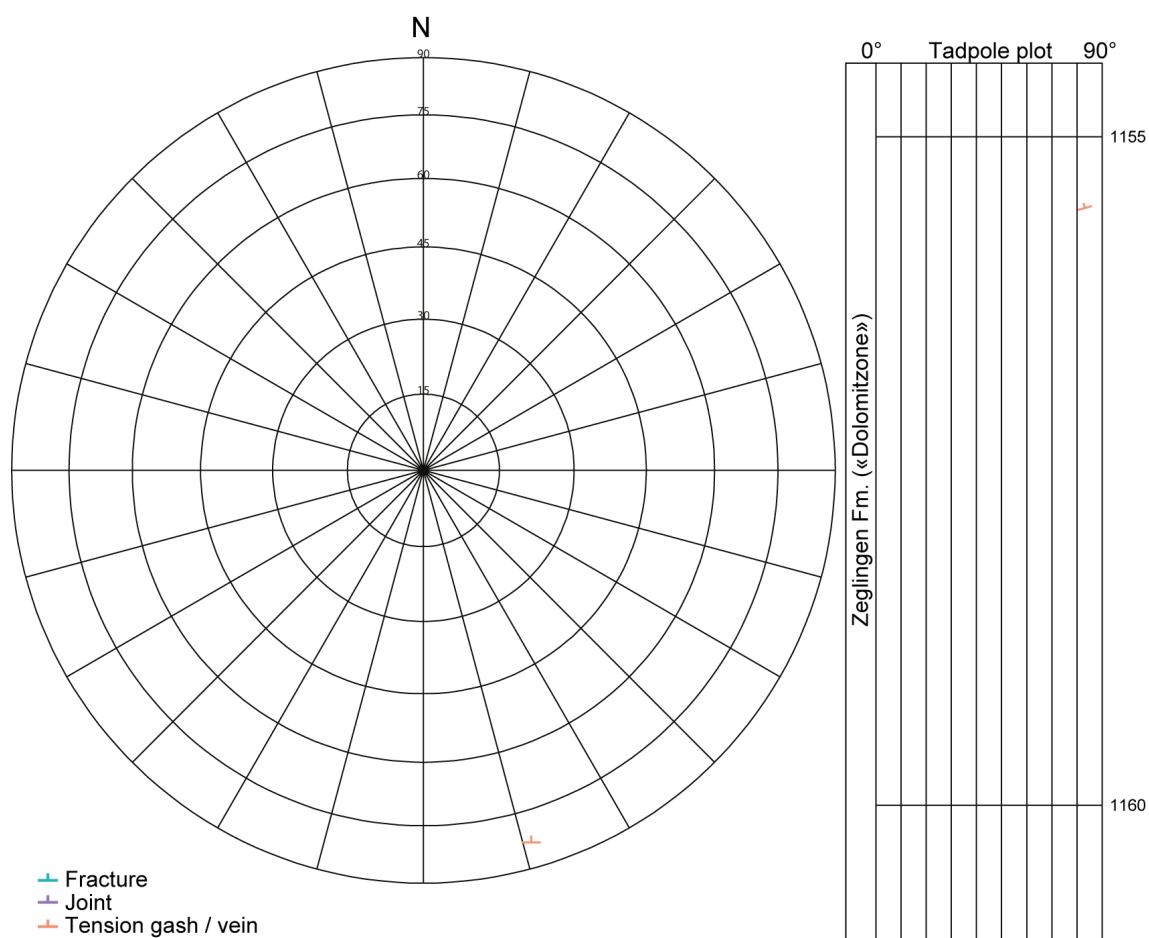


Fig. 4-67: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures («Dolomitzone»)

Fractures ($n = 0$), joints ($n = 0$) and tension gashes / veins ($n = 1$).

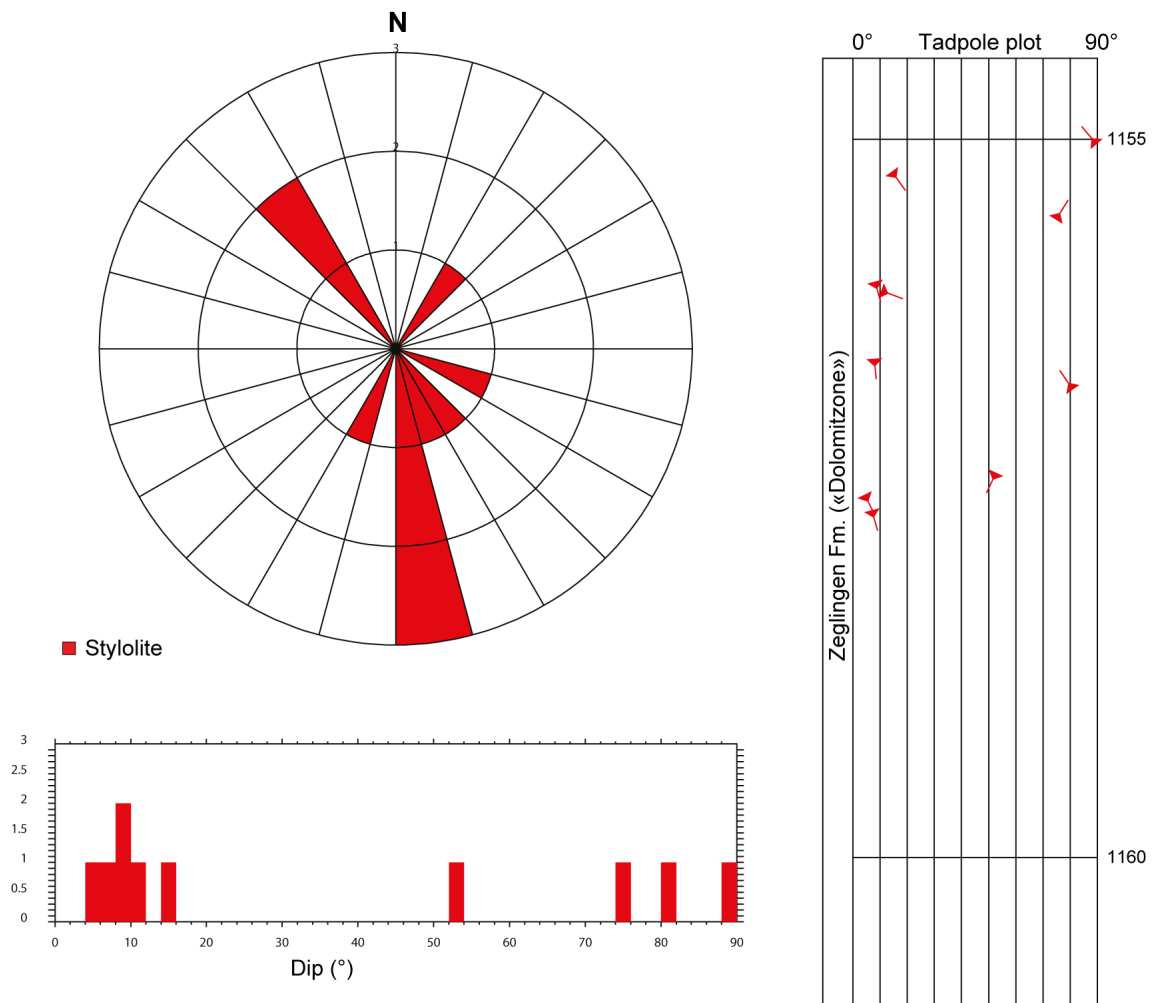


Fig. 4-69: Azimuth rose diagram, dip histogram and depth plot of stylolites («Dolomitzone», n = 10)

5 Main structural findings

There were several interesting geological features within the studied interval 498.00 – 1'161.03 m MD log depth. Four particularly significant tectonic zones / features deserve a more detailed examination and are evaluated below.

5.1 Decoupling of the present-day stress field within the «Felsenkalke» + «Massenkalk»

The FMI and UBI data provide information on the present-day stress field along the studied borehole section. Breakouts (BO) occur on opposite sides of the borehole, in the direction perpendicular to the maximum compressive horizontal stress (SHmax). Conversely, drilling-induced tensile fractures (DITF) develop on opposite borehole walls, in the direction parallel to the maximum horizontal stress (SHmax) and thus include 90° with BO. The orientation of DITF and BO in the «Felsenkalke» + «Massenkalk» is presented in Figs. 5-1 and 5-2.

There is an obvious change in the orientation of SHmax within the «Felsenkalke» + «Massenkalk» at 600 m MD log depth. This depth interval coincides with a distinct fault zone at 593.34 – 593.45 m MD log depth characterised by disintegrated drill core (FDC 3) and 22° – 54° SW-dipping faults. The latter apparently leads to a change in the orientation of the maximum horizontal stress from NW-SE (136°) above 600 m MD log depth and to NNW-SSE (158°) below 600 m MD log depth (Fig. 5-2).

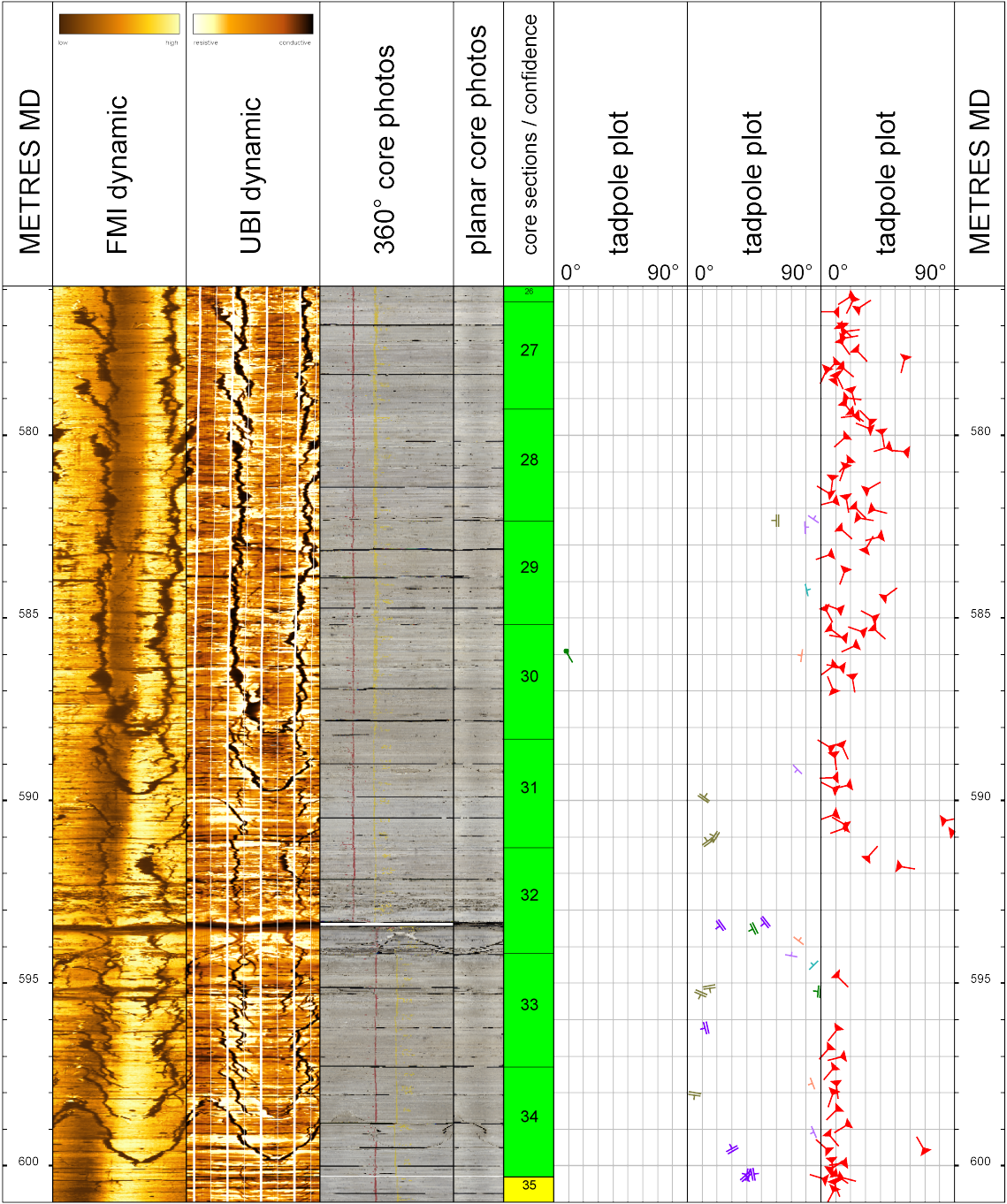


Fig. 5-1: Overview plot of the UBI ad FMI acquired within the «Felsenkalke» + «Massenkalk» at 576 – 601 m MD log depth

Note the prominent, conductive (dark) drilling-induced tensile fractures (DITF) seen on the UBI and FMI images (left) as well as the fault zone at 593.40 m . The latter governs a change of the present-day stress field orientation in TRU1-1.

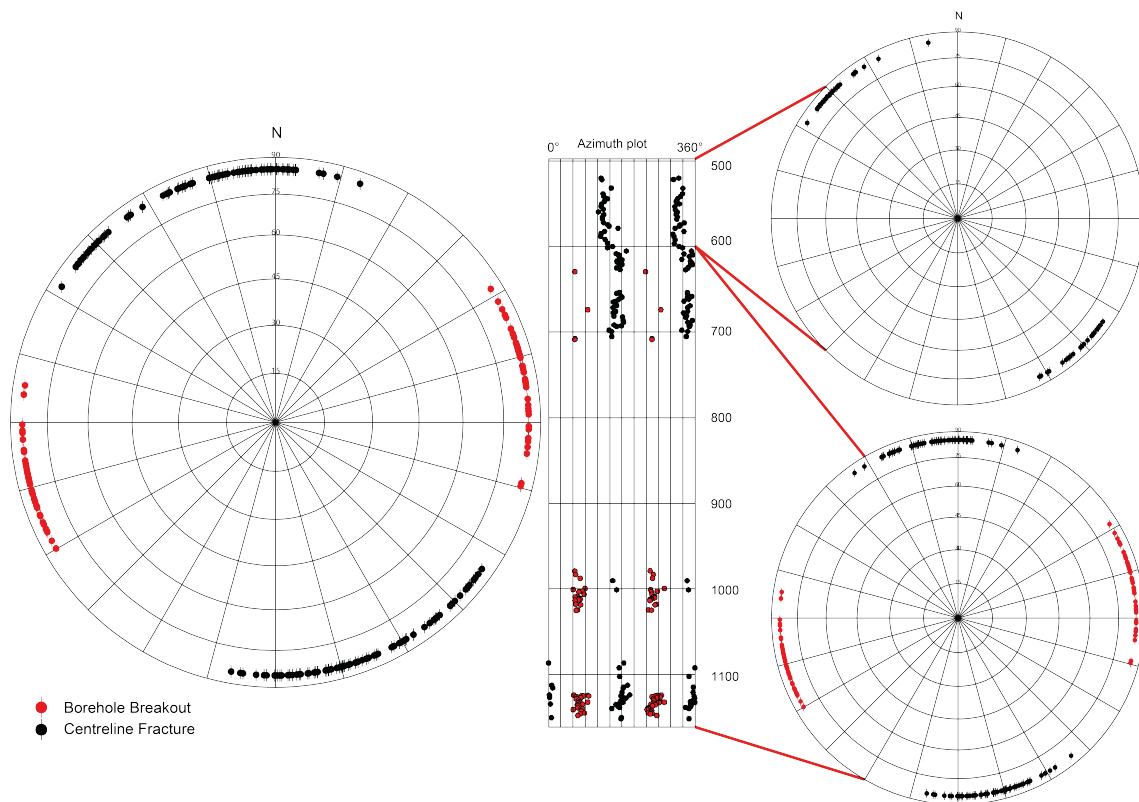


Fig. 5-2: Stereogram and depth plot for borehole breakout and drilling-induced tensile fractures

(Left): Orientation of all interpreted BO ($n = 99$, red) and DITF ($n = 166$, black) within the study interval 498.00 – 1161.03 m MD log depth. (Upper right): DITF ($n = 46$) within the uppermost borehole section at 498.00 – 600.00 m MD log depth. (Lower right): DITF ($n = 120$) and BO ($n = 99$) from 600 m MD – 1161.03 m MD log depth. Note the change in S_H max orientation from NW-SE (136°) above 600 m MD log depth to NNW-SSE (158°).

5.2 Faulting within the Opalinus Clay at 842 – 850 m MD log depth

Abundant faults associated with normal faulting (Fig. 5-3) and sinistral strike-slip faulting (Fig. 5-4) have been observed in the Opalinus Clay from 842 to 850 m MD log depth. In drill cores, this zone showed a complex network of intersecting mirror-like fault planes as well as fault planes locally associated with synkinematic calcite mineralisation. In addition, a distinct fault zone has been interpreted from 842.00 to 842.50 m MD log depth (Fig. 5-5). The latter causes a tilt of the generally shallow to moderately ($9 - 15^\circ$) dipping strata. The dip direction is predominantly towards the SSE above the fault zone and NNW within the fault zone itself (Fig. 5-5).

In the stereogram of Fig. 5-6, the faults reveal sub-horizontal to steep ($3 - 60^\circ$) dip angles and dip directions predominantly towards E and S. The observed striations were commonly associated with dip-parallel slip.

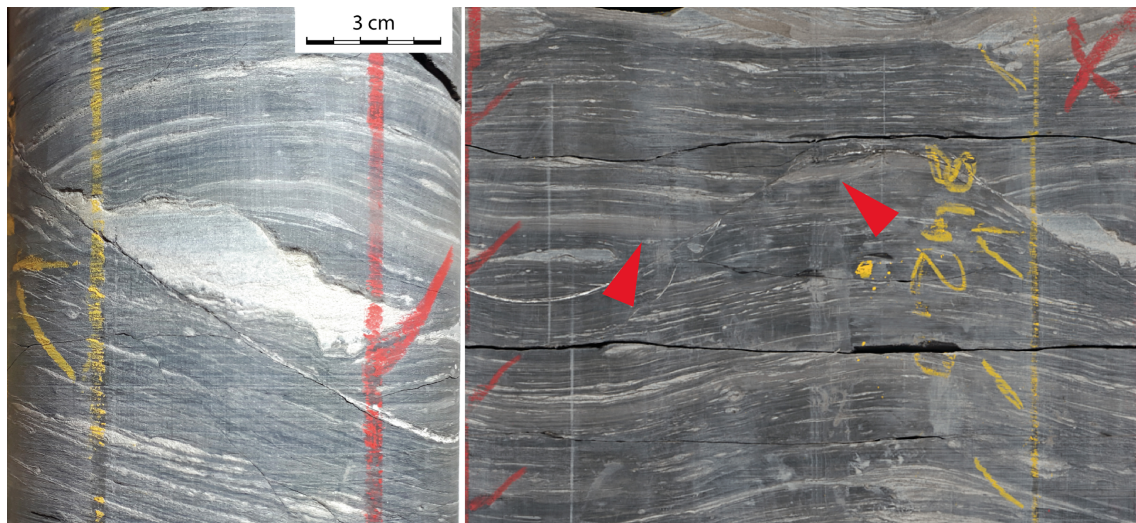


Fig. 5-3: Mirror-like fault plane (346/33) in the Opalinus Clay at 842.00 m MD core depth

Note the patchy, synkinematic calcite mineralisation along the fault plane (left). Same structure seen in a 360° core photograph (length 30 cm; right). The shear sense suggesting downward movement related to normal faulting is clearly indicated by the displaced lamination (red arrows).

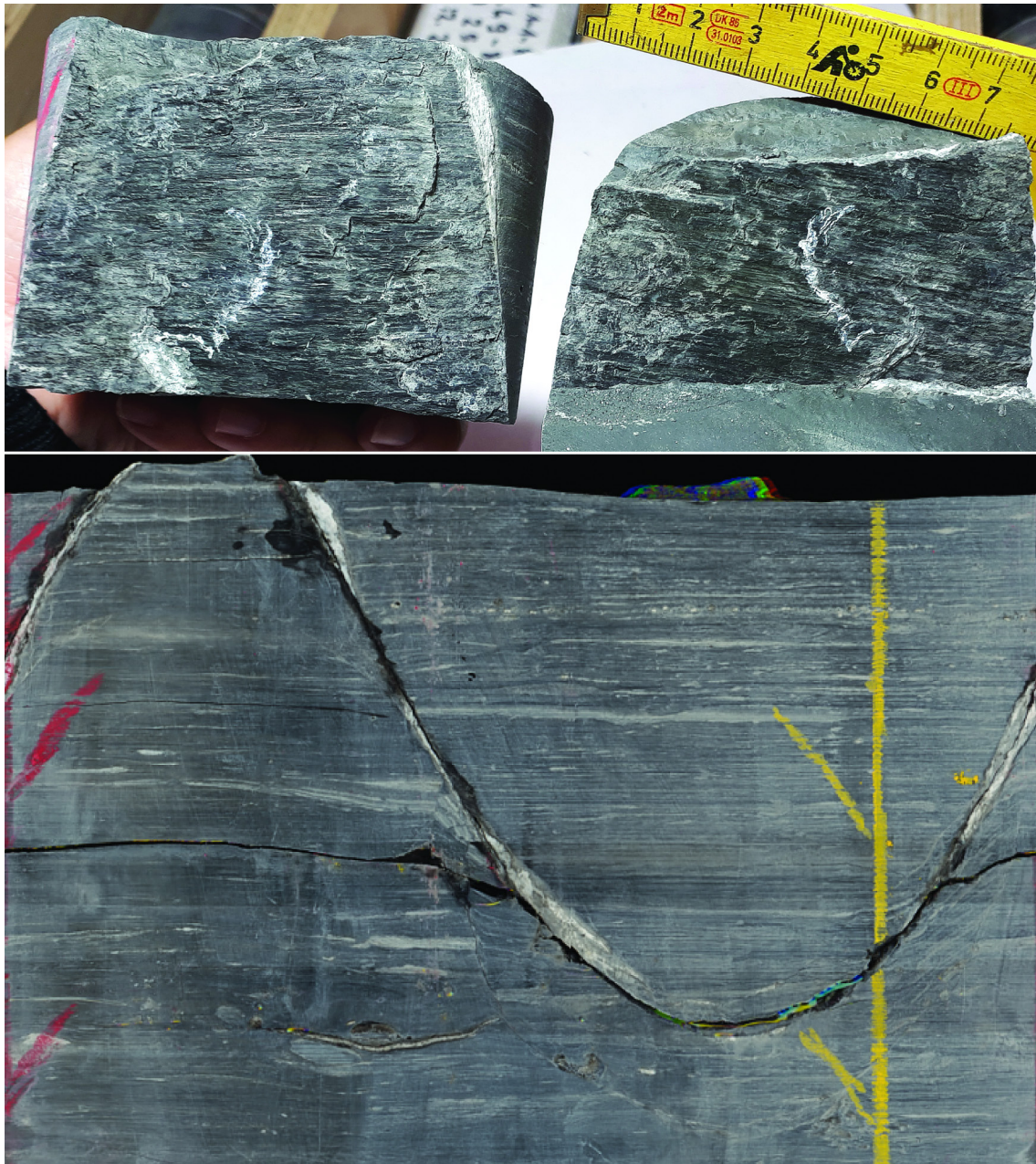


Fig. 5-4: Example of a fault plane (oriented 096/59) within the Opalinus Clay at 846.78 m MD core depth

Note the sinistral sense of shear and synkinematic calcite mineralisation as seen in the drill core (above) and 360° core photograph (below; length 30 cm).

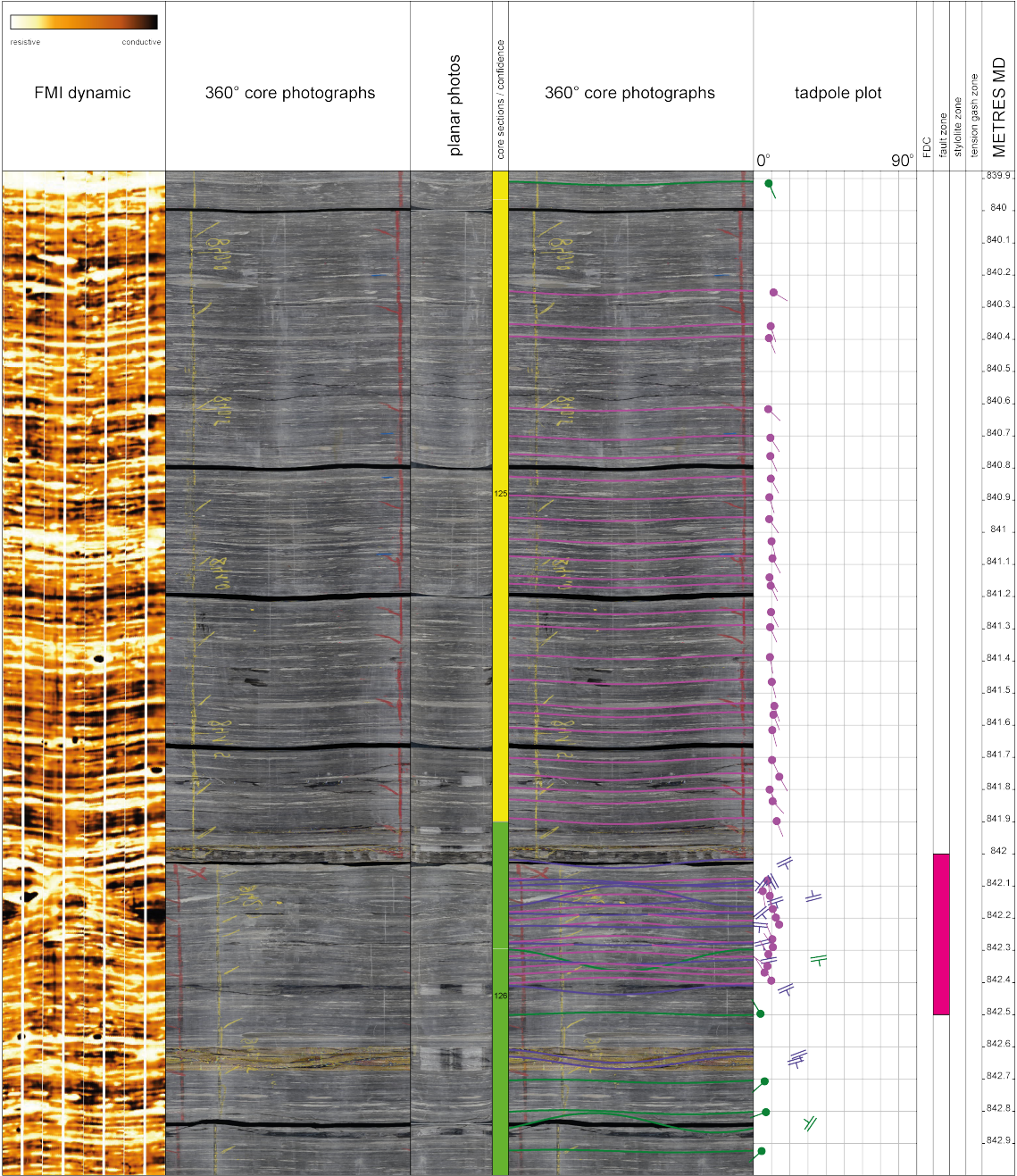


Fig. 5-5: Overview plot for the Opalinus Clay from 839.90 to 843.00 m MD log depth
Note the change in dip of bedding at the fault zone from 842.00 to 842.50 m MD log depth.

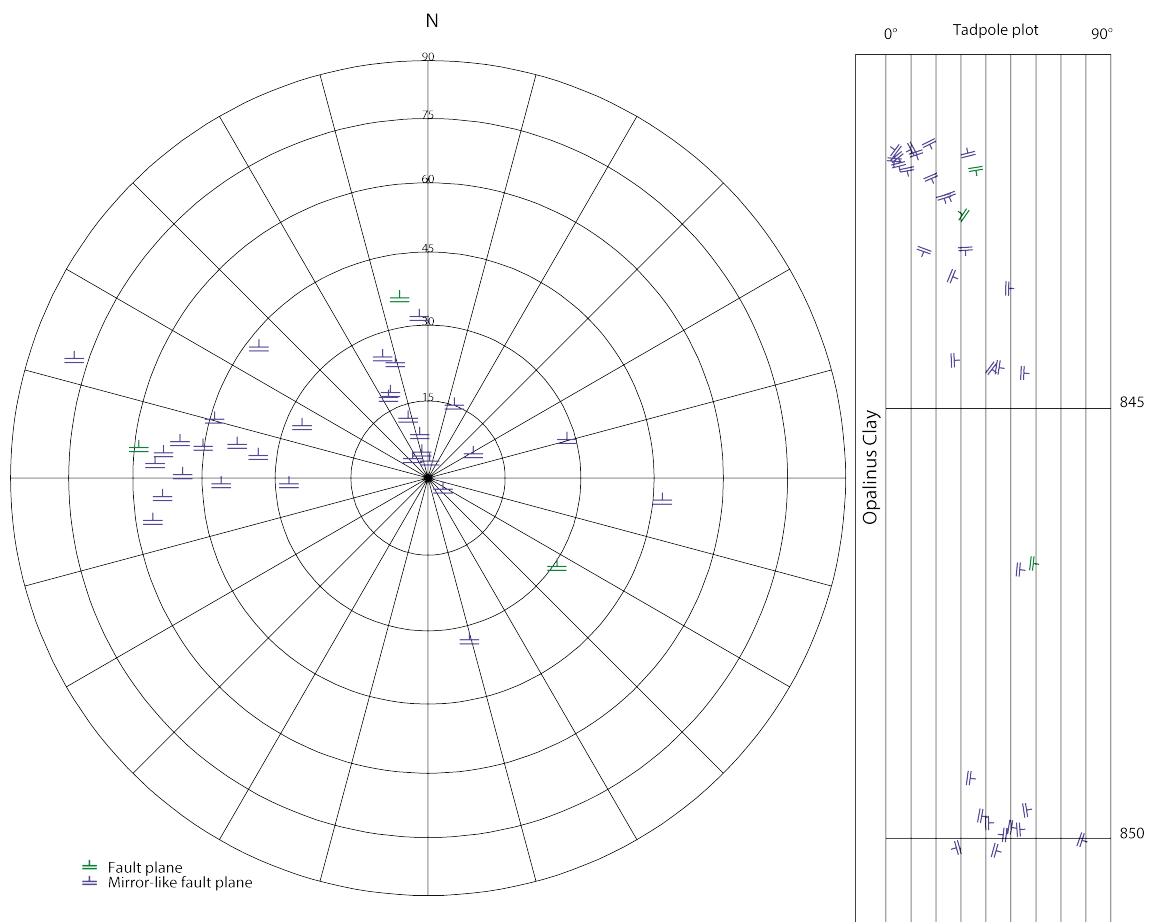


Fig. 5-6: Stereogram with fault orientations at 841.00 – 851.00 m MD log depth (Opalinus Clay)

Note the predominance of approximately E- and S-dipping faults.

5.3 Bedding deformation within the Bänkerjoch Formation

A deformation zone was observed from 1'073.70 m to 1'084.22 m MD log depth, at the base of the Bänkerjoch Formation. This zone mainly comprised massive to well-bedded anhydrite with thin clay intercalations resulting in confident bedding indicators. The dip angles are variable, ranging from 10° to 60° with fairly consistent SSW and SW dip azimuths (Figs. 5-7 and 5-8). The observed dip change is gradual in nature and most likely governed by folding. Indeed, a few cm-sized folds with sub-horizontal fold axes plunging towards ESE (n = 3) and SW (n = 1) were recorded (Fig. 5-9 and Tab. 5-1). These folds were observed only in a few cm-thick anhydrite and clay-rich bands, most likely indicating a synsedimentary origin.

Tab. 5-1: Recorded fold axes within the Bänkerjoch Formation

Depth [m MD log depth]	Plunge direction [°]	Plunge [°]
1'075.65	120	05
1'075.71	115	10
1'077.40	220	35
1'083.68	108	06

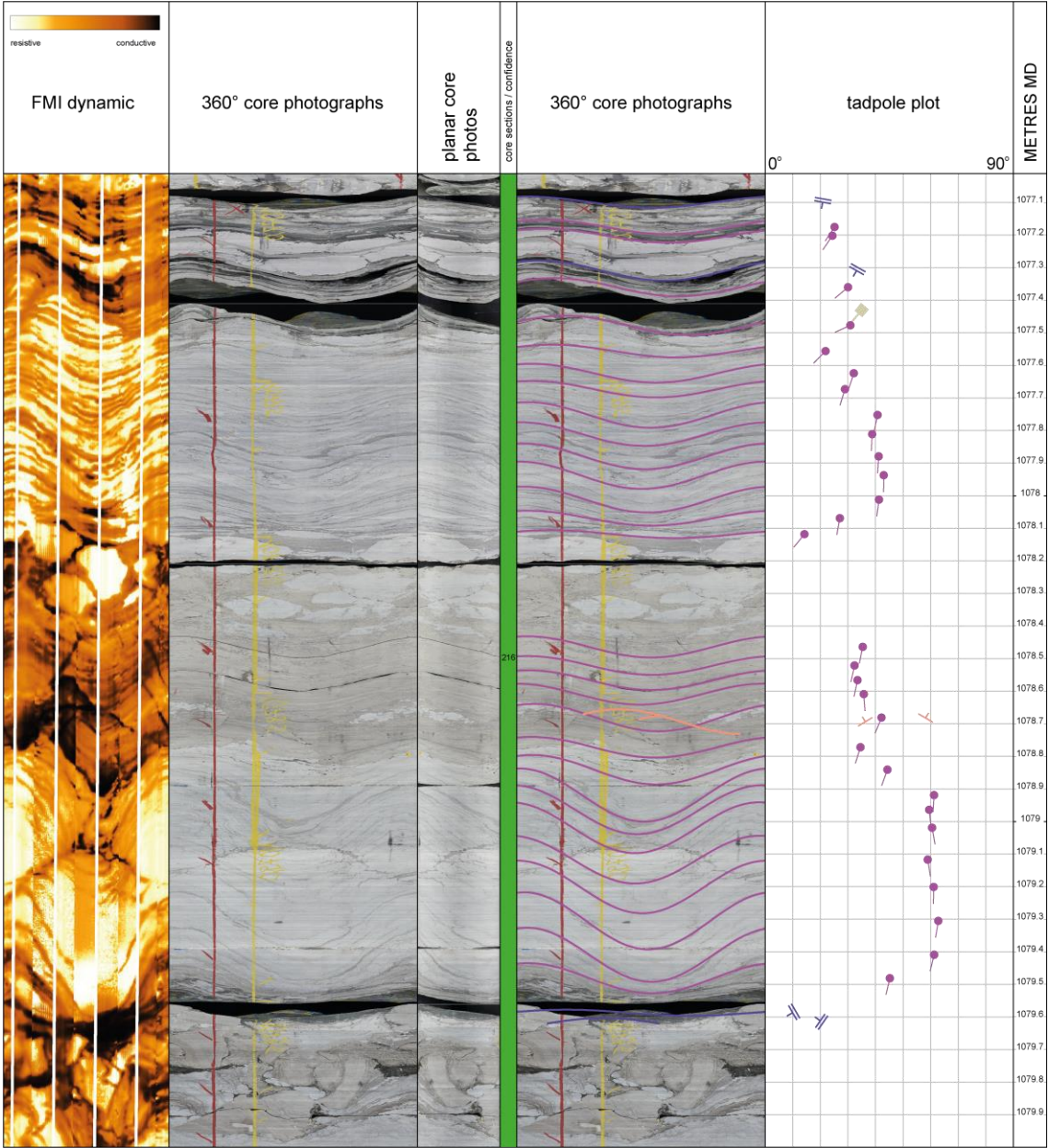


Fig. 5-7: Bedding with variable dip angles in the Bänkerjoch Formation at 1'077.00 – 1'080.00 m MD log depth

Note the gradually changing dip angles most likely associated with folding.

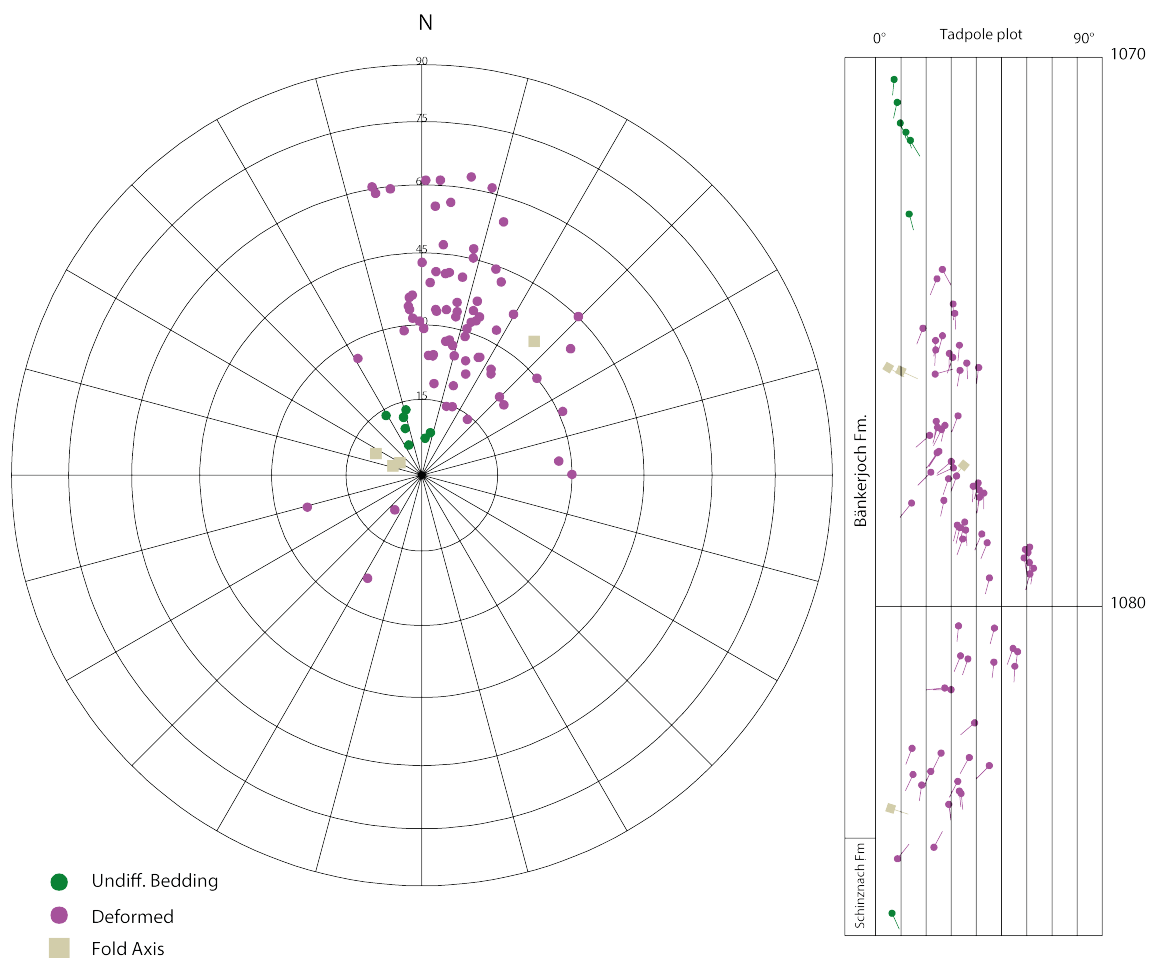


Fig. 5-8: Stereogram showing the deformed bedding in the Bänkerjoch Formation

The displayed interval is from 1'070.00 to 1'086.00 m MD log depth. Note the gradual dip angle changes and the consistent SSW- and SW-directed dip azimuths. Fold axes (n = 4) trend mainly WNW-ESE. Displayed dips are: undiff. bedding (n = 7, green), deformed bedding (n = 74, purple) and fold axes (n = 4, beige).

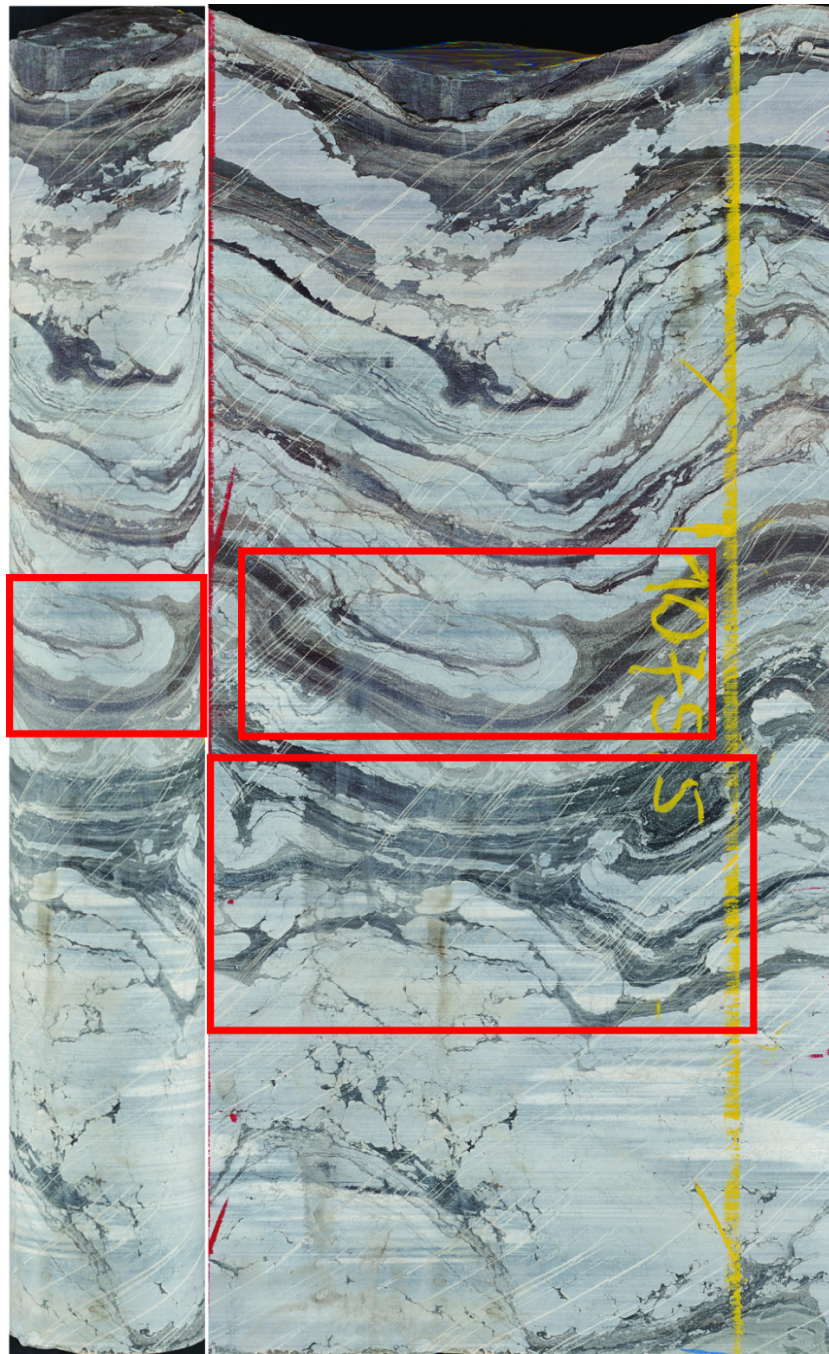


Fig. 5-9: Drill cores from the Bänkerjoch Formation with cm-scale folding at around 1'075.70 mMD core depth

5.4 Tension gashes / veins within the Variansmergel Formation

The Variansmergel Formation from 727.13 m to 738.97 m MD log depth was composed of argillaceous limestone and silty claystone alternation leading to heterogeneities in mechanical properties of the individual layers. This results in strain concentration within the competent carbonate-rich beds and development of bed-confined tension gashes / veins.

Drill core examples of prominent veins at 736.71 m, 736.73 m, 738.18 m and 738.53 m MD core depth are provided in Fig. 5-10. They are sub-vertical and calcite-mineralised (up to 10 mm thick). They are oriented perpendicular to the bedding and were observed exclusively within competent limestone beds (15 to 30 cm thick). They terminate sharply at the lithological bed boundaries to the mechanically weaker silty claystone / silty marl. In addition, local shear movements were observed along some tension gashes as indicated in Fig. 5-10. Locally, some veins penetrate the entire sedimentary sequence and apparently stop at the clay-rich beds and then continue uninterrupted in the adjacent calcareous beds (Fig. 5-10).

736.65 m MD



737.00 m MD

738.04 m MD



738.82 m MD

Fig. 5-10: Examples of bed-confined veins in the Variansmergel Formation

(Left): Sub-vertical, NNE-SSW-striking partly calcite-filled veins at 736.71 m and 736.73 m MD core depth developed within a 20 cm thick argillaceous limestone bed; the right vein is 9 mm thick. (Right): Sub-vertical, roughly N-S-striking tension gashes up to 5 mm thick at 738.18 m and 738.53 m MD core depth developed within 17 cm (lower) to 25 cm (upper) thick and competent argillaceous limestone beds. Note the sharp termination at the boundaries to the mechanically weaker claystone / silty marl. Potential pinch-and-swell structures represented by thinning at the point of shearing are indicated by red arrows.

6 References

- Barton, N. (1976): The shear strength of rock and rock joints. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 13/9, 255-279.
- Barton, N. & Choubey, V. (1977): The shear strength of rock joints in theory and practice. *Rock mechanics* 10/1-2, 1-54.
- Bauer, H., Schröckenfuchs, T. & Decker, K. (2016): Hydrogeological properties of fault zones in a karstified carbonate aquifer (Northern Calcareous Alps, Austria). *Hydrogeology Journal* 24, 1147-1170.
- Hancock, P.L. (1985): Brittle microtectonics: Principles and practice. *Journal of Structural Geology* 7/3-4, 437-457.
- Isler, A., Pasquier, F. & Huber, M. (1984): Geologische Karte der zentralen Nordschweiz 1:100'000. Herausgegeben von der Nagra und der Schweiz. Geol. Komm.
- Ebert, A. & Decker, K. (2019): Structural Analysis Manual. Nagra Arbeitsbericht NAB 19-12.
- Nagra (2014): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage. Geologische Grundlagen. Dossier II: Sedimentologische und tektonische Verhältnisse. Nagra Technischer Bericht NTB 14-02.
- Passchier, C.W. & Trouw, R.A.J. (1996): *Microtectonics*. Springer, 289 pp.
- Peacock, D.C.P., Nixon, C.W., Rotevatn, A., Sanderson, D.J. & Zuluaga, L.F. (2016): Glossary of fault and other fracture networks. *Journal of Structural Geology* 92, 12-29.
- Pietsch, J. & Jordan, P. (2014): Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2013 (SGT E2) und ausgewählte Auswertungen. Nagra Arbeitsbericht NAB 14-02.