

Arbeitsbericht NAB 21-20

**TBO Marthalen-1-1:
Data Report**

**Dossier V
Structural Geology**

September 2021

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

Hardstrasse 73
P.O. Box 280
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11

www.nagra.ch

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Structural Geology**

September 2021

A. Ebert¹, L. Gregorczyk¹, E. Hägerstedt¹,
S. Cioldi¹ & M. Gysi²

¹Geologiegemeinschaft Strukturgeologie-Experten
Nagra Tiefbohrungen

²Nagra

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MAR1-1, 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 (core description, core photograph picking, writing and QC)

L. Gregorczyk (core description, core photograph picking, core goniometry, writing and QC)

S. Cioldi (core description, core photograph picking and core goniometry)

E. Hägerstedt (core description, core photograph picking and core goniometry)

K. Decker (QC)

M. Gysi (project management, conceptualisation and QC)

Editorial work: Geomecon, P. Blaser and M. Unger

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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- App. C-1: Structural geology profile Marthalen -1-1, 1:100, 450.00 m to 725.00 m MD log depth
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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 ("Tiefbohrungen", TBO) 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 Marthalen-1-1 borehole.

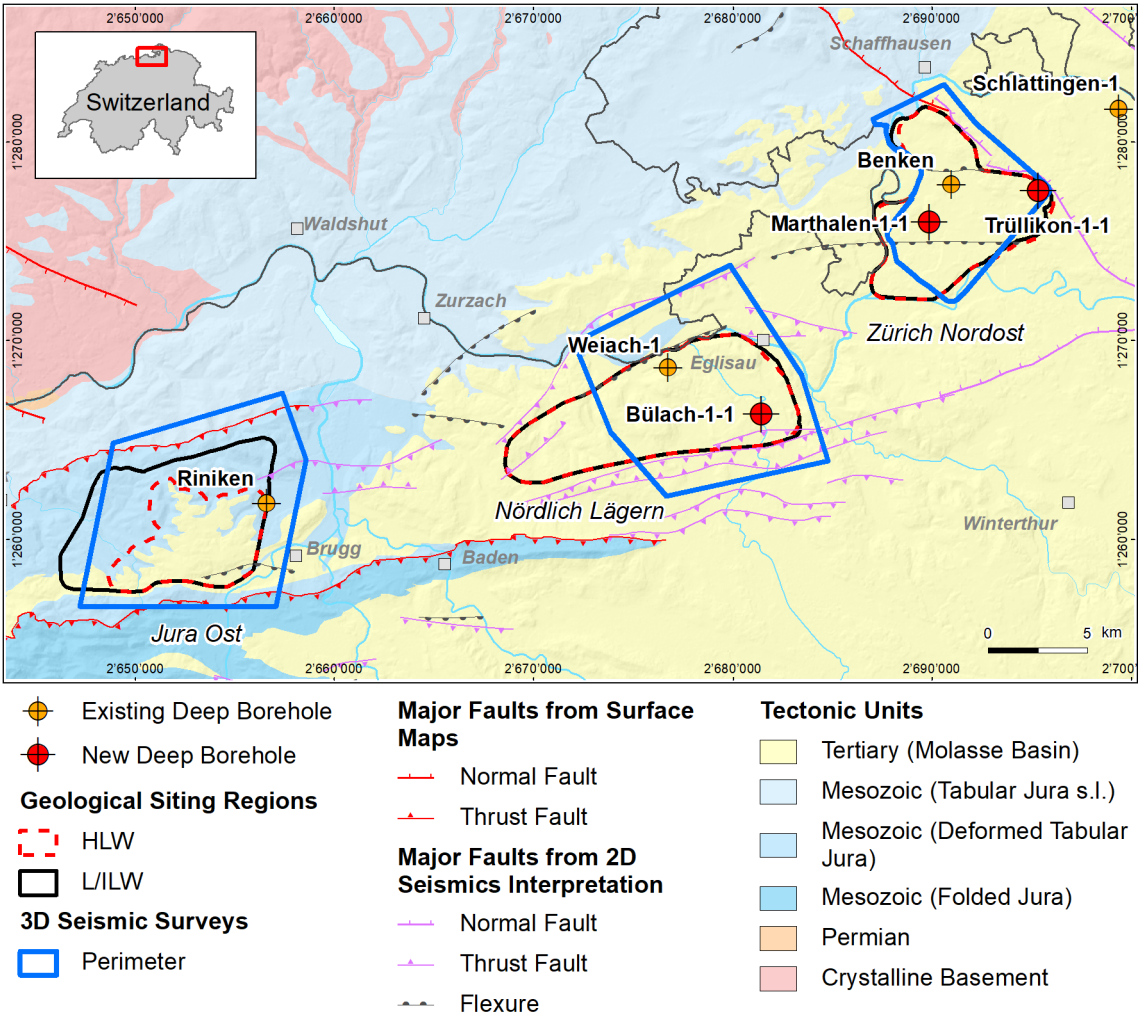


Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Marthalen-1-1 (MAR1-1) exploratory borehole is the third borehole drilled within the framework of the TBO project. The drill site is located in the western part of the Zürich Nordost siting region (Fig. 1-2). The vertical borehole reached a final depth of 1'099.25 m (MD)¹. The borehole specifications are provided in Tab. 1-1.

Tab. 1-1: General information about the MAR1-1 borehole

Siting region	Zürich Nordost
Municipality	Marthalen (Canton Zürich / ZH), Switzerland
Drill site	Marthalen-1 (MAR1)
Borehole	Marthalen-1-1 (MAR1-1)
Coordinates	LV95: 2'689'889.946 / 1'275'956.932
Elevation	Ground level = top of rig cellar: 399.48 m above sea level (asl)
Borehole depth	1'099.25 m measured depth (MD) below ground level (bgl)
Drilling period	9th February 2020 – 14th July 2020 (spud date to end of rig release)
Drilling company	Daldrup & Söhne AG
Drilling rig	Wirth B 152t
Drilling fluid	Water-based mud with various amounts of different components such as ² : 55 – 460 m: Bentonite & polymers 460 – 881 m: Potassium silicate & polymers 881 – 961 m: Sodium silicate & polymers 961 – 1'099.25 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 MAR1-1 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.

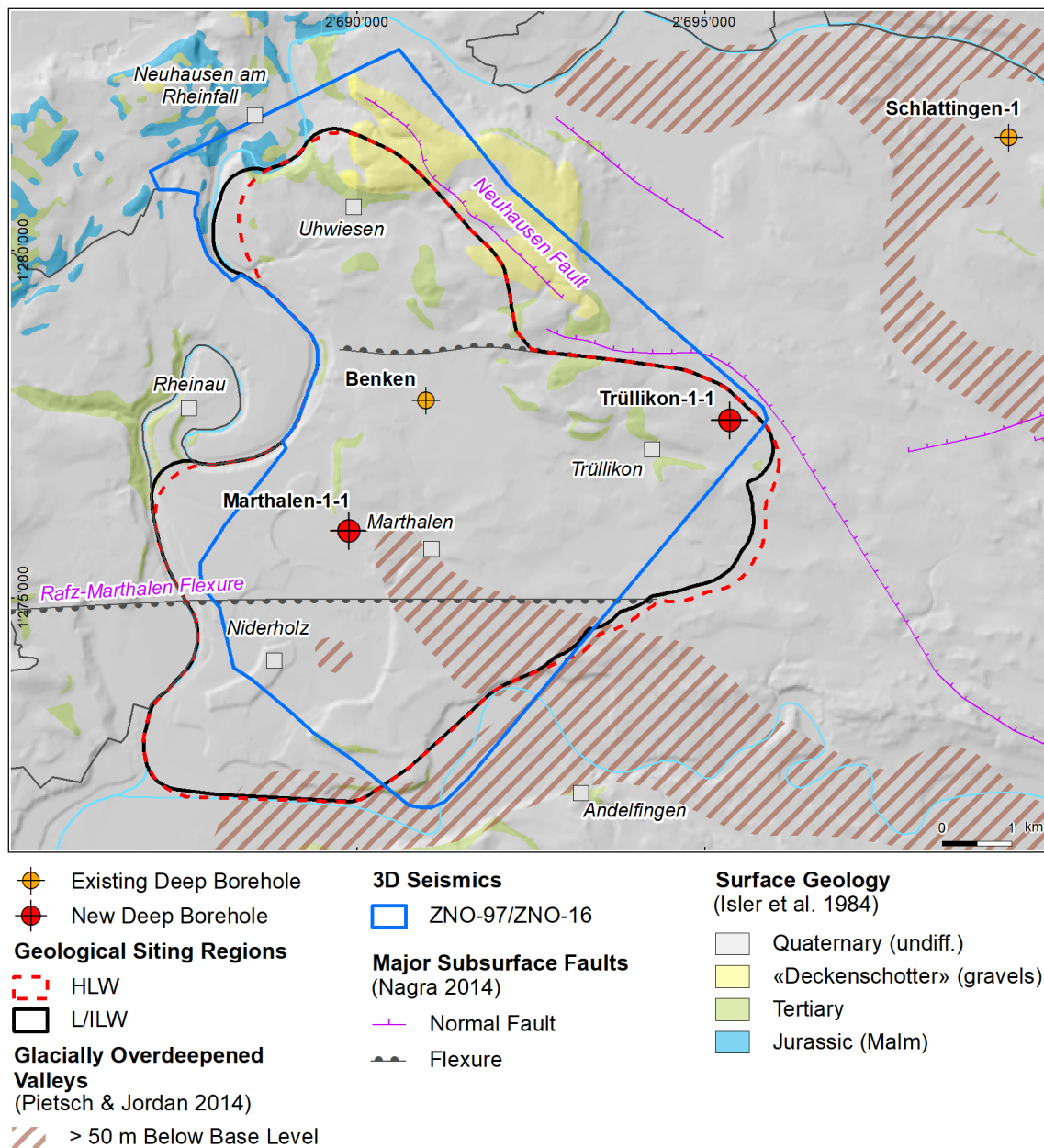


Fig. 1-2: Overview map of the investigation area in the Zürich Nordost siting region with the location of the MAR1-1 borehole in relation to the boreholes Benken, Schlattingen-1 and TRU1-1.

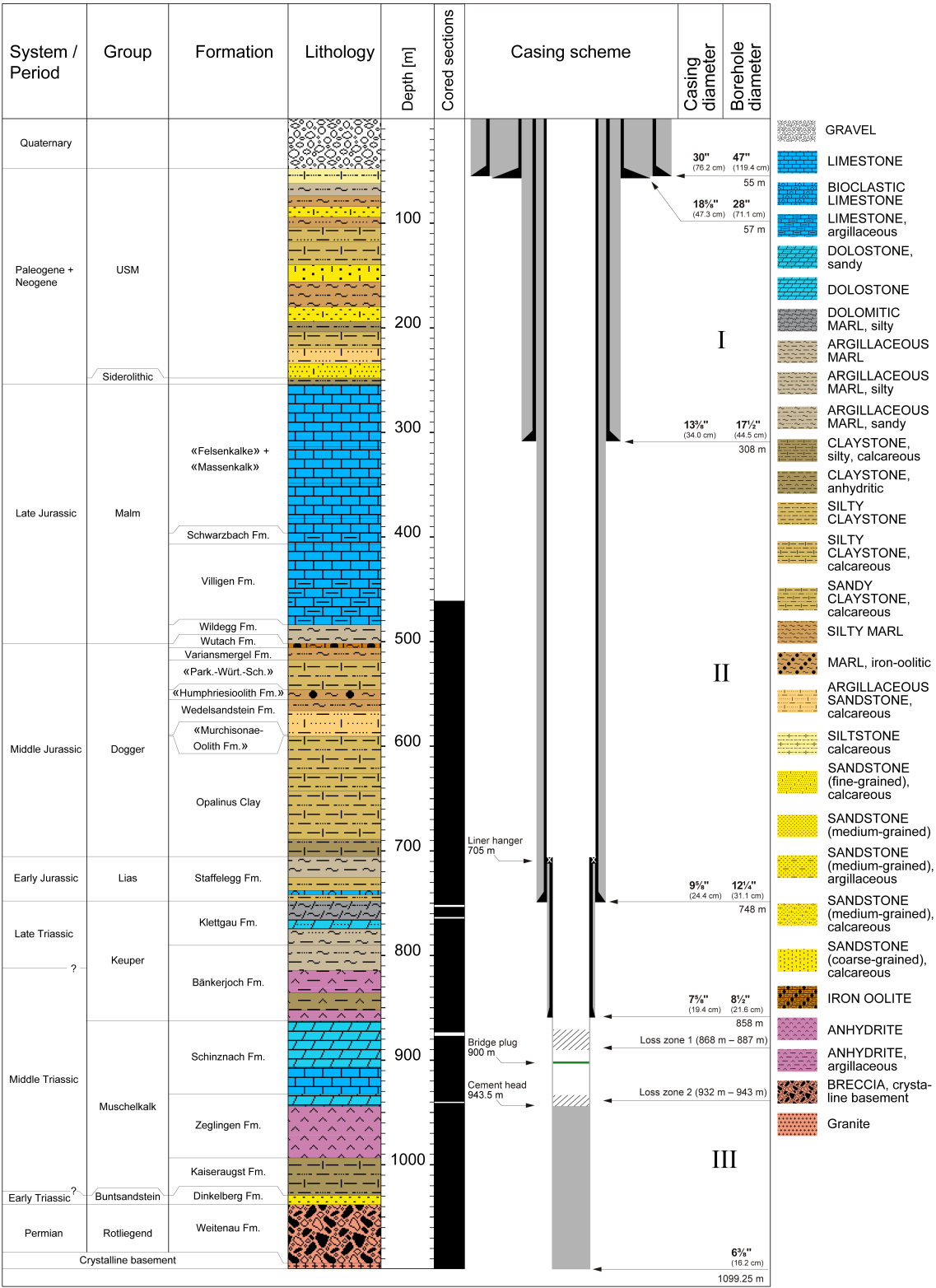


Fig. 1-3: Lithostratigraphic profile and casing scheme for the MAR1-1 borehole⁴

⁴ For detailed information see Dossier I and Dossier III.

Tab. 1-2: Core and log depth for the main lithostratigraphic boundaries in the MAR1-1 bore-hole⁵

System / Period	Group	Formation	Core depth in m (MD)	Log
Quaternary			48	—
Paleogene + Neogene	USM		248	—
	Siderolithic		254	—
		«Felsenkalke» + «Massenkalk»	396.1	—
	Malm	Schwarzbach Formation	406.9	—
		Villigen Formation	484.02	484.22 —
		Wildeggen Formation	501.80	501.92 —
		Wutach Formation	505.75	506.03 —
		Variansmergel Formation	517.43	517.57 —
Jurassic		«Parkinsoni-Württembergica-Schichten»	545.93	546.12 —
	Dogger	«Humphriesioolith Formation»	555.23	555.47 —
		Wedelsandstein Formation	589.17	589.19 —
		«Murchisonae-Oolith Formation»	590.35	590.37 —
		Opalinus Clay	705.40	705.52 —
	Lias	Staffelegg Formation	747.83	747.89 —
	Keuper	Klettgau Formation	790.12	790.34 —
		Bänkerjoch Formation	862.52	862.77 —
		Schinznach Formation	932.24	932.47 —
Triassic	Muschelkalk	Zeglingen Formation	993.50	993.97 —
		Kaiseraugst Formation	1029.45	1029.95 —
	Buntsandstein	Dinkelberg Formation	1037.98	1038.23 —
Permian	Rotliegend	Weitenau Formation	1094.08	1094.08 —
		Crystalline Basement	1099.25	final depth

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

1.3 Documentation structure for the MAR1-1 borehole

NAB 21-20 documents the majority of the investigations carried out in the MAR1-1 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 MAR1-1 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 21-20

Black indicates the dossier at hand.

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

The cored section of MAR1-1 is almost vertical, with a slight deviation towards NNW and a distinct change in deviation towards NW at about 875 m MD. The maximum deviation at 1'099.25 m MD is about 22 m to the NW (Fig. 1-4).

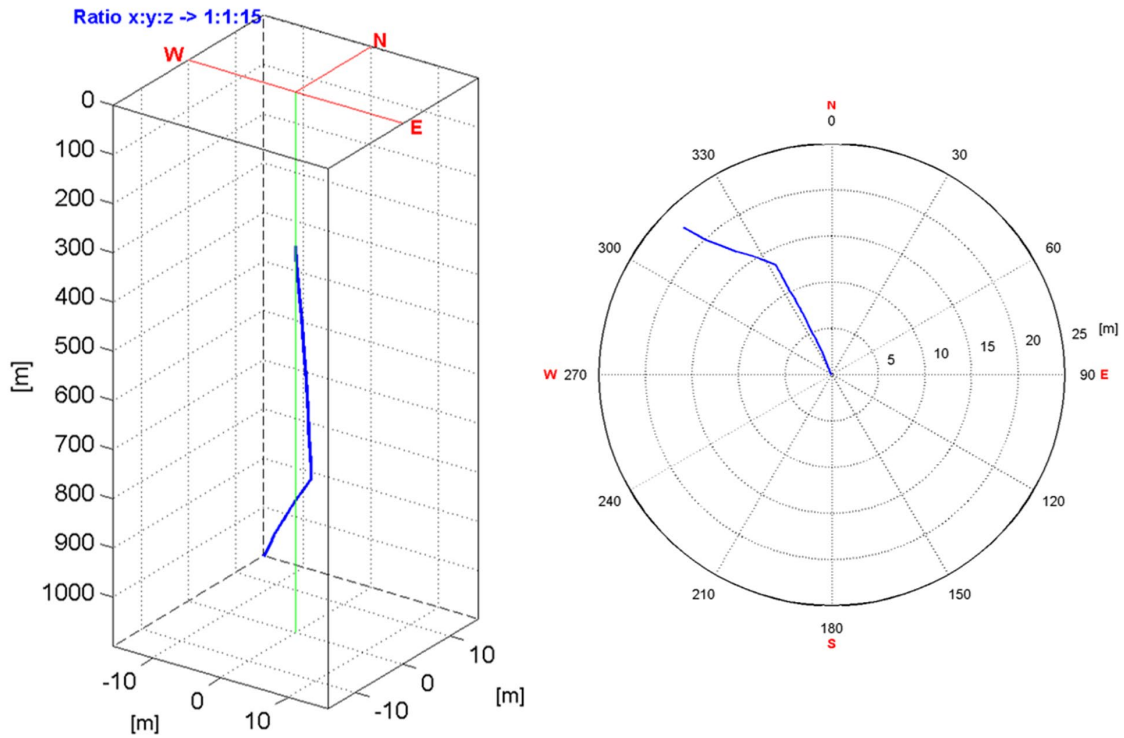


Fig. 1-4: Borehole deviation within the cored section

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 460.00 m to 1'099.25 m MD. The data were delivered as 985 circumferential and 1'051 planar photographs in TIF format. However, the original photographs with a resolution of 10 pixels/mm were too large to be handled with 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 were of good to excellent quality. Further relevant data included auxiliary borehole data, core orientation line and core section listings, lithostratigraphic boundaries 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 looking from the inside of the borehole. 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 (gamma ray) 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, 203 distinct depth shift values were applied for the core sections of the entire cored borehole; these varied from - 0.14 m to + 0.50 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 uphole 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 detailed structural core analysis and the structural inventory metadata), completeness of records and the accurate characterisation of the recorded tectonic features.

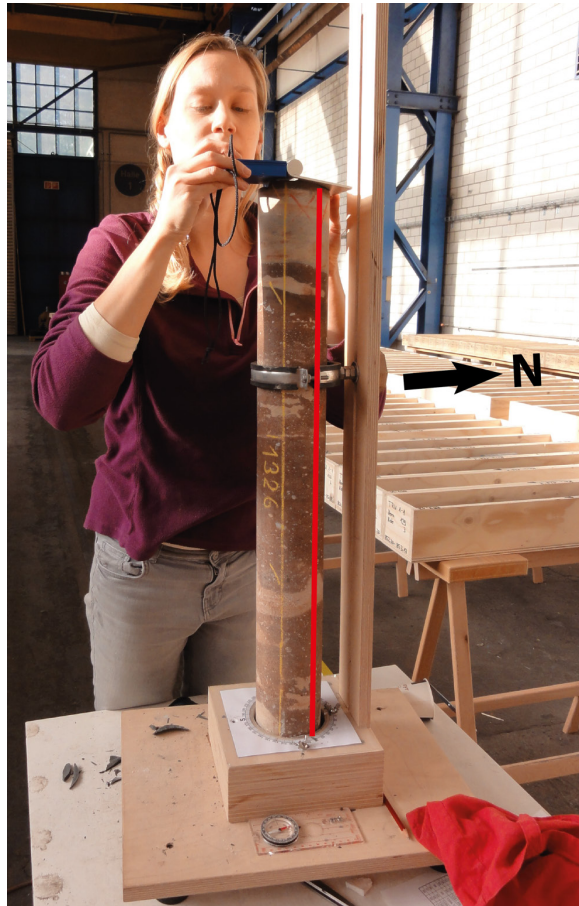


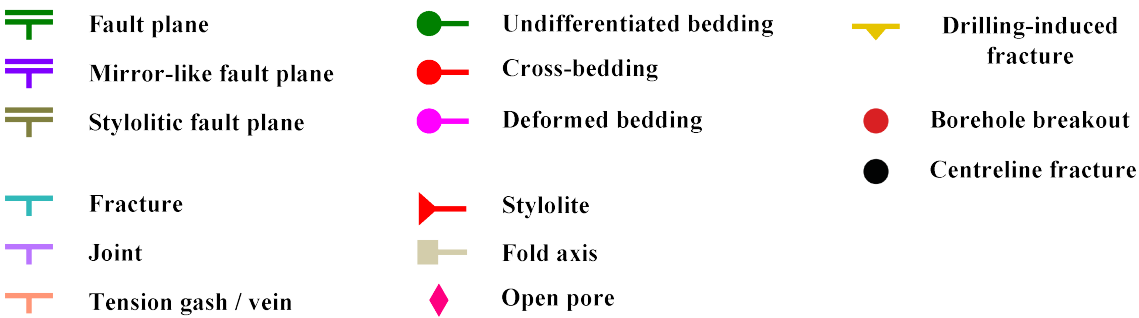
Fig. 2-1: Using a goniometer to determine kinematic indicators along faults
Note the red core orientation line defining the position of the drill core in the goniometer.

2.1.3 Dip picking and dip type classification

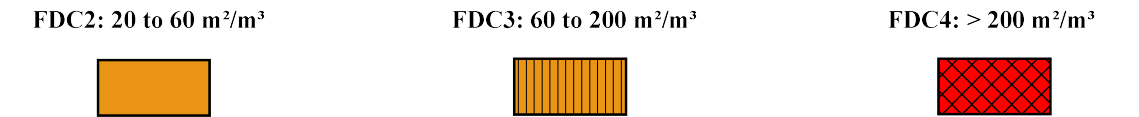
Due to higher accuracy and reliability compared to automated methods, a manual sinusoid method and a point-to-point method were used to pick all relevant features on the 360° core photographs. In a cylindrical borehole, a perfect plane will appear as a sine wave on the circumferential core photograph 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 were defined in TerraStation II (Fig. 2-2).

Dip Types



Fracture density classes



TectonicsFP symbols

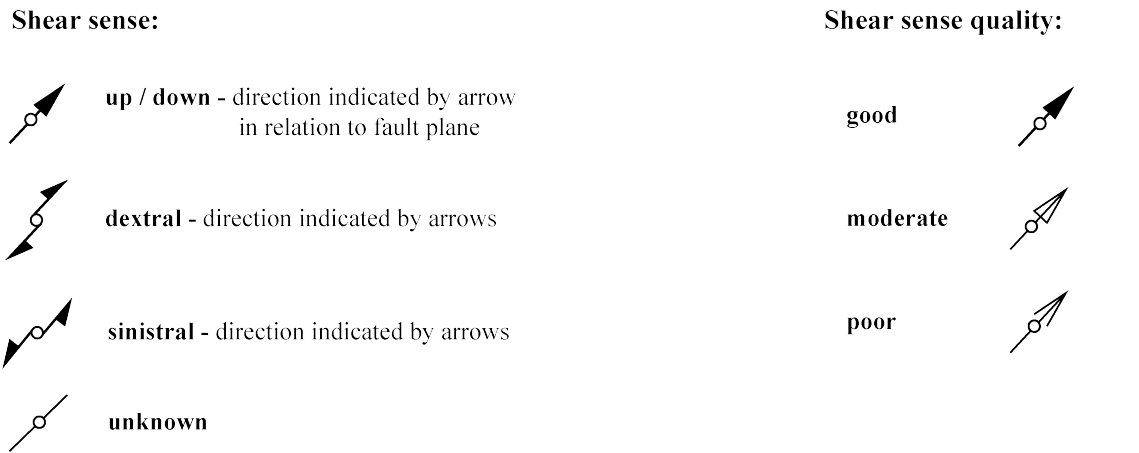


Fig. 2-2: Symbols for dip types, fracture density classes and kinematic data used for this study

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 as described above, 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.

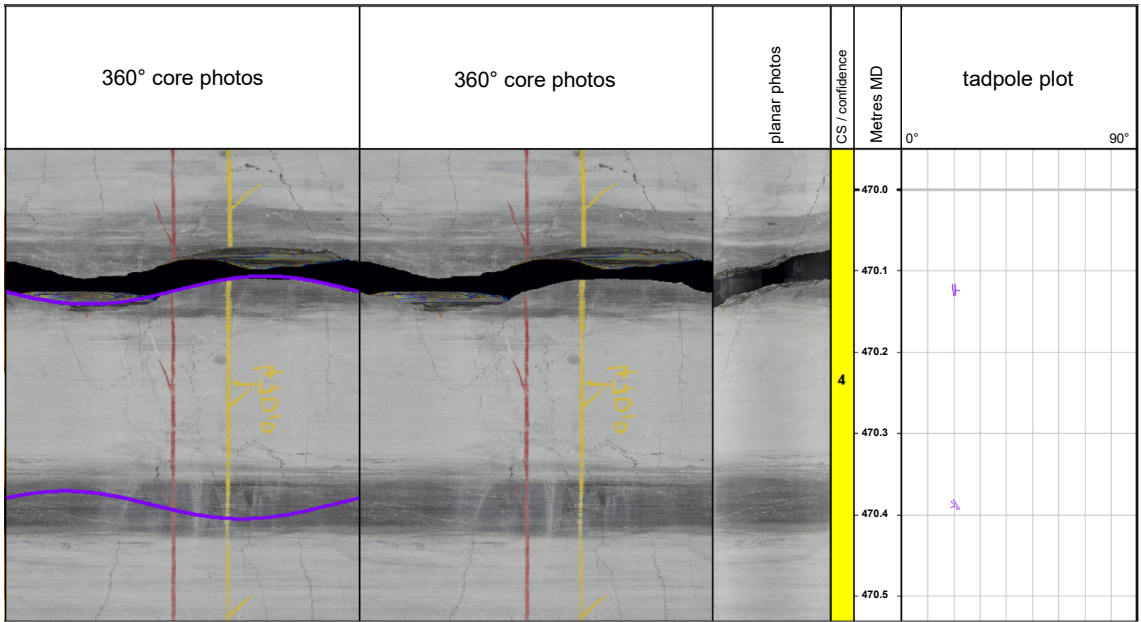


Fig. 2-3: Two mirror-like fault planes identified at 470.12 m and 470.39 m MD log depth (Villigen Formation)

The latter was determined within the drill core.

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 of the structure at 470.39 m MD (log depth) is not visible in the 360° core photo of the dark layer. The fault plane was therefore implemented from the core analysis and the orientation obtained from a compass measurement.

2.1.4 Dip data for non-oriented and missing cores

Due to a lack of correlated features, poor data quality or missing image log data (from 1'054 to 1'099 m MD core depth), 123.09 m of the available drill cores remained non-oriented. Within these non-oriented drill cores a total of 11 bedding planes and 282 tectonic / drilling-induced discontinuities could be observed and picked. 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 data set 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 visualization (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 of Terrastation (see Fig. 2-5).

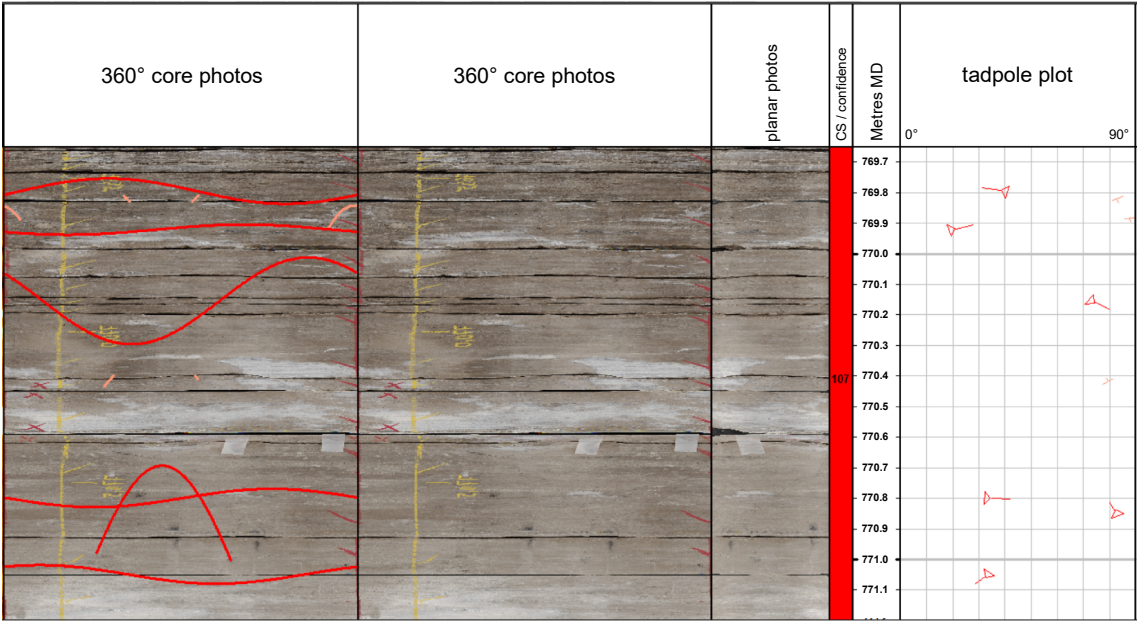


Fig. 2-4: Example of dip data in a non-oriented core interval displayed as hollow tadpoles
The goniometry confidence is set to "core not oriented" (red). Example from the Klettgau Formation from 769.70 m to 771.20 m MD log depth.

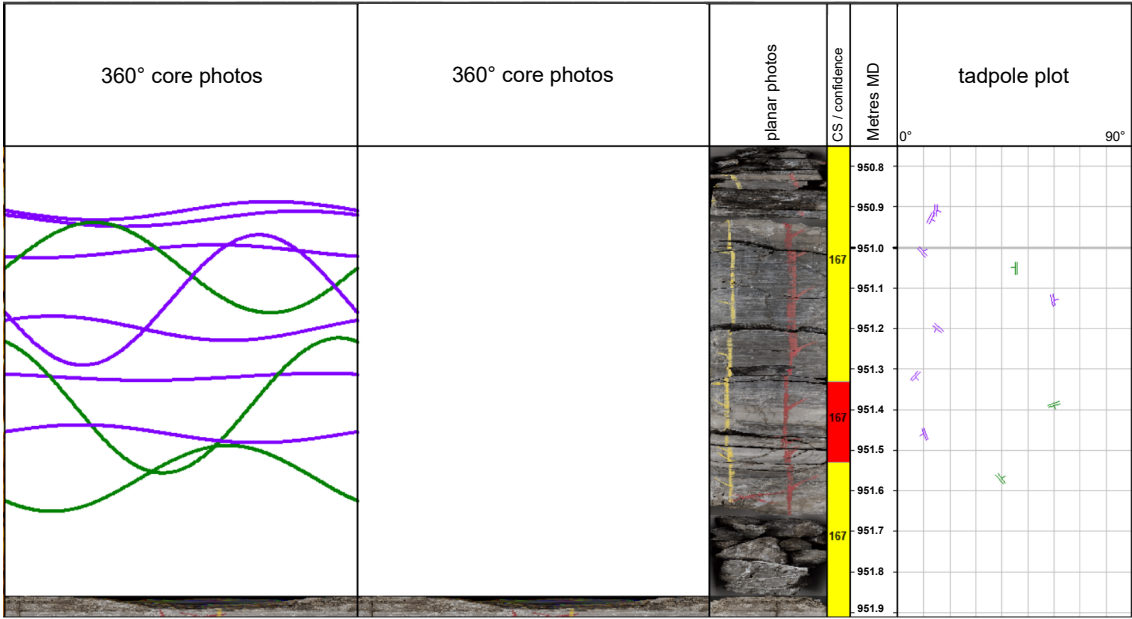


Fig. 2-5: Interval without 360° core photographs at 950.8 m MD to 951.9 m MD log depth (Zeglingen Formation)

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 for this core section is partly moderate (yellow) and partly non-orientated (red).

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 ($< 15^\circ$). The features used for the core goniometry are listed in Appendix E-2 along with the coherent COLs. 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 (Appendices B and C). The confidence 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 contains 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 gives an overview of the core goniometry confidence assessment. The procedure described in Section 2.1.2 resulted in a successful orientation of 509.34 m out of the total 632.43 m of drill cores (81%), retrieved from the cored interval from 460.00 to 1'099.25 m MD (log depth).

Tab. 2-1: Core goniometry confidence assessment

Interval			Goniometry confidence								
Top	Bottom	Length	High			Moderate			Not oriented		
[m MD log depth]			[m]	[%]	No. of COLs	[m]	[%]	No. of COLs	[m]	[%]	No. of COLs
460.00	1'099.25	632.43	238.20	38	24	271.14	43	44	123.09	19	36

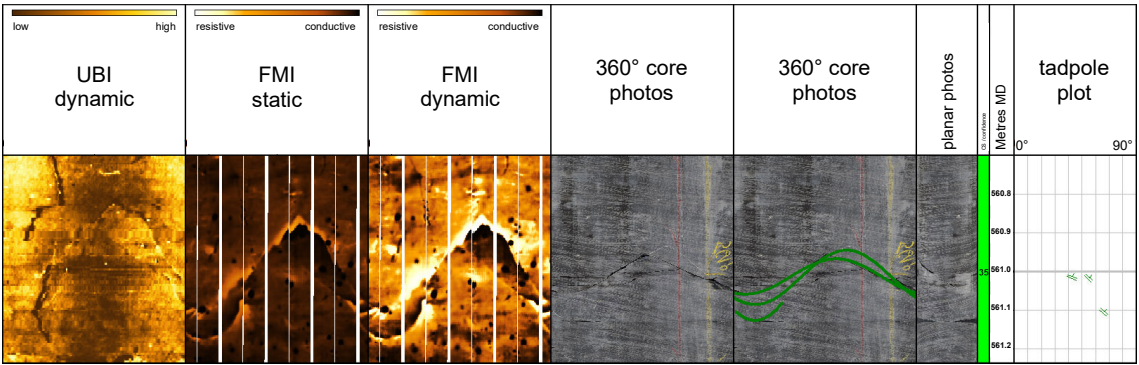


Fig. 2-6: Core – FMI / UBI correlation for a fault at 561.03 m MD log depth

This prominent 58° SE-dipping fault was unequivocally correlated across the UBI and FMI logs and the core photographs, 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 without (left) and with (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 (60 cm). A tadpole plot with true orientations of manually picked planes is also displayed.

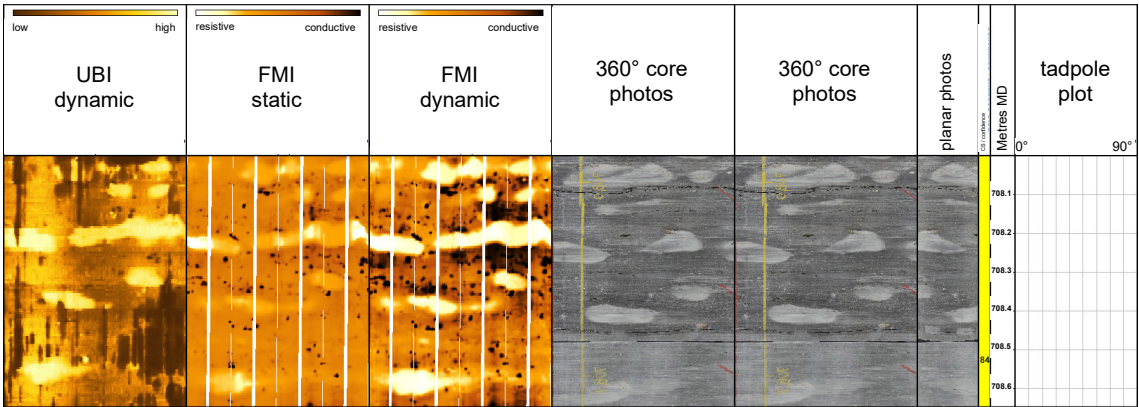


Fig. 2-7: Core – FMI / UBI correlation in the Staffelegg Formation at 708.00 m MD to 708.60 m MD log depth

These unique structures represent elongated nodules which appear bright (high amplitude) on the UBI and resistive on the FMI images. They were used to orientate the core section 84. Due to their heterogeneous nature, they are considered as limited indicators for the core goniometry and assigned a moderate confidence level (yellow).

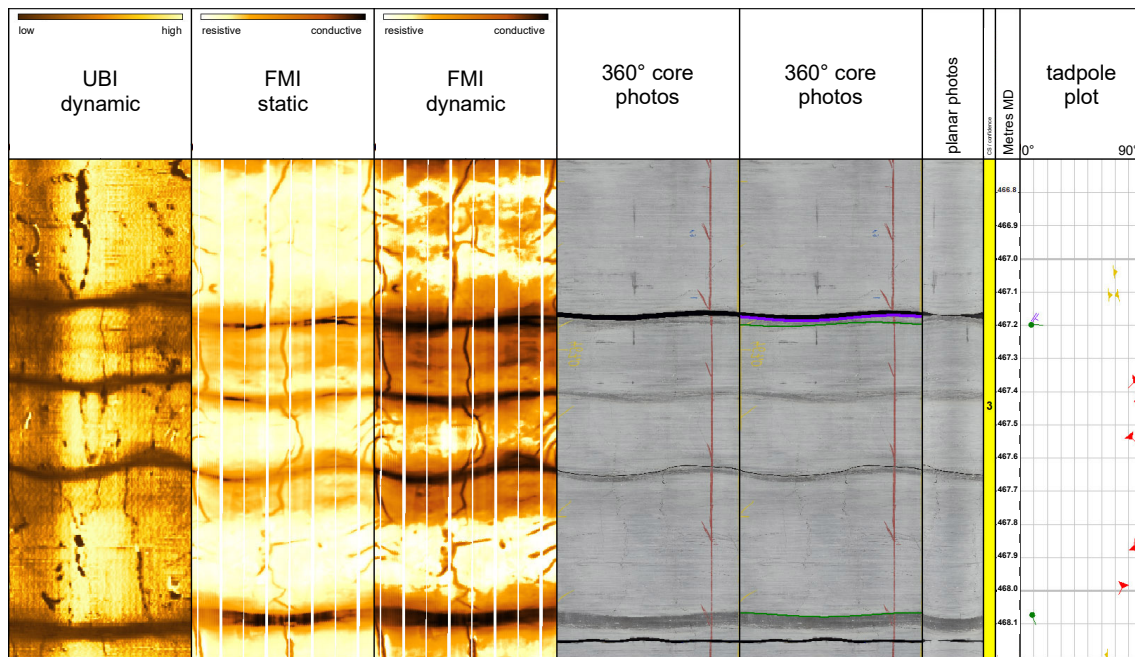


Fig. 2-8: Core – FMI correlation for sub-horizontal to shallow dipping bedding

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

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 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° to 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
- 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 (460.00 m to 1'099.25 m MD log depth), some data gaps occurred. The missing core sections are mostly due to pilot holes for formation integrity tests, hence no core photographs could be taken. In case of highly fractured or disintegrated cores, 360° core photographs have not been recorded as these intervals were not suitable for circumferential photography

- 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 (see Appendix E-2)
- 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 were 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 recording was usually finalised within a few weeks.

The overall core quality was excellent. Only cores from clay-rich lithologies (particularly Dogger) were affected by progressive discing but were still suitable for structural analysis. Due to 398 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 the 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 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 varied between –0.14 m and +0.50 m 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.

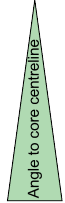
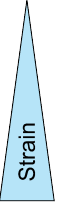
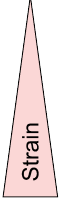
Mohr-Coulomb type brittle failure			Viscous (ductile) deformation	
Fractures			Without cohesion loss	
Drilling-induced	Extensional	Shear	Carbonate solution	Ductile shear
 Centreline fracture Petal fracture Core discing	 Joint Vein (Tension gash)	 Fault plane Fault zone	Stylolite / Dissolution seam Stylobreccia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

Tab. 2-2: continued

Discontinuity group	Structure type	Characteristics
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.
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.

Tab. 2-2: continued

Discontinuity group	Structure type	Characteristics
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.
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.

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 (TERRASCIENCES Inc.). This provides several advanced modules for the import, processing, visualisation and analysis of all types of available borehole data such as petro-physical 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 in Chapter 4, 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 data sets, 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 MAR1-1 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 – 3-29) is 95 mm.

3.1 Examples of fault planes



Fig. 3-1: Fault plane

Characteristics: Example of a fault plane with striation and mm-thick synkinematic calcite fibres. Shear sense is top up (reverse fault).

Formation: Wildegg Formation, Depth: 488.47 m MD (core depth)



Fig. 3-2: Fault plane

Characteristics: Example of a fault plane with striation and mm-thick synkinematic anhydrite. Shear sense is top up (reverse fault).

Formation: Zeglingen Formation, Depth: 983.05 m MD (core depth)



Fig. 3-3: Fault plane

Characteristics: Example of a discrete fault plane. The striation shows sub-vertical slip. Shear sense is top down (normal fault).

Formation: Villigen Formation, Depth: 471.90 m MD (core depth)



Fig. 3-4: Mirror-like fault plane

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

Formation: Zeglingen Formation, Depth: 984.87 m MD (core depth)



Fig. 3-5: Mirror-like fault plane

Characteristics: Example of a sub-horizontal dipping fault plane with a smooth mirror-like slip surface.

Formation: Opalinus Clay, Depth: 621.57 m MD (core depth)

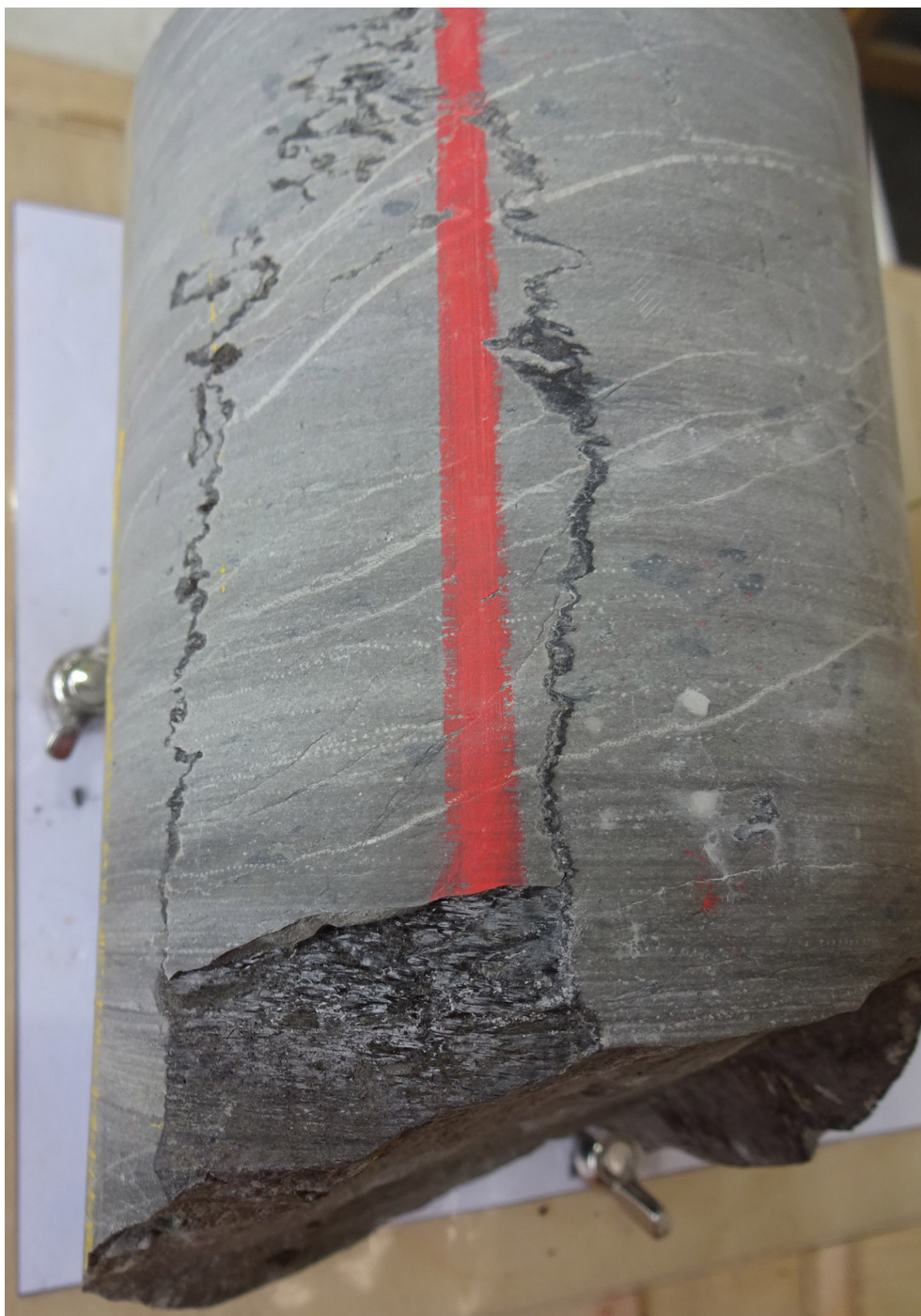


Fig. 3-6: Stylolitic fault plane

Characteristics: Example of a sub-vertical stylolitic fault plane with sub-horizontal striation generated by stylolitic dissolution and displacement sub-parallel to the plane.

Formation: Villigen Formation, Depth: 482.02 m MD (core depth)



Fig. 3-7: Stylolitic fault plane

Characteristics: Example of a sub-vertical stylolitic fault plane with sub-horizontal striation generated by stylolitic dissolution and displacement sub-parallel to the plane.

Formation: Zeglingen Formation, Depth: 937.17 m MD (core depth)



Fig. 3-8: Stylolitic fault plane (indicated by white arrows)

Characteristics: Transition of a steeply dipping stylolite into a sub-horizontal stylolitic fault plane with sub-horizontal striation generated by stylolitic dissolution and displacement sub-parallel to the plane.

Formation: Villigen Formation, Depth: 479.88 m MD (core depth)



Fig. 3-9: Synsedimentary fault planes

Characteristics: Example of synsedimentary fault planes limited to individual cm-thick layers.

Formation: Zeglingen Formation, Depth: 953.26 m MD (core depth)

3.2 Examples of fault zones



Fig. 3-10: Fault zone with FDC 2

Characteristics: Example of a fault zone with numerous individual and intersecting mirror-like fault planes. The core disintegration level corresponds to fracture density class 2.

Formation: Zeglingen Formation, Depth: 950.42 – 950.60 m MD (core depth)



Fig. 3-11: Fault zone

Characteristics: Example of a fault zone filled with fault breccia. At the wall surface a striation and synkinematic calcite and anhydrite fibres are visible, indicating sub-horizontal slip (white triangle).

Formation: Zeglingen Formation, Depth: 943.80 m MD (core depth)

3.3 Examples of joints



Fig. 3-12: Joint

Characteristics: A 20 cm long, sub-vertical joint characterised by the absence of slip indications.

Formation: Zeglingen Formation, Depth: 932.40 m MD (core depth)

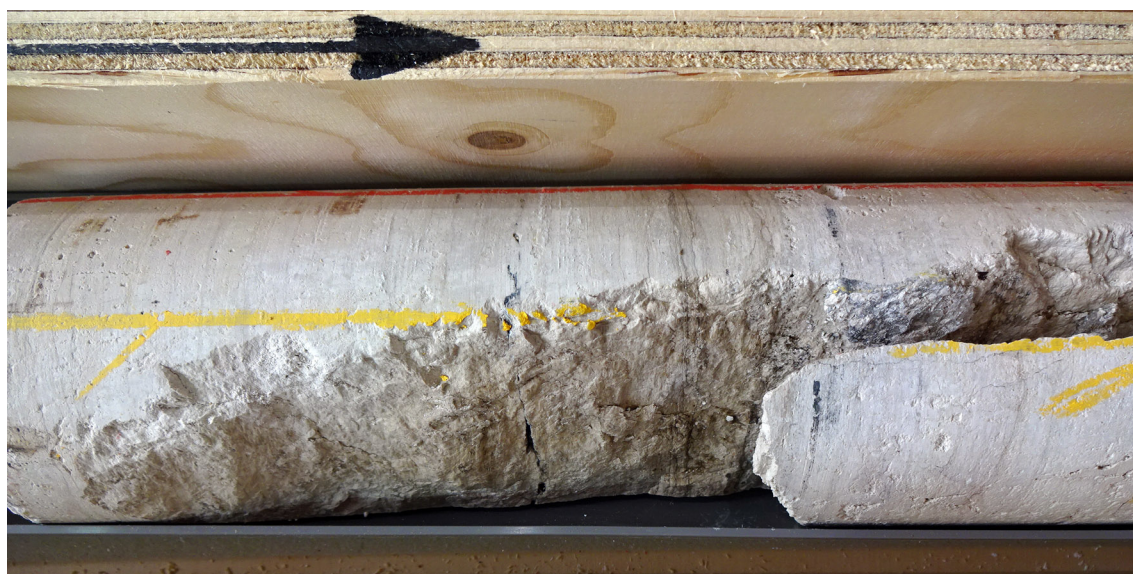


Fig. 3-13: Joint

Characteristics: A 100 cm long, sub-vertical joint characterised by a rough surface and the absence of slip indications.

Formation: Zeglingen Formation, Depth: 936.65 m MD (core depth)

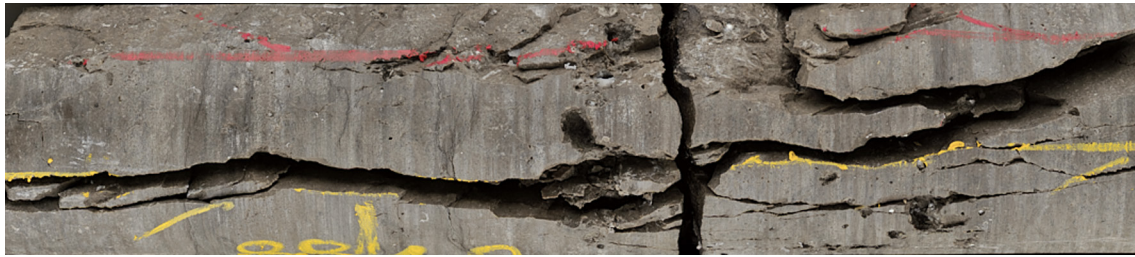


Fig. 3-14: Joints

Characteristics: Typical set of sub-vertical and sub-parallel joints characterising the joint zone where mud losses occurred.

Formation: Schinznach Formation, Depth: from 880.88 m MD to 881.31 m MD (core depth)

3.4 Examples of veins / tension gashes



Fig. 3-15: Vein / tension gash

Characteristics: Example of a thin, sub-vertical calcite-filled vein.

Formation: Opalinus Clay, Depth: 681.23 m MD (core depth)

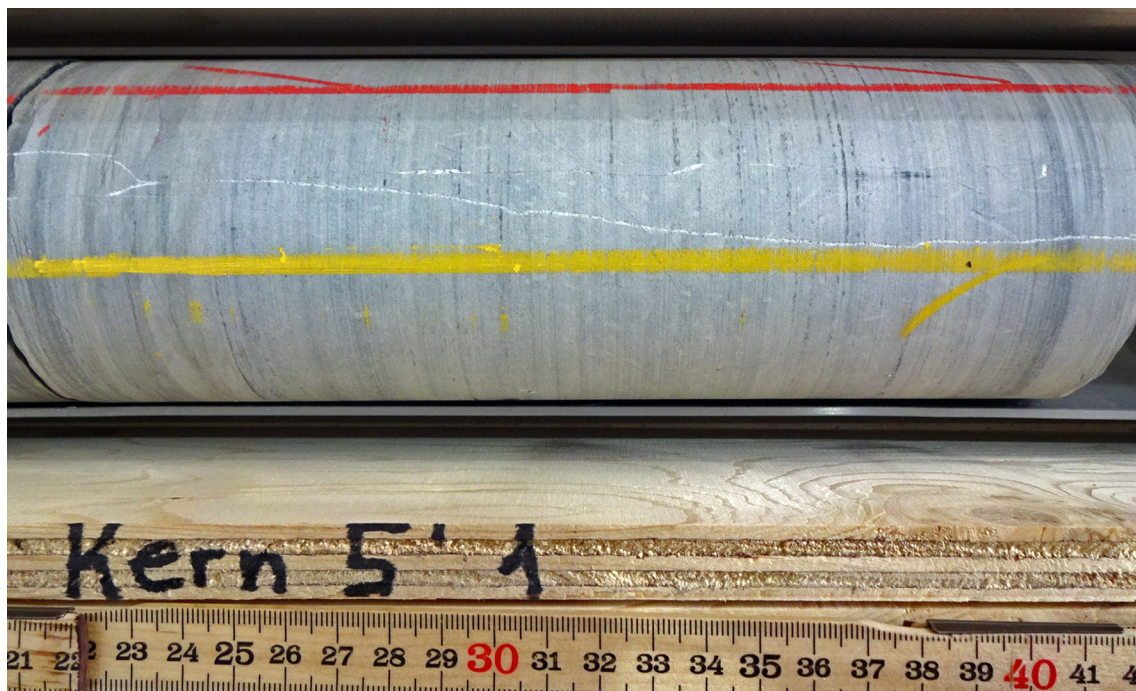


Fig. 3-16: Vein / tension gash

Characteristics: Example of a sub-vertical calcite vein.

Formation: Villigen Formation, Depth: 472.28 m MD (core depth)



Fig. 3-17: Vein / tension gash

Characteristics: Example of a sub-vertical, thick and irregular-shaped calcite vein.

Formation: Staffelegg Formation, Depth: 746.57 m MD (core depth)

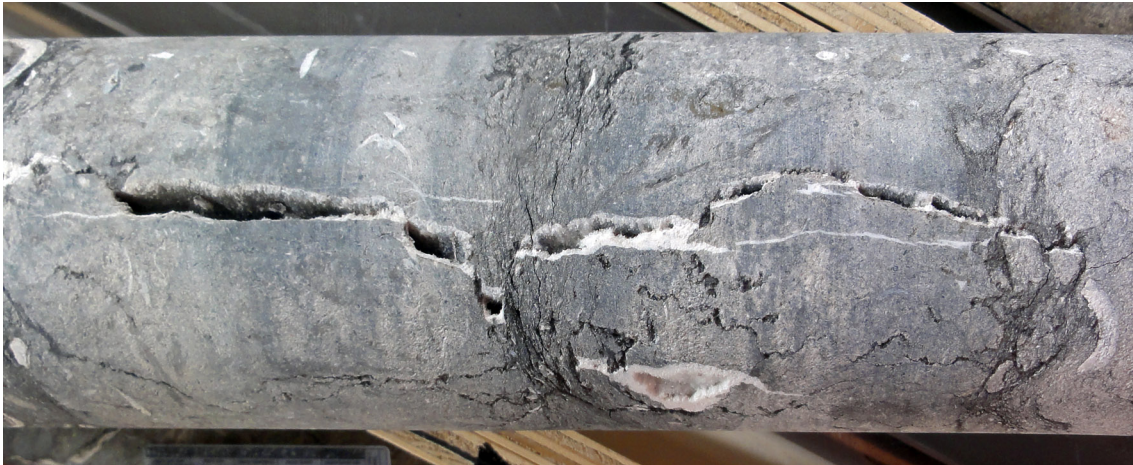


Fig. 3-18: Vein / tension gash

Characteristics: Example of a sub-vertical calcite vein that is partly open.

Formation: Staffelegg Formation, Depth: 738.42 m MD (core depth)



Fig. 3-19: Vein / tension gash

Characteristics: Two examples of anhydrite veins in the Bänkerjoch Formation, which generally show an irregular-shaped contact with the argillaceous marl.

Formation: Bänkerjoch Formation, Depth: 812.36 m MD (core depth)

3.5 Examples of stylolites

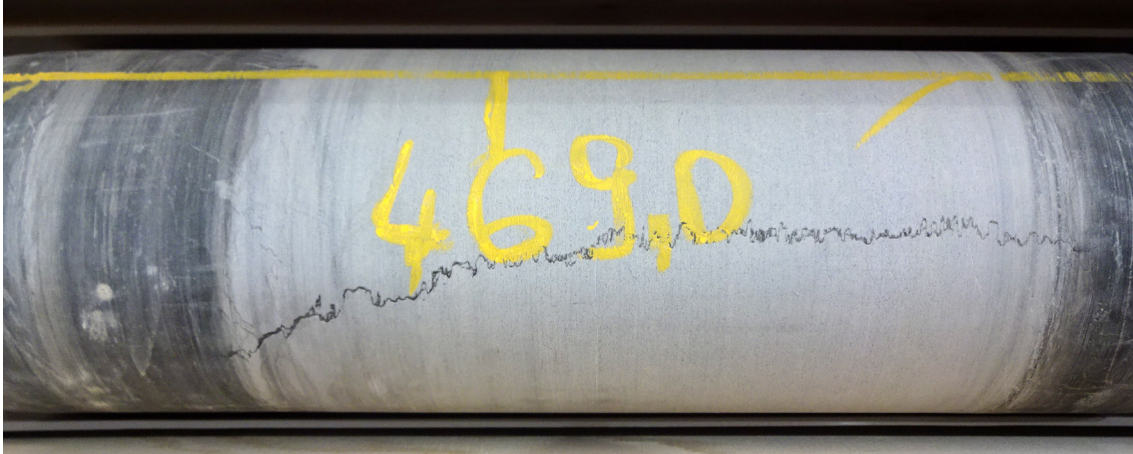


Fig. 3-20: Stylolite

Characteristics: Example of a sub-vertical stylolite delimited to a calcareous layer.

Formation: Villigen Formation, Depth: 469.04 m MD (core depth)

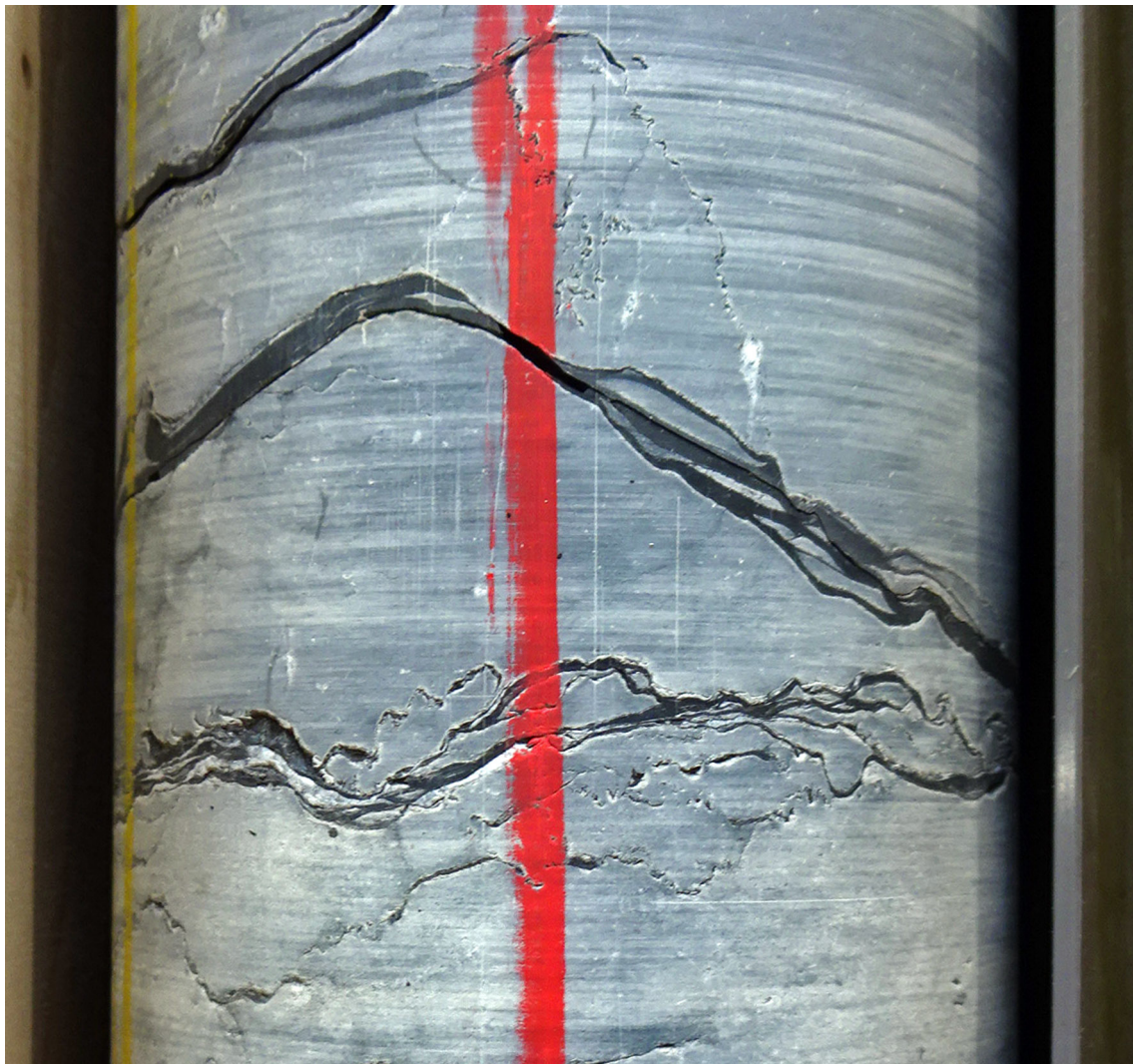


Fig. 3-21: Stylolite

Characteristics: Example of a sub-horizontal stylolite.

Formation: Schinznach Formation, Depth: 925.30 m MD (core depth)



Fig. 3-22: Stylolite

Characteristics: Sub-vertical stylolite with sub-horizontal teeth.

Formation: Villigen Formation, Depth: 465.01 m MD (core depth)

3.6 Examples of open pores



Fig. 3-23: Open pores

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

Formation: Zeglingen Formation, Depth: 940.79 m MD (core depth)



Fig. 3-24: Open pores

Characteristics: Example of small-sized open pores. Typical layer found in the dolostone within the Muschelkalk with a dense network of mm-sized pores without mineralisation.

Formation: Zeglingen Formation, Depth: 932.60 m MD (core depth)

3.7 Examples of drilling-induced fractures

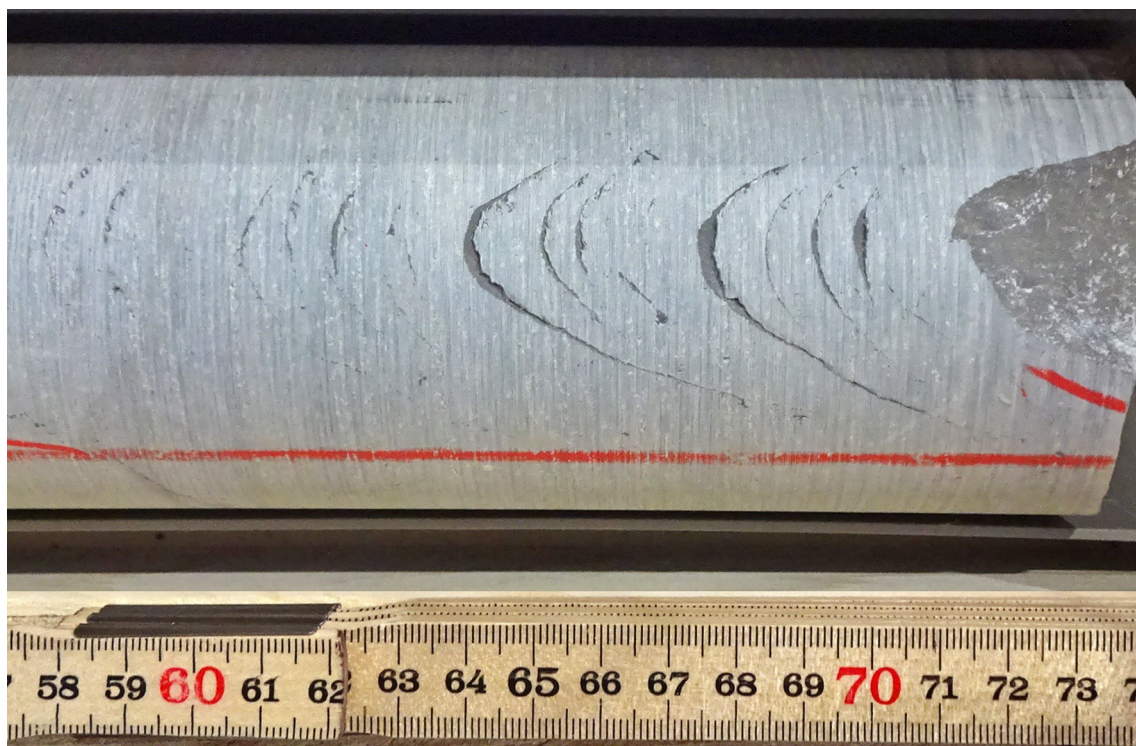


Fig. 3-25: Petal fractures

Characteristics: Sets of typical petal fractures of small, curved and broken core pieces.

Formation: Villigen Formation, Depth: 463.70 m MD (core depth)



Fig. 3-26: Centreline fracture

Characteristics: Example of a sub-vertical centreline fracture. At the top it is associated with petal fractures.

Formation: Villigen Formation, Depth: 463.83 m MD (core depth)



Fig. 3-27: 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. Here, fracturing nucleated from the shell in the centre of the core, visible by the plumose structure.

Formation: Opalinus Clay, Depth: 689.24 m MD (core depth)

3.8 Examples of folding

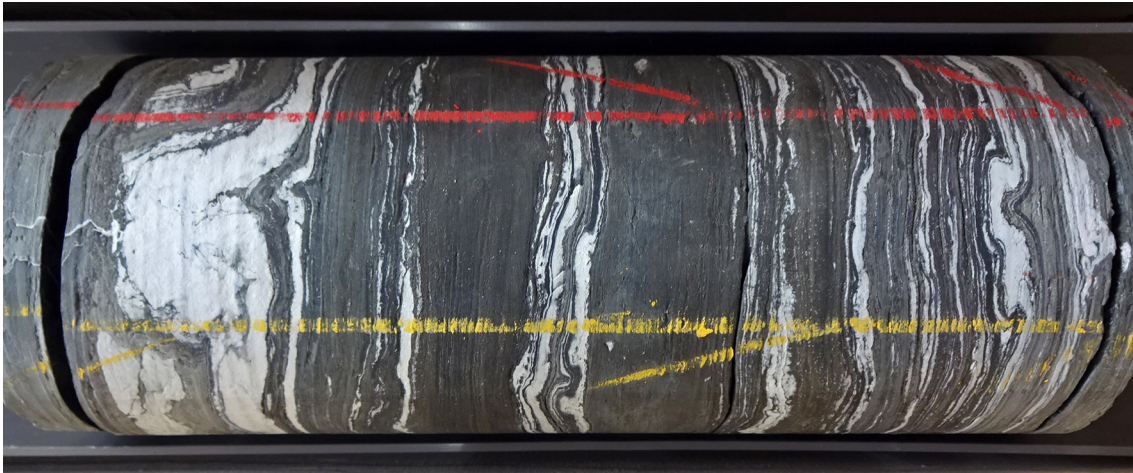


Fig. 3-28: Folding

Characteristics: Examples of folded anhydrite layers in all scales. Folding is often limited to specific layers and most likely of synsedimentary origin.

Formation: Zeglingen Formation, Depth: 984.80 m MD (core depth)

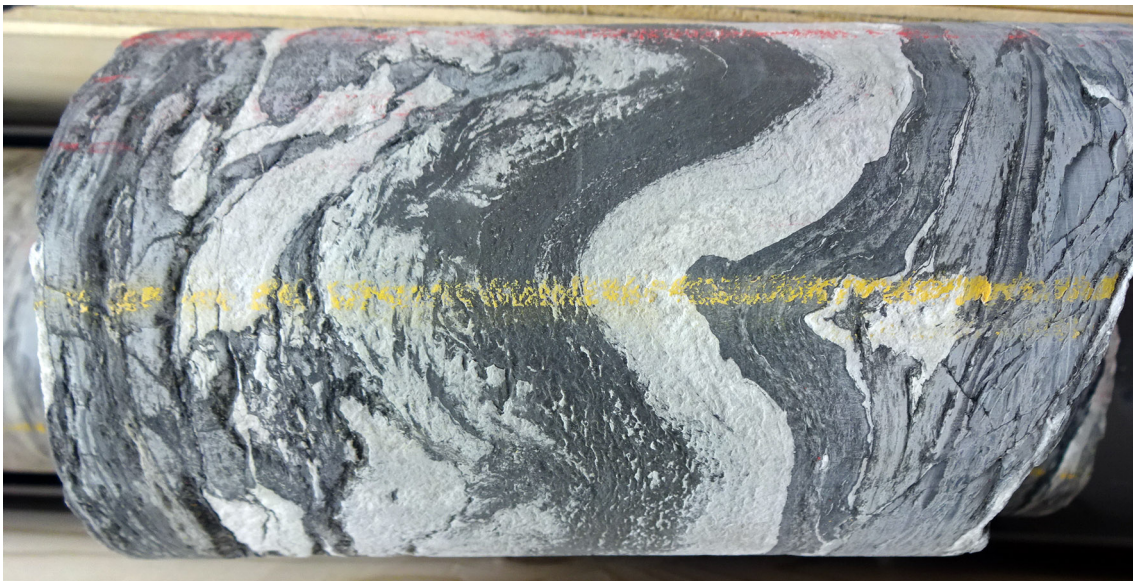


Fig. 3-29: Folding

Characteristics: Example of folded anhydrite layer, most likely of synsedimentary origin.

Formation: Zeglingen Formation, Depth: 965.22 m MD (core depth)

4 Geo-statistical evaluation: Results

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 (see Tab. 4-1). Note that bedding dips and structural discontinuities recorded in non-oriented cores (n = 293) 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 for bedding planes and structural discontinuities (Azim: azimuth)

	Cluster 1 (main)			Cluster 2 (subordinate)			Cluster 3 (subordinate)		
	Azim	Dip	No.	Azim	Dip	No.	Azim	Dip	No.
Bedding	128	06	482						
Faults	150	06	325						
Tension gashes, joints, fractures	-	-	-						
Stylolites	128	06	86	014	76	50			

4.1 Entire cored borehole section (460.00 m to 1'099.25 m MD log depth)

A total of 2'603 individual planar and non-planar features were identified during the core analysis and manual dip picking of the 632.43 m cores. They are visualised in different scales in the structural composite plots of Appendices B and C and are evaluated briefly below.

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 and 4-2 and in the vector azimuth plot in Fig. 4-3.

The studied borehole interval (460.00 m to 1'099.25 m MD log depth) ranging from the Malm to the Crystalline basement reveals a sub-horizontal to shallow (1° to 10°) SE structural dip that is consistent throughout. The overall mean is 128/06 [dip direction / dip angle] (n = 482; see Tab. 4-1). However, there were a number of local, abrupt changes in dip orientation associated with evident in-borehole faults / fault zones, e.g. at 604 m MD (log depth), from 620.88 m to 621.90 m MD (log depth), from 668 m to 680 m MD (log depth), at 740 m MD (log depth) and at 969 m MD (log depth). These dip changes are well reflected and highlighted in the dip vector azimuth plot of Fig. 4-3. Consequently, faulting may be considered as the main deformation mechanism controlling the structural dip in the current borehole.

Mentionable dip anomalies were also observed in the Zeglingen Formation from 954 m to 981 m MD (log depth). This borehole interval is characterised by variable dip directions and sub-horizontal to steep (5° to 40°) dip angles related to folding. However, a more detailed structural dip evaluation is outside the scope of this study.

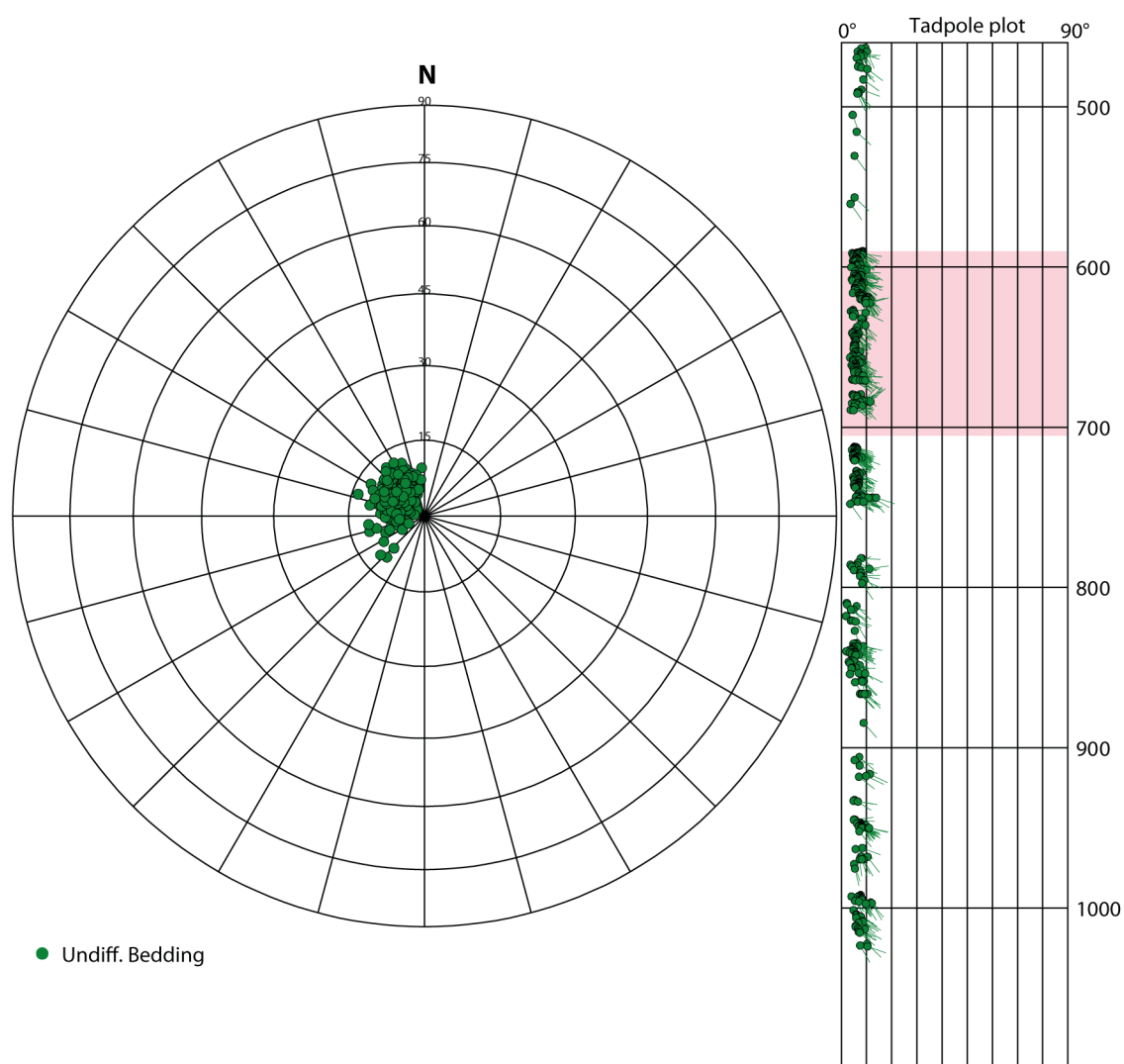


Fig. 4-1: Stereogram and depth plot for bedding planes ($n = 490$) for the entire cored borehole section

Note the predominance of 0° to 10° SE dips with an overall mean of $128/06$ ($n = 482$). Depth range is 460.00 m to 1'099.25 m MD (log depth). In the tadpole plot the Opalinus Clay interval is shaded in red.

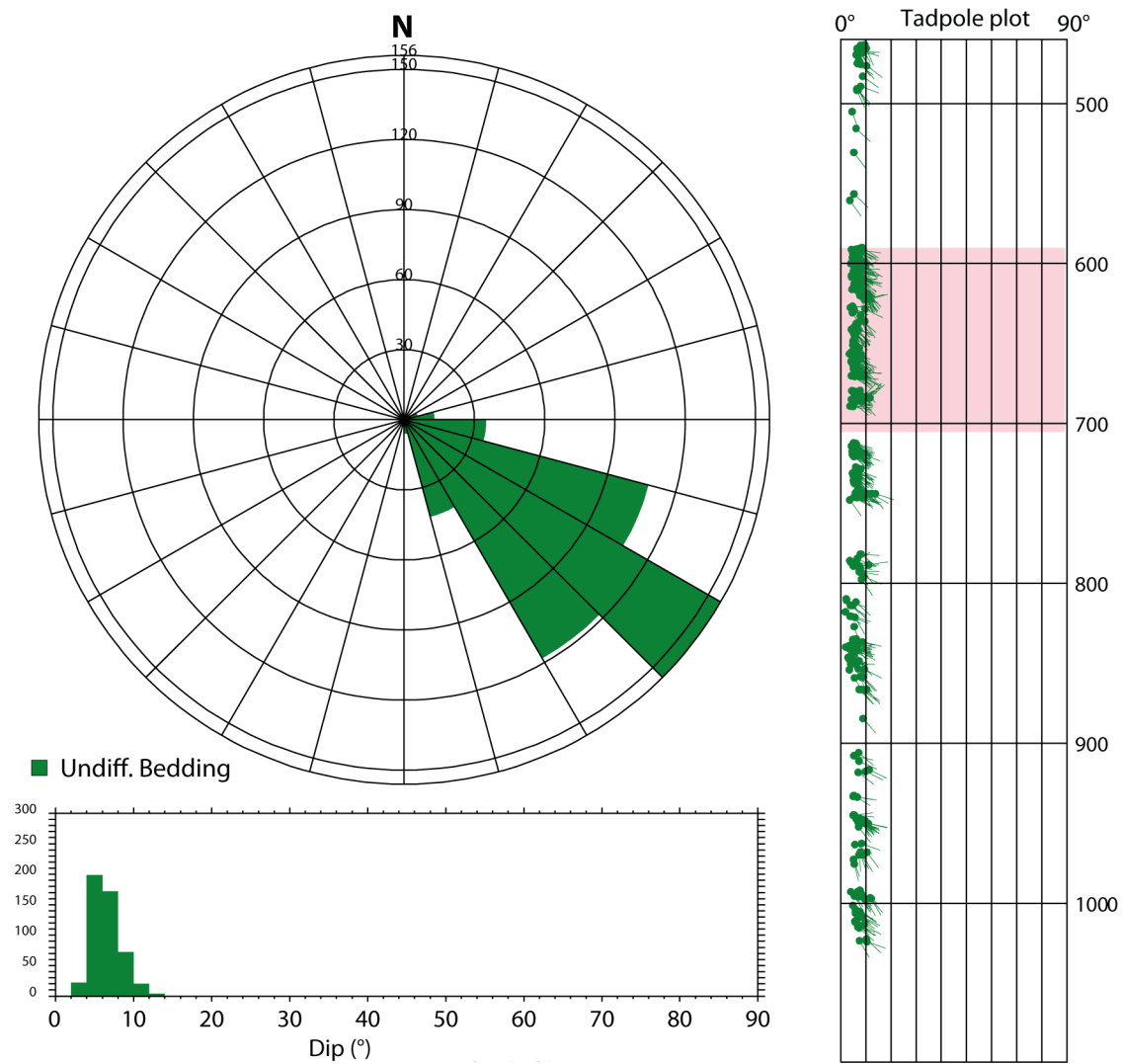


Fig. 4-2: Azimuth rose diagram, dip histogram and depth plot for bedding planes (n = 490) for the entire cored borehole section

Note the predominance of dip directions towards the SE. Depth range is 460.00 m to 1'099.25 m MD (log depth). In the tadpole plot the Opalinus Clay interval is shaded in red.

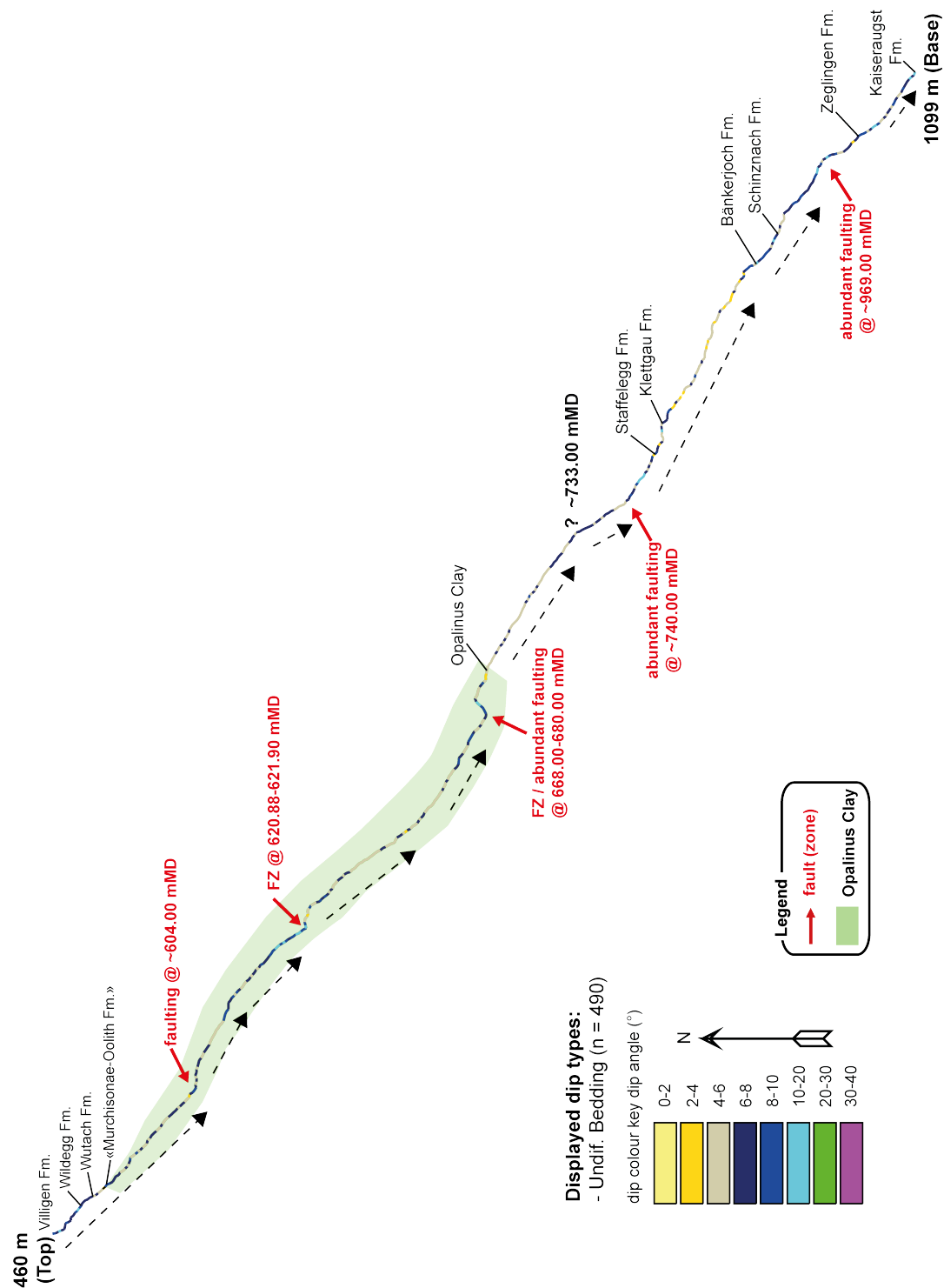


Fig. 4-3: Vector azimuth (or walkout) plot with bedding dips (n = 490) in oriented cores

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. Black arrows point in the direction of the overall dip direction. Lithostratigraphic formation boundaries (bottoms) are indicated as well as faulting / fault zones (red arrows) and the Opalinus Clay interval (shaded in green). Note that commonly steeper, deformed bedding planes and those from non-oriented cores are excluded from this plot.

4.1.2 Natural structural discontinuities

Fault planes

In total, 931 individual faults were recorded in the MAR1-1 borehole. Faults are planes of shear failure, i.e. planes with plane-parallel movement (Ebert & Decker 2019). Depending on their appearance in the drill core, three types were distinguished: (1) fault planes ($n = 235$), (2) mirror-like fault planes ($n = 644$) and (3) stylolitic fault planes ($n = 52$). Out of all recorded faults, 788 (85%) were detected in oriented cores and are included in this evaluation.

Several structurally complex intervals along the MAR1-1 borehole were interpreted 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 26 individual fault zones were defined for the entire cored interval along with their FDC for each zone (see Tab. 4-2).

Faults are unevenly distributed along the borehole as shown in Fig. 4-4 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 a scattered orientation with variable dip directions and dip angles ranging from horizontal to sub-vertical (1° to 85°). However, there was a predominance of sub-bedding-parallel and SE- to SSE-dipping faults with an overall mean of 150/06 ($n = 325$; mean of selected cluster). Associated kinematic data could be measured on 689 fault planes out of 931 and are further evaluated in Section 4.1.4.

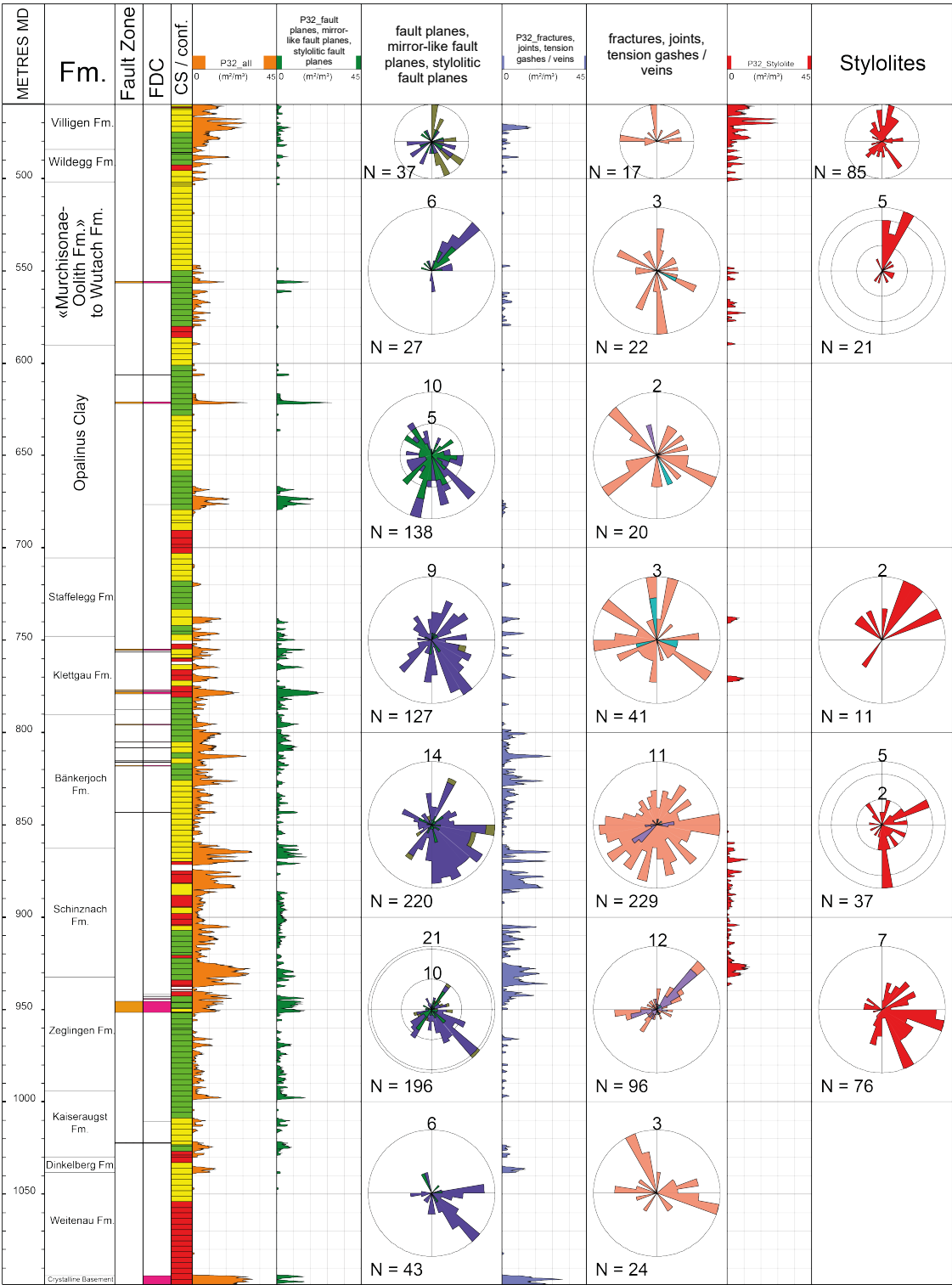


Fig. 4-4: Overview plot showing P32 fracture densities along the MAR1-1 borehole

In addition, lithostratigraphic subdivision, core sections and goniometry confidence as well as fault zones associated with intense fracturing (expressed by fracture density classes; see Tab. 4-2) are shown. Note that the rose diagrams with the respective number of planes are displayed for 100 m intervals.

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

Fault zones				FDC
Top [m MD log depth]	Bottom [m MD log depth]	Thickness [m]	Type	Type
555.67	556.64	0.97	Fault zone	FDC2
606.28	606.43	0.15	Fault zone	FDC2
620.88	621.90	1.02	Fault zone	FDC2
676.49	676.52	0.03	Fault zone	
754.90	755.51	0.61	MirFP zone	FDC2
756.40	756.48	0.08	MirFP zone	FDC2
776.92	777.28	0.36	MirFP zone	FDC2
778.00	779.20	1.20	MirFP zone	FDC3
787.43	787.47	0.04	MirFP zone	FDC2
795.49	795.98	0.49	MirFP zone	FDC2
804.98	805.21	0.23	MirFP zone	FDC2
808.00	808.34	0.34	Fault zone	FDC2
815.22	815.44	0.22	Fault zone	FDC2
816.05	816.38	0.33	Fault zone	FDC2
817.76	818.38	0.62	Fault zone	FDC2
843.19	843.35	0.26	Fault zone	FDC2
941.68	941.73	0.05	Fault zone	
942.78	943.00	0.22	Fault zone	
943.58	944.46	0.88	Fault zone	
945.50	950.73	5.23	MirFP zone	FDC2
950.73	950.91	0.18	MirFP zone	FDC3
950.91	951.70	0.79	MirFP zone	FDC2
1'010.49	1'010.63	0.14	Fault zone	
1'022.11	1'022.37	0.26	Fault zone	FDC3
1'022.67	1'022.83	0.16	Fault zone	FDC3
1'094.12	1'099.25	5.13	Fault zone	

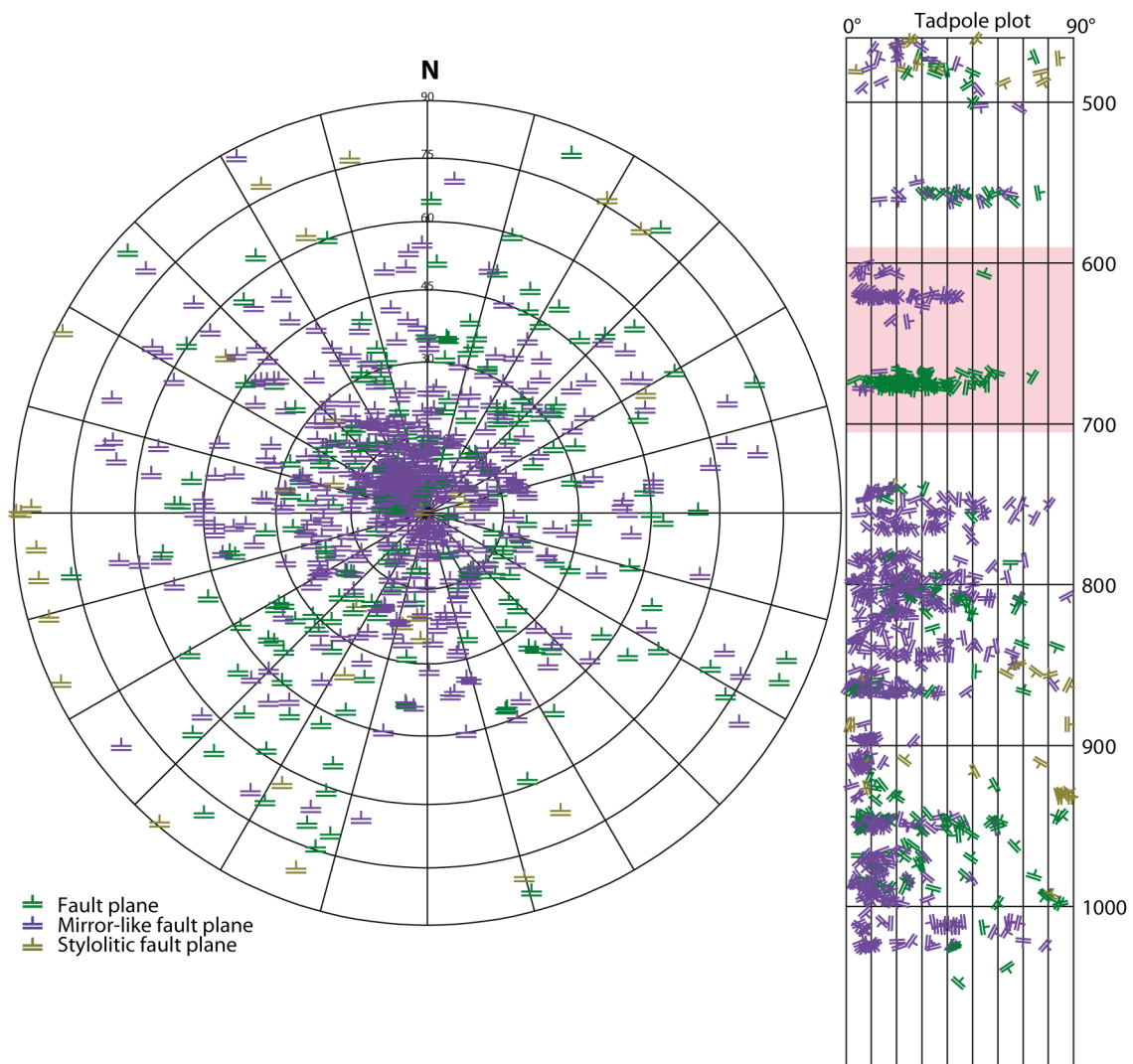


Fig. 4-5: Stereogram and depth plot of fault planes for the entire cored interval

A total of 788 fault planes in oriented cores are plotted: fault planes ($n = 213$), mirror-like fault planes ($n = 541$) and stylolitic fault planes ($n = 34$). Depth range is 460.00 m to 1'099.25 m MD (log depth). In the tadpole plot the Opalinus Clay interval is shaded in red.

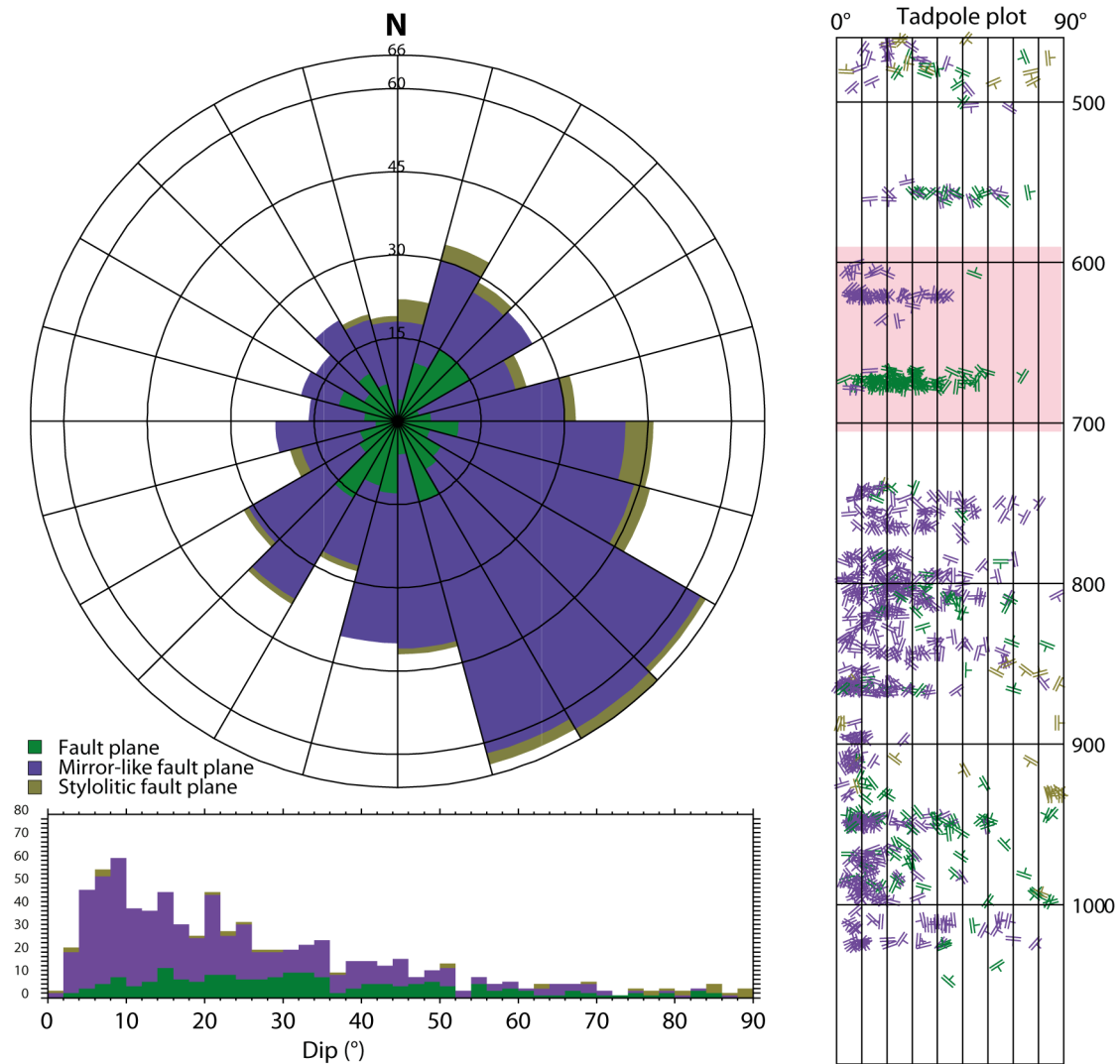


Fig. 4-6: Azimuth rose diagram, dip histogram and depth plot for fault planes in the entire cored interval

A total of 788 fault planes in oriented cores are plotted: fault planes ($n = 213$), mirror-like fault planes ($n = 541$) and stylolitic fault planes ($n = 34$). Depth range is 460.00 m to 1'099.25 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 = 397) and joints (n = 118). Also included are fractures (n = 18) which could not be assigned to a specific class of structure. With a total of 534 individual structures, they represent a smaller group of structural discontinuities than the fault planes. Out of these 534 structures, 449 (84%) planes were recorded in oriented cores.

The spatial distribution of tension gashes / veins, joints and unassigned fractures along the MAR1-1 borehole is presented in Fig. 4-4 and discussed in Section 4.1.4. They reveal a larger orientation scatter as shown in Figs. 4-7 and 4-8.

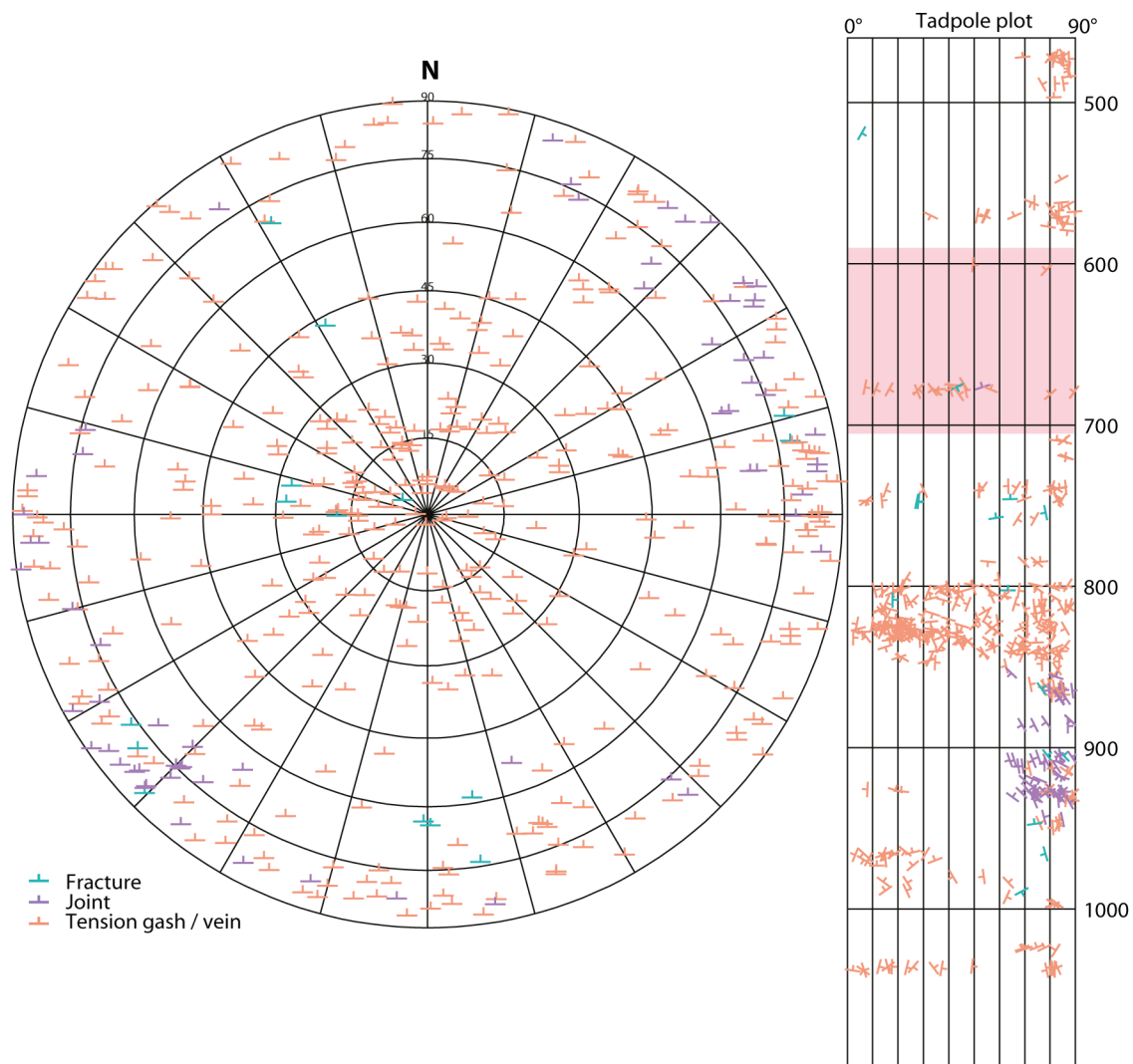


Fig. 4-7: Stereogram and depth plot for tension gashes / veins, unassigned fractures and joints in the entire cored interval

A total of 449 structures are displayed: tension gashes / veins (n = 368), joints (n = 66) and unassigned fractures (n = 15). Depth range is 460.00 m to 1'099.25 m MD (log). In the tadpole plot, the Opalinus Clay interval is shaded in red.

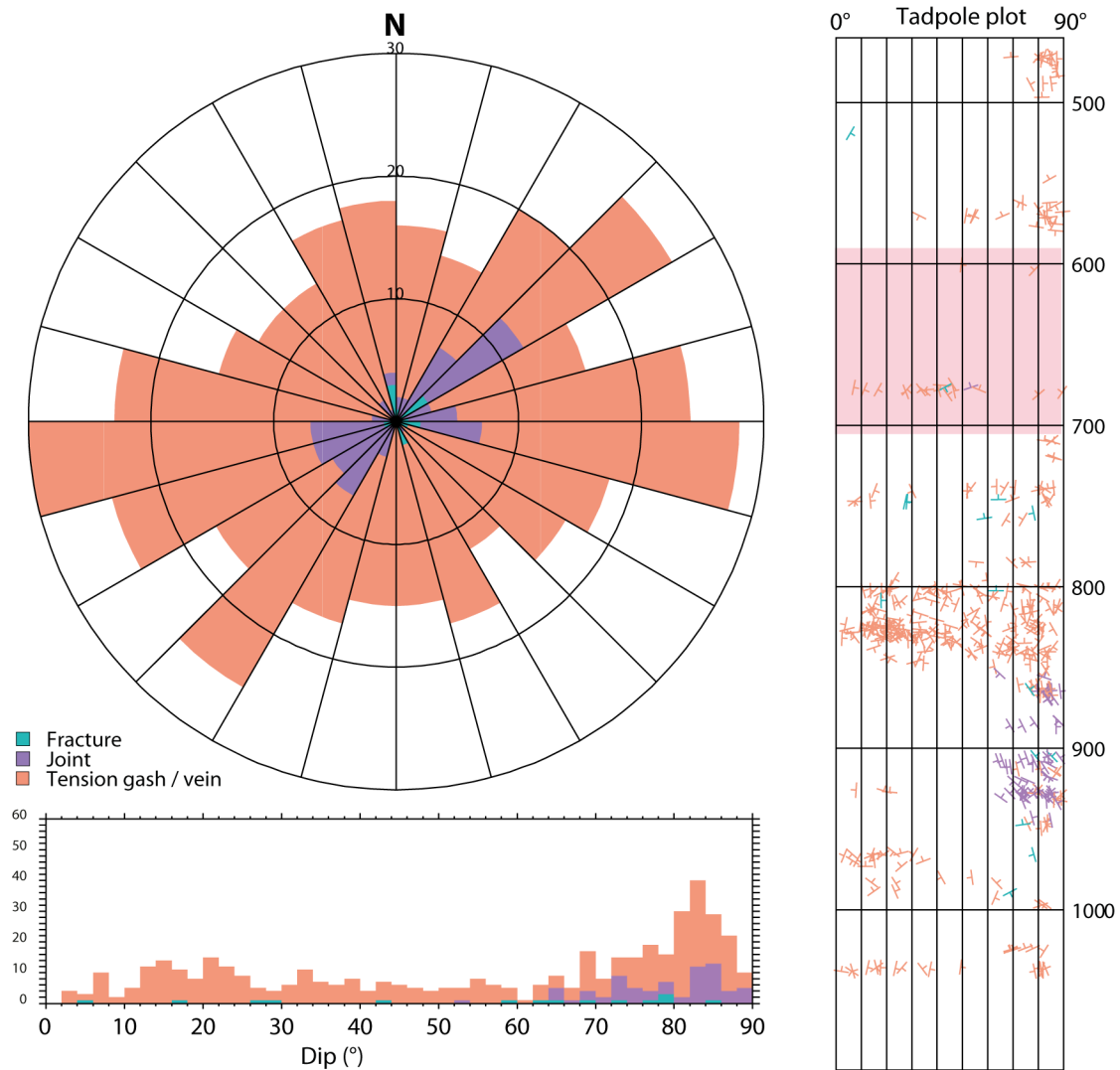


Fig. 4-8: Azimuth rose diagram of tension gashes / veins, unassigned fractures and joints in the entire cored interval

A total of 449 structures are displayed: tension gashes / veins ($n = 368$), joints ($n = 66$) and unassigned fractures ($n = 15$). Depth range is 460 m to 1'099.25 m MD (log depth). In the tadpole plot the Opalinus Clay interval is shaded in red.

Stylolites

A total of 283 stylolites and 5 stylolite-rich zones were identified in MAR1-1. Out of this, 230 (80%) were recorded in oriented cores. Particularly in stylolite-rich intervals such as the Malm and the Schinznach Formation (see Fig. 4-9), not all individual stylolites could be picked or documented and only the dominant stylolites which could be clearly observed in core photographs were recorded and categorised. Intervals with high densities of stylolites were defined as stylolitic zones.

Stylolites depict two well-developed orientation clusters (Figs. 4-9, 4-10 and Tab. 4-1): a sub-horizontal to gently inclined (1° to 16°) ENE- to SSE-dipping cluster (overall mean of $128/06$; $n = 86$) and a steep to sub-vertical (60° to 90°) cluster dipping to NNE (overall mean of $014/76$; $n = 50$).

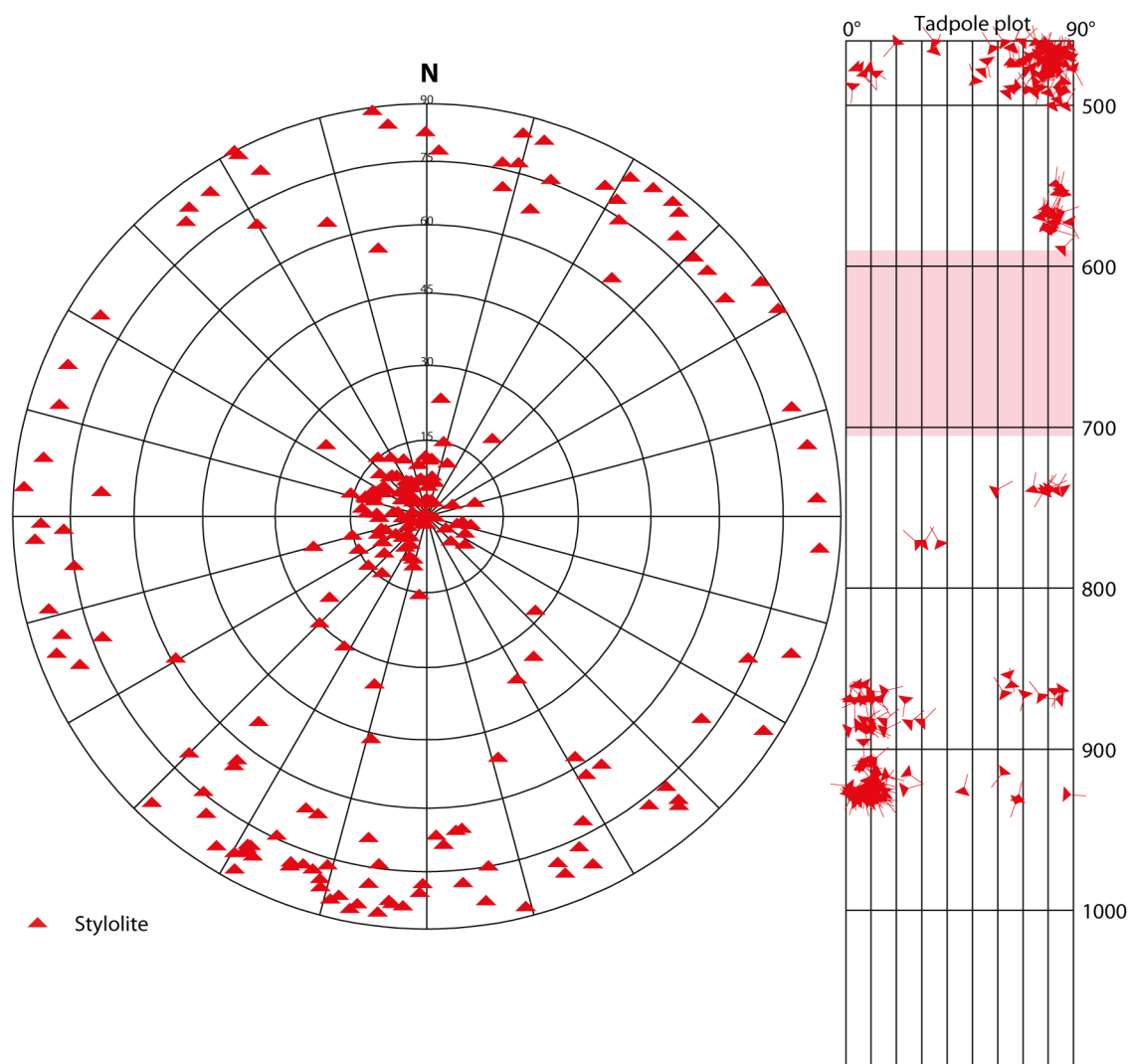


Fig. 4-9: Stereogram and depth plot for stylolites ($n = 230$) along the cored MAR1-1 borehole. Depth range is 460.00 m to 1'099.25 m MD (log depth). In the tadpole plot the Opalinus Clay interval is shaded in red.

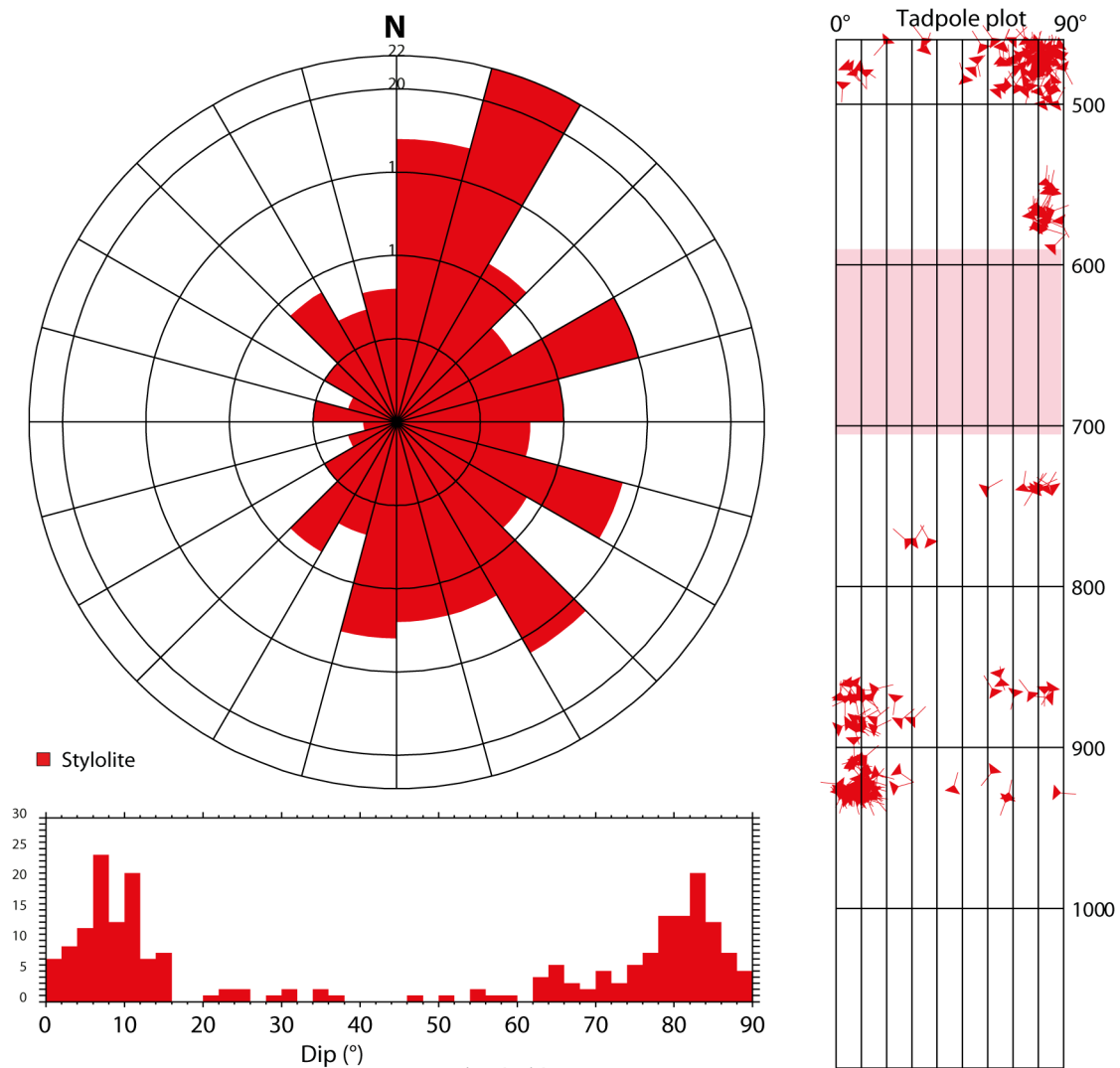


Fig. 4-10: Azimuth rose diagram and depth plot for stylolites in the entire cored interval

Depth range is 460.00 m to 1'099.25 m MD (log depth), $n = 230$. In the tadpole plot the Opa-linus Clay interval is shaded in red.

4.1.3 Fracture density (P32) and distribution

Density histograms were calculated in order to evaluate the spatial fracture distribution (see Fig. 4-4). As mentioned above, structures recorded in non-oriented cores ($n = 293$) were considered in the fracture density calculations.

Fault planes are unevenly distributed along the cored interval. Elevated fault counts were present particularly within the lower borehole interval from 735 m to 1'000 m MD (log depth) covering the lowermost Staffelegg Formation, the entire Keuper and the Muschelkalk. However, the highest densities of fault planes with up to 29 planes per metre were observed within the fault zones in the Opalinus Clay from 620.88 m to 621.90 m (log depth) and from 672 m to 677 m MD (log depth), as well as in the Klettgau Formation from 777 m to 780 m MD (log depth). Abundant faults commonly form prominent fault zones associated with intensely fractured and partly dis-integrated drill cores (FDC 2 – 3; see Tab. 4-2 and Fig. 4-4). The overall average density of fault planes for the entire cored borehole section was 1.7 planes per metre.

Tension gashes / veins, joints and fractures are particularly abundant from approximately 800 m to 950 m MD (log depth) within the Bänkerjoch, Schinznach and Zeglingen Formations (see Fig. 4-4). However, the highest density with up to 32 structures per metre was encountered within the Crystalline basement below 1'094 m MD (log depth) and is related to sub-vertical planes. In addition, abundant sub-vertical and open joints striking NW-SE formed distinct fracture zones between 850 m and 950 m MD (log depth) in the Muschelkalk. The overall average density was about 1.8 per metre.

Stylolites reveal an irregular distribution along the borehole and occur almost exclusively within the carbonate-rich lithologies of the Malm (from 460 m to 500 m MD log depth) and the Muschelkalk (from 860 m to 935 m MD log depth). The highest density with up to 27 stylolites per metre was observed within the Villigen Formation at 470 m MD log depth. The overall average density for the borehole section was ~ 0.8 per metre.

4.1.4 Kinematic indicators

Striations could be measured on 689 fault planes. In total, 86% of the striations ($n = 591$) were collected in oriented cores. The orientations of the striations in oriented cores are given in Figs. 4-11 to 4-16. There is a slight predominance of S-dipping striations. The vast majority has sub-horizontal to inclined (0° to 40°) 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 117 shear indicators was identified as thrusts / reverse faults (Tab. 4-3). A similar number was classified as normal faults ($n = 108$; Tab. 4-3). In contrast, only 35 were identified as strike-slip faults (Tab. 4-3). However, the shear sense of most fault planes ($n = 433$) was uncertain (Tab. 4-3).

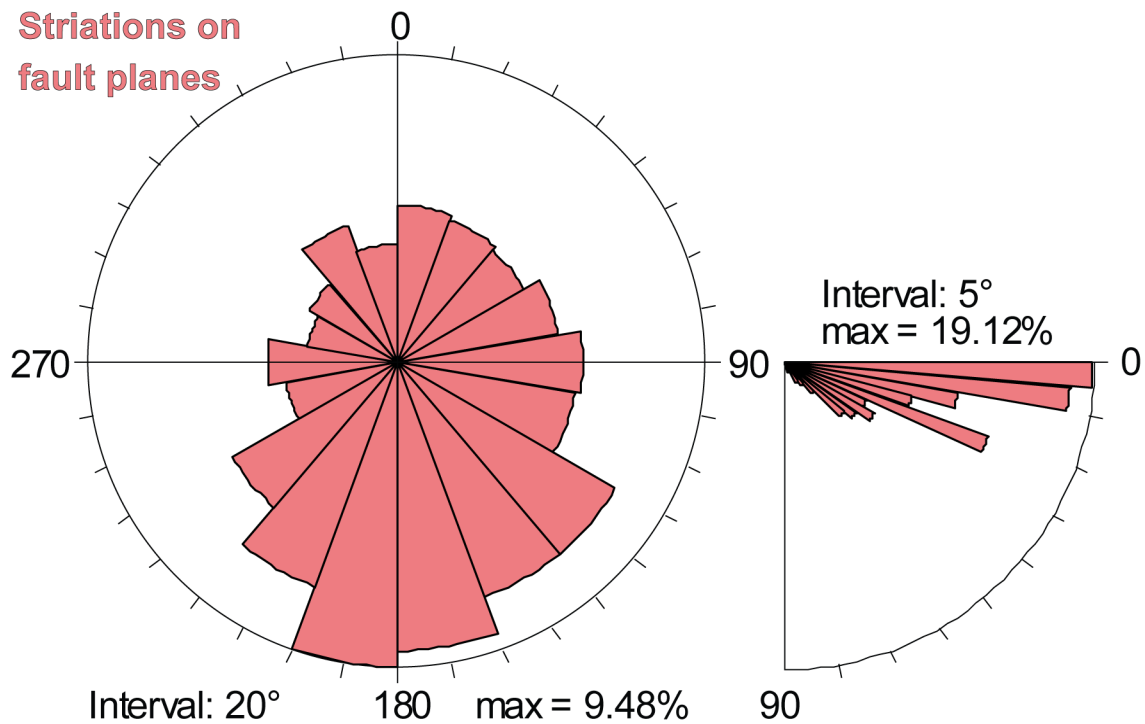


Fig. 4-11: Dip direction of striations along fault planes in the entire cored interval

The striations (n = 596) from oriented cores of the entire core interval from the Malm to the Crystalline Basement are presented. Left: azimuth rose diagram, right: dip histogram. Depth range is 460.00 m to 1'099.25 m MD (log depth).

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

Shear sense	Number
Up	117
Down	108
Sinistral	17
Dextral	18
Unknown	434
In oriented cores	596
In non-oriented cores	98
Total measured lineations	694

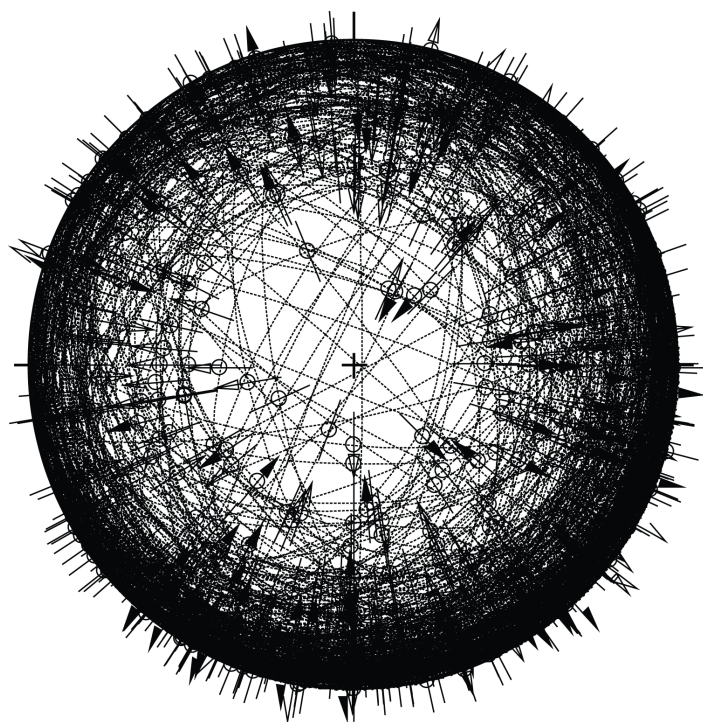


Fig. 4-12: Stereogram of striations on all oriented fault planes (including multiple lineations on a single fault plane) and associated kinematic data

Up (n = 100), down (n = 103), dextral (n = 14), sinistral (n = 15) and unknown (n = 364).
Depth range is 460.00 m to 1'099.25 m MD (log depth).

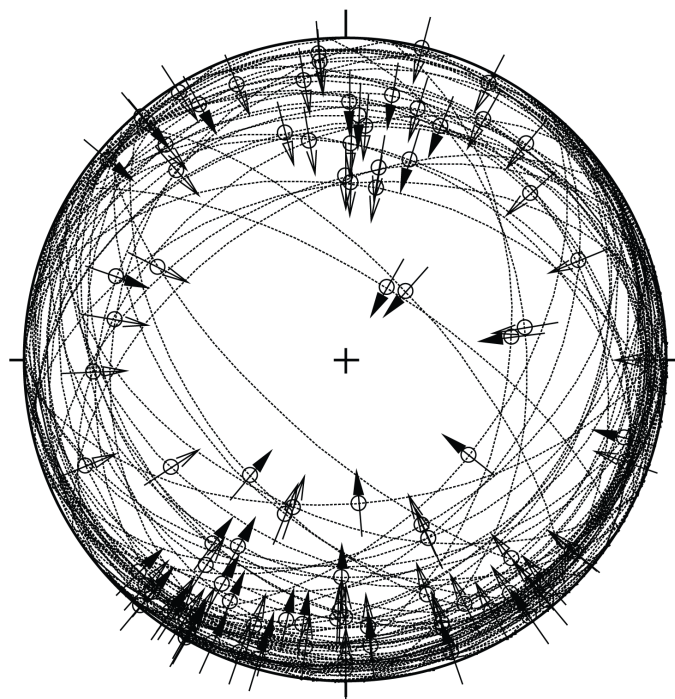


Fig. 4-13: Stereogram with striations of oriented thrust / reverse fault planes (including multiple lineations on a single fault plane)

Up (n = 100). Depth range is 460.00 m to 1'099.25 m MD (log depth).

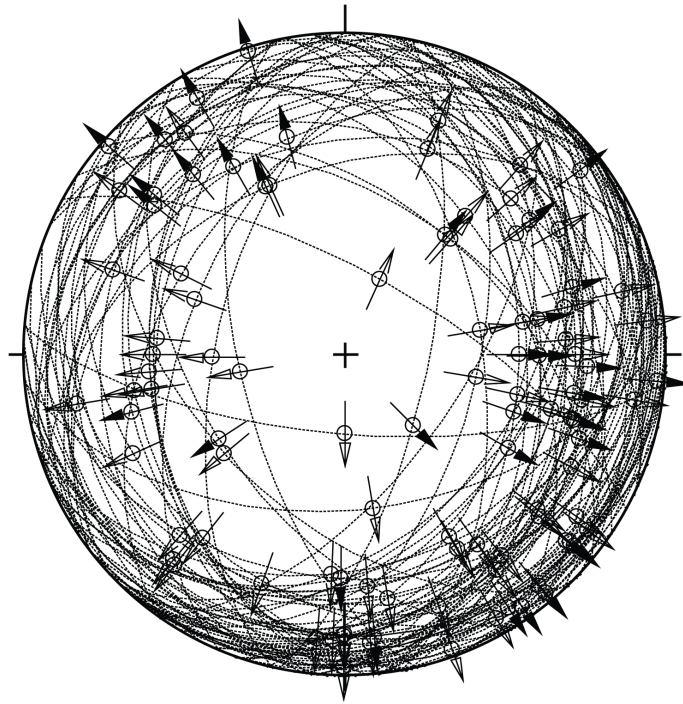


Fig. 4-14: Stereogram of striations on all oriented normal fault planes (including multiple lineations on a single fault plane)

Down ($n = 103$). Depth range is 460.00 m to 1'099.25 m MD (log depth).

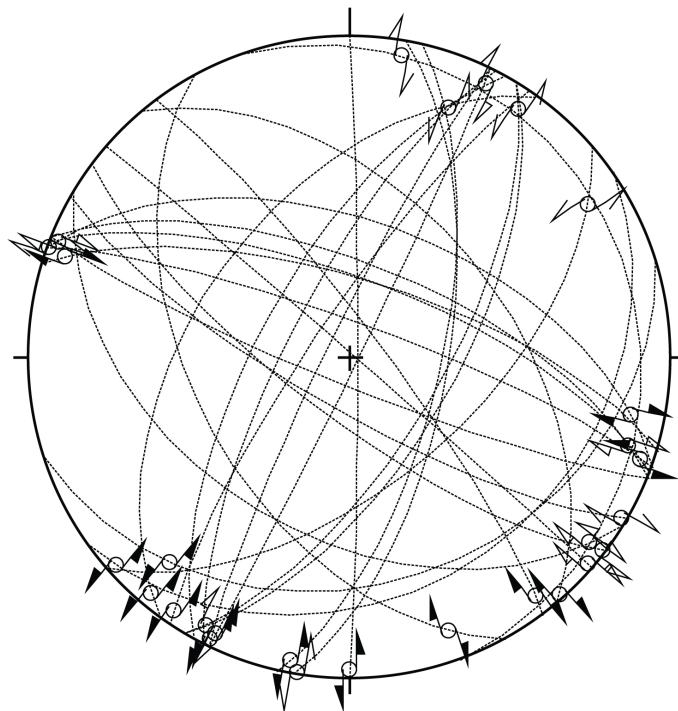


Fig. 4-15: Stereogram with all oriented strike-slip fault planes (including multiple lineations on a single fault plane)

Dextral ($n = 14$), sinistral ($n = 15$). Depth range is 460.00 m to 1'099.25 m MD (log depth).

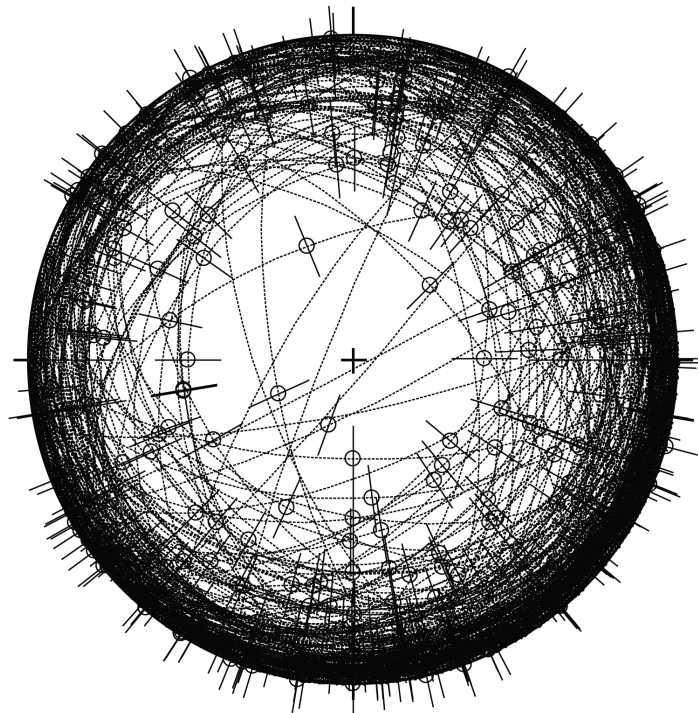


Fig. 4-16: Stereogram of striations on all fault planes with unknown shear sense (including multiple lineations on a single fault plane)

Unknown ($n = 364$). Depth range is 460.00 m to 1'099.25 m MD (log depth).

4.2 Malm

The cored Malm interval (460.00 m to 501.92 m MD log depth) showed abundant stylolites. They are generally steep and randomly oriented. Fault planes and veins are rare. Fault planes are homogeneously distributed and show an irregular dip and azimuth. Veins are generally sub-vertical and randomly oriented.

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

4.2.1 Villigen Formation

The orientation and spatial distribution of structural data in the Villigen Formation (460.00 m to 484.22 m MD log depth) are visualised in Figs. 4-17 to 4-23.

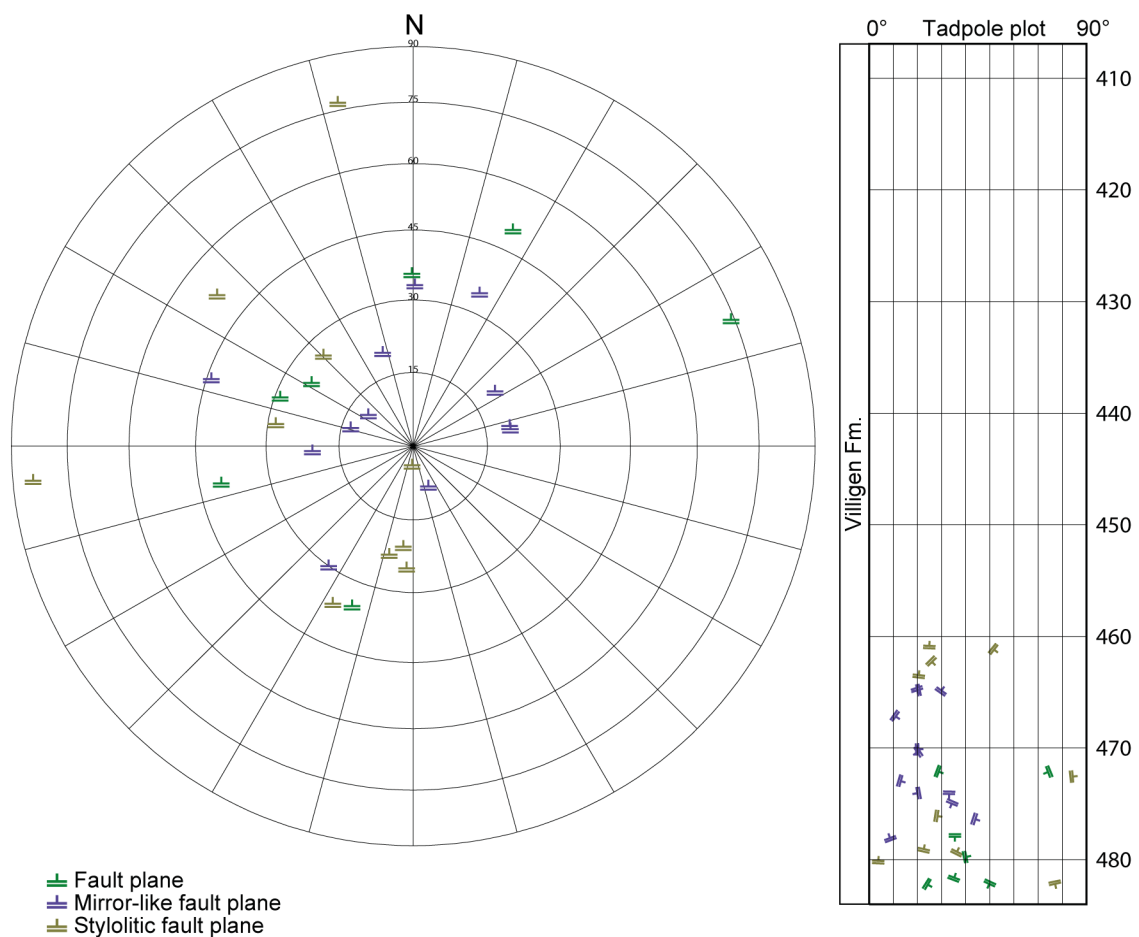


Fig. 4-17: Stereogram and depth plot of fault planes (Villigen Formation)

Fault planes (n = 7), mirror-like fault planes (n = 13) and stylolitic fault planes (n = 10).

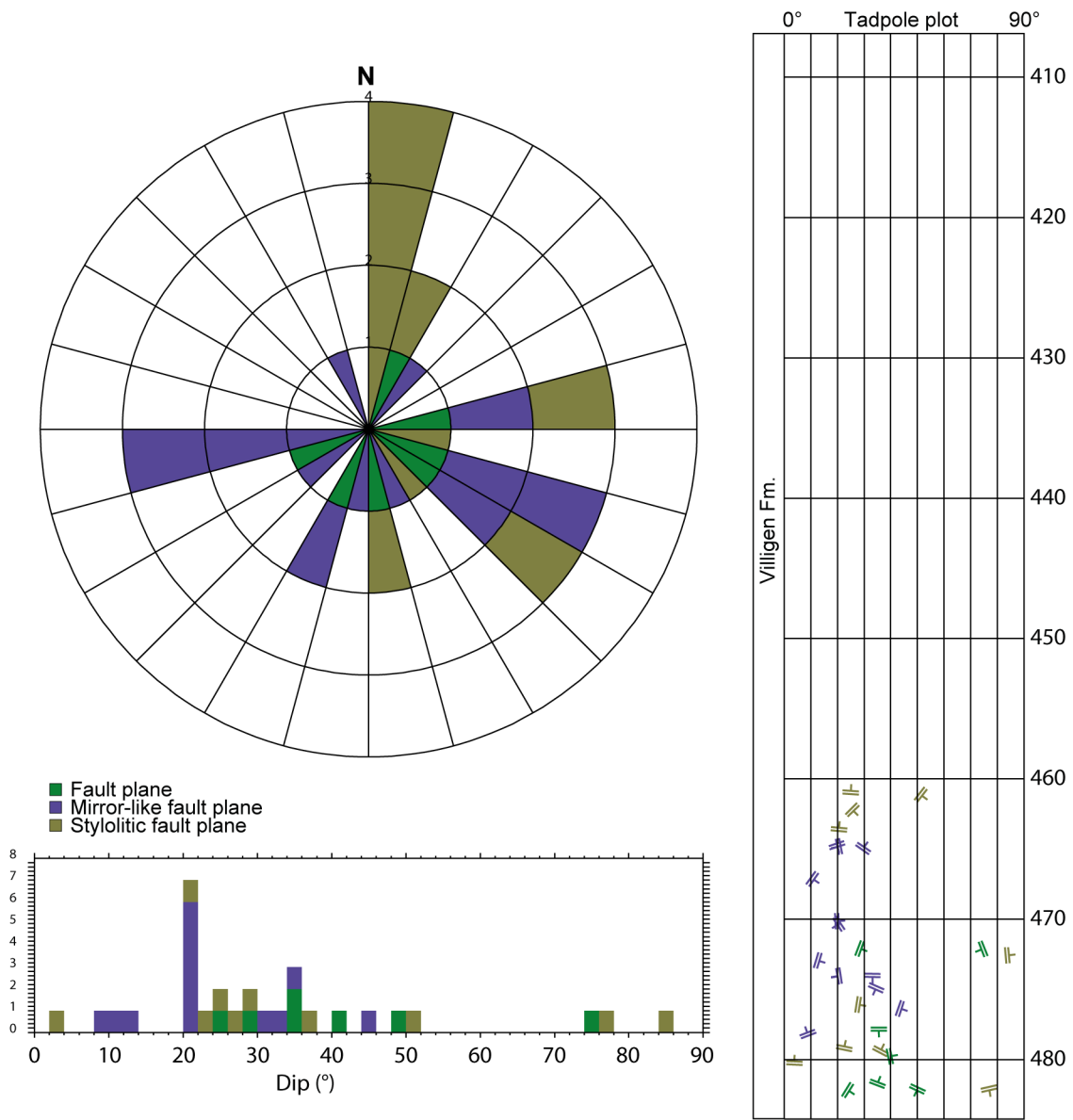


Fig. 4-18: Azimuth rose diagram, dip histogram and depth plot of fault planes (Villigen Formation)

Fault planes (n = 7), mirror-like fault planes (n = 13) and stylolitic fault planes (n = 10).

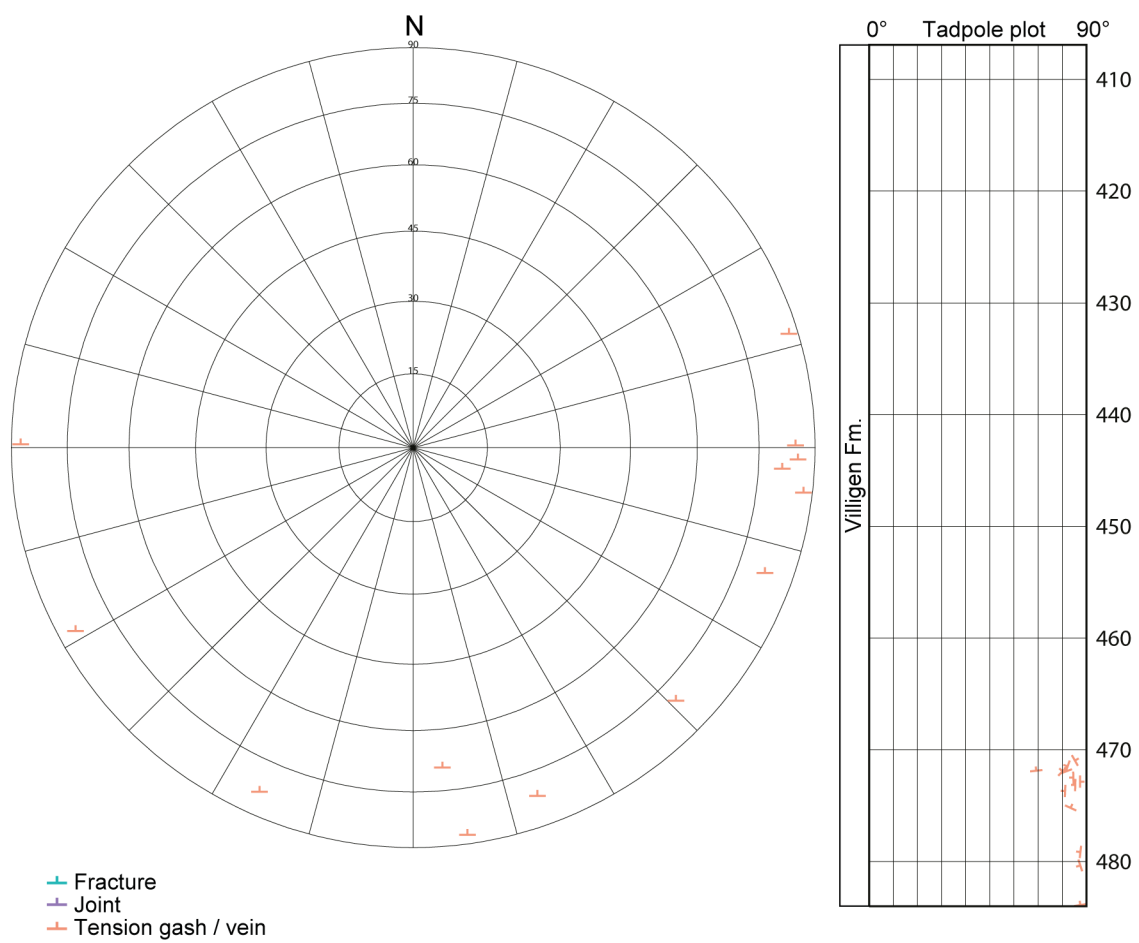


Fig. 4-19: Stereogram and depth plot of tension gashes / veins and unassigned fractures (Villigen Formation)

Tension gashes / veins (n = 13).

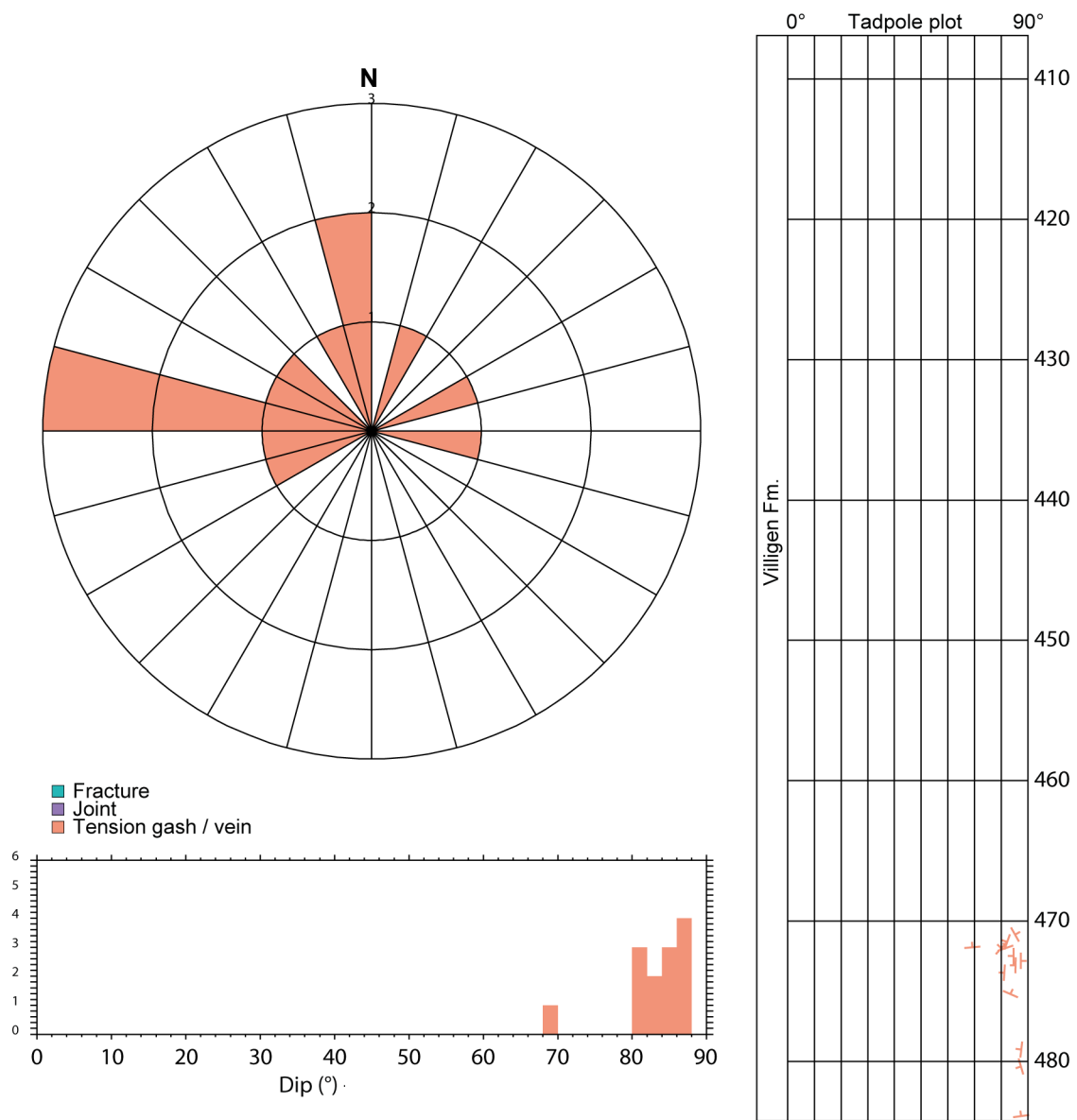


Fig. 4-20: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Villigen Formation)
Tension gashes / veins (n = 13).

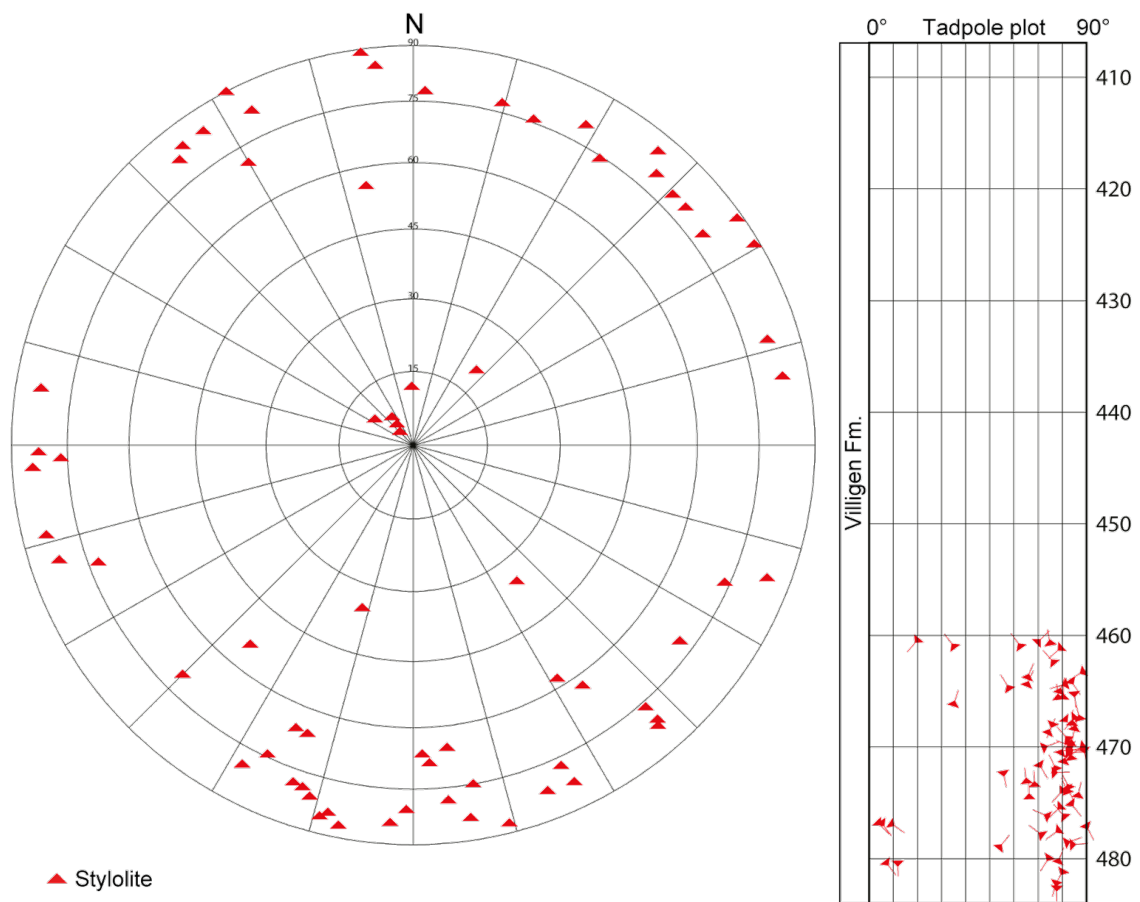


Fig. 4-21: Stereogram and depth plot of stylolites (Villigen Formation, $n = 70$)

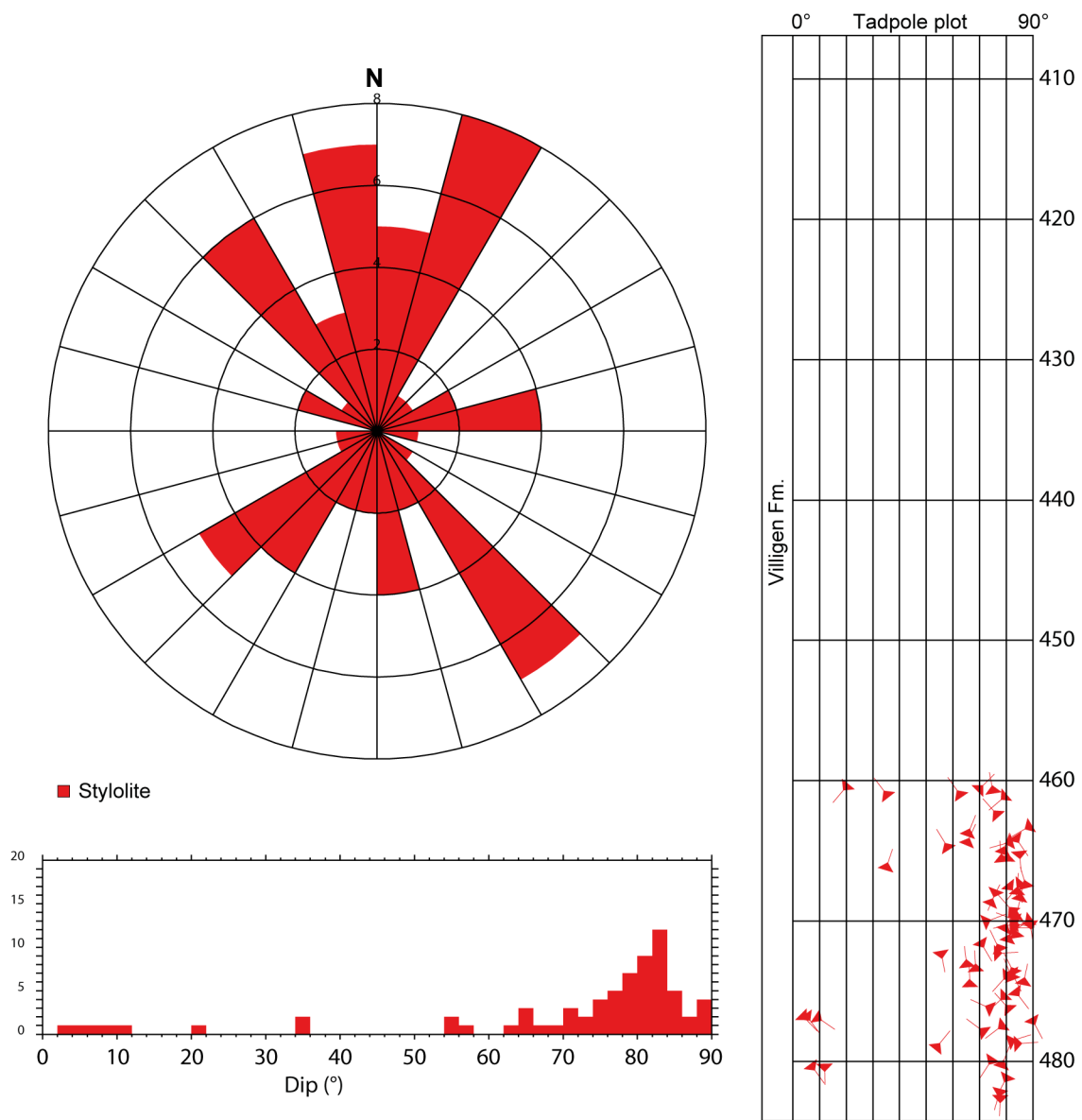


Fig. 4-22: Azimuth rose diagram, dip histogram and depth plot of stylolites (Villigen Formation, n = 70)

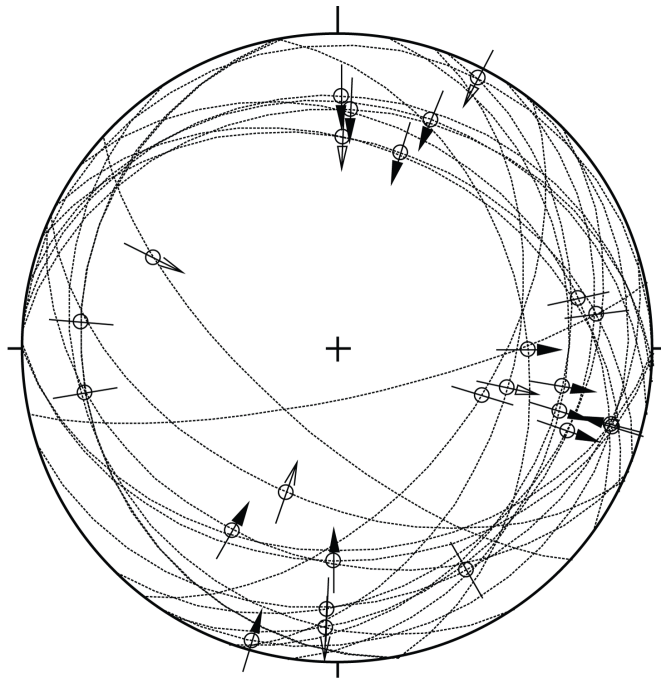


Fig. 4-23: Stereogram of fault planes with striations (including multiple lineations on a single fault plane; Villigen Formation, $n = 27$)

4.2.2 Wildegg Formation

The orientation and spatial depth distribution of recorded structures in the Wildegg Formation (484.22 m to 501.92 m MD log depth) are shown in Figs. 4-24 to 4-28. Only a few fault planes and steeply dipping veins and stylolites could be identified along this borehole interval.

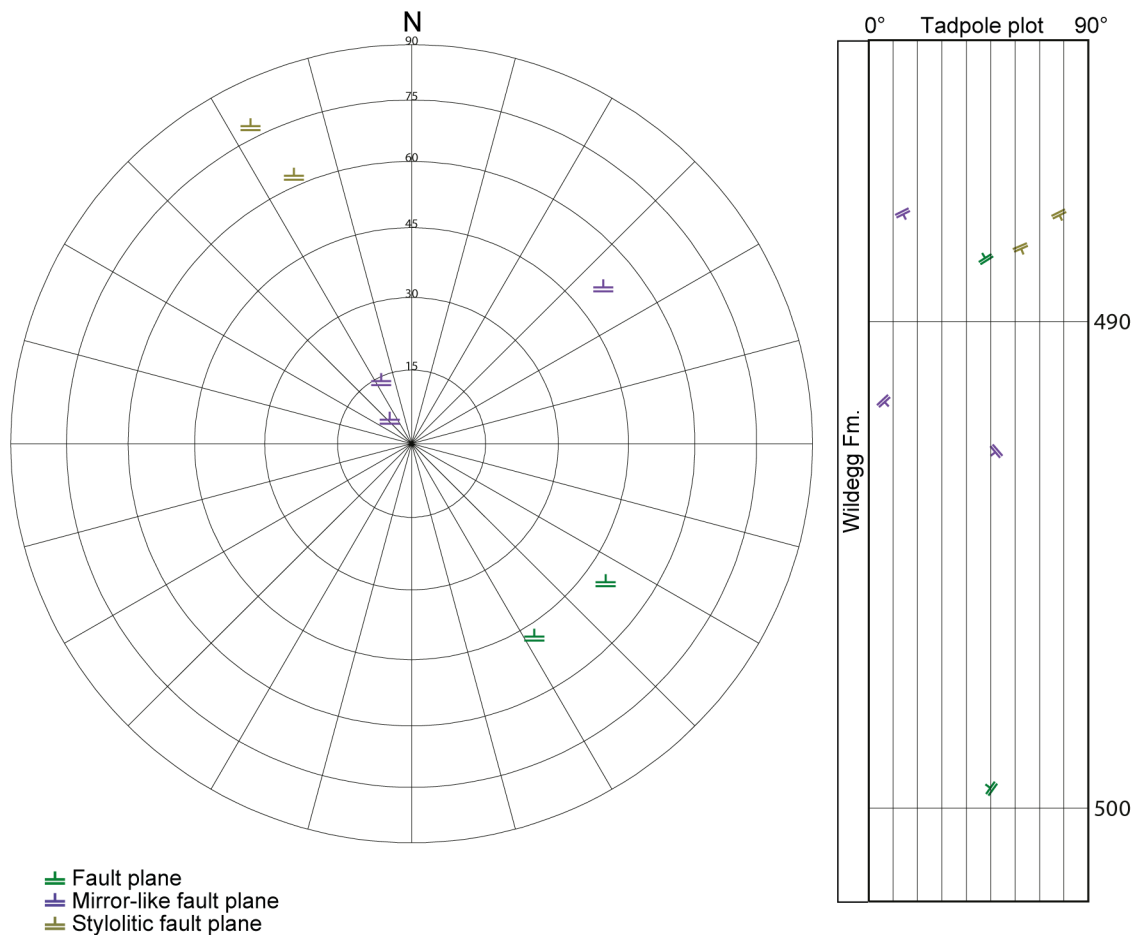


Fig. 4-24: Stereogram and depth plot of fault planes (Wildegg Formation)

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

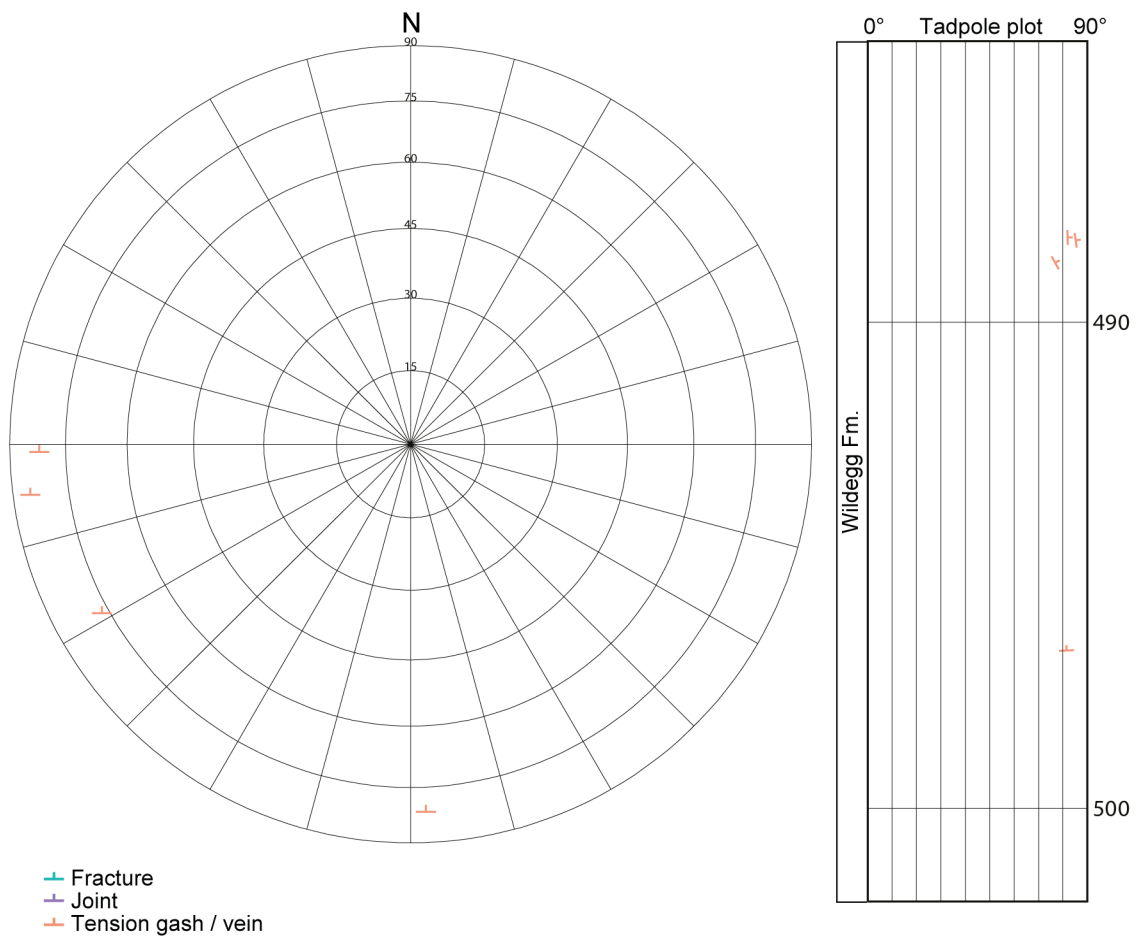


Fig. 4-25: Stereogram and depth plot of tension gashes / veins and unassigned fractures (Wildegge Formation)

Tension gashes / veins ($n = 4$).

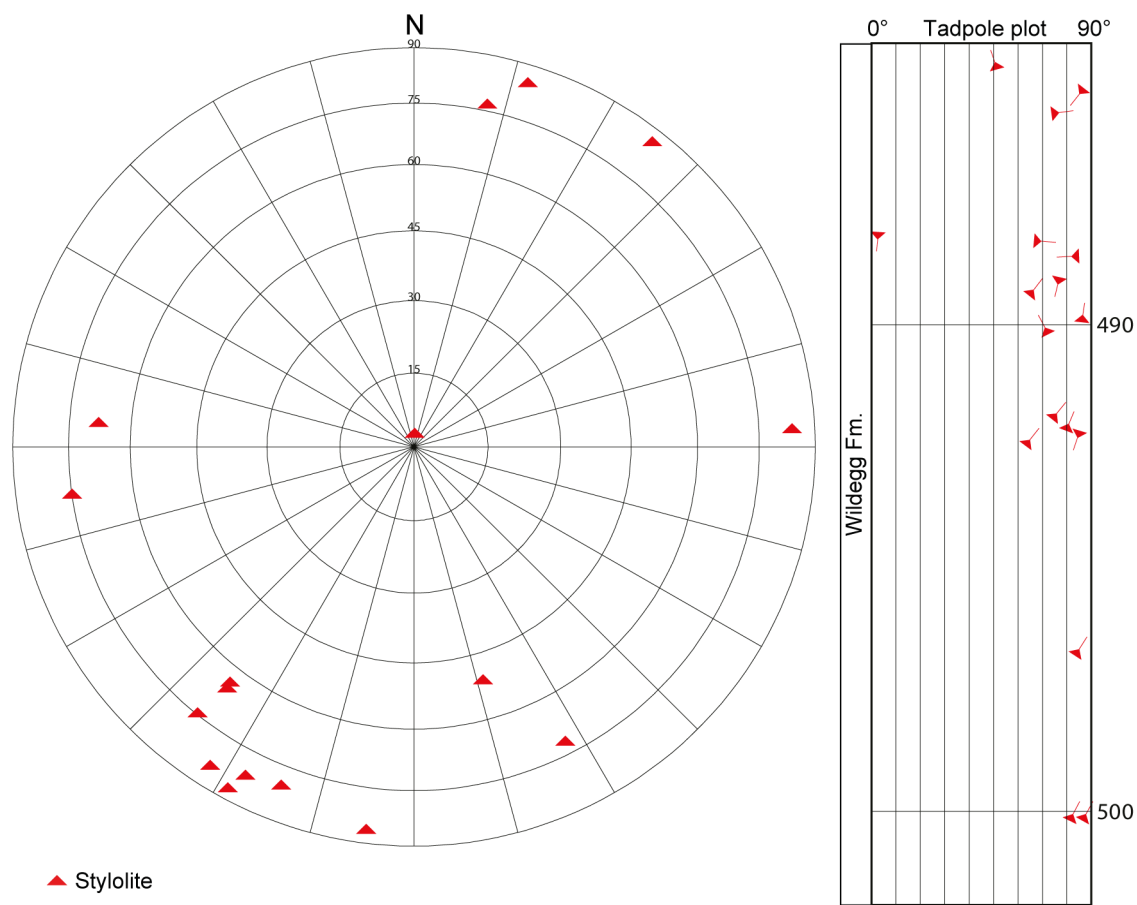


Fig. 4-26: Stereogram and depth plot of stylolites (Wildegg Formation, n = 17)

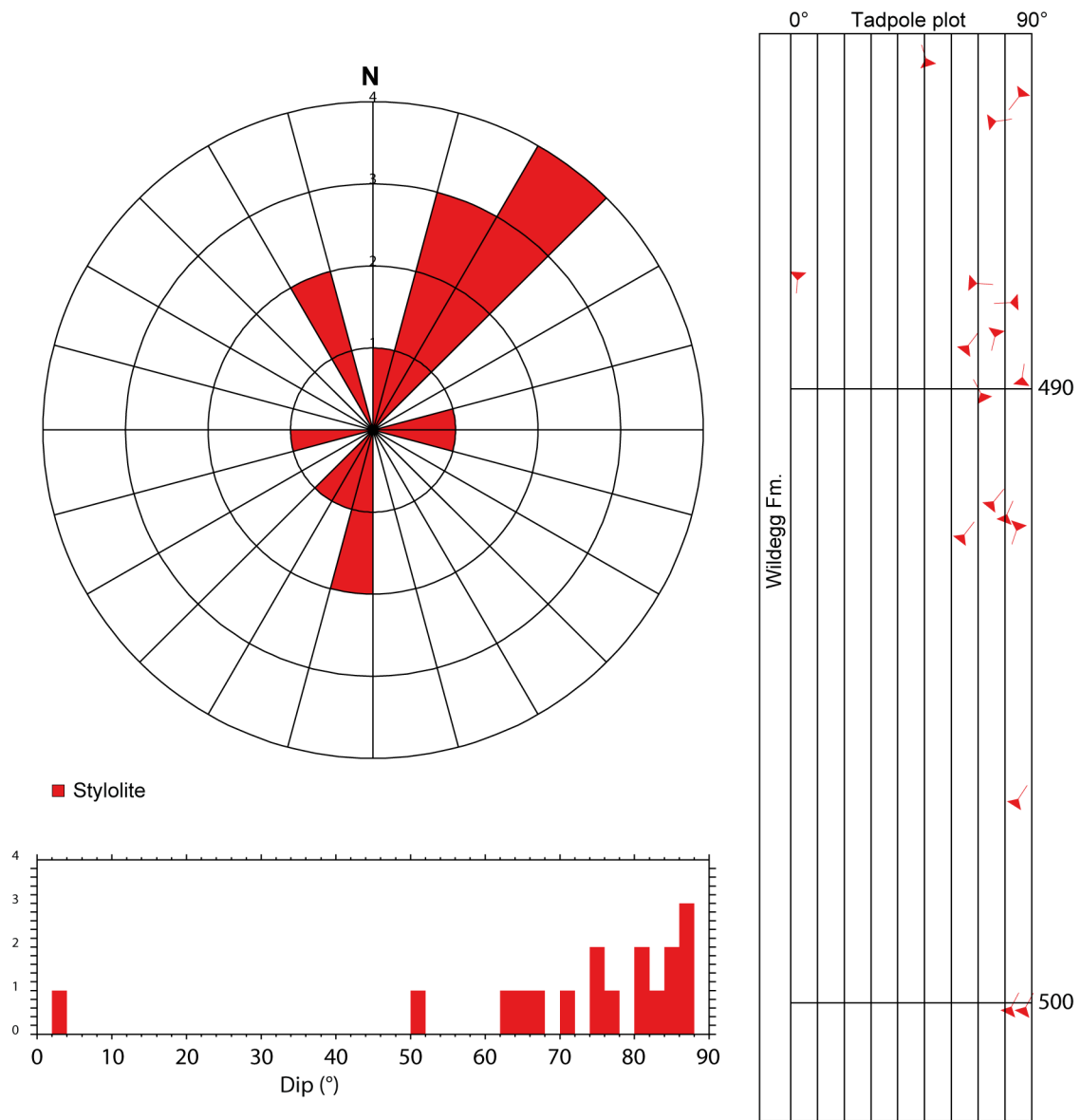


Fig. 4-27: Azimuth rose diagram, dip histogram and depth plot of stylolites (Wildegge Formation, n = 17)

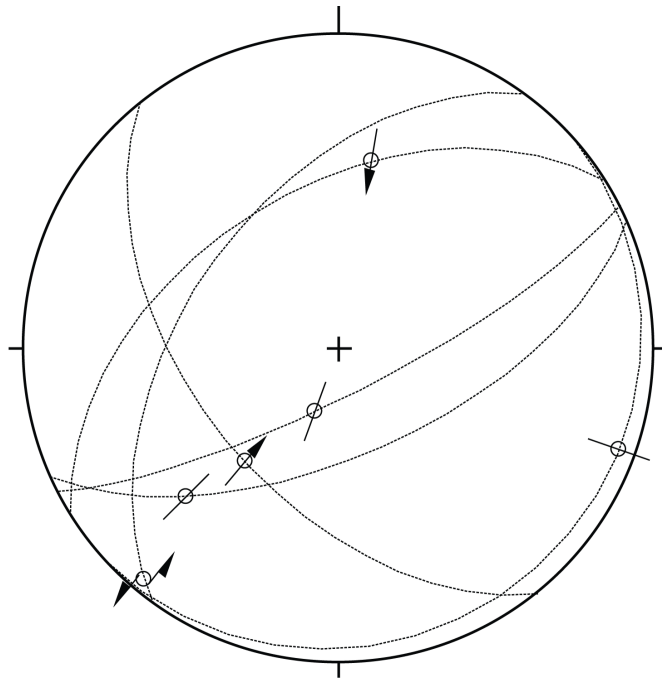


Fig. 4-28: Stereogram of fault planes with striations (Wildegge Formation, $n = 6$)

4.3 Dogger

For the detailed stereographic evaluation, the Dogger was subdivided into two units: the «Brauner Dogger» and the Opalinus Clay.

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

The orientation and spatial distribution of structural discontinuities within the «Brauner Dogger» are visualised in Figs. 4-29 to 4-35. Only the data from oriented cores are presented. The «Brauner Dogger» (501.92 m to 590.37 m MD log depth), an informal lithostratigraphic unit summarising predominantly claystone-rich lithologies from the Wutach Formation to the «Murchisonae-Oolith Formation», showed a low density of fault planes, tension gashes / veins and stylolites.

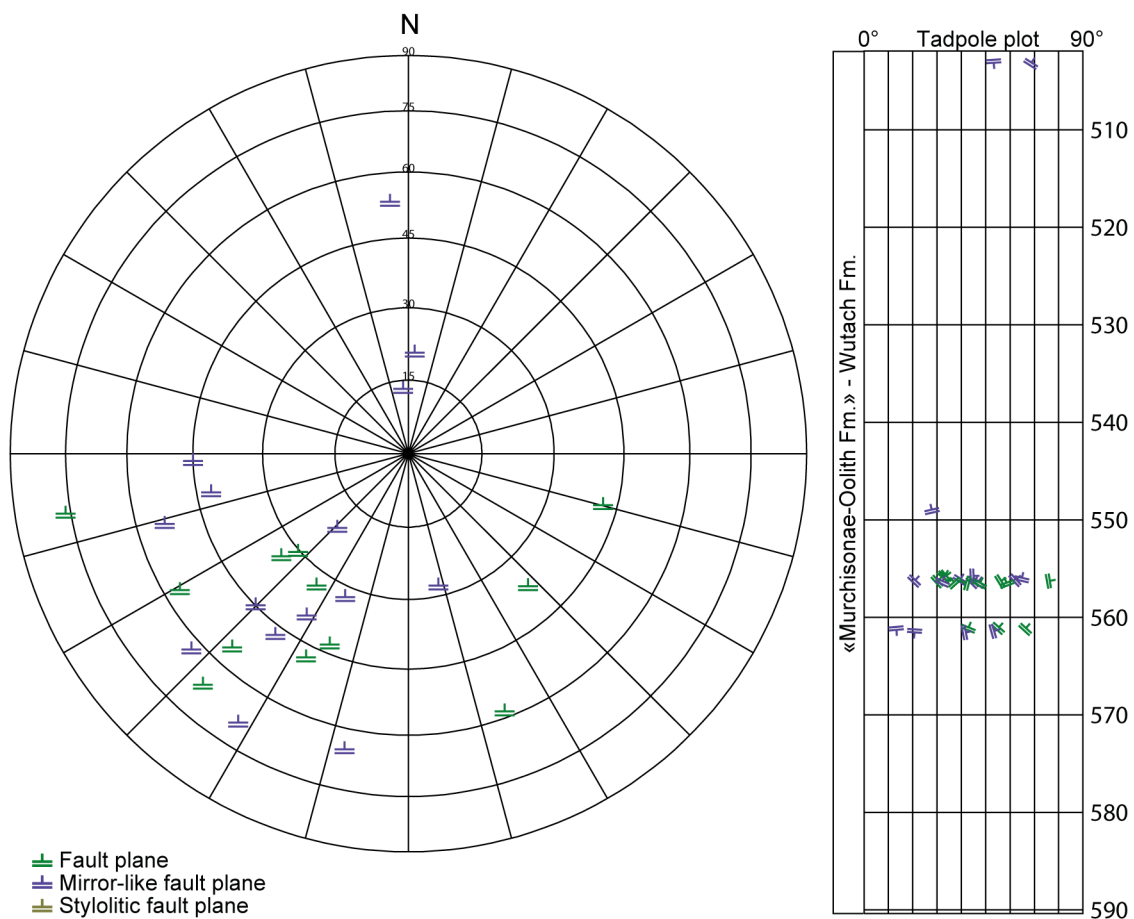


Fig. 4-29: Stereogram and depth plot of fault planes («Brauner Dogger»)

Fault planes (n = 12), mirror-like fault planes (n = 15) and stylolitic fault planes (n = 0).

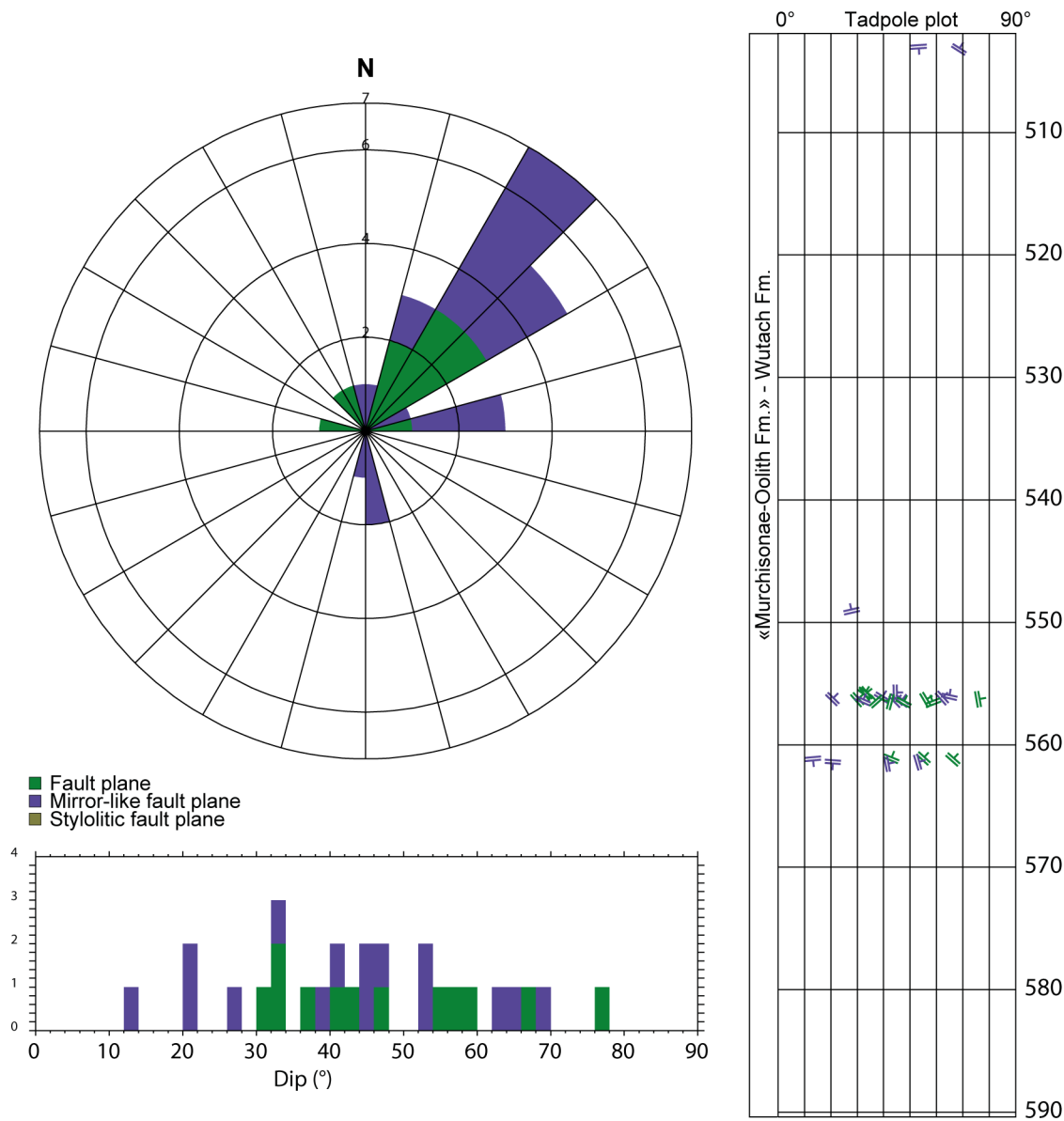


Fig. 4-30: Azimuth rose diagram, dip histogram and depth plot of fault planes («Brauner Dogger»)

Fault planes (n = 12), mirror-like fault planes (n = 15) and stylolitic fault planes (n = 0).

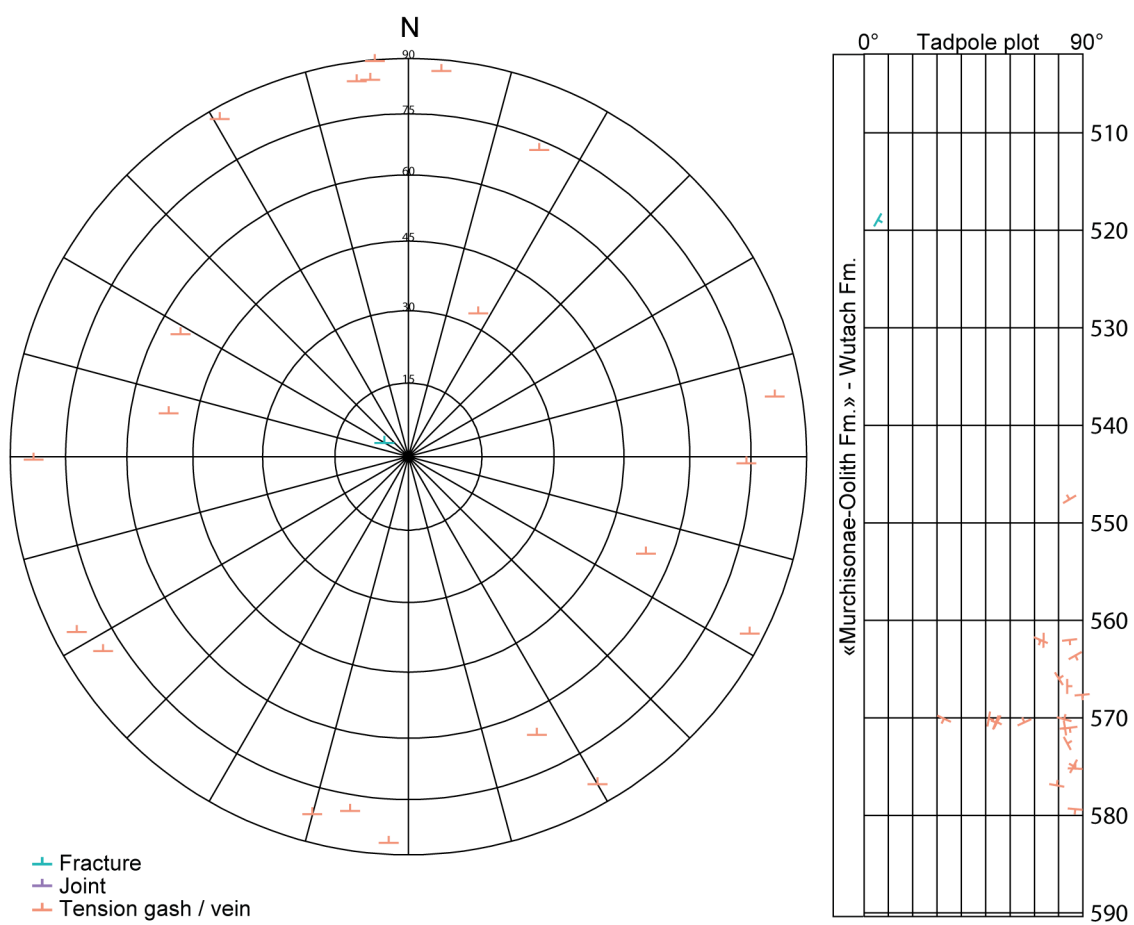


Fig. 4-31: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures («Brauner Dogger»)

Fractures (n = 1), joints (n = 0) and tension gashes / veins (n = 21).

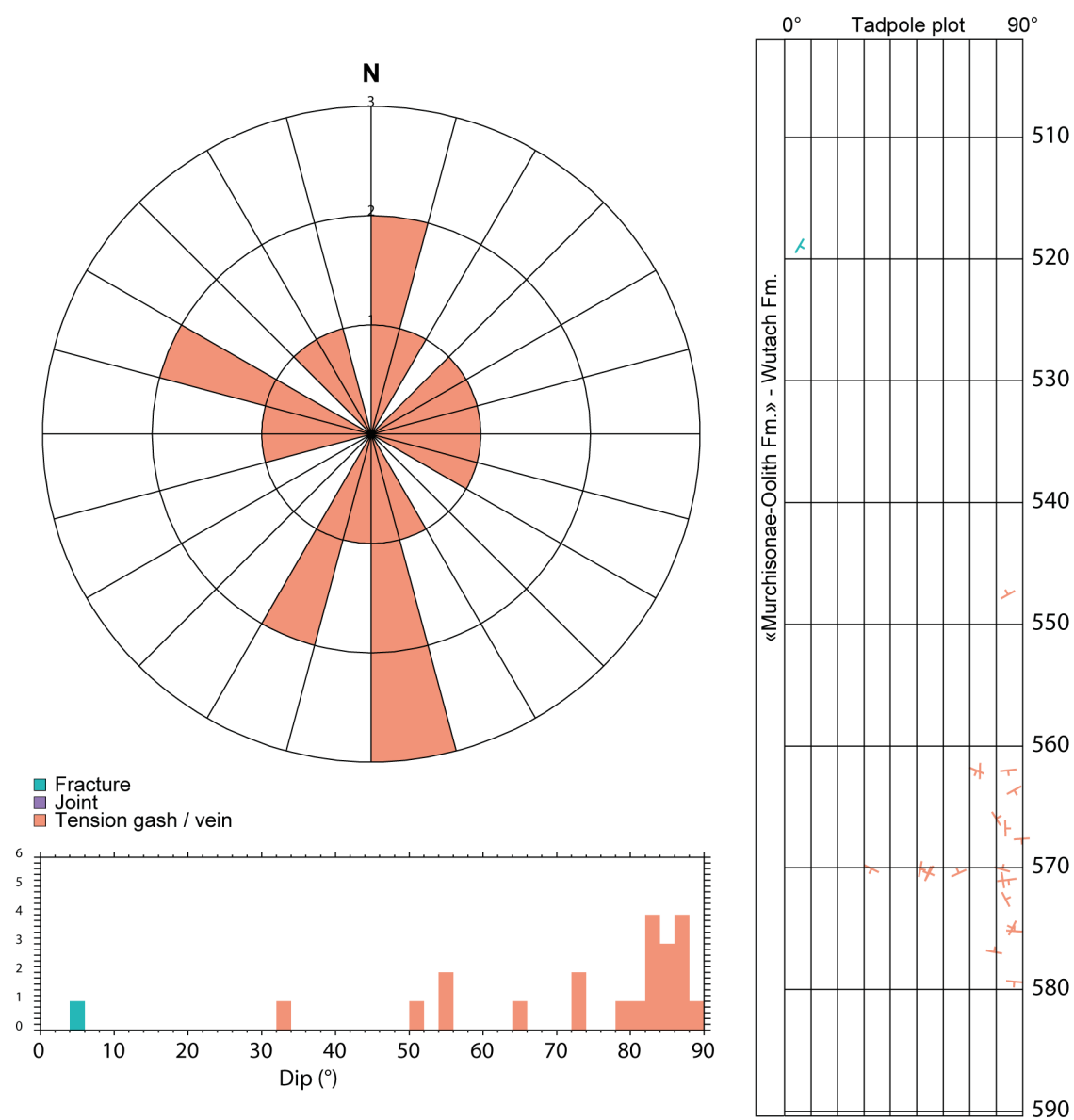


Fig. 4-32: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures («Brauner Dogger»)

Fractures (n = 1), joints (n = 0) and tension gashes / veins (n = 21).

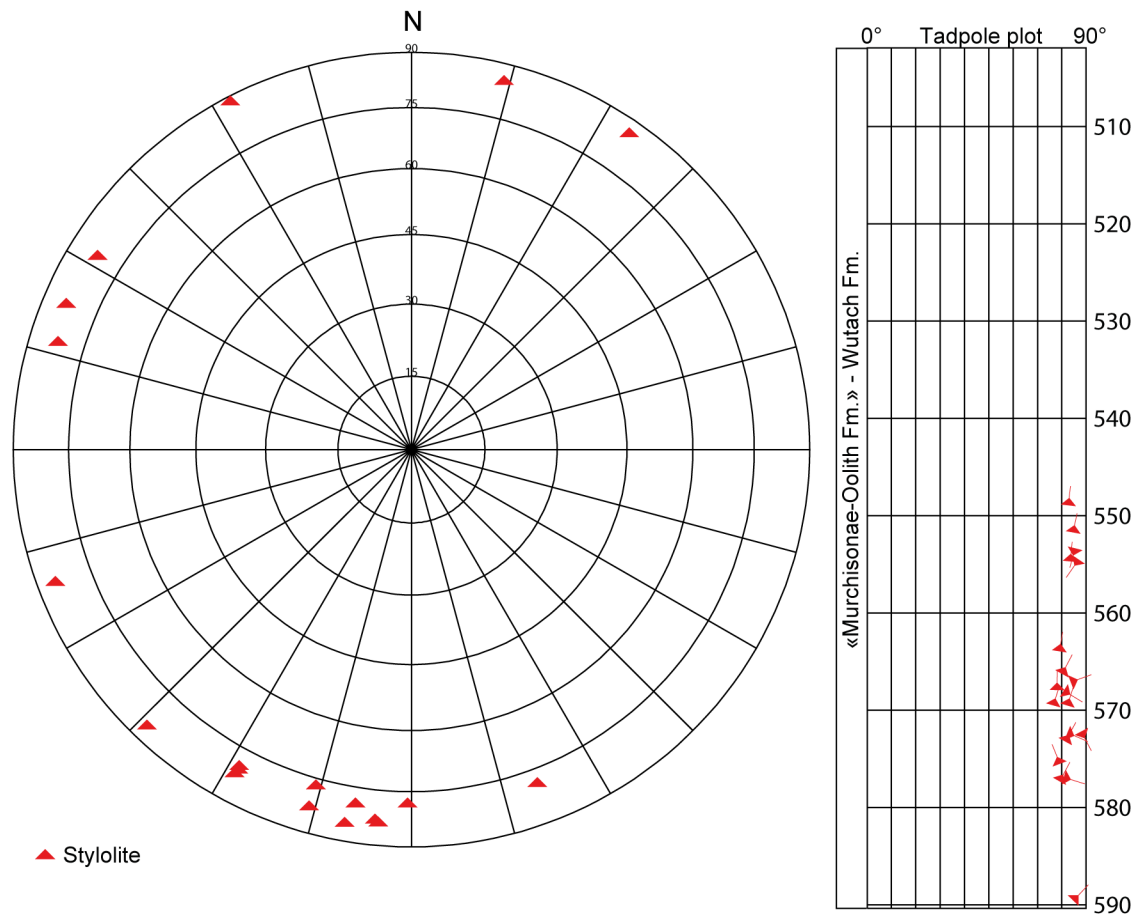


Fig. 4-33: Stereogram and depth plot of stylolites («Brauner Dogger», n = 19)

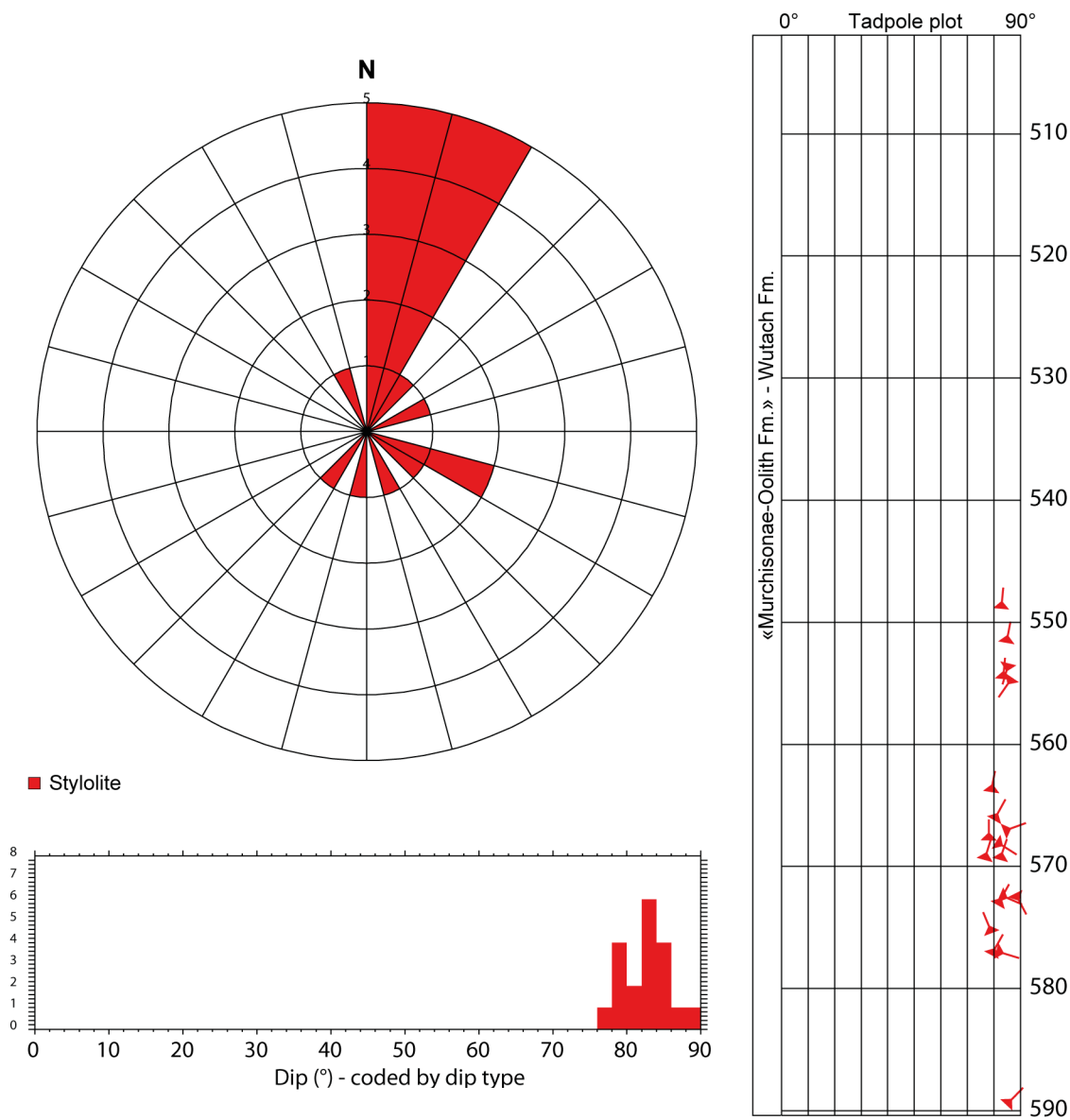


Fig. 4-34: Azimuth rose diagram, dip histogram and depth plot of stylolites («Brauner Dogger», n = 19)

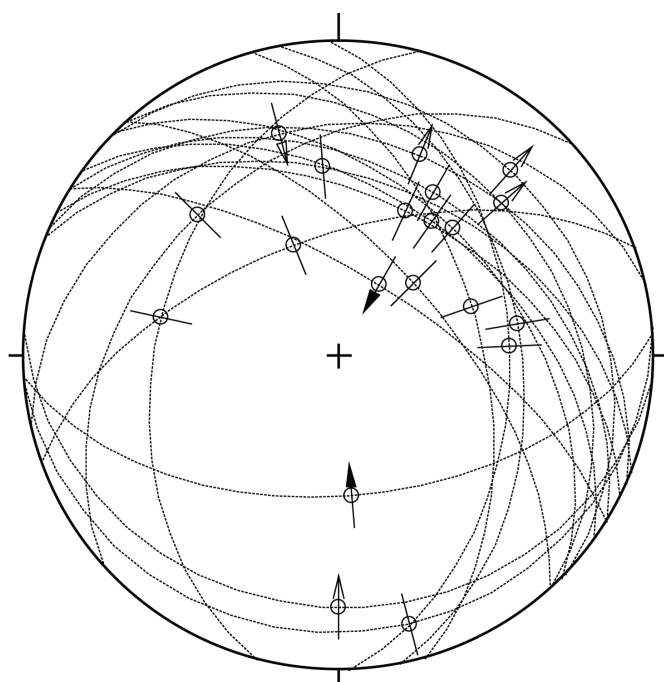


Fig. 4-35: Stereogram of fault planes with striations (including multiple lineations on a single fault plane; «Brauner Dogger», $n = 20$)

4.3.2 Opalinus Clay

The Opalinus Clay (590.37 m to 705.52 m MD log depth) reveals an overall sub-horizontal to shallow SE-bedding. In general, the fracture density is low. However, two zones with abundant fractures were observed. The two zones contain a total of 158 structures: (1) the upper zone is located from 620.88 m to 621.90 m MD (log depth) and is characterised by abundant mirror-like fault planes forming a fault zone. Faults show variable (5° to 50°) dip angles and scattered dip directions. The dominant shear sense is normal; (2) the lower zone from 667 m to 680 m MD (log depth) reveals numerous fault planes with synkinematic calcite fillings and veins, which are commonly less than 1 mm thick and are randomly oriented. The predominant shear senses indicate normal faulting. Stylolites were not observed in the Opalinus Clay.

The structural inventory for the Opalinus Clay is presented in Figs. 4-36 to 4-40.

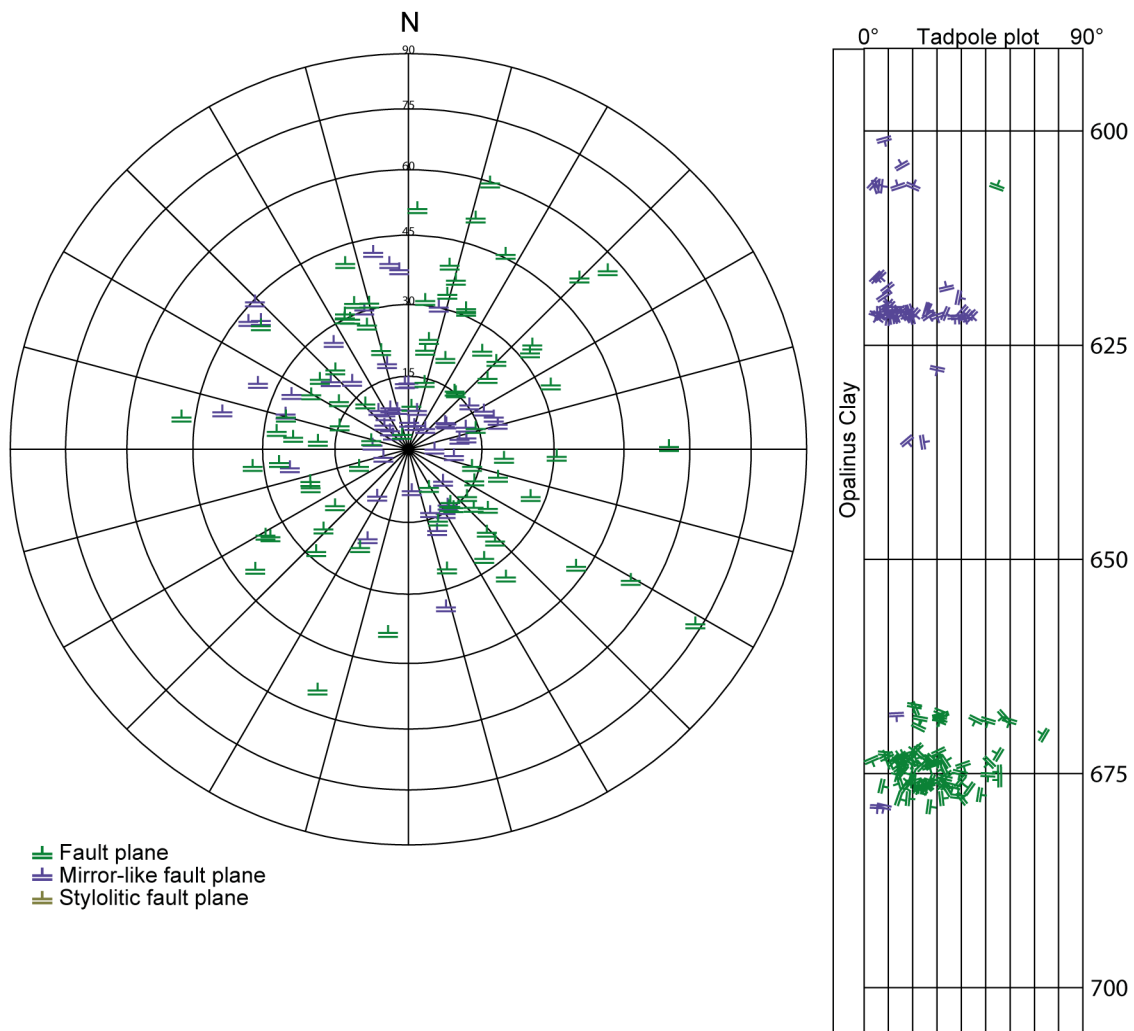


Fig. 4-36: Stereogram and depth plot of fault planes (Opalinus Clay)

Fault planes ($n = 86$), mirror-like fault planes ($n = 52$) and stylolitic fault planes ($n = 0$).

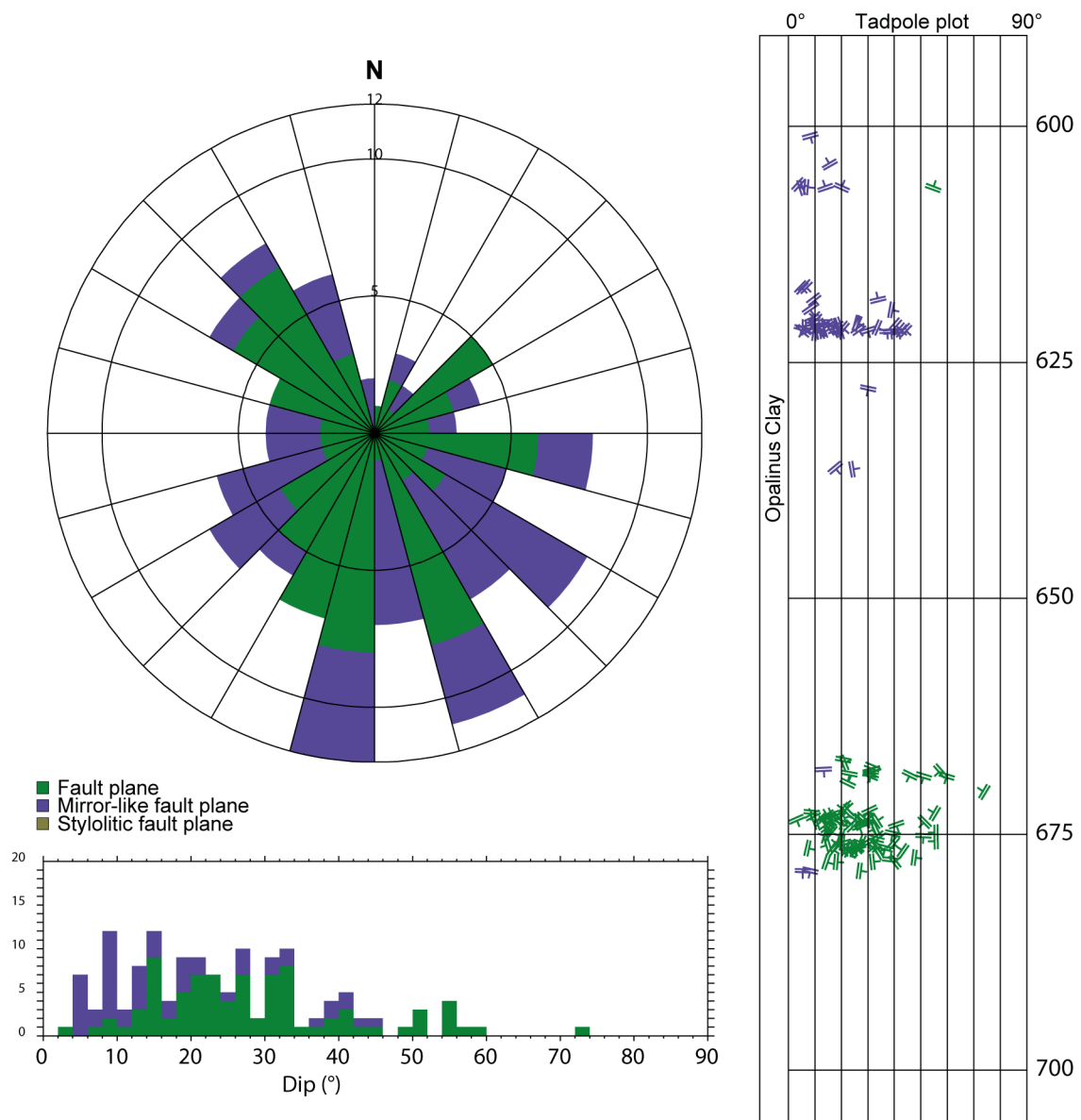


Fig. 4-37: Azimuth rose diagram, dip histogram and depth plot of fault planes (Opalinus Clay)
 Fault planes (n = 86), mirror-like fault planes (n = 52) and stylolitic fault planes (n = 0).

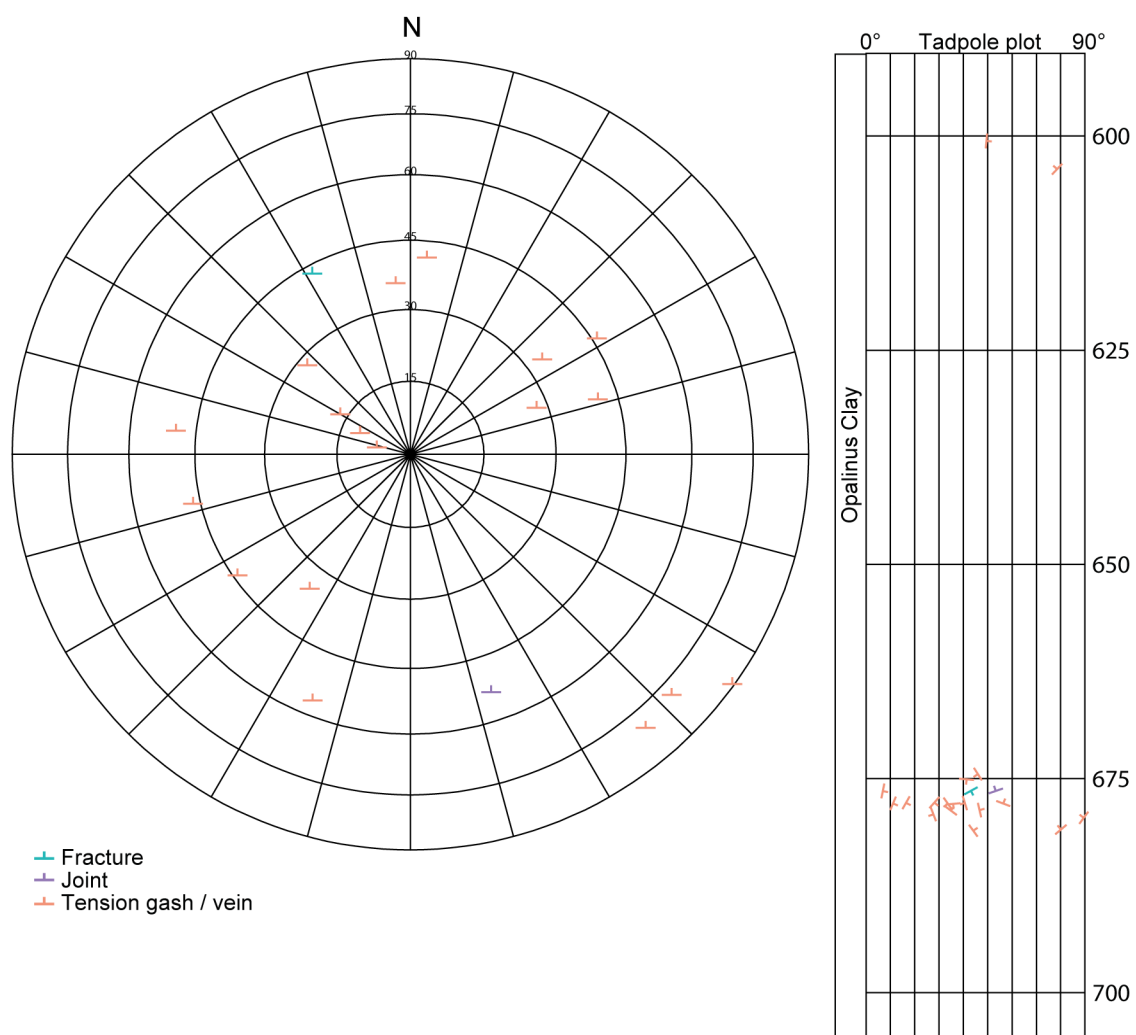


Fig. 4-38: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Opalinus Clay)

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

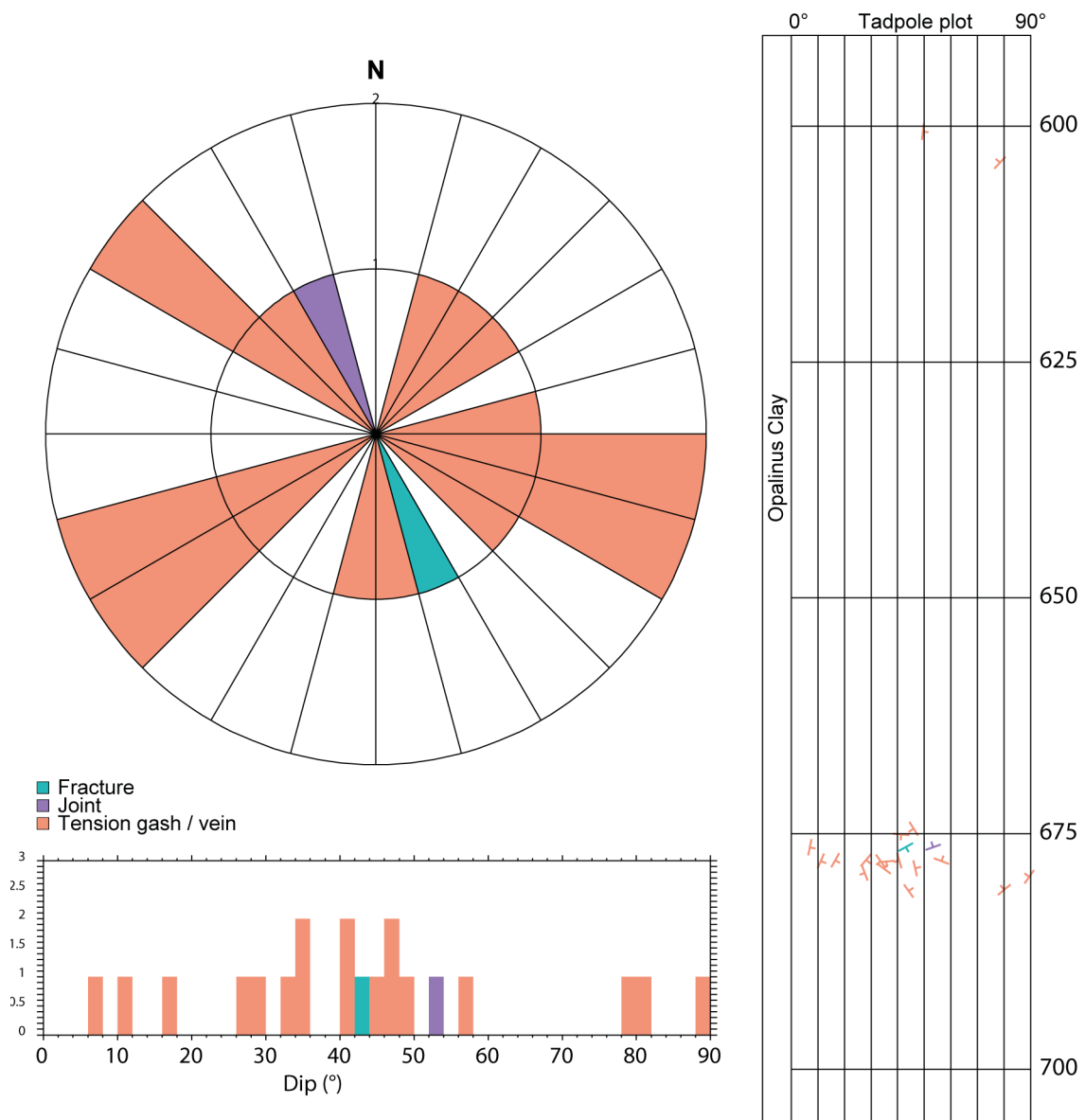


Fig. 4-39: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Opalinus Clay)

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

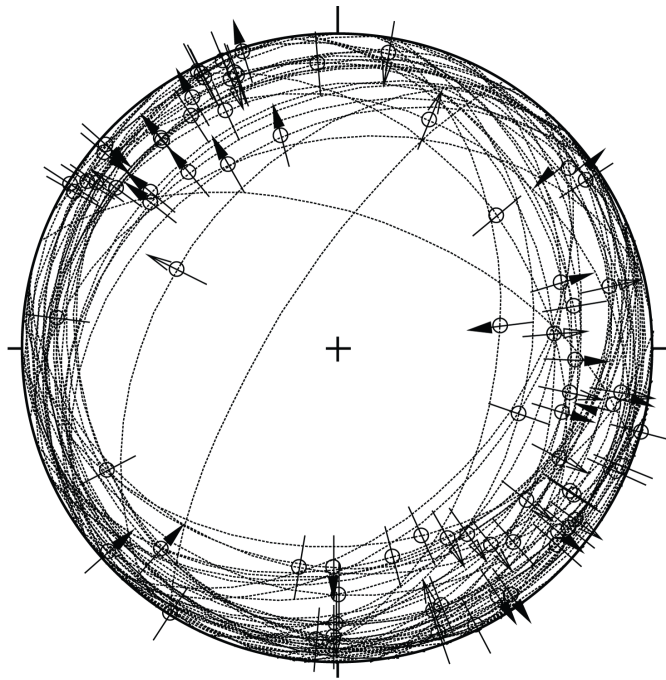


Fig. 4-40: Stereogram of fault planes with striations (including multiple lineations on a single fault plane) (Opalinus Clay, $n = 78$)

4.4 Lias (Staffelegg Formation)

As presented in Figs. 4-41 to 4-46, the Lias (705.52 m to 747.89 m MD log depth) is characterised by a low number of fractures. Only the data for oriented cores are presented.

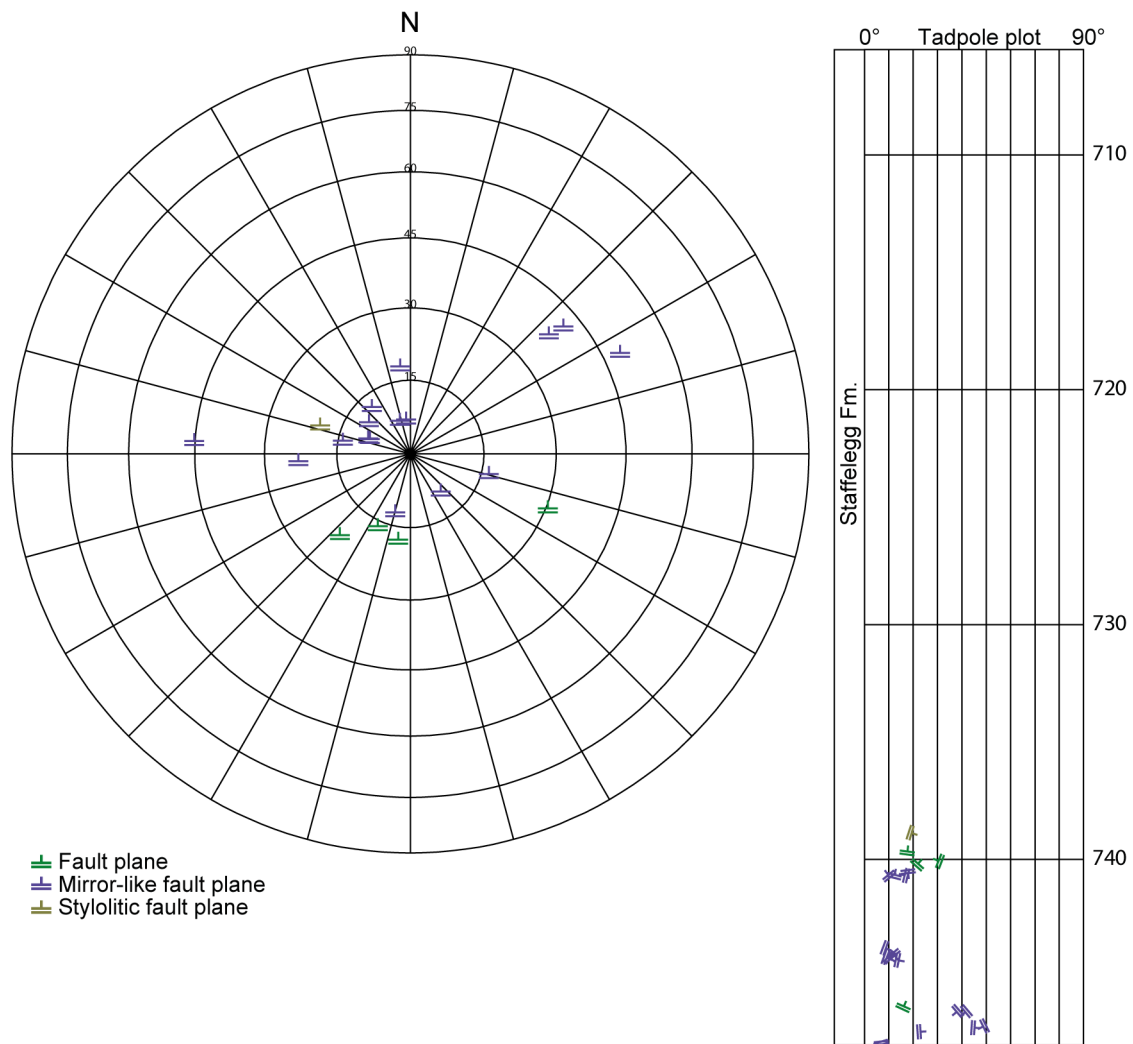


Fig. 4-41: Stereogram and depth plot of fault planes (Lias)

Fault planes (n = 4), mirror-like fault planes (n = 16) and stylolitic fault planes (n = 1).

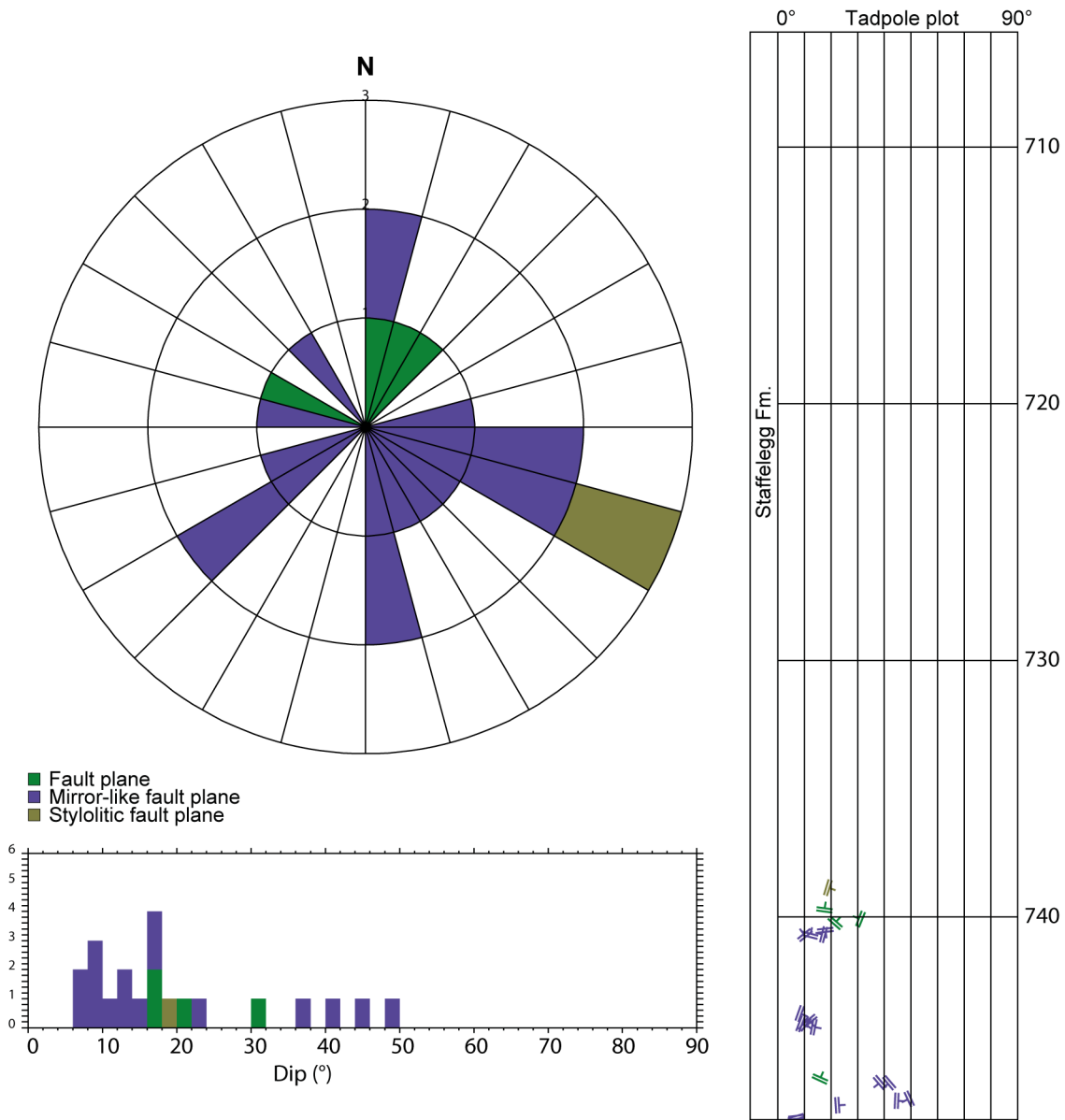


Fig. 4-42: Azimuth rose diagram, dip histogram and depth plot of fault planes (Lias)
Fault planes (n = 4), mirror-like fault planes (n = 16) and stylolitic fault planes (n = 1).

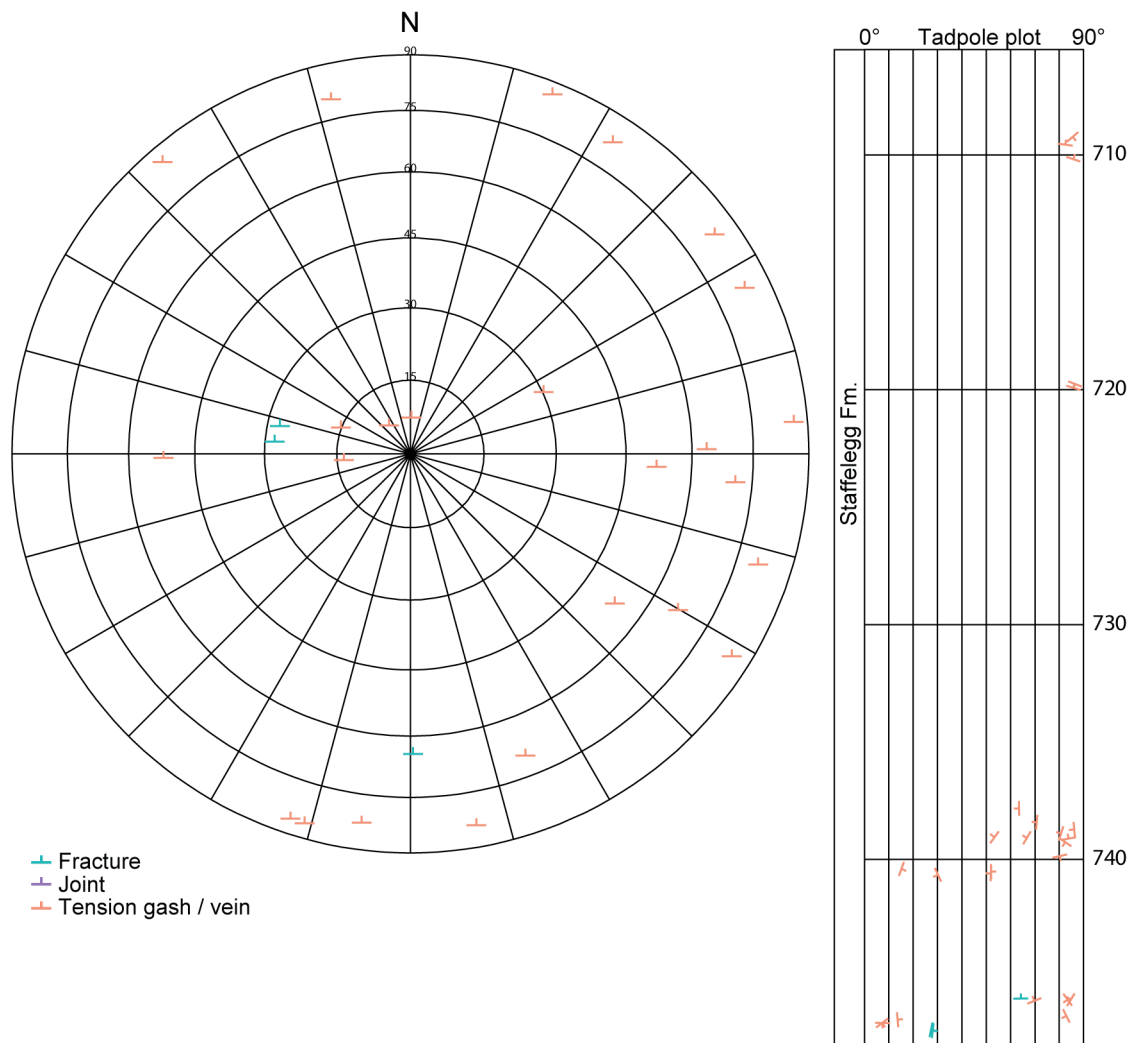


Fig. 4-43: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Lias)

Fractures (n = 3), joints (n = 0) and tension gashes / veins (n = 25).

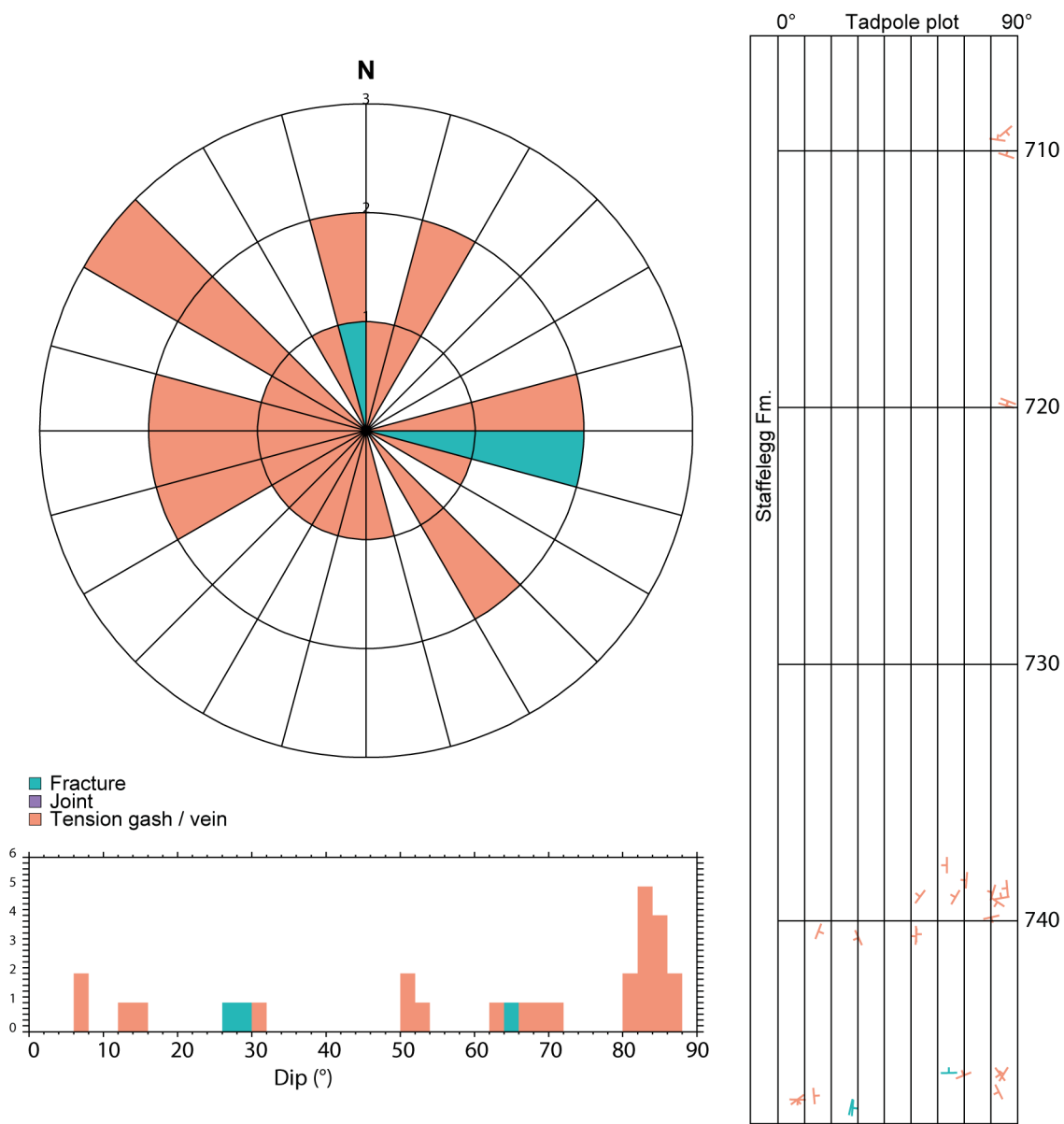


Fig. 4-44: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Lias)

Fractures (n = 3), joints (n = 0) and tension gashes / veins (n = 25).

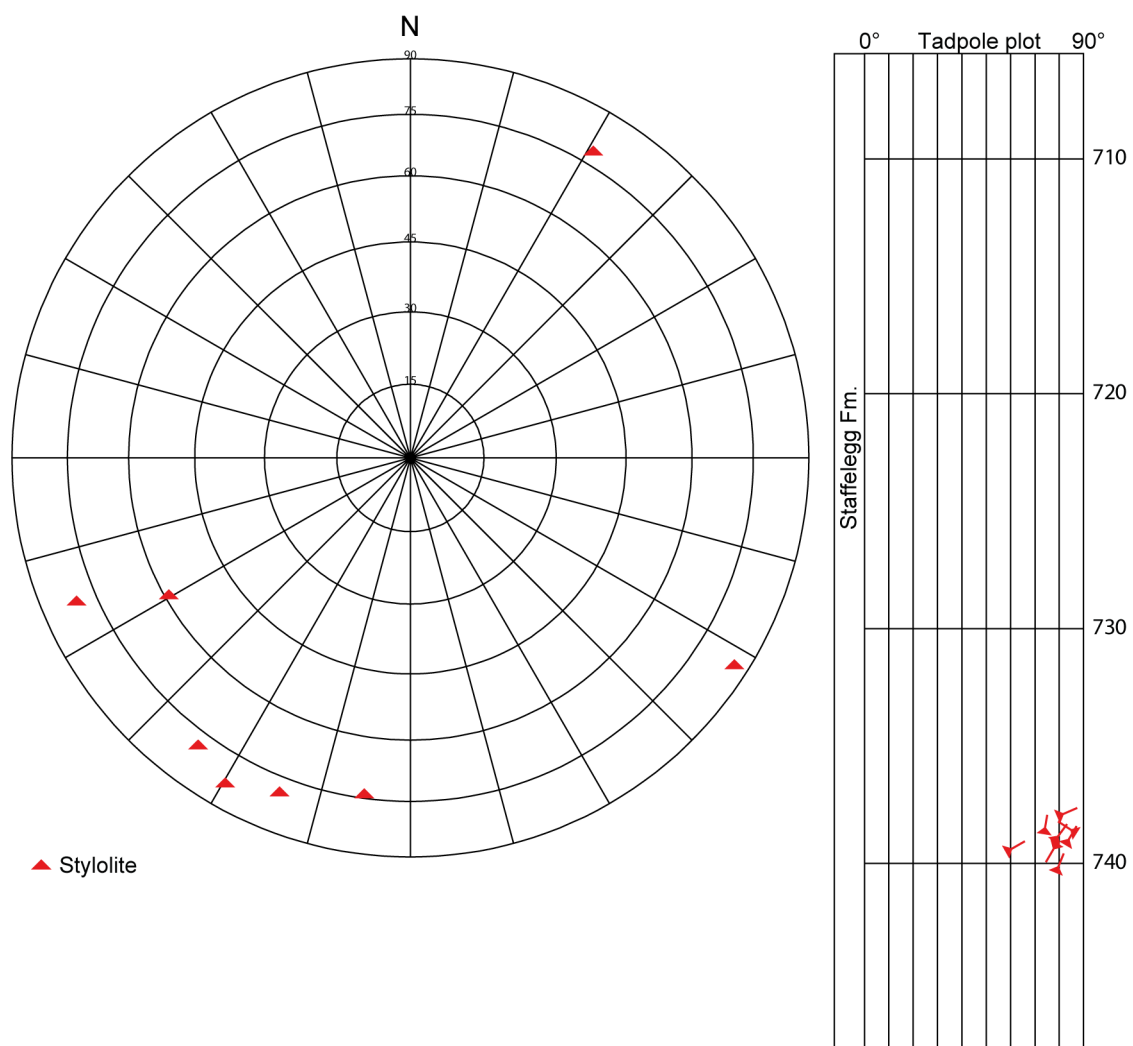


Fig. 4-45: Stereogram and depth plot of stylolites (Lias, $n = 8$)

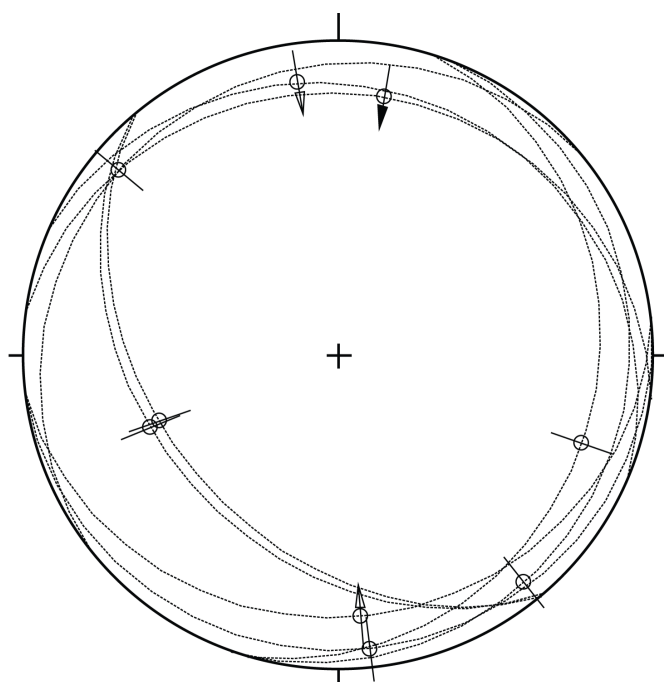


Fig. 4-46: Stereogram of fault planes with striations (Lias, $n = 9$)

4.5 Keuper

The Keuper (747.89 m to 862.77 m MD log depth) revealed the highest average fracture density of 4.8 fractures per metre. Mirror-like fault planes and tension gashes / veins prevailed. The latter were mainly found within the Bänkerjoch Formation and show a random orientation. The fault planes display a preferred dip of 0° to 50°. The rose diagram of dip directions shows two dip maxima towards SE and NE. No preferred shear sense was observed. 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 (747.89 m to 790.34 m MD log depth) are visualised in Figs. 4-47 to 4-51.

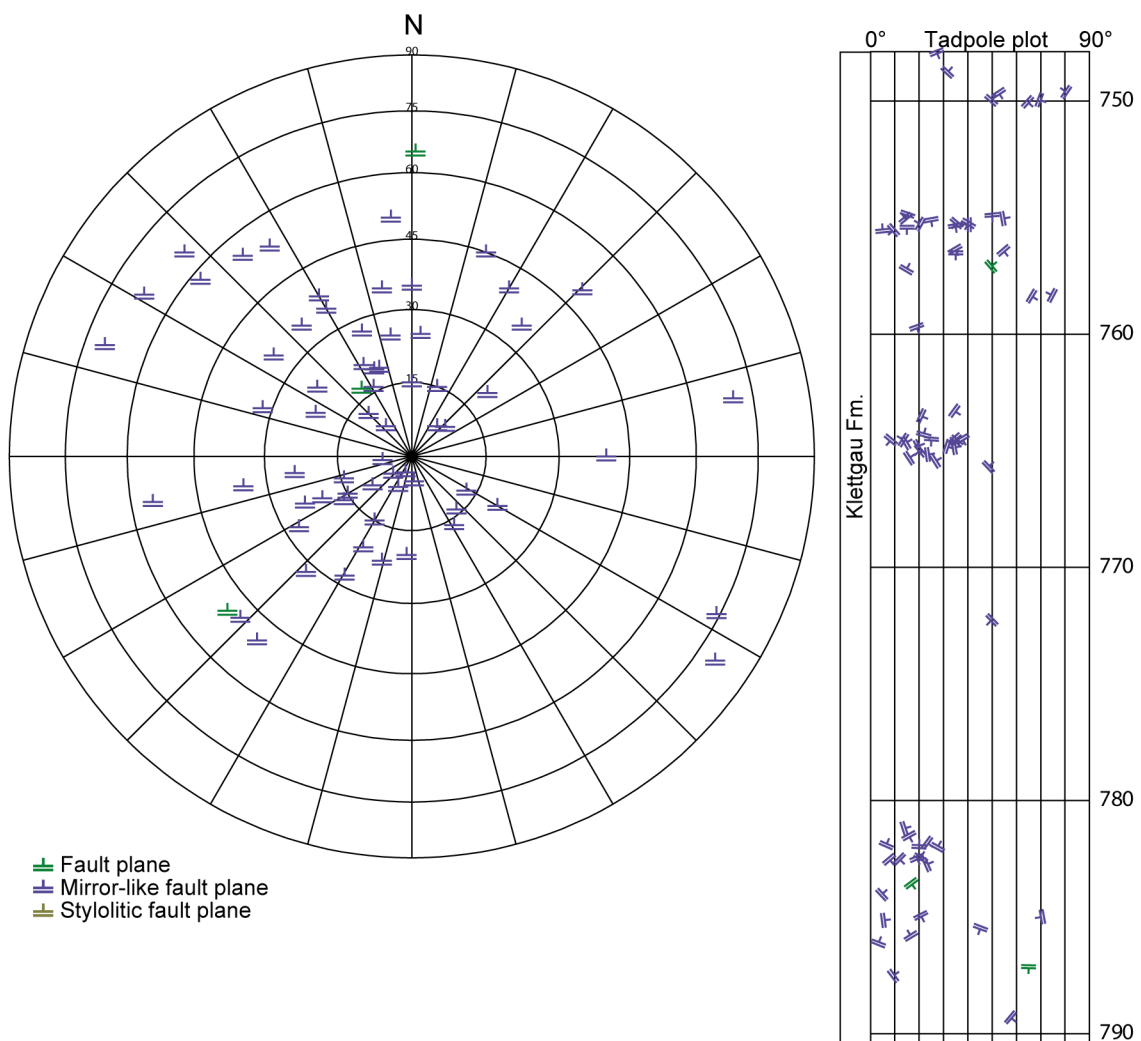


Fig. 4-47: Stereogram and depth plot of faults (Klettgau Formation)

Fault planes (n = 3), mirror-like fault planes (n = 67) and stylolitic fault planes (n = 0).

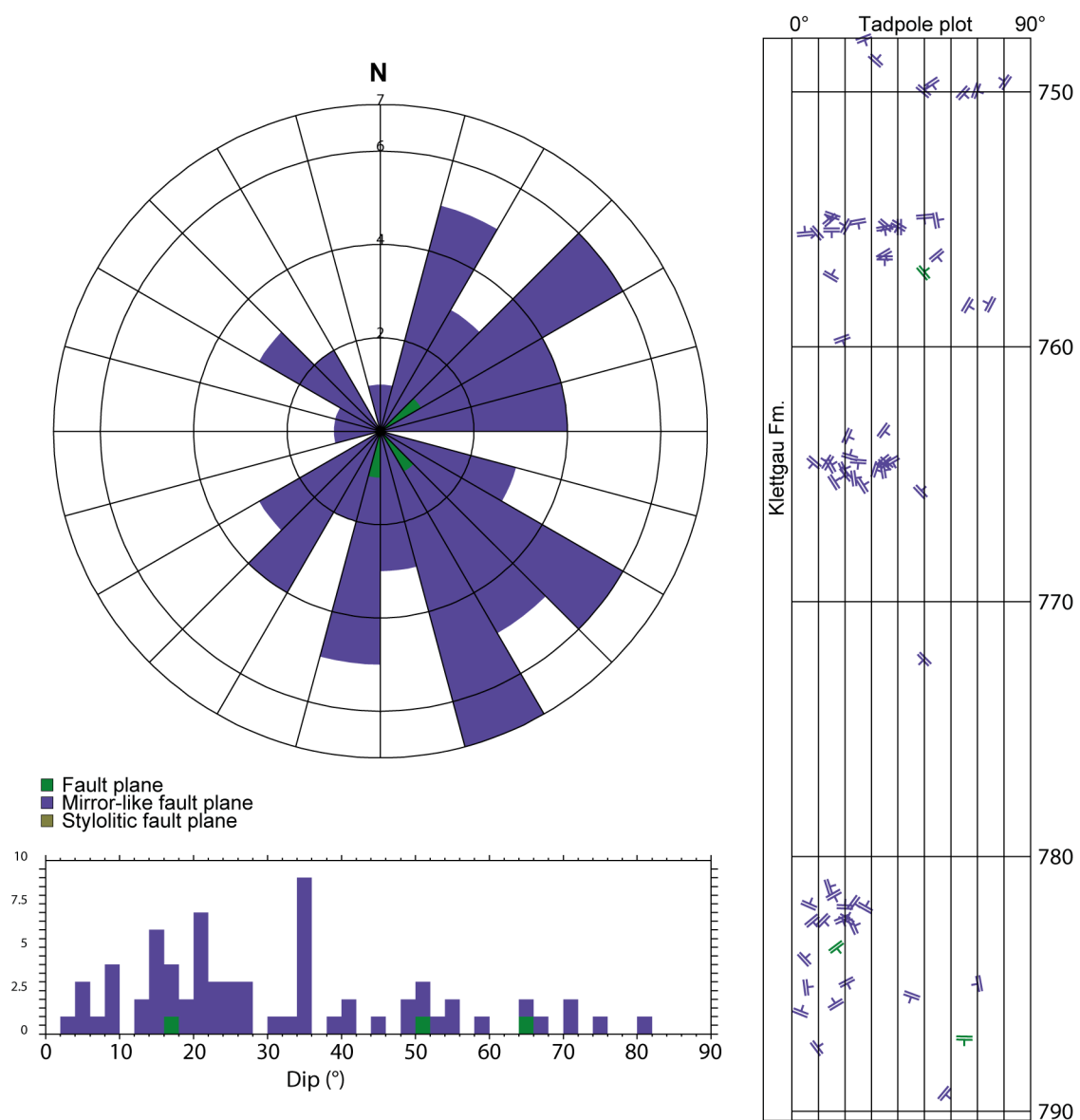


Fig. 4-48: Azimuth rose diagram, dip histogram and depth plot of faults (Klettgau Formation)
 Fault planes (n = 3), mirror-like fault planes (n = 67) and stylolitic fault planes (n = 0).

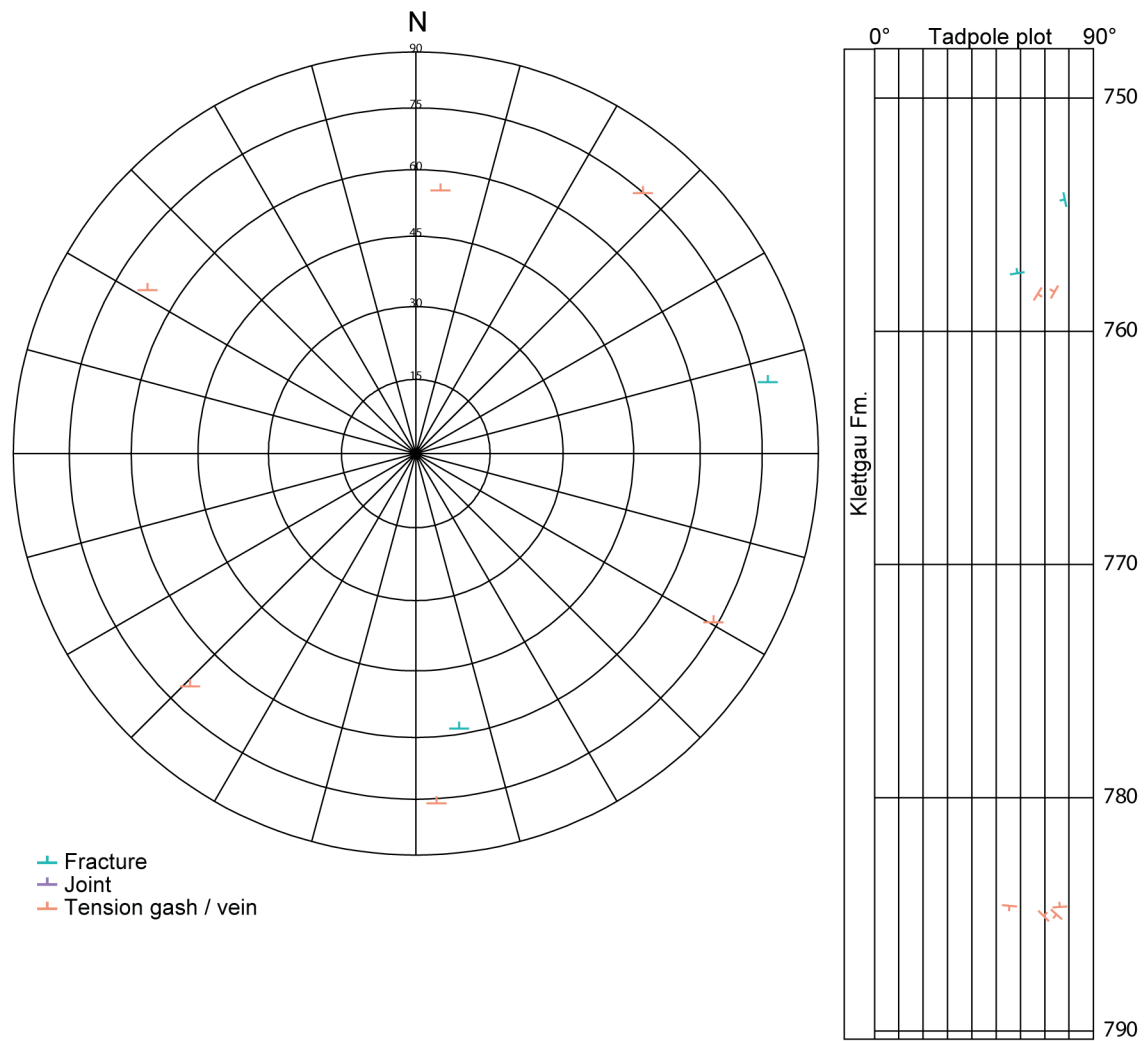


Fig. 4-49: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Klettgau Formation)

Fractures (n = 2), joints (n = 0) and tension gashes / veins (n = 6).

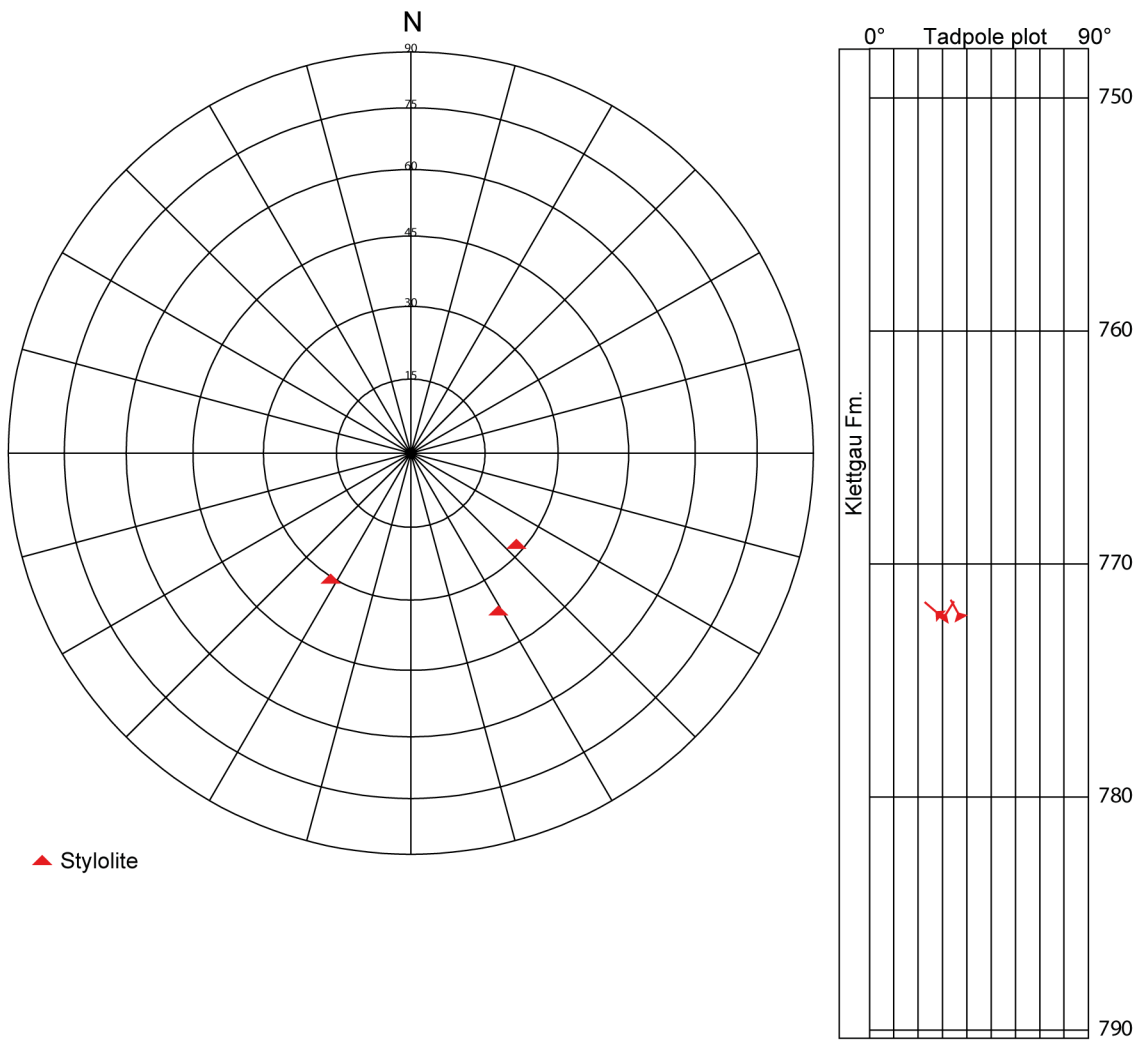


Fig. 4-50: Stereogram and depth plot of stylolites (Klettgau Formation, n = 3)

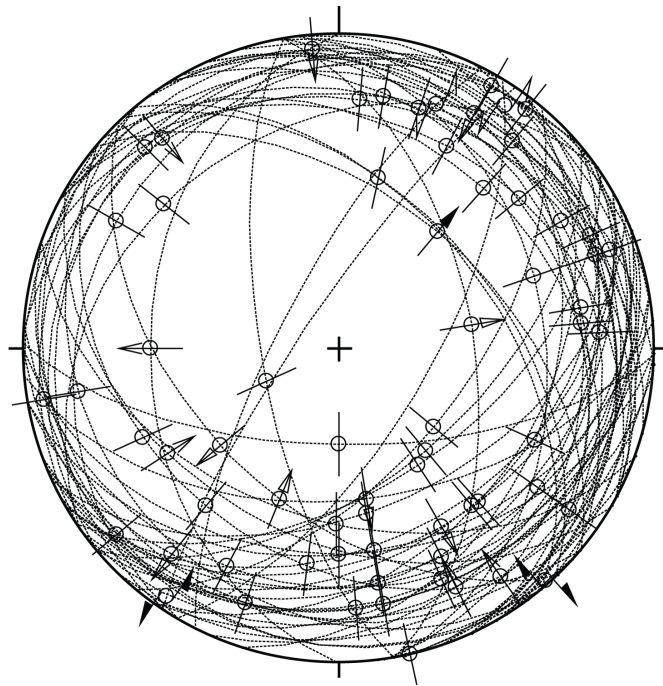


Fig. 4-51: Stereogram of fault planes with striations (including multiple lineations on a single fault plane; Klettgau Formation, n = 68)

4.5.2 Bänkerjoch Formation

The orientation and spatial distribution of the structural inventory of the Bänkerjoch Formation (790.34 m to 862.77 m MD log depth) are shown in Figs. 4-52 to 4-57.

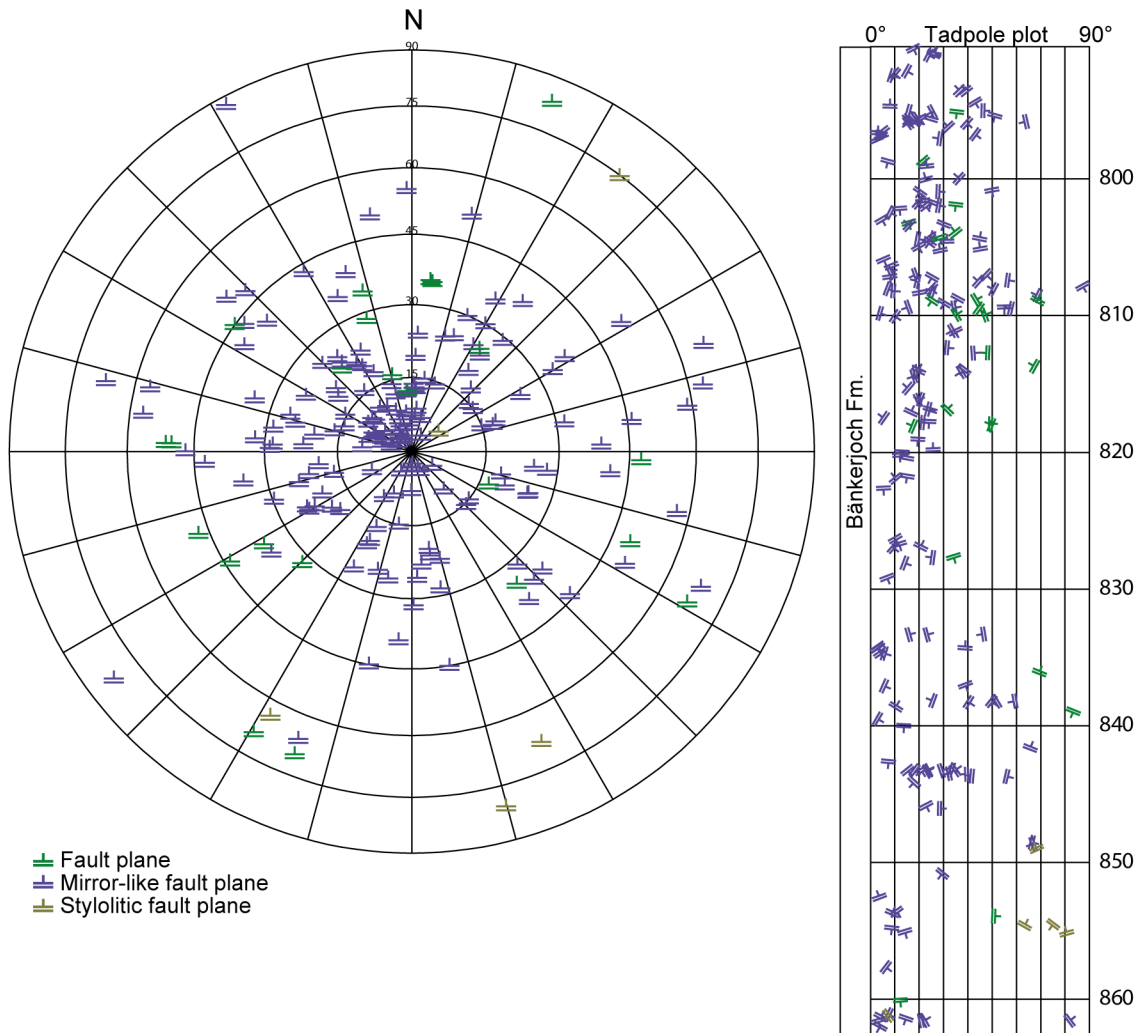


Fig. 4-52: Stereogram and depth plot of faults (Bänkerjoch Formation)

Fault planes (n = 23), mirror-like fault planes (n = 168) and stylolitic fault planes (n = 5).

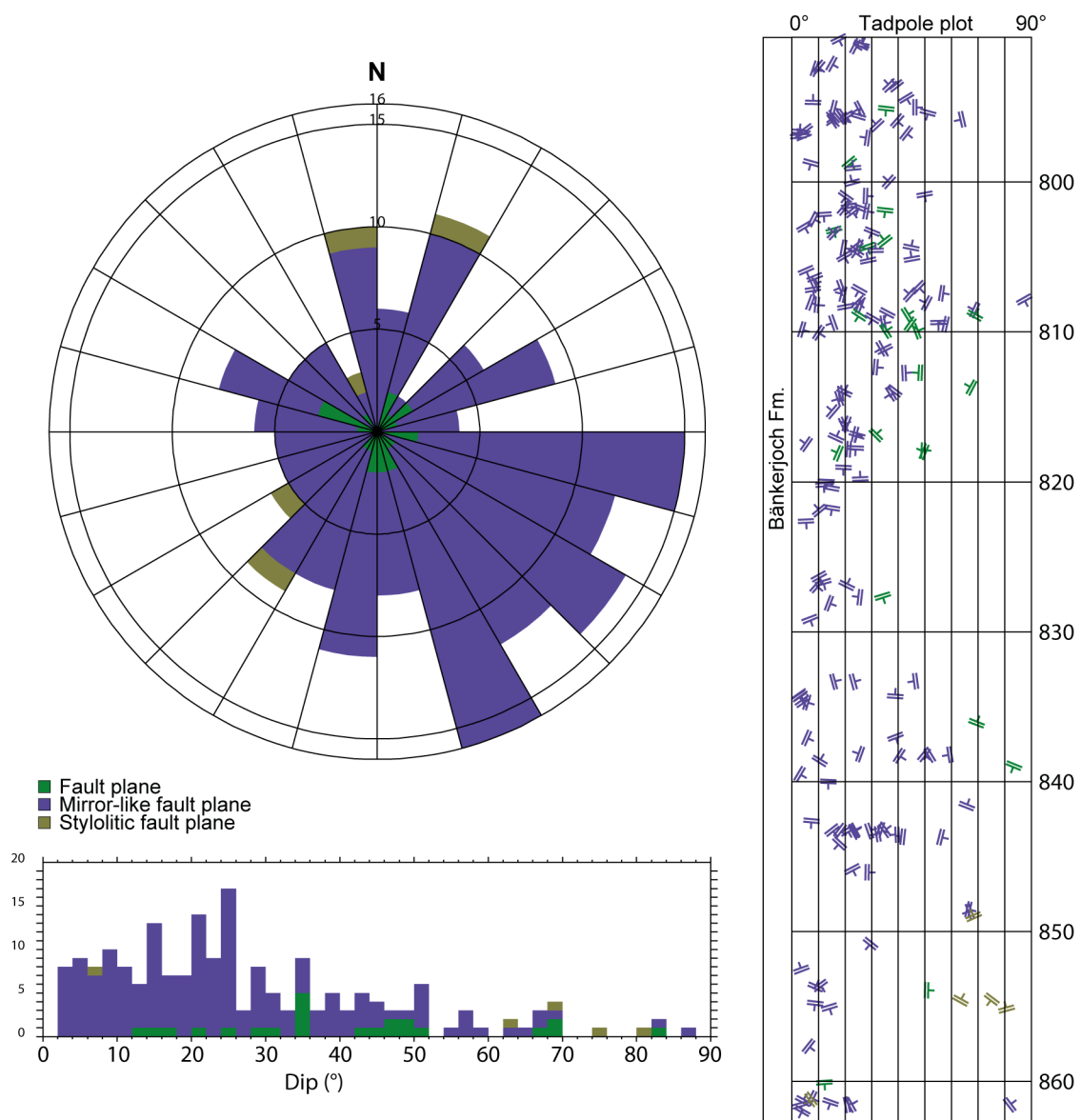


Fig. 4-53: Azimuth rose diagram, dip histogram and depth plot of faults (Bänkerjoch Formation)

Fault planes (n = 23), mirror-like fault planes (n = 168) and stylolitic fault planes (n = 5).

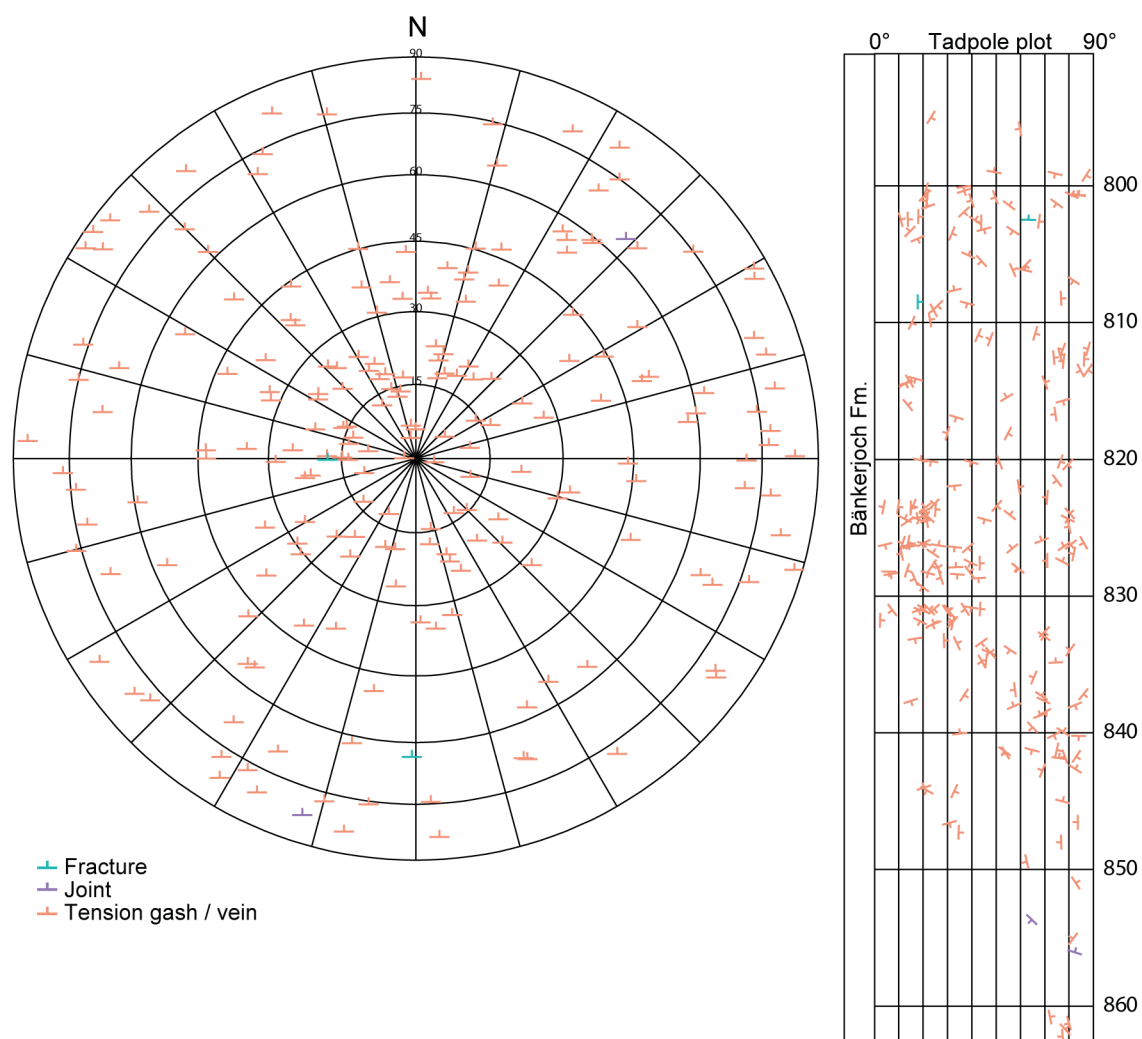


Fig. 4-54: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Bänkerjoch Formation)

Fractures (n = 2), joints (n = 2) and tension gashes / veins (n = 204).

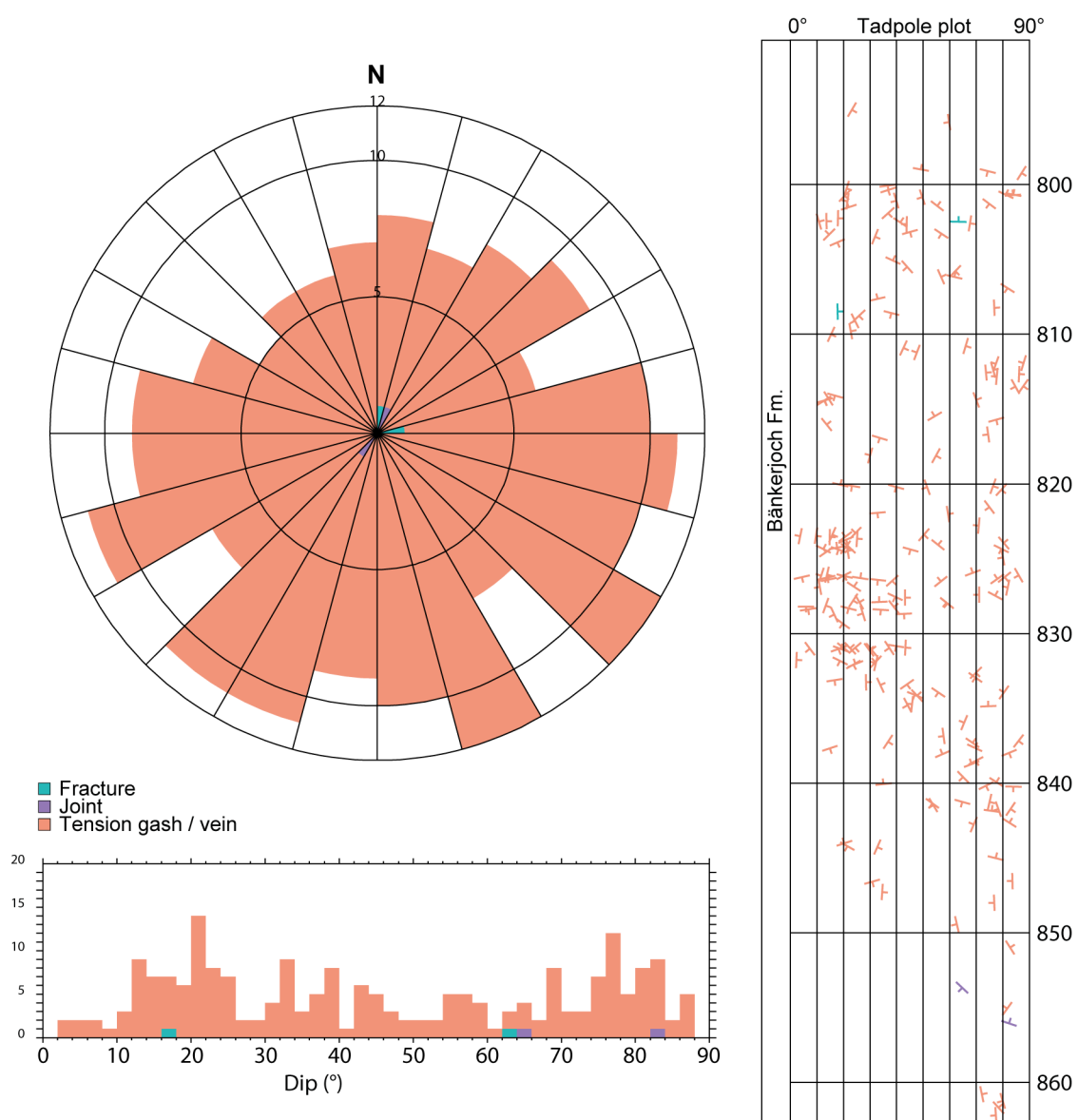


Fig. 4-55: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Bänkerjoch Formation)

Fractures (n = 2), joints (n = 2) and tension gashes / veins (n = 204).

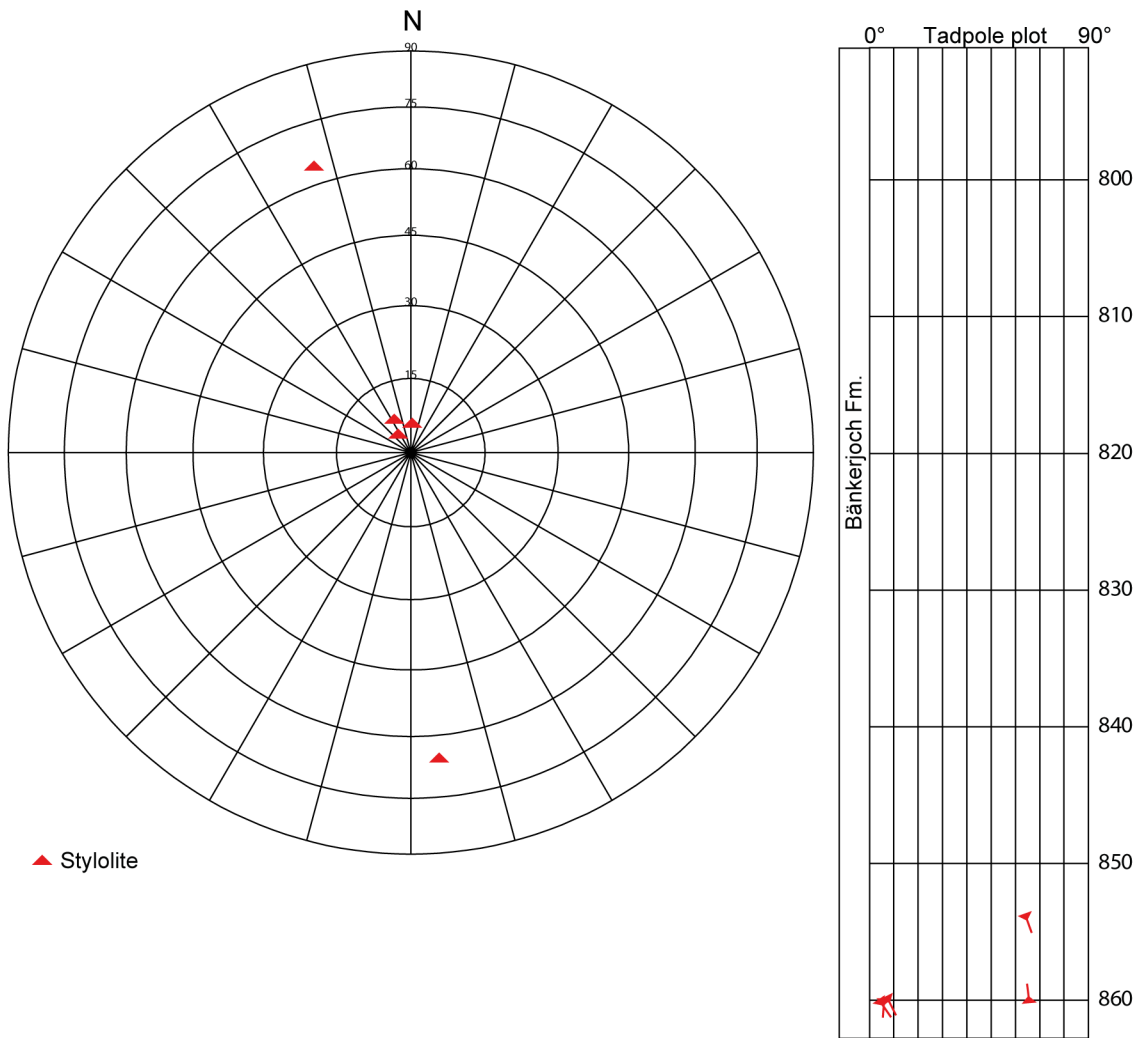


Fig. 4-56: Stereogram and depth plot of stylolites (Bänkerjoch Formation, n = 5)

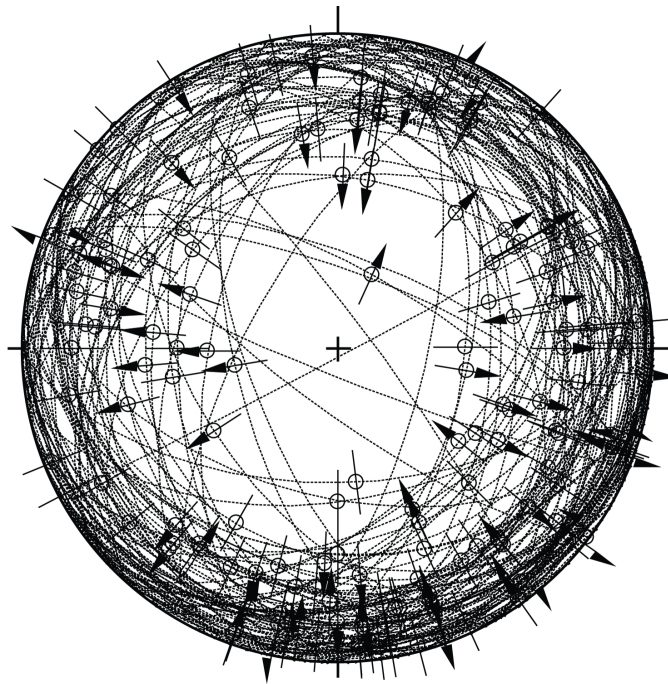


Fig. 4-57: Stereogram of fault planes with striations (including multiple lineations on a single fault plane; Bänkerjoch Formation, $n = 165$)

4.6 Muschelkalk

The Muschelkalk (862.77 m to 1'029.95 m MD log depth) shows high densities of all structure types. The dominant structures were mirror-like fault planes followed by stylolites, other fault planes, joints and veins. In addition, abundant millimetre- to centimetre-sized open pores (vugs) were observed. The latter particularly occurred within the dolostone of the Schinznach and Zegglingen Formations.

Note that only the data for oriented cores are presented. Some cores could not be oriented, and therefore some structures are not displayed in the following diagrams.

4.6.1 Schinznach Formation

The orientations and spatial distributions of structures observed in the Schinznach Formation (862.77 m to 932.47 m MD log) are shown in Figs. 4-58 to 4-64. The Schinznach Formation displays a high density of all structure types. While the fault planes and stylolites have a shallow dip angle, unassigned fractures show a predominant sub-vertical dip.

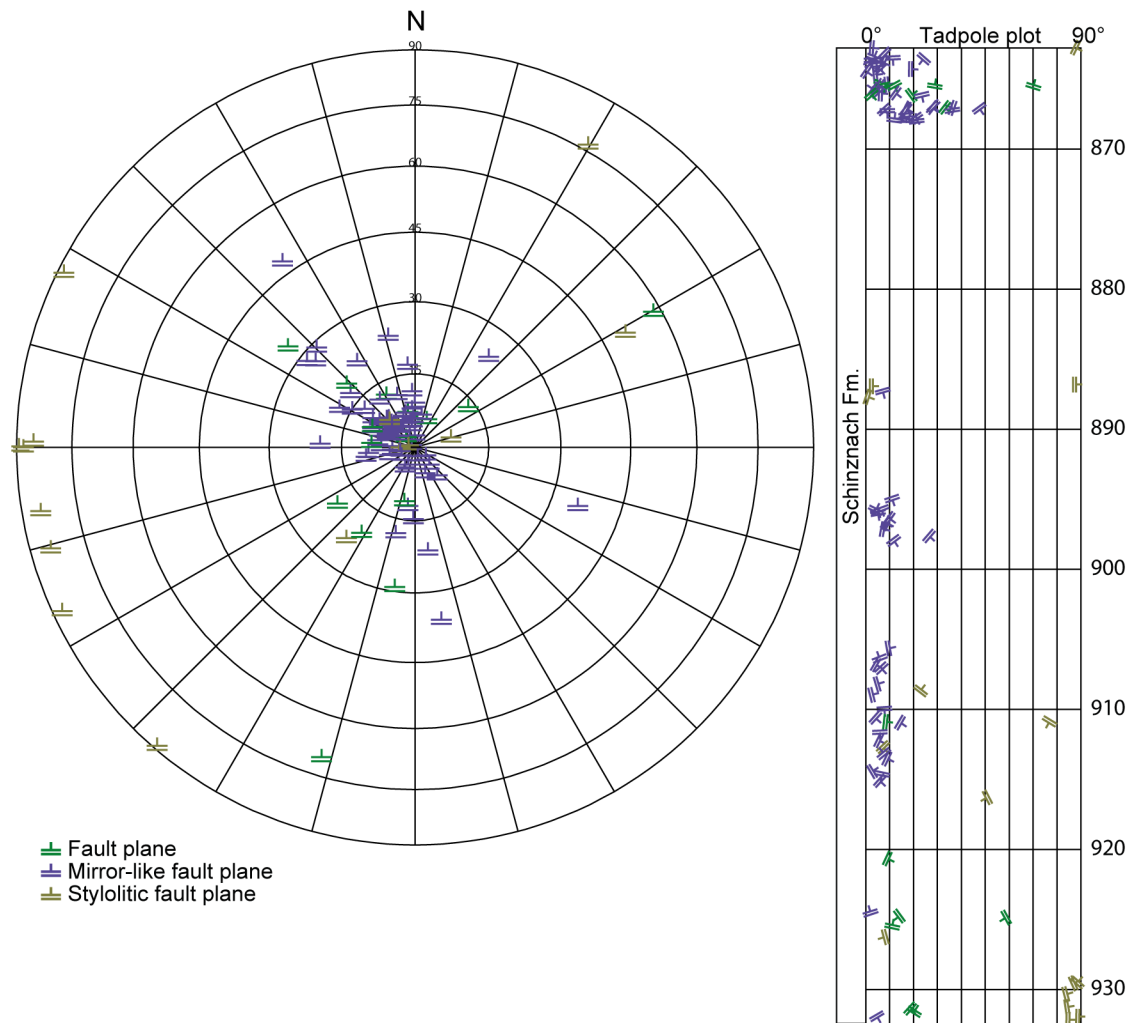


Fig. 4-58: Stereogram and depth plot of fault planes (Schinznach Formation)

Fault planes (n = 15), mirror-like fault planes (n = 66) and stylolitic fault planes (n = 15).

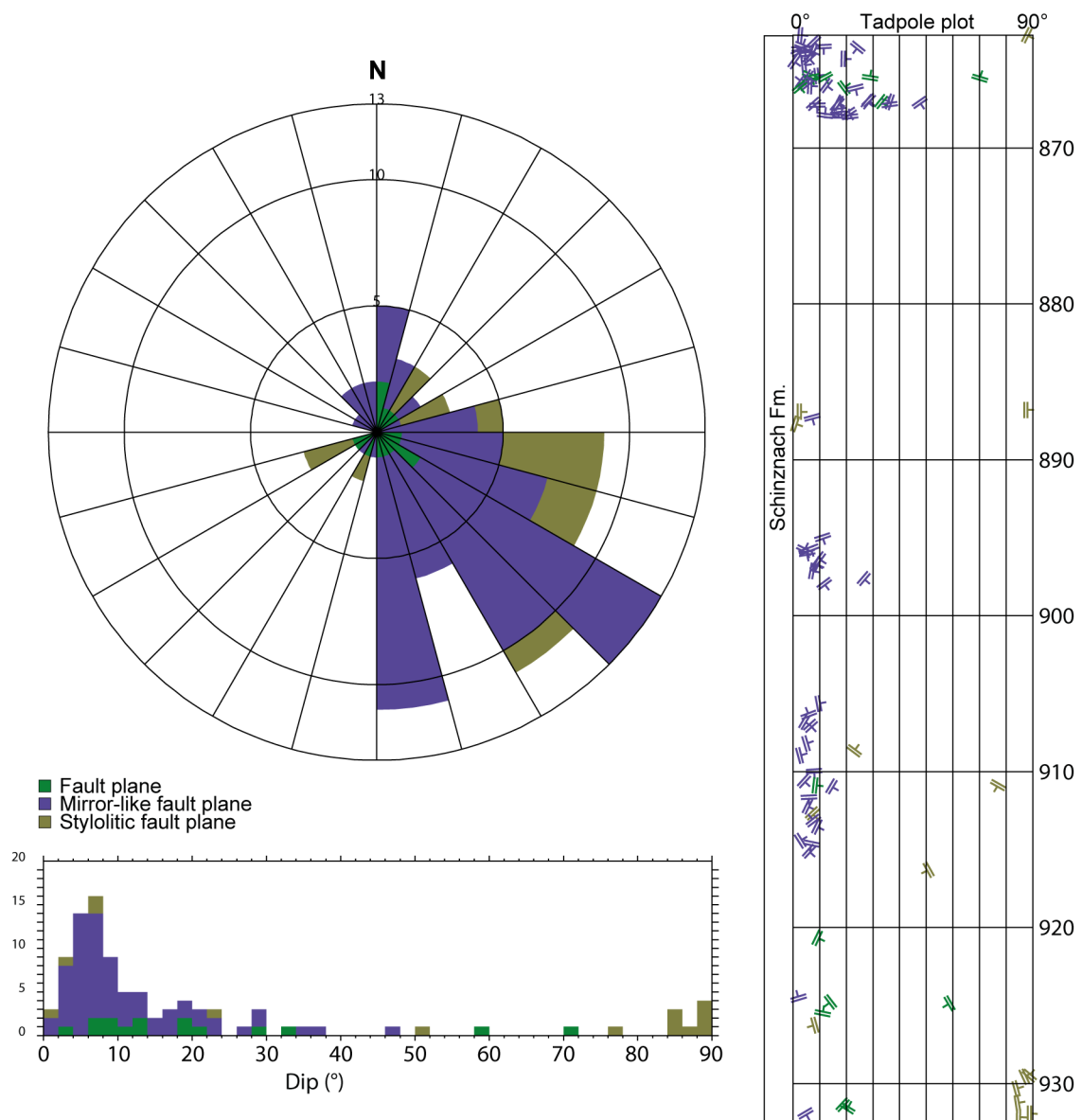


Fig. 4-59: Azimuth rose diagram, dip histogram and depth plot of fault planes (Schinznach Formation)

Fault planes ($n = 15$), mirror-like fault planes ($n = 66$) and stylolitic fault planes ($n = 15$).

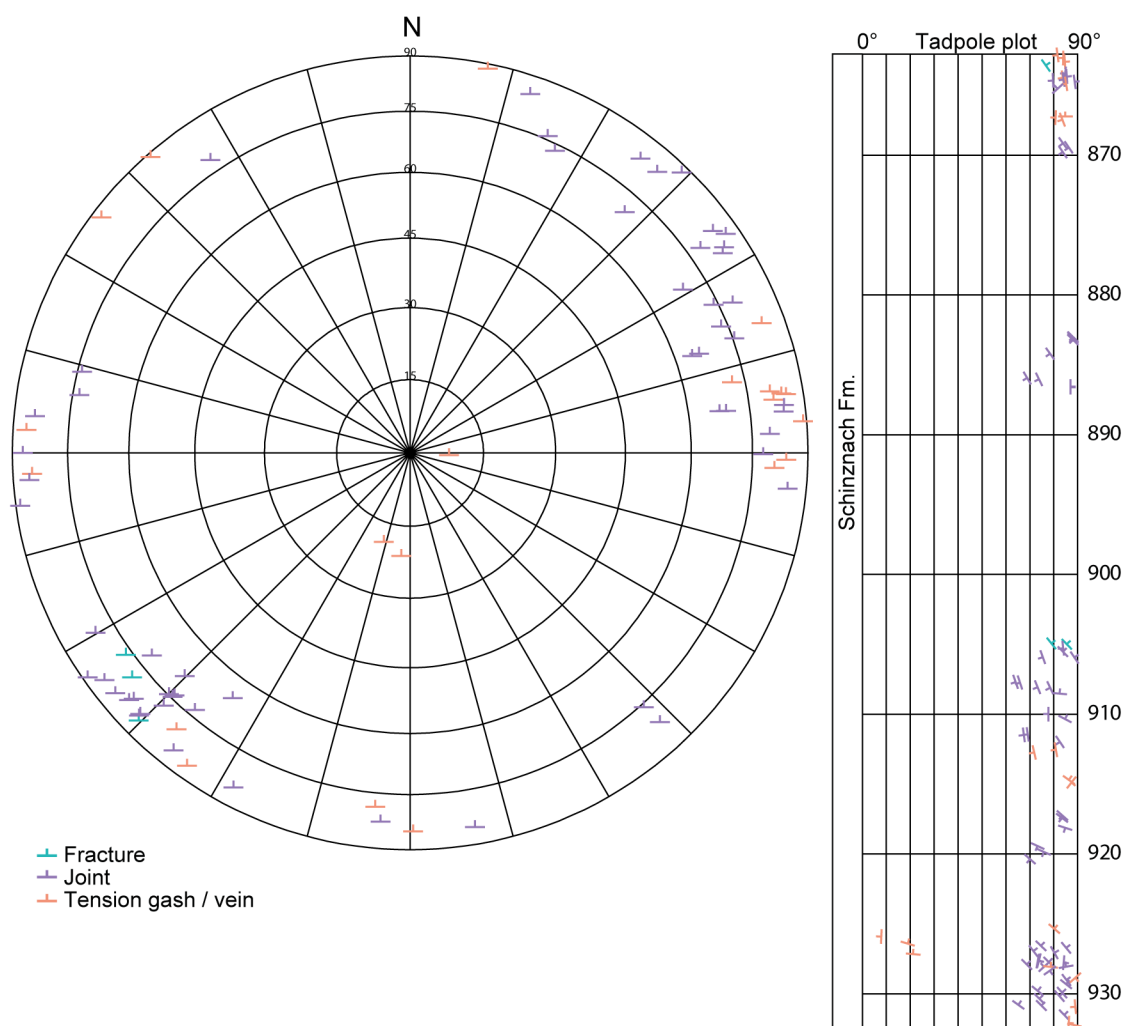


Fig. 4-60: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Schinznach Formation)

Fractures (n = 3), joints (n = 58) and tension gashes / veins (n = 21).

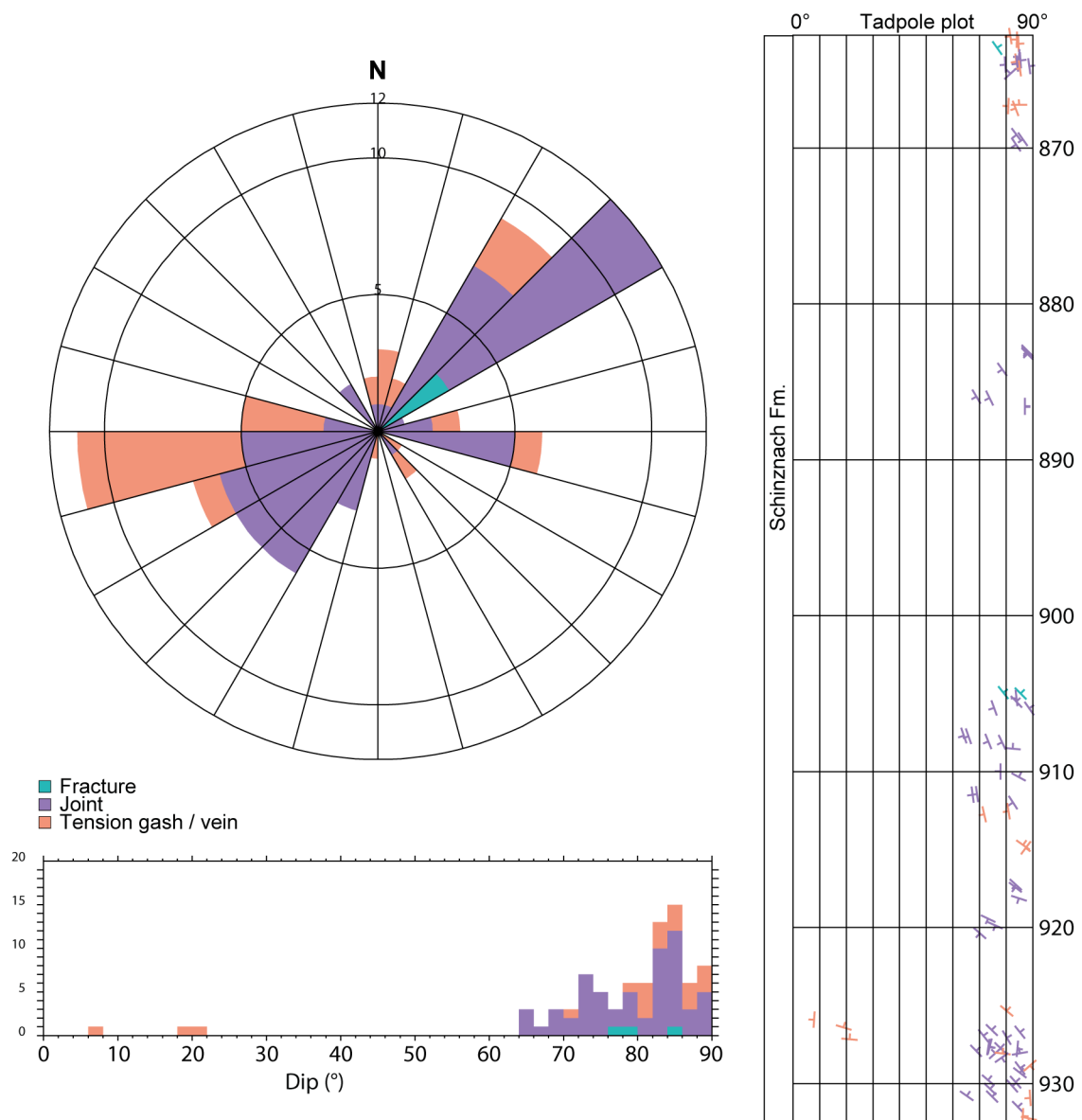


Fig. 4-61: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Schinznach Formation)

Fractures (n = 3), joints (n = 58) and tension gashes / veins (n = 21).

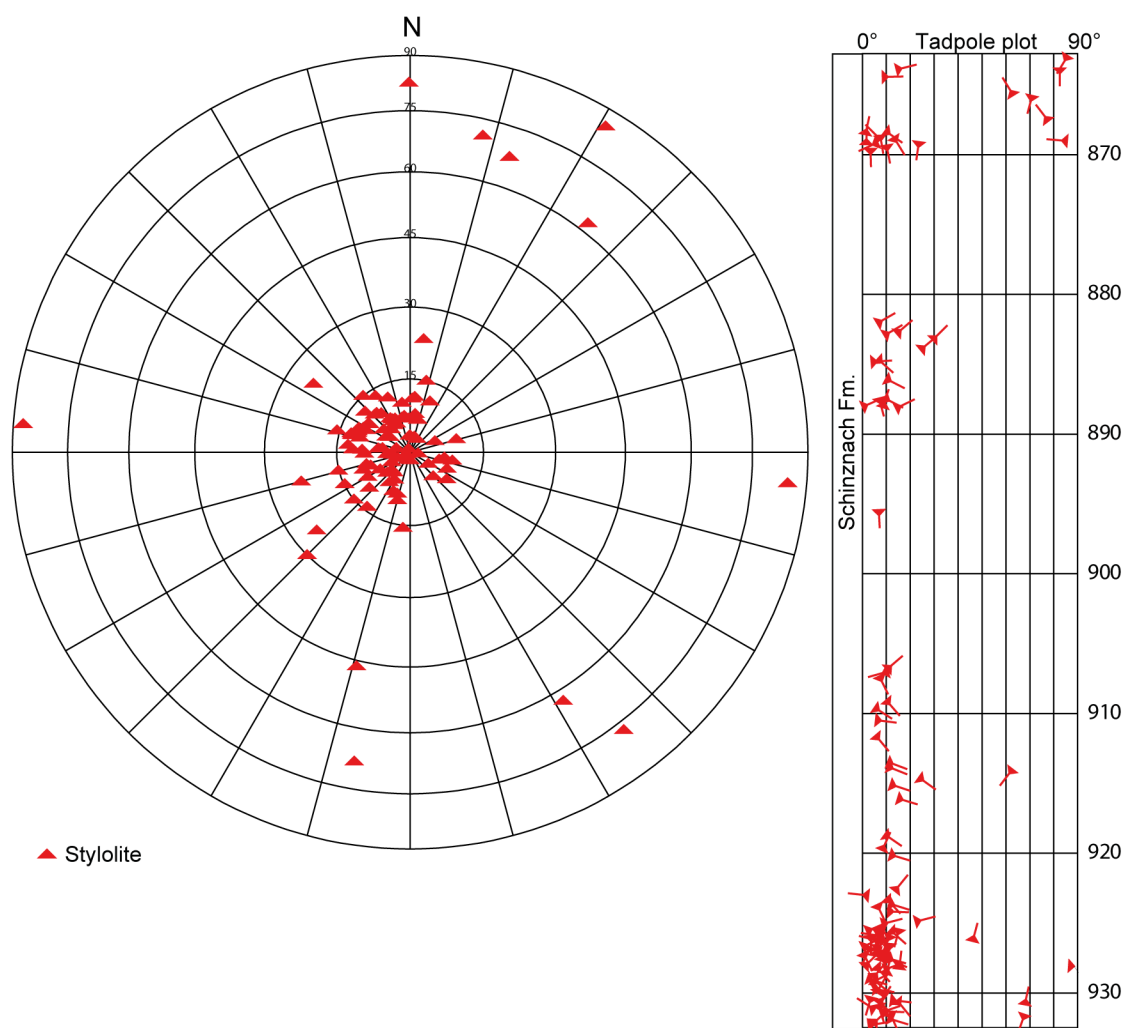


Fig. 4-62: Stereogram and depth plot of stylolites (Schinznach Formation, n = 108)

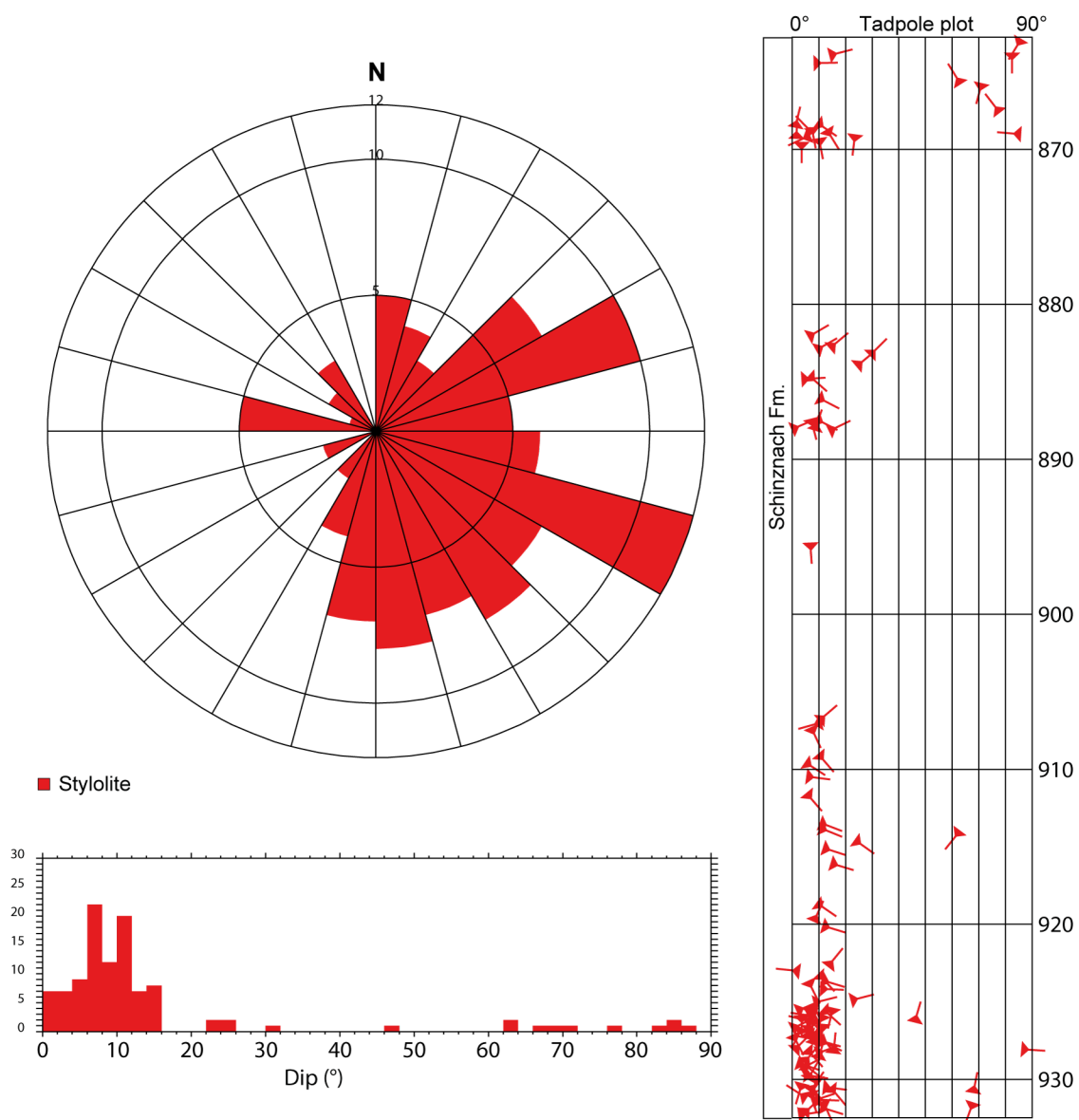


Fig. 4-63: Azimuth rose diagram, dip histogram and depth plot of stylolites (Schinznach Formation, n = 108)

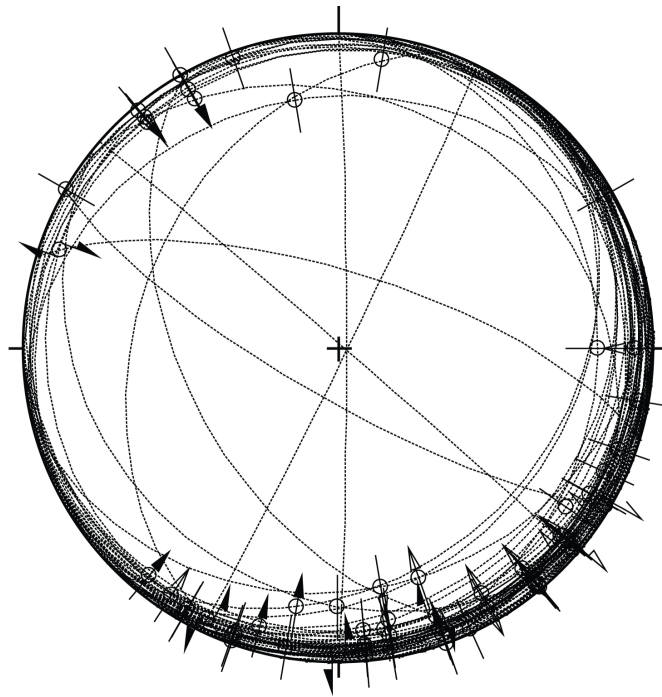


Fig. 4-64: Stereogram of fault planes with striations (including multiple lineations on a single fault plane; Schinznach Formation, $n = 66$)

4.6.2 Zeglingen Formation

The orientations and spatial distributions of the structures observed in the Zeglingen Formation (932.47 m to 993.97 m MD log depth) are shown in Figs. 4-65 to 4-69. This formation is rich in fault planes and veins. The structures are evenly distributed throughout the formation. Stylolites are absent.

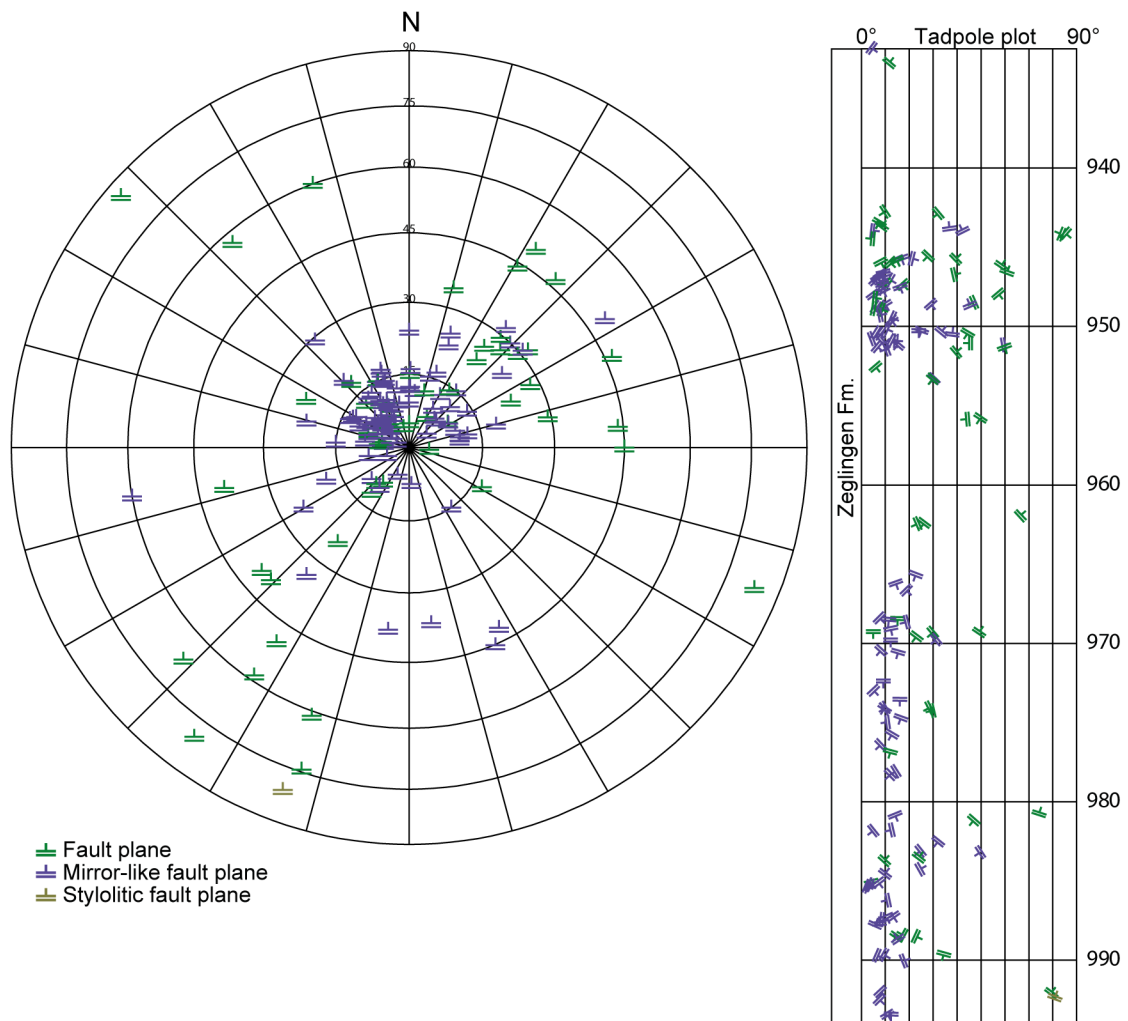


Fig. 4-65: Stereogram and depth plot of fault planes (Zeglingen Formation)

Fault planes (n = 52), mirror-like fault planes (n = 92) and stylolitic fault planes (n = 1).

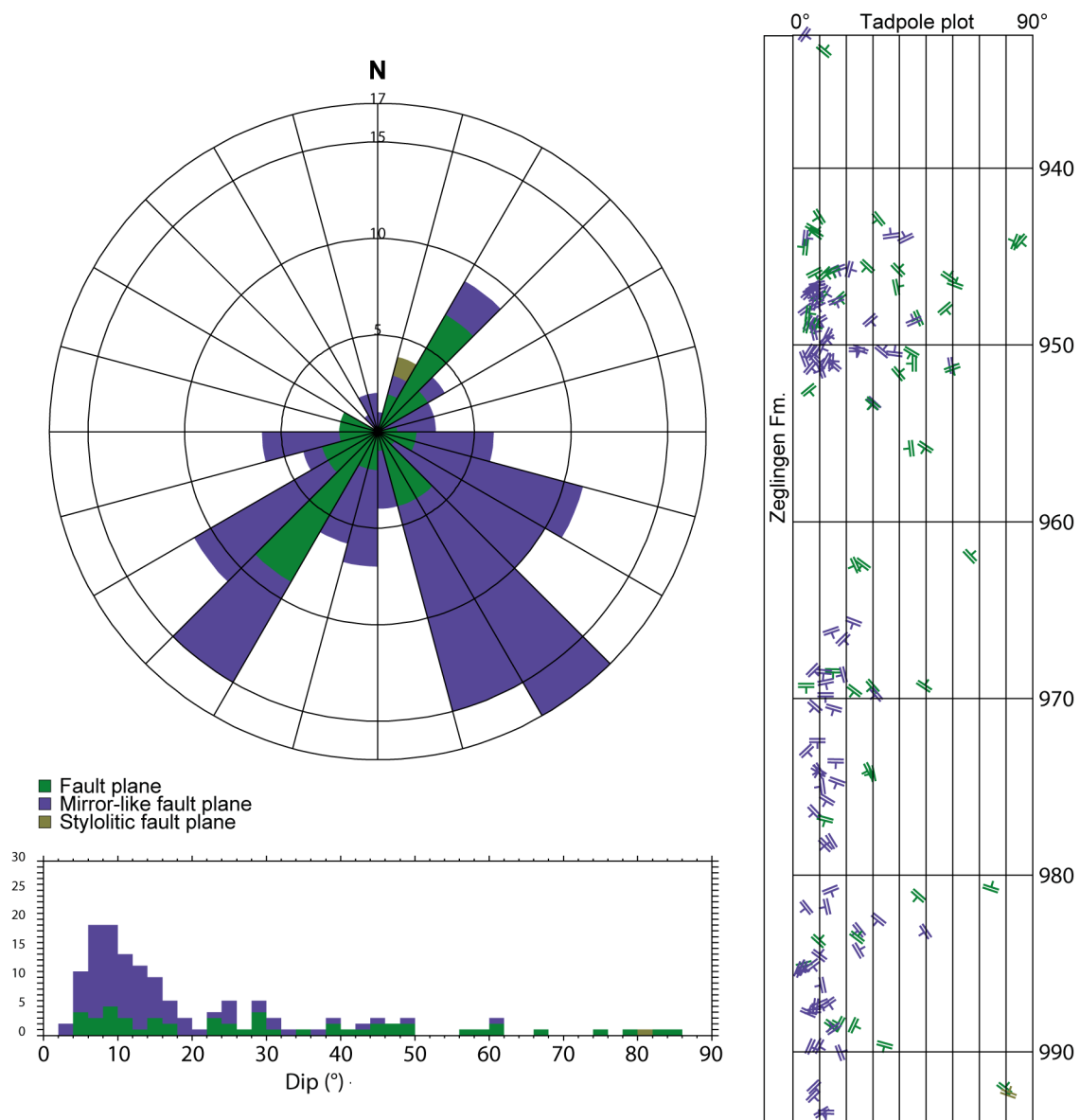


Fig. 4-66: Azimuth rose diagram, dip histogram and depth plot of fault planes (Zeglingen Formation)

Fault planes ($n = 52$), mirror-like fault planes ($n = 92$) and stylolitic fault planes ($n = 1$).

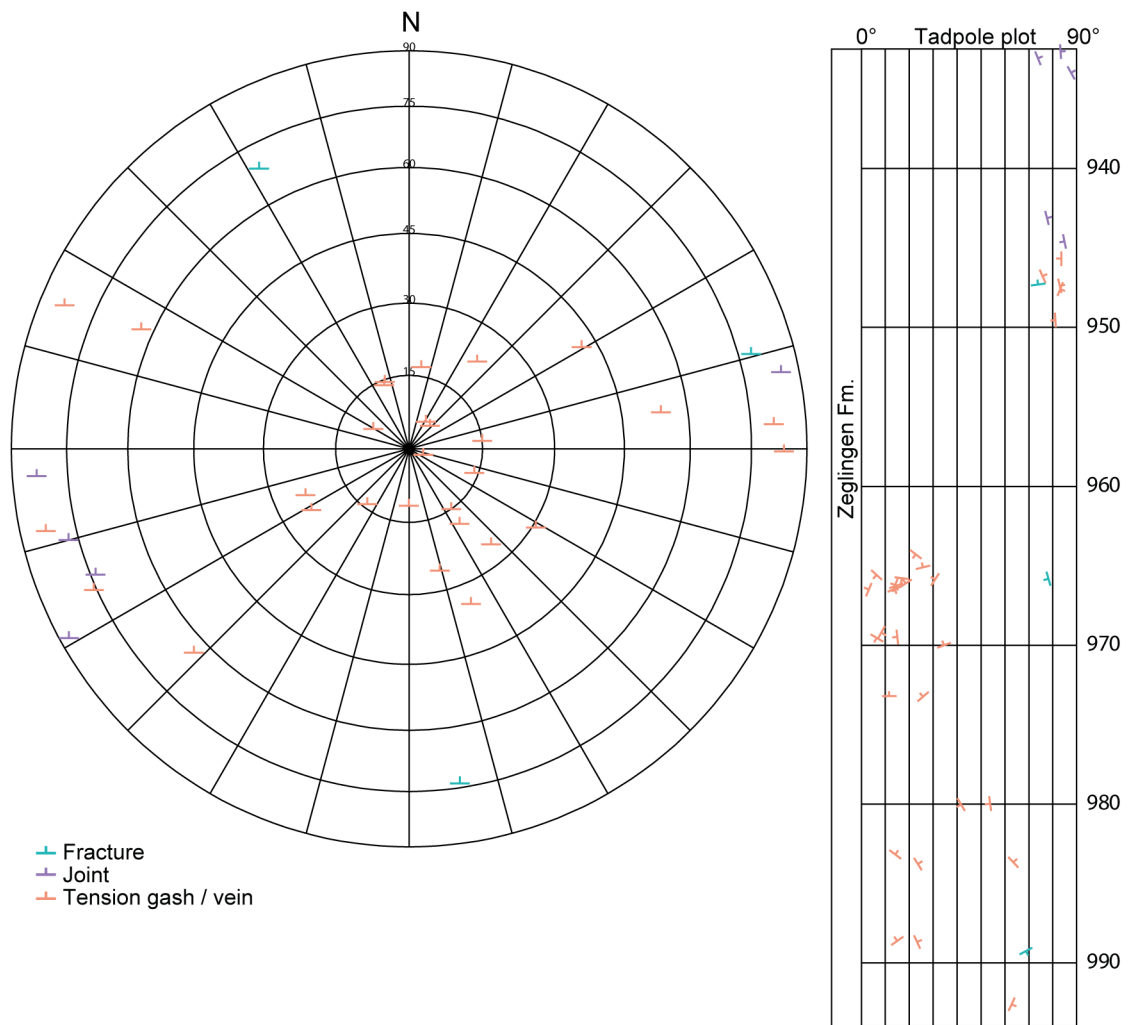


Fig. 4-67: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Zeglingen Formation)

Fractures (n = 3), joints (n = 5) and tension gashes / veins (n = 29).

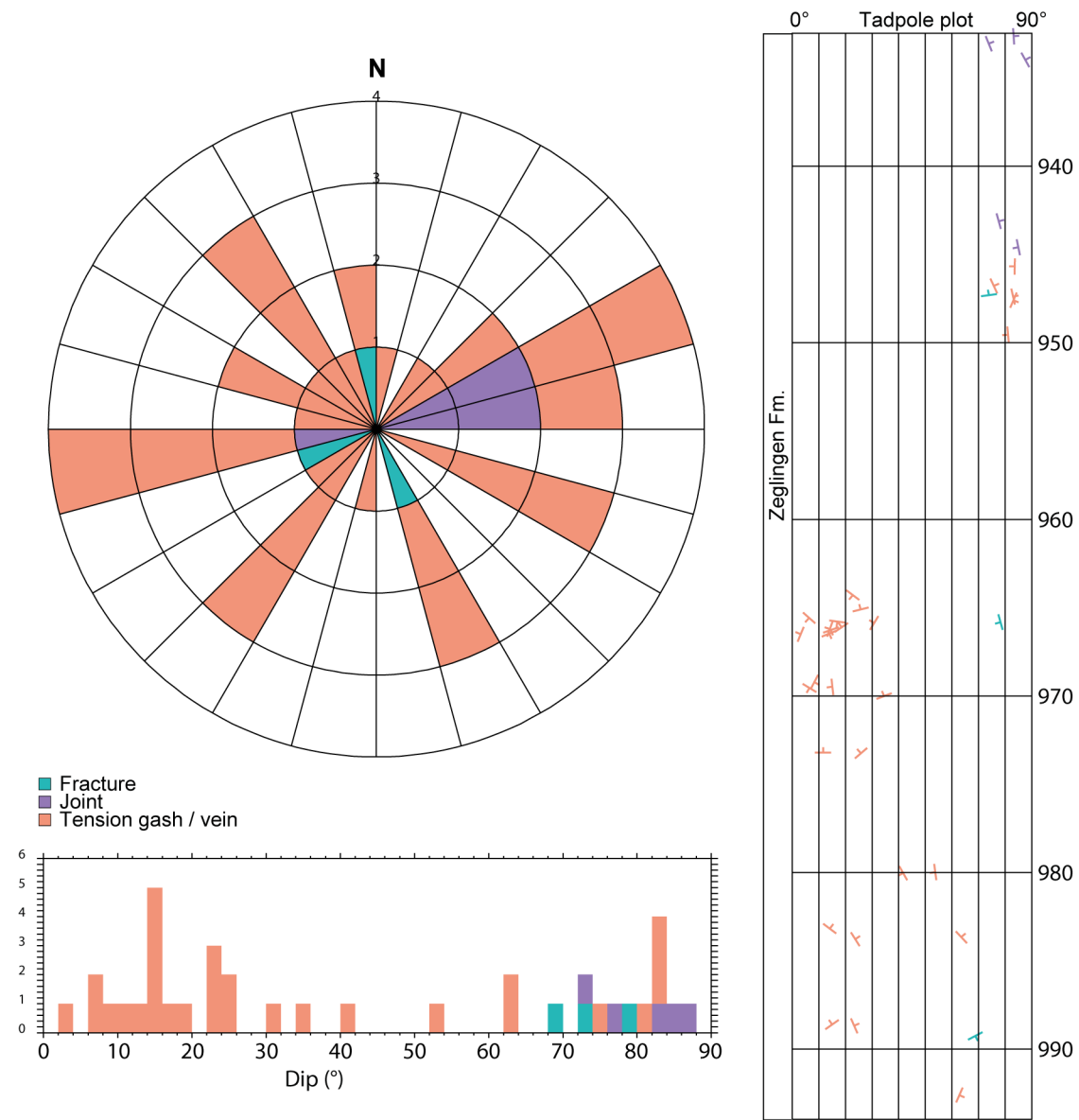


Fig. 4-68: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Zeglingen Formation)

Fractures (n = 3), joints (n = 5) and tension gashes / veins (n = 29).

d

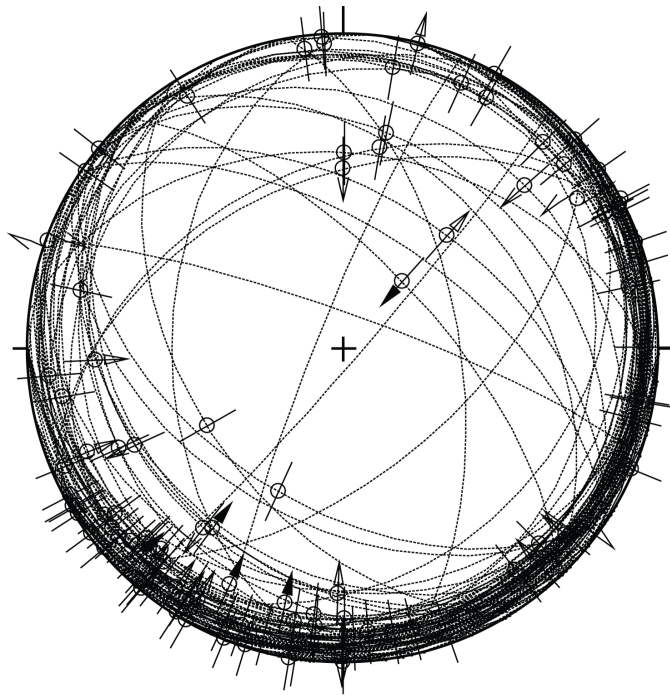


Fig. 4-69: Stereogram of fault planes with striations (including multiple lineations on a single fault plane; Zeglingen Formation, $n = 106$)

4.6.3 Kaiseraugst Formation

The orientations and spatial distributions of the structures observed in the Kaiseraugst Formation (993.97 m to 1'029.95 m MD log depth) are shown in Figs. 4-70 to 4-73. The dominant structures are mirror-like fault planes. Stylolites are absent.

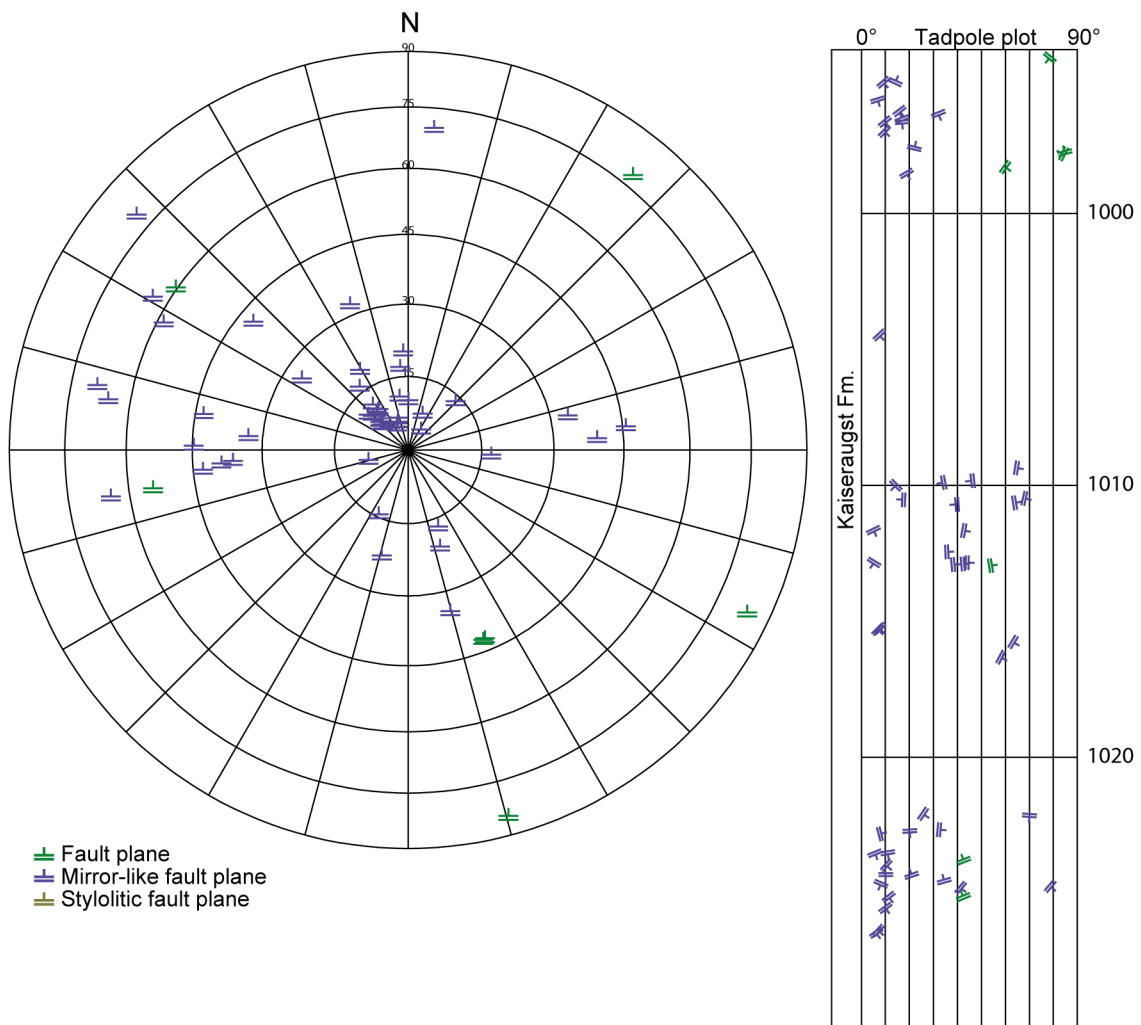


Fig. 4-70: Stereogram and depth plot of fault planes (Kaiseraugst Formation)

Fault planes ($n = 7$) and mirror-like fault planes ($n = 49$). Stylolitic fault planes were not observed ($n = 0$).

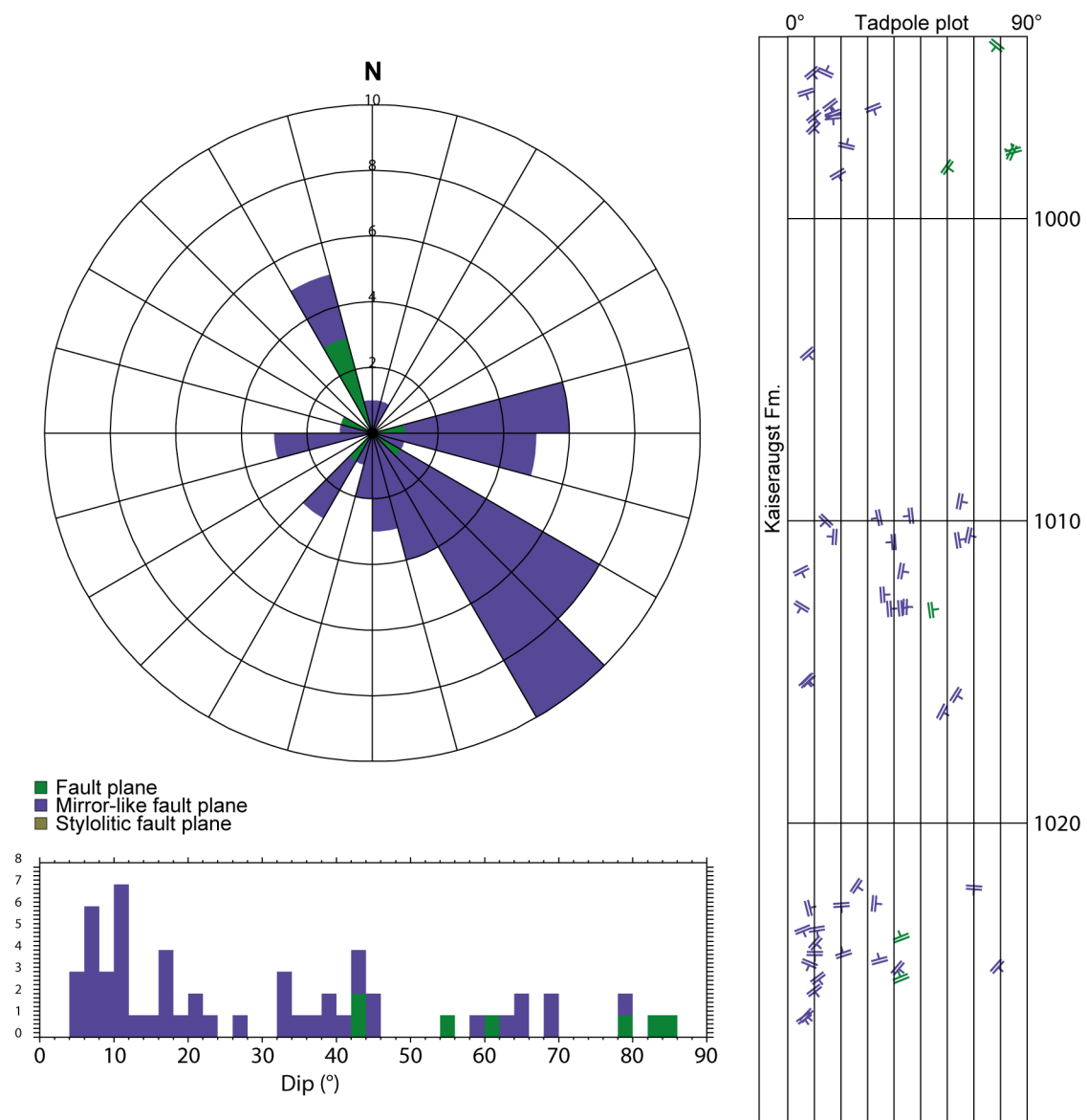


Fig. 4-71: Azimuth rose diagram, dip histogram and depth plot of fault planes (Kaiseraugst Formation)

Fault planes ($n = 7$) and mirror-like fault planes ($n = 49$). Stylolitic fault planes were not observed ($n = 0$).

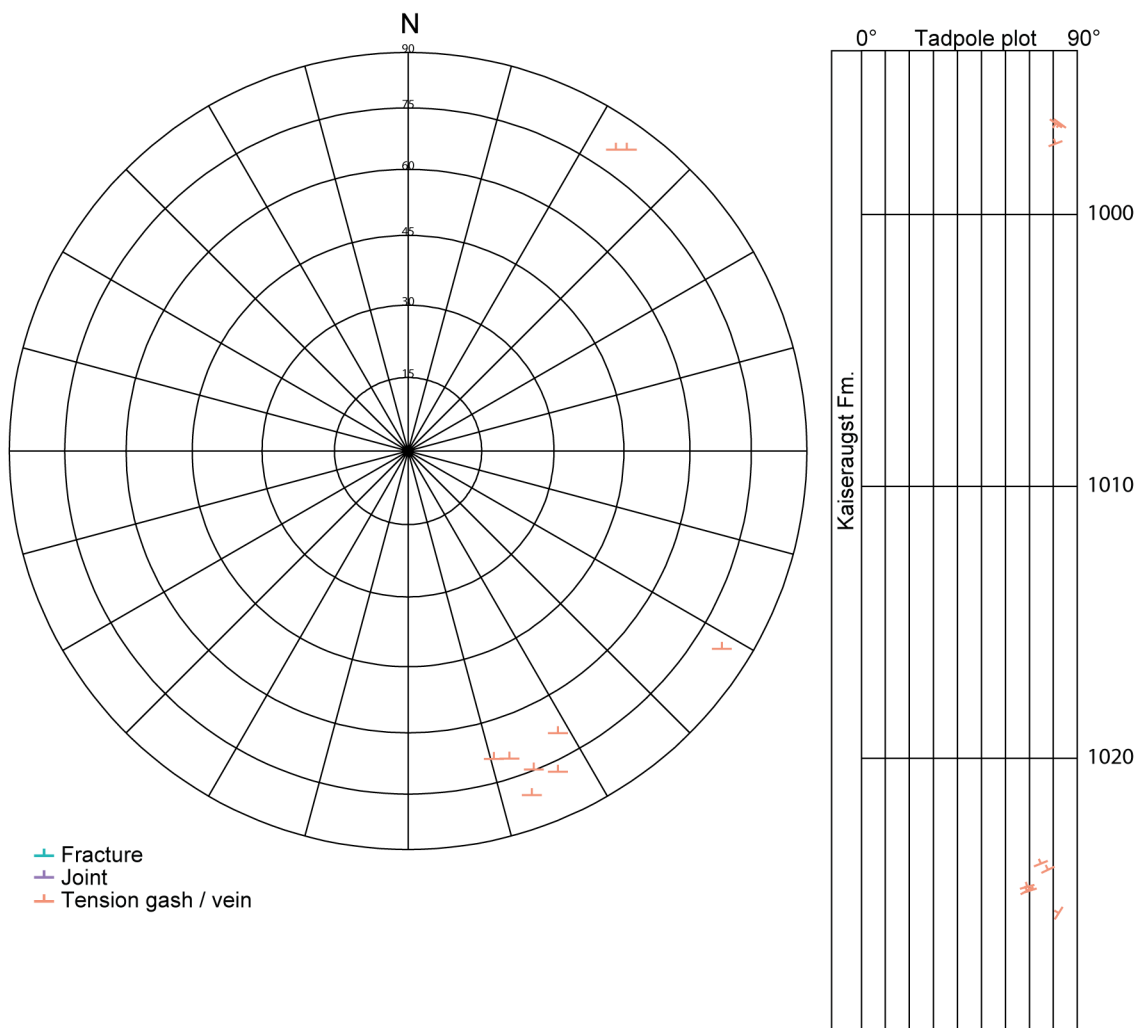


Fig. 4-72: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Kaiseraugst Formation)
Fractures (n = 0), joints (n = 0) and tension gashes / veins (n = 9).

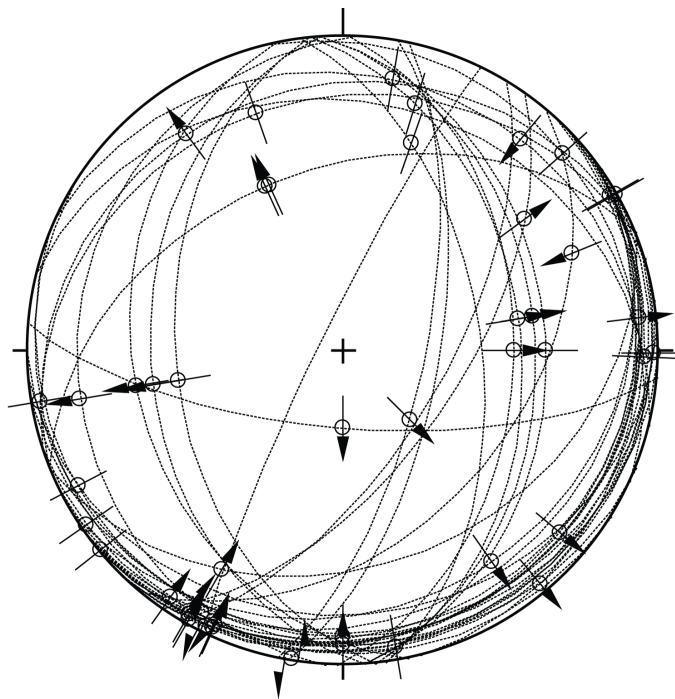


Fig. 4-73: Stereogram of fault planes with striations (including multiple lineations on a single fault plane; Kaiseraugst Formation, $n = 45$)

4.7 Dinkelberg Formation, Weitenau Formation and Crystalline basement

The orientations and spatial distributions of the structures observed in the Dinkelberg Formation, the Weitenau Formation and the Crystalline basement (1'029.95 to 1'099.25 m MD; base of cored section) are shown in Figs. 4-74 to 4-78. This zone is characterised by a very low number of structures; however, FMI log was not available blow 1'054 m MD log depth and therefore, the drill cores could not be oriented. Stylolites are absent.

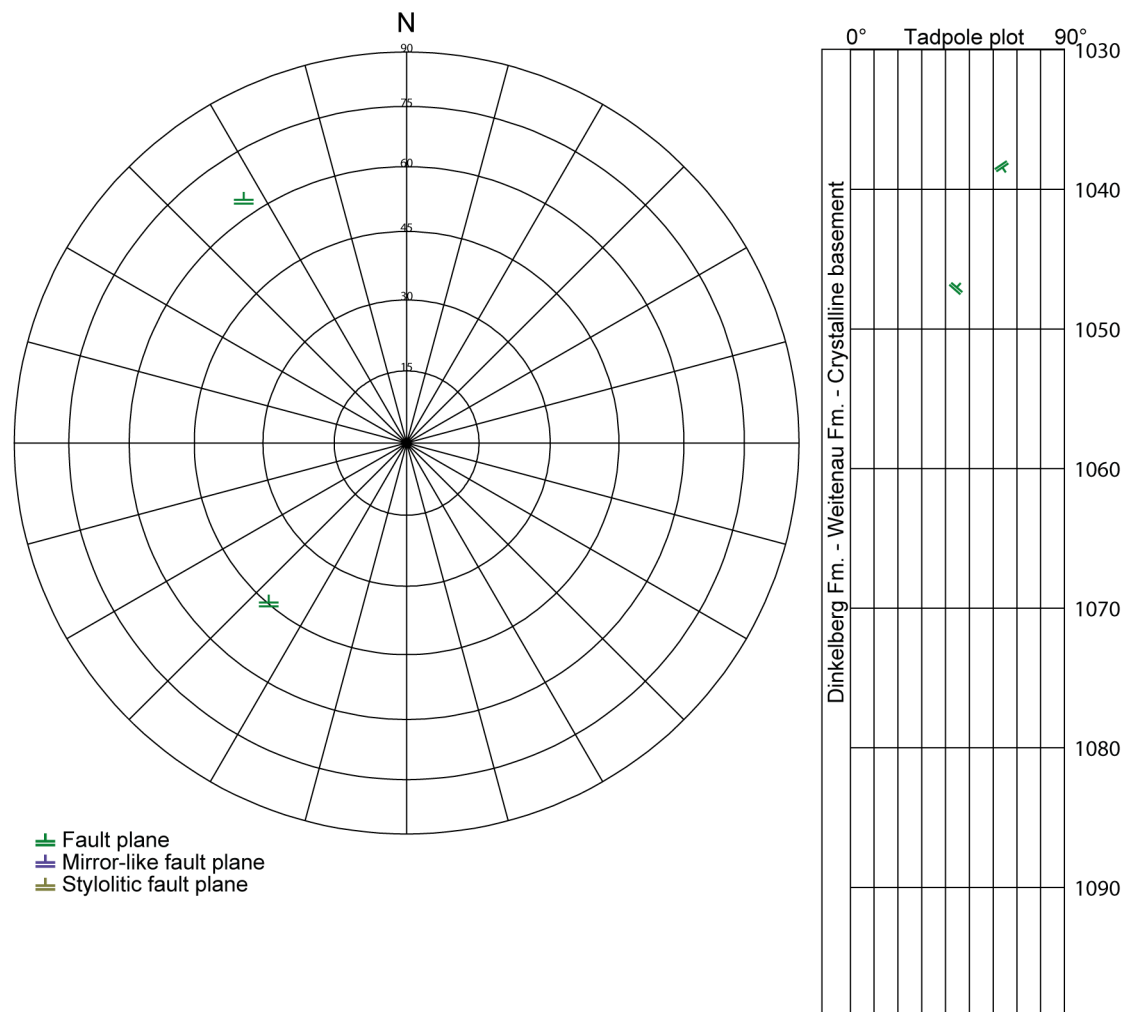


Fig. 4-74: Stereogram and depth plot of fault planes (Dinkelberg Formation, Weitenau Formation and Crystalline basement)

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

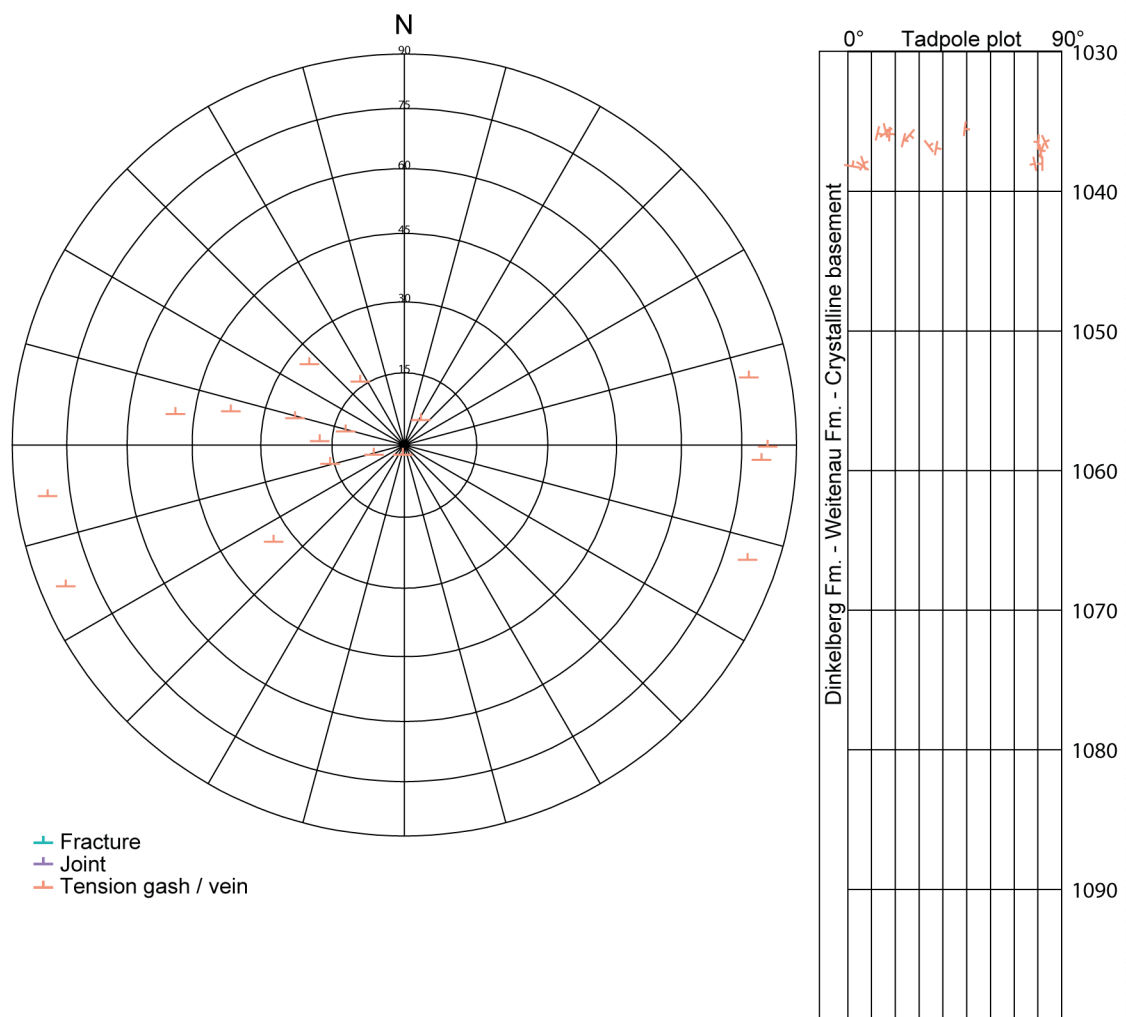


Fig. 4-75: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures (Dinkelberg Formation, Weitenau Formation and Crystalline basement)

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

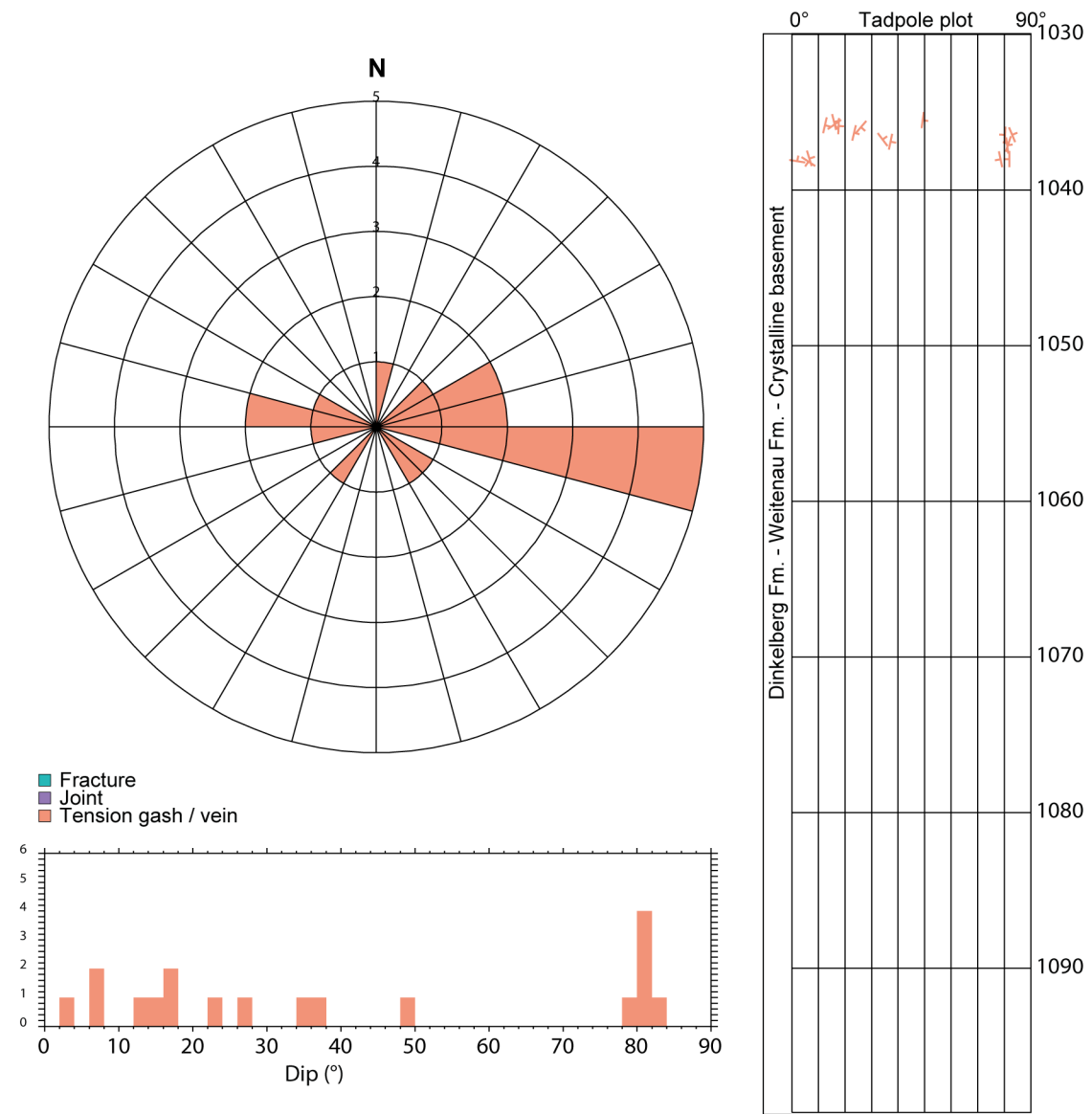


Fig. 4-76: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures (Dinkelberg Formation, Weitenau Formation and Crystalline basement)

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

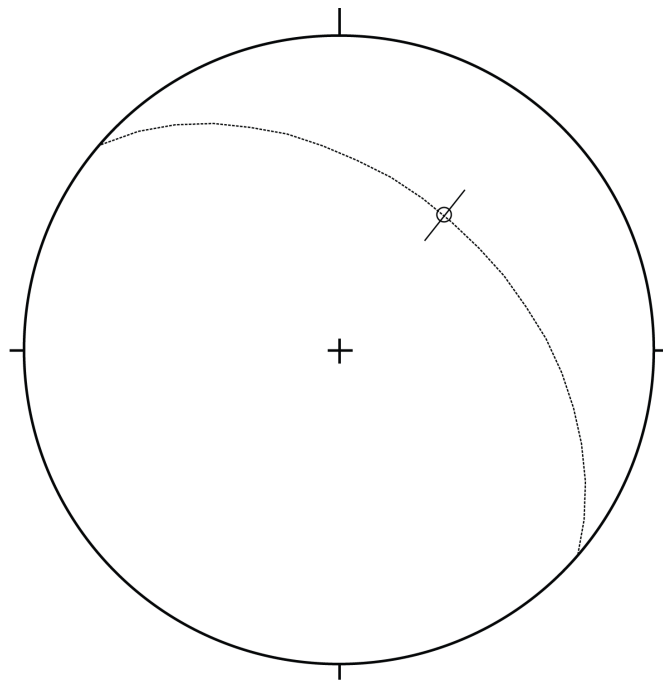


Fig. 4-77: Stereogram of fault planes with striations (Dinkelberg Formation, Weitenau Formation and Crystalline basement, $n = 1$)

5 Main structural findings

Among the relevant geological features within the study interval 460.00 m to 1'099.25 m MD (log depth) presented in Chapters 3 and 4, two particularly prominent zones deserve a more detailed examination.

5.1 Deformed Opalinus Clay at 668.00 m to 679.30 m MD (log depth)

A distinct deformation zone was encountered within the Opalinus Clay from 668.00 m to 679.30 m MD log depth (see Fig. 5-1). This zone is characterised by disturbed non-horizontal bedding with bedding planes inclined up to 30° and dip azimuths towards NE, E, SE and SW. An example of variably oriented bedding planes is provided in Fig. 5-2. There is a prominent and abrupt change in dip angle and dip direction at 676.50 m MD (log depth) from strata dipping 10° ESE to strata dipping slightly steeper (15°) towards SW below 676.50 m MD (log depth).

The majority of structures interpreted in this zone are fault planes ($n = 83$) and tension gashes ($n = 14$). Examples are provided in Fig. 5-2 to Fig. 5-5. Most fault planes ($n = 63$) are mineralised with thin, synkinematic, often fibrous calcite (not exceeding 0.5 mm in thickness, see Figs. 5-2, 5-3 and 5-5). The latter clearly correlates with the FMI images causing a characteristic halo effect and a resistive response on the FMI (Fig. 5-2). In addition, sixteen non-mineralised faults were also interpreted as exemplified in Fig. 5-4. Commonly, the faults do not crosscut the whole drill core and terminate at adjacent beds (Figs. 5-3 to 5-5). They are commonly associated with offsets of bedding on the millimetre- to centimetre-scale, however, not exceeding 3 cm (see Fig. 5-4).

In the stereogram of Fig. 5-6, fault planes show variable dip angles (5° to 60°) with predominantly SE- (mean 140/07; $n = 27$) and NW- (mean 310/19; $n = 19$) dipping planes. In addition, there is also a SW-dipping fault cluster (mean 207/25; $n = 23$). The fracture density in this zone is relatively high (8 faults per metre; $P32 = 7 \text{ m}^2/\text{m}^3$). Locally, dense fracturing, e.g. between 673 m and 677 m MD (log depth), leads to even higher fracture densities with up to 19 faults per metre (up to $P32 = 20 \text{ m}^2/\text{m}^3$; Fig. 5-1).

Striations at fault planes are generally weakly developed in this zone. From the total of 83 faults recorded in this zone, 34 kinematic indicators associated with almost exclusively dip-parallel slip could be measured (Fig. 5-6). Although the vertical offsets along faults were small (millimetre up to 3 cm in scale), they were clearly visible on the intact cores and allowed the determination of 23 shear senses. The vast majority ($n = 20$) of these shear senses are associated with SE- and NW-dipping normal faults (see Fig. 5-7).

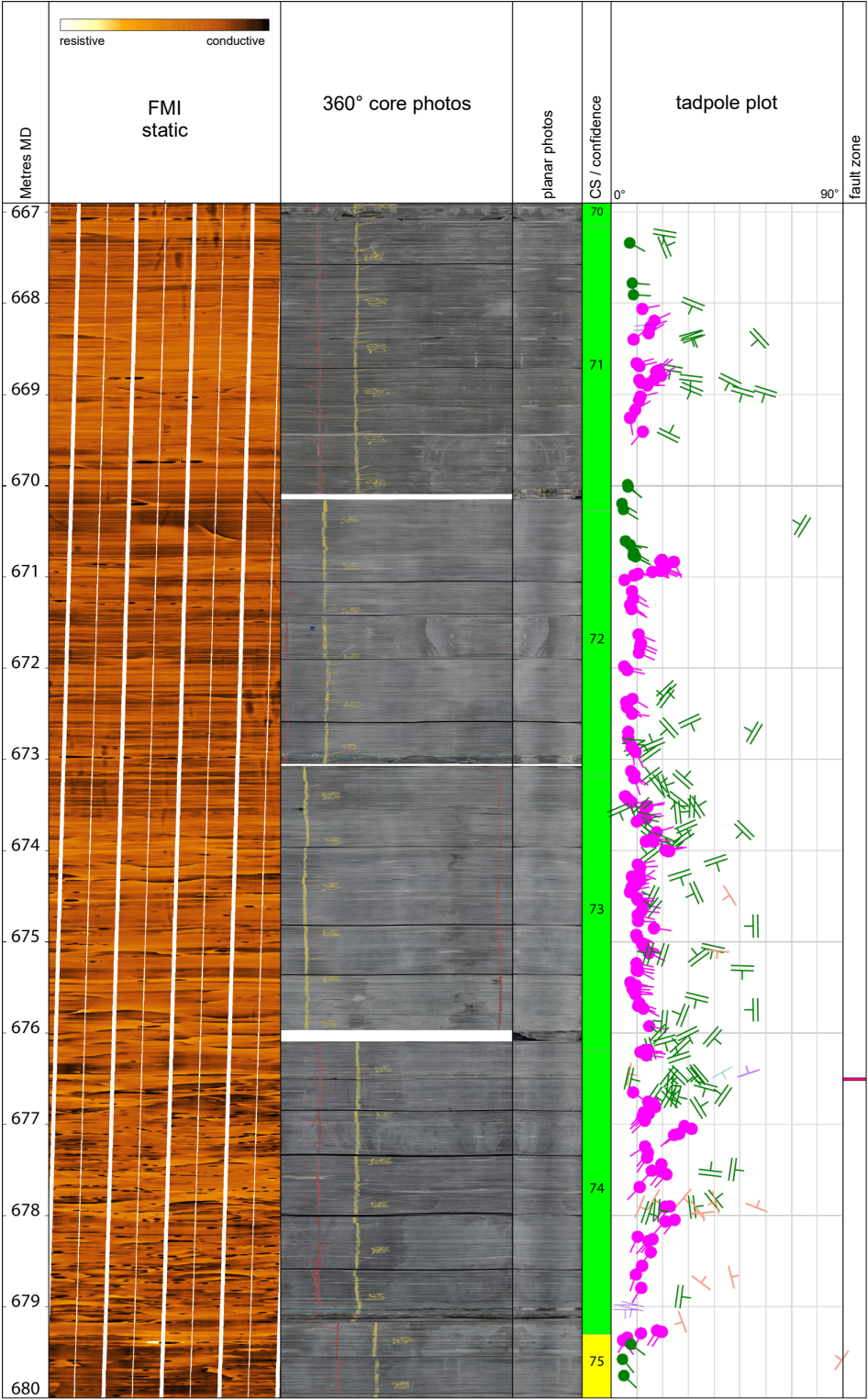


Fig. 5-1: Overview plot of the Opalinus Clay interval from 667 m to 680 m MD (log depth)
Note the abrupt changes in bedding orientation (magenta tadpoles) along fault planes, e.g. at 669 m MD (log depth), at 674 m MD (log depth) and at 676.5 m MD (log depth).

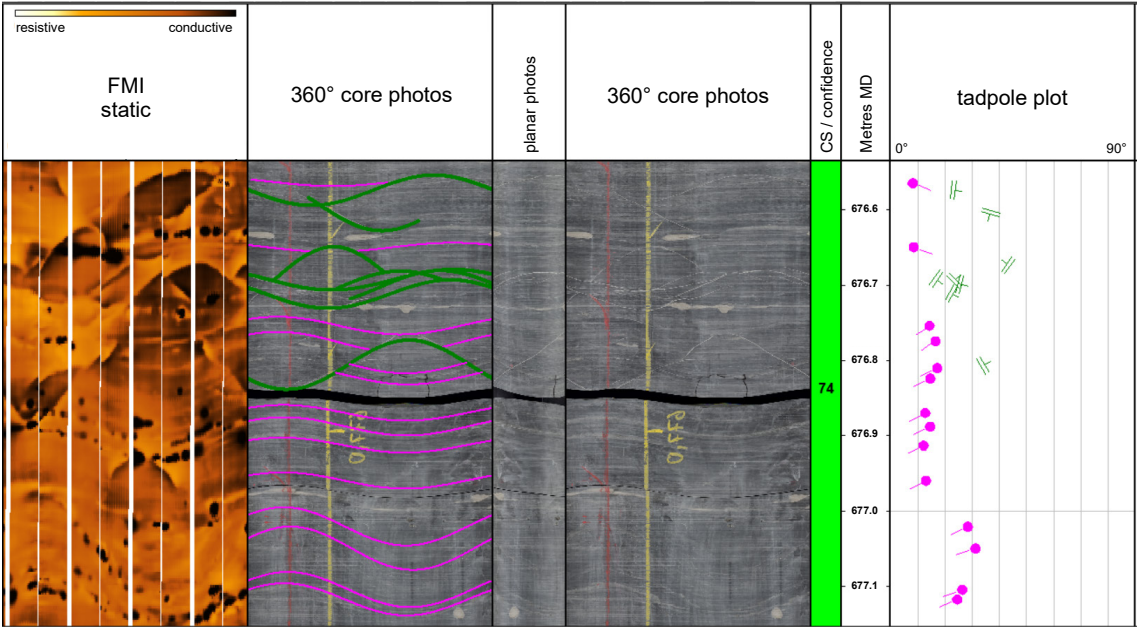


Fig. 5-2: Deformed bedding in Opalinus Clay at 676.80 m MD (log depth)

Note the abrupt change in dip angle and dip azimuth along the faults at 676.70 m MD (log depth). The resistive FMI image response (left hand track) of the fault planes, e.g. at 676.70 m MD (log depth) and at 676.82 m MD (log depth) causes a halo effect along their traces and confirms the cemented character as observed in drill cores.

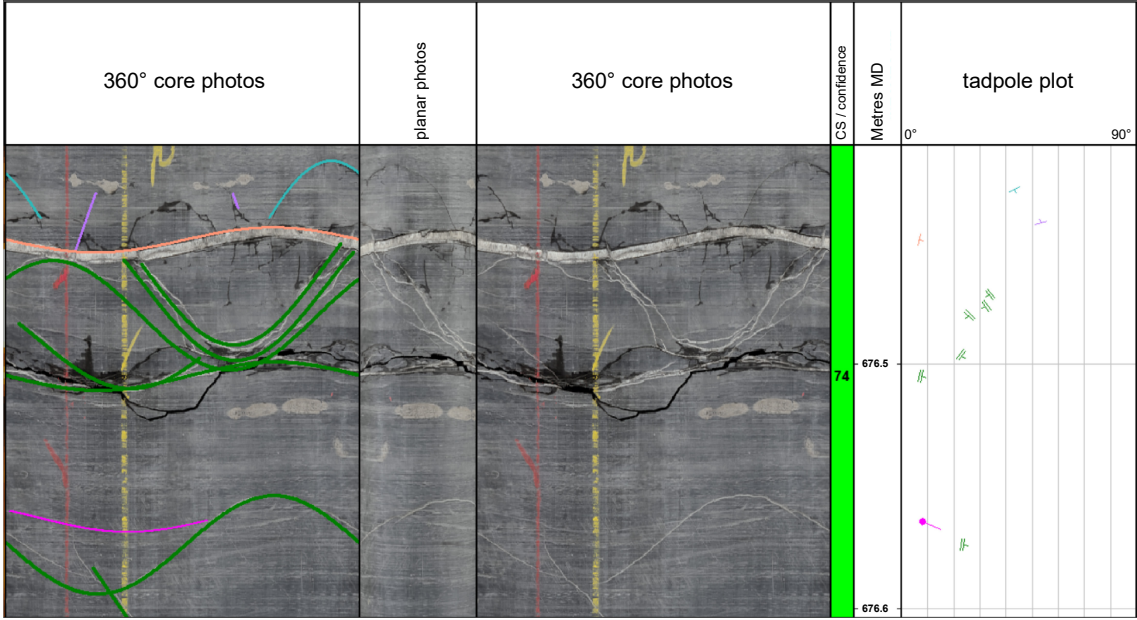


Fig. 5-3: Bedding-confined, cemented faults in the Opalinus Clay at 676.50 m MD (log depth)

Note the 4 mm thick tension gash (TG) at 676.45 m MD (log depth) characterised by fibrous calcite crystals oriented perpendicular to the plane. The TG is offset by about 2 mm by the normal fault below at 676.47 m MD (log depth), while other fault planes terminate against the lower boundary of the TG.

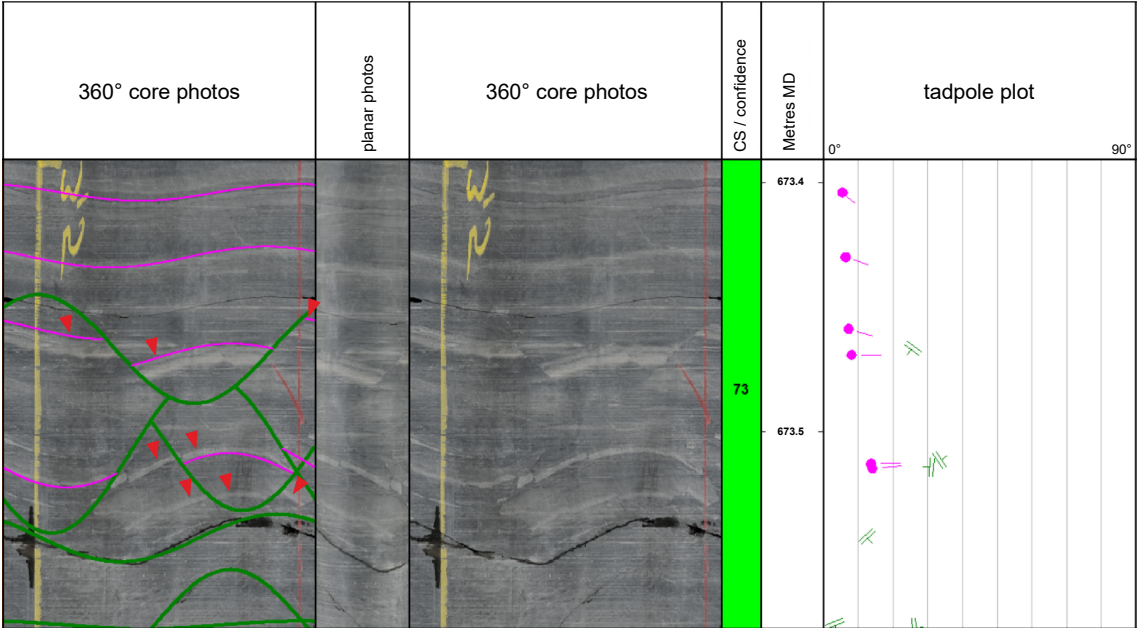


Fig. 5-4: Non-mineralised normal faults within the Opalinus Clay at 673.50 m MD (log depth)
Note the clear truncation of beds and millimetre- to centimetre-scale displacements related to normal faults at 673.47 m MD (log depth) and 673.51 m MD (log depth). The offset / truncated beds are indicated by red arrows.

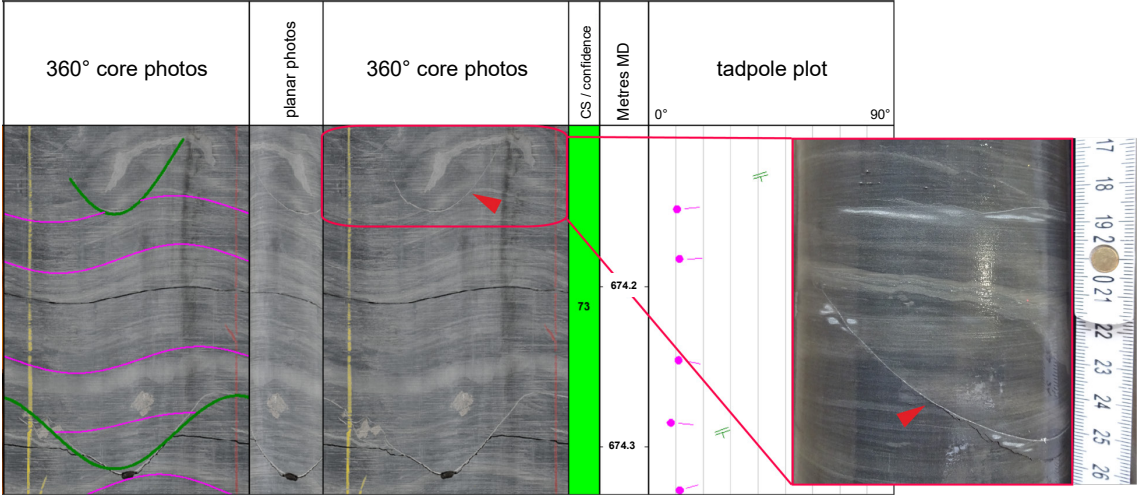


Fig. 5-5: Synsedimentary faulting in the Opalinus Clay
The calcitic (white) mineralised fault plane at 674.13 m MD (log depth, red arrow) does not crosscut the whole drill core and abuts on a sedimentary bed. It is therefore interpreted as a synsedimentary fault which was most likely reactivated at a later stage, allowing the calcite precipitation.

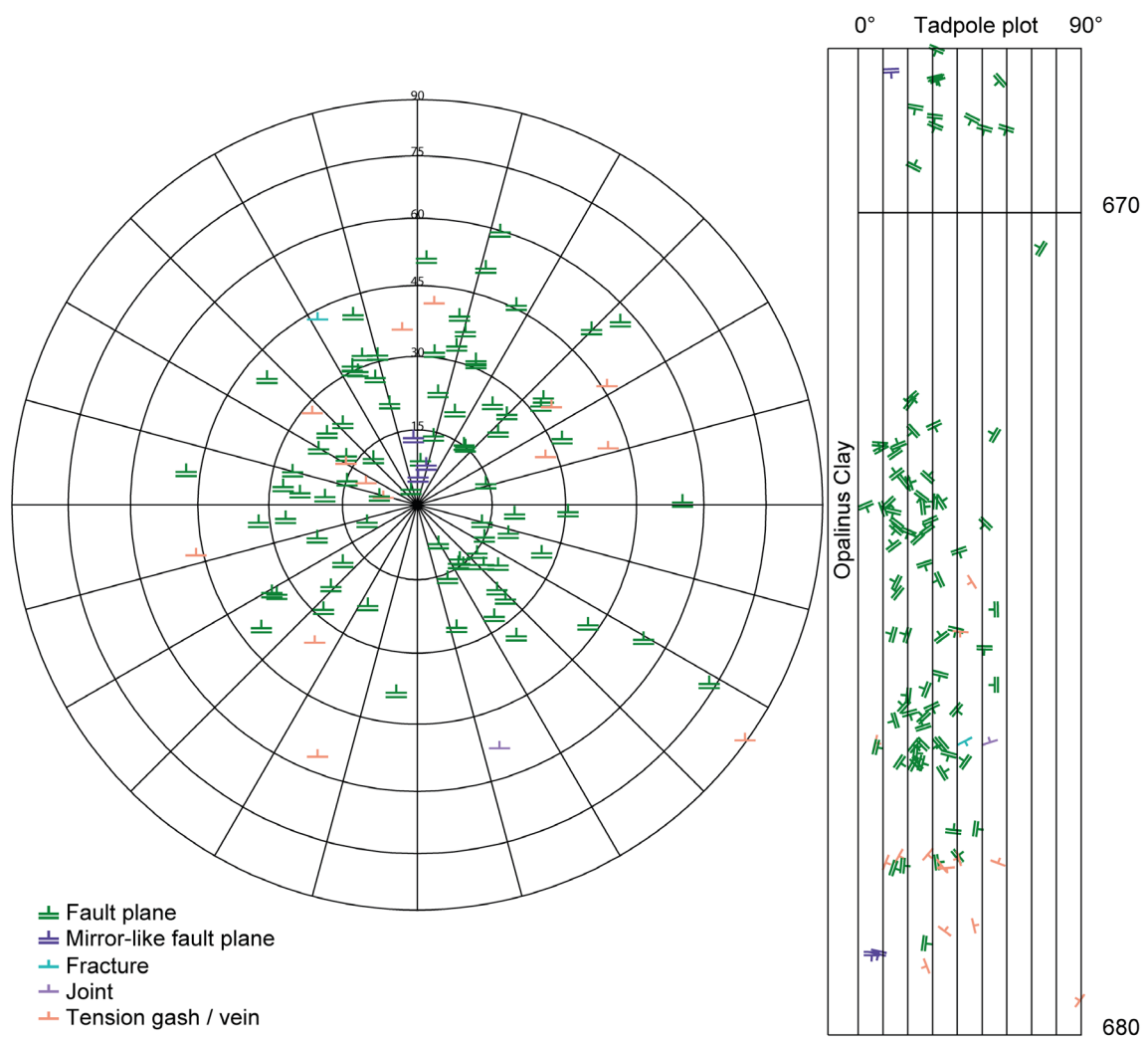


Fig. 5-6: Stereogram with faults and fractures in the Opalinus Clay between 668 m and 680 m MD (log depth)

Fault planes (n = 83), mirror-like fault planes (n=3), fractures (n = 1), joints (n = 1) and tension gashes / veins (n = 14).

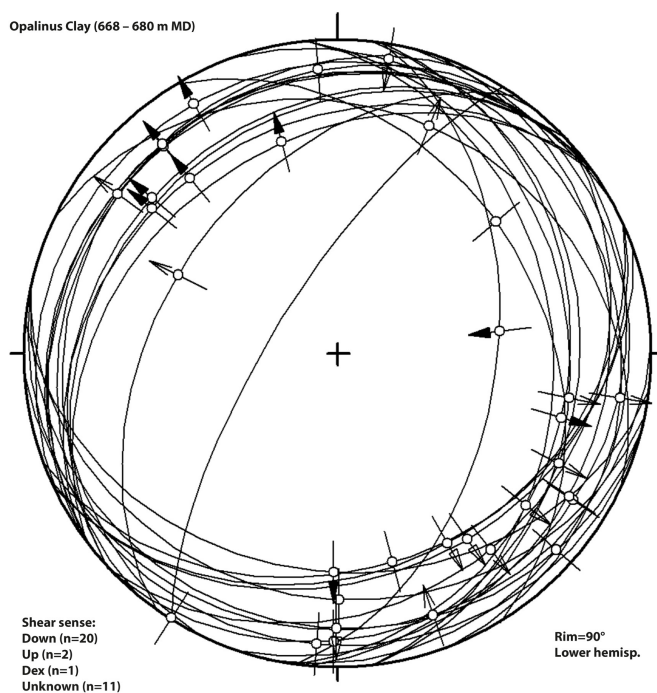


Fig. 5-7: Stereogram of fault planes and associated striations (including multiple lineations on a single fault plane) in the deformed Opalinus Clay

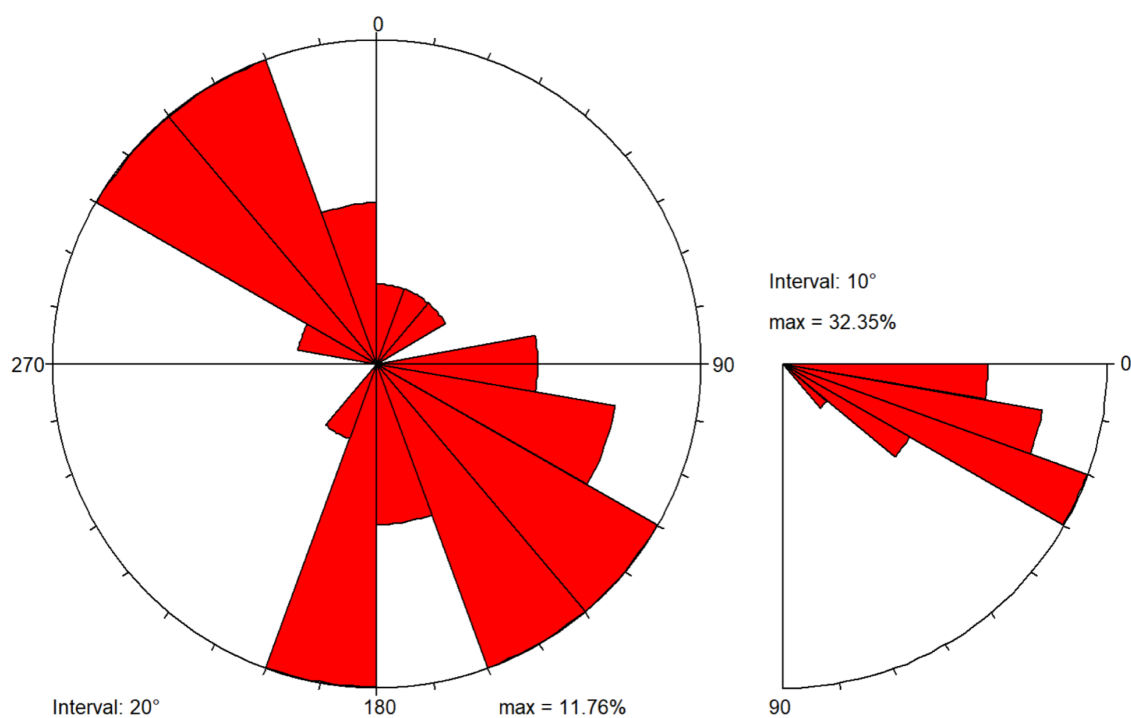


Fig. 5-8: Azimuth rose diagram and dip histogram of striation in the deformed Opalinus Clay
The depth range is 668 m to 680 m MD (log depth), n = 34.

5.2 Fracture zones within the Muschelkalk

A distinct tectonic zone was penetrated from approximately 860 m to 950 m MD (log depth) comprising carbonates of the lowermost Bänkerjoch, the Schinznach and the uppermost Zeglingen Formations. This borehole section is characterised by abundant sub-vertical fractures with an irregular spatial distribution. They are concentrated particularly within three intervals with prominent open (up to 5 mm wide) gashes (see Fig. 5-9):

- 869.00 m to 887.50 m MD (log depth): main fracture zone shown in Fig. 5-9
- 910.00 m to 920.00 m MD (log depth)
- 926.00 m to 941.00 m MD (log depth)

These zones represent corridors with fractures and open gashes acting as fluid conduits. The fractures led to a total mud loss of 1'709 m³ and caused coring / drilling issues (cf. Dossier I). The first mud losses occurred at 869.00 m MD (core depth) within the main fracture zone (Fig. 5-9), coring continued with dynamic mud losses down to 1'099.25 m MD (core depth).

In addition to joints and open gashes, abundant large open pores (up to 40 mm wide and 60 mm long) were also common (Fig. 5-10). In the FMI images, the sub-vertical fractures as well as the open pores have a conductive image response confirming their open character (Fig. 5-9).

In the stereograms of Figs. 5-11 and 5-12 there is a clear predominance of sub-vertical (65° to 90°) joints and tension gashes / veins with a well-defined NW-SE strike (overall means of 256/79, n = 33 and 048/79, n = 25). In addition, a total of 208 faults were interpreted in this zone, of which 39 fault planes, 102 mirror-like fault planes and 16 stylolitic fault planes were recorded within oriented drill cores (Figs. 5-13 and 5-14). The latter are bedding-parallel features with low dip angles (2° to 25°) and SE-dipping azimuths (mean of 134/06; n = 111). However, few sub-vertical faults also had a NW-SE strike similar to the joints.

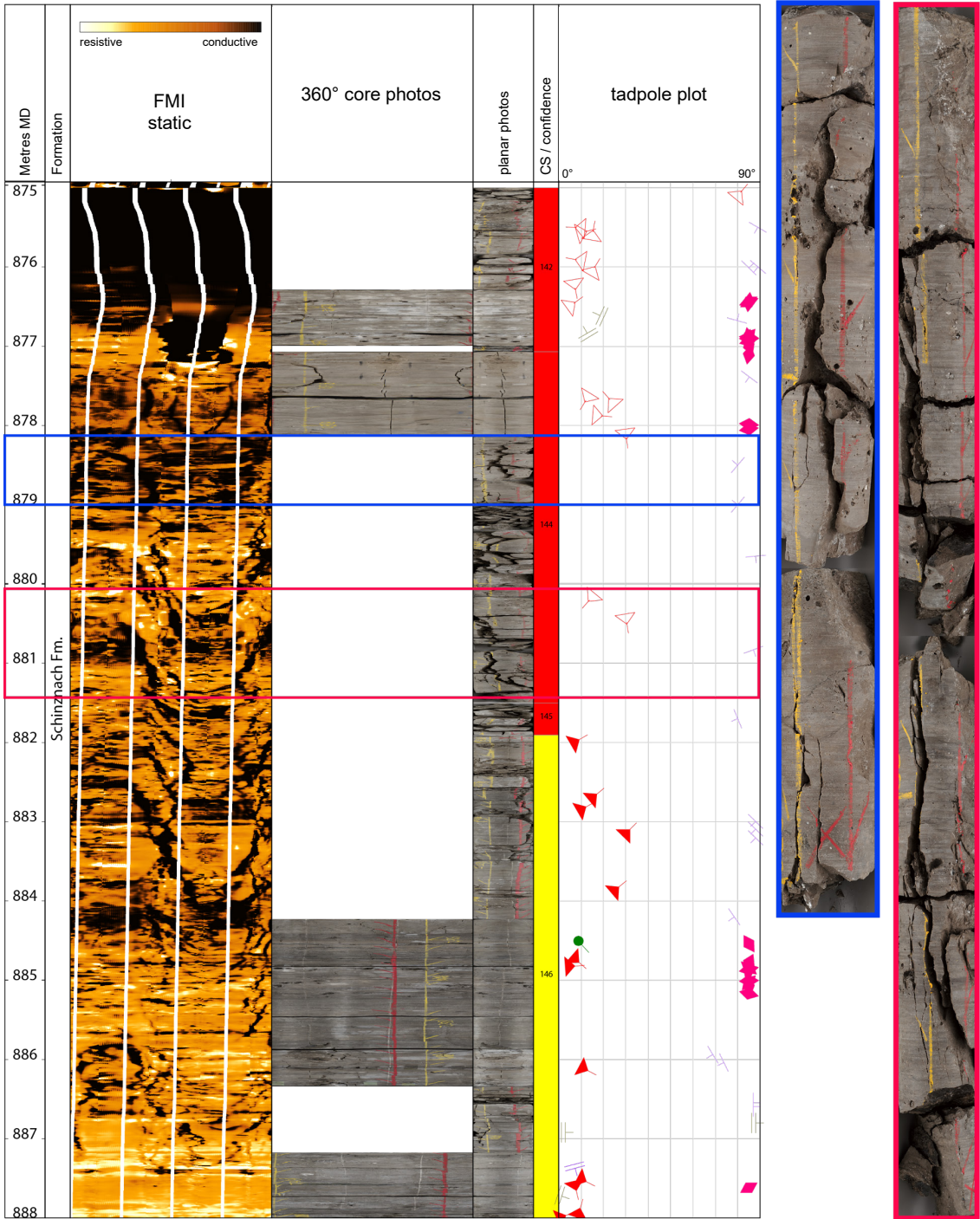


Fig. 5-9: Overview plot for the main fracture zone at 875.00 m to 887.50 m MD (log depth)

This zone is located in the Schinznach Formation and characterised by sub-vertical open fractures appearing conductive (dark) in FMI images (left track). Their open character is confirmed in the drill core as exhibited by, e.g. the 1 m long and open (5 mm opening width) fracture at 880.83 m MD (log depth).

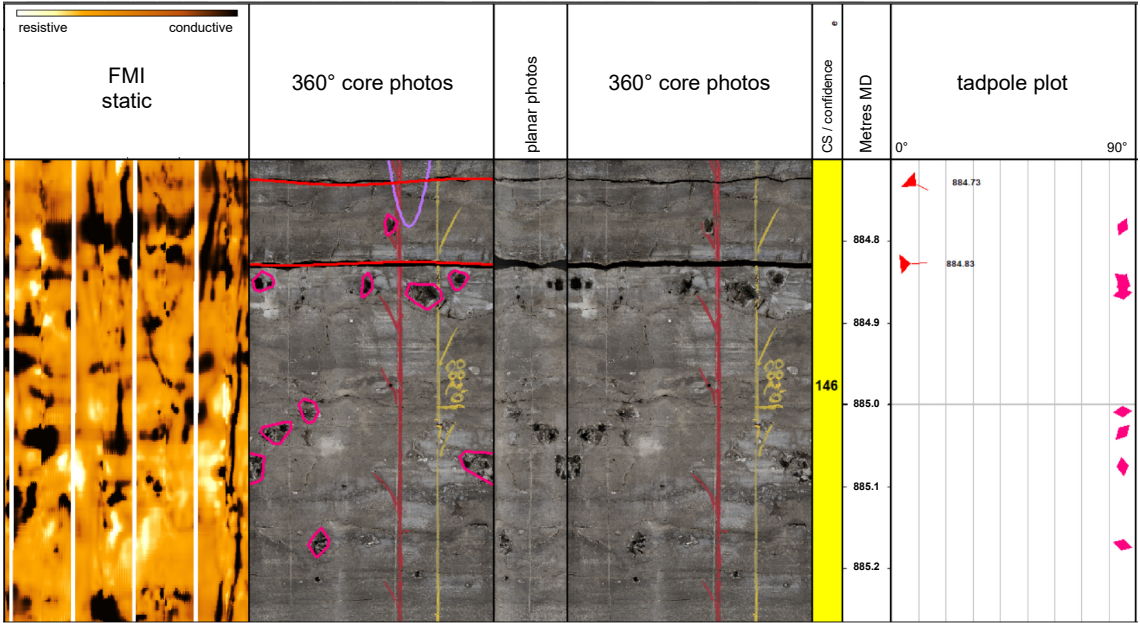


Fig. 5-10: Example of open pores (vugs) within the Schinznach Formation at 884.70 m to 885.25 m MD (log depth)

In the FMI image (left) vugs are represented by sub-rounded conductive (dark) spots supporting their open character. The large vug at e.g. 884.86 m MD (log depth) has a width of 30 mm and length of 45 mm in the drill core.

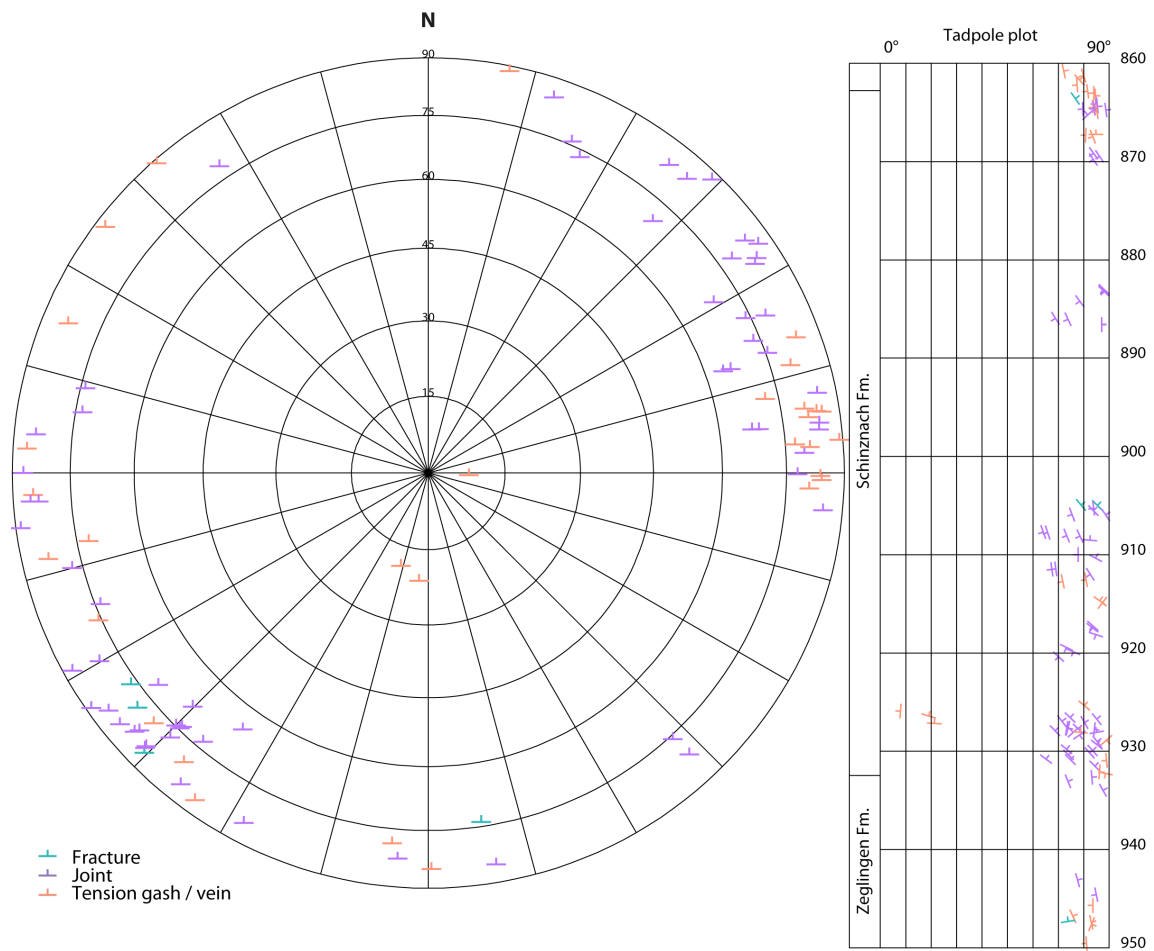


Fig. 5-11: Stereogram and depth plot of tension gashes / veins, joints and unassigned fractures from the depth interval 860 m to 950 m MD (log depth)

Fractures ($n = 4$), joints ($n = 63$) and tension gashes / veins ($n = 30$). Note that only oriented planes are shown.

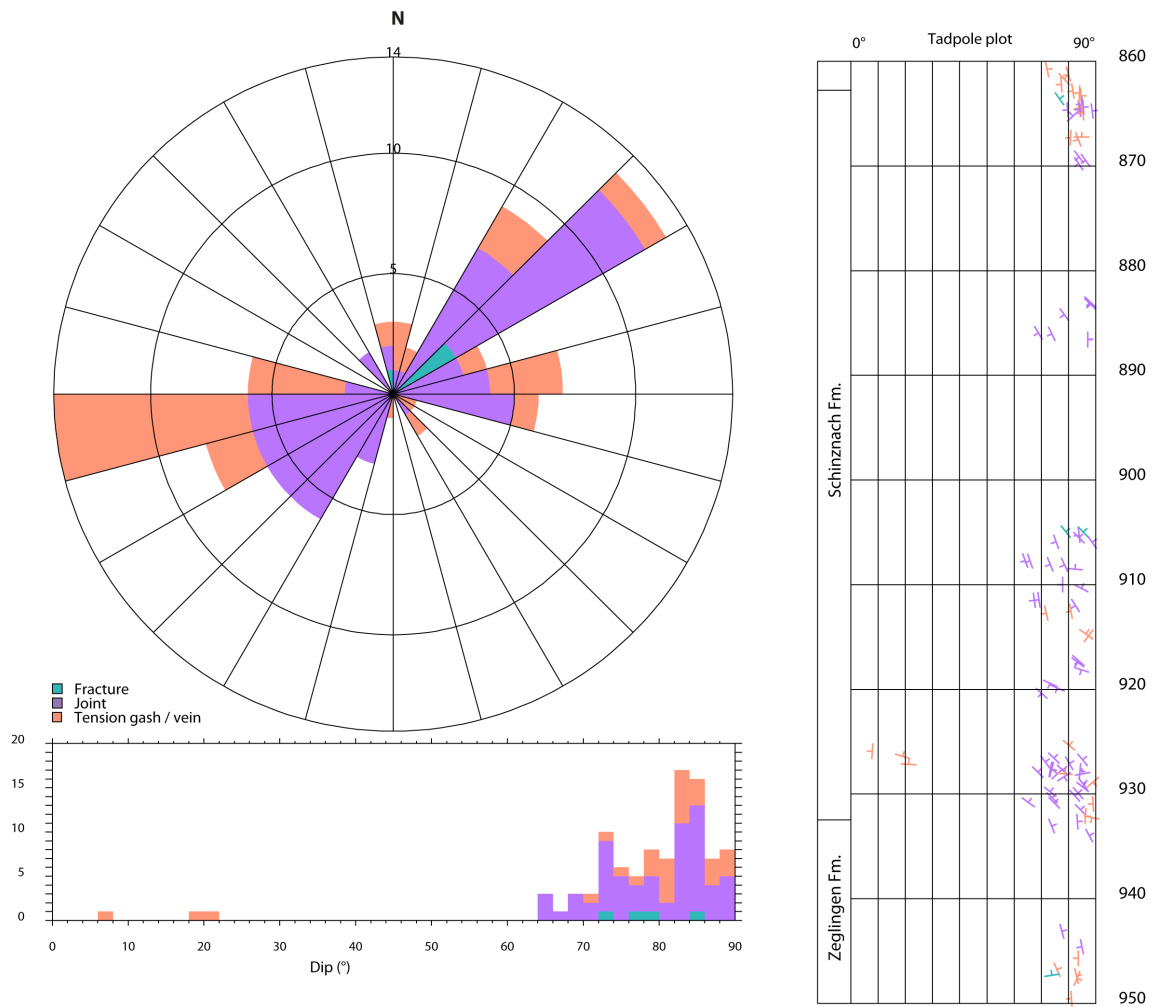


Fig. 5-12: Azimuth rose diagram, dip histogram and depth plot of tension gashes / veins, joints and unassigned fractures from the depth interval 860 m to 950 m MD (log depth)

Fractures ($n = 4$), joints ($n = 63$) and tension gashes / veins ($n = 30$). Note that only oriented planes are shown.

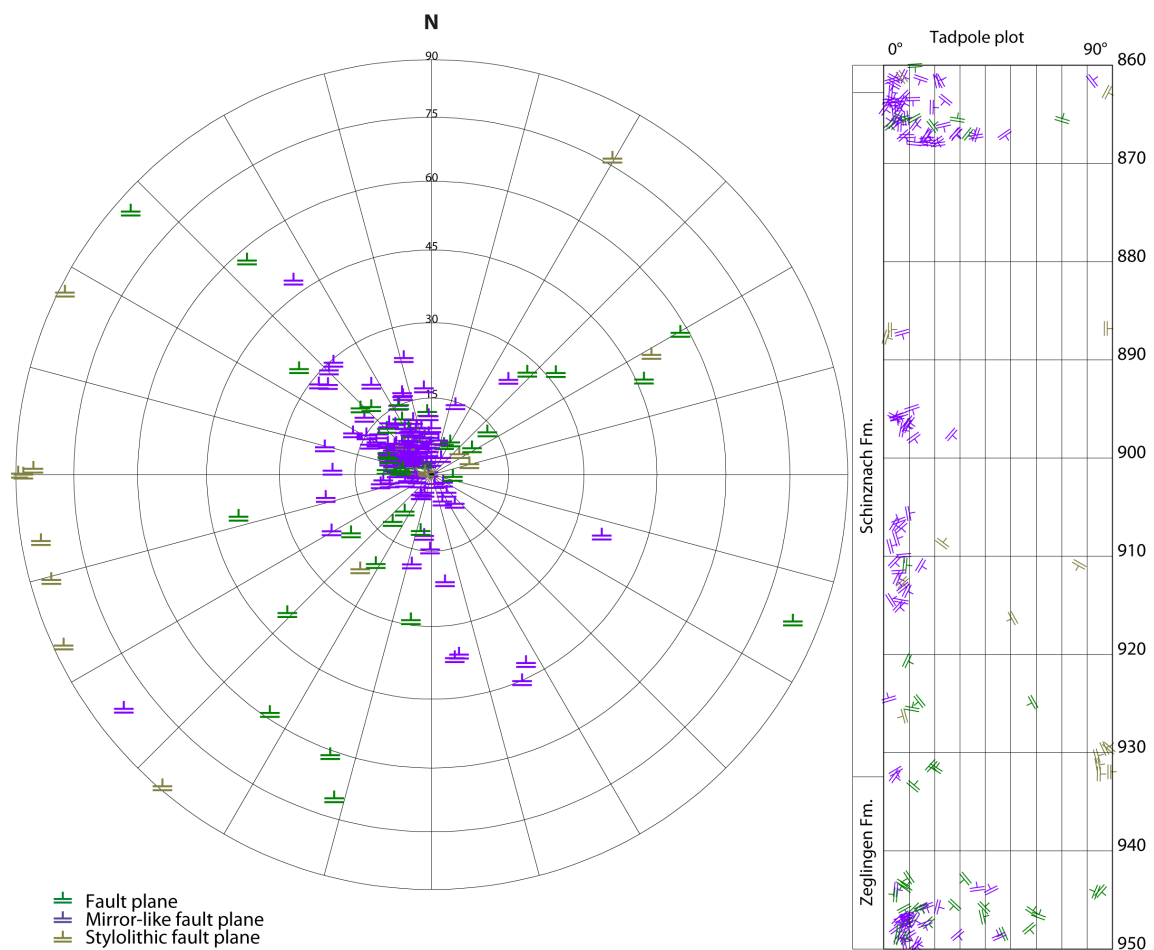


Fig. 5-13: Stereogram and depth plot of fault planes from the depth interval between 860 m to 950 m MD (log depth)

Fault planes ($n = 39$), mirror-like fault planes ($n = 102$) and stylolitic fault planes ($n = 16$). Note that only oriented planes are shown.

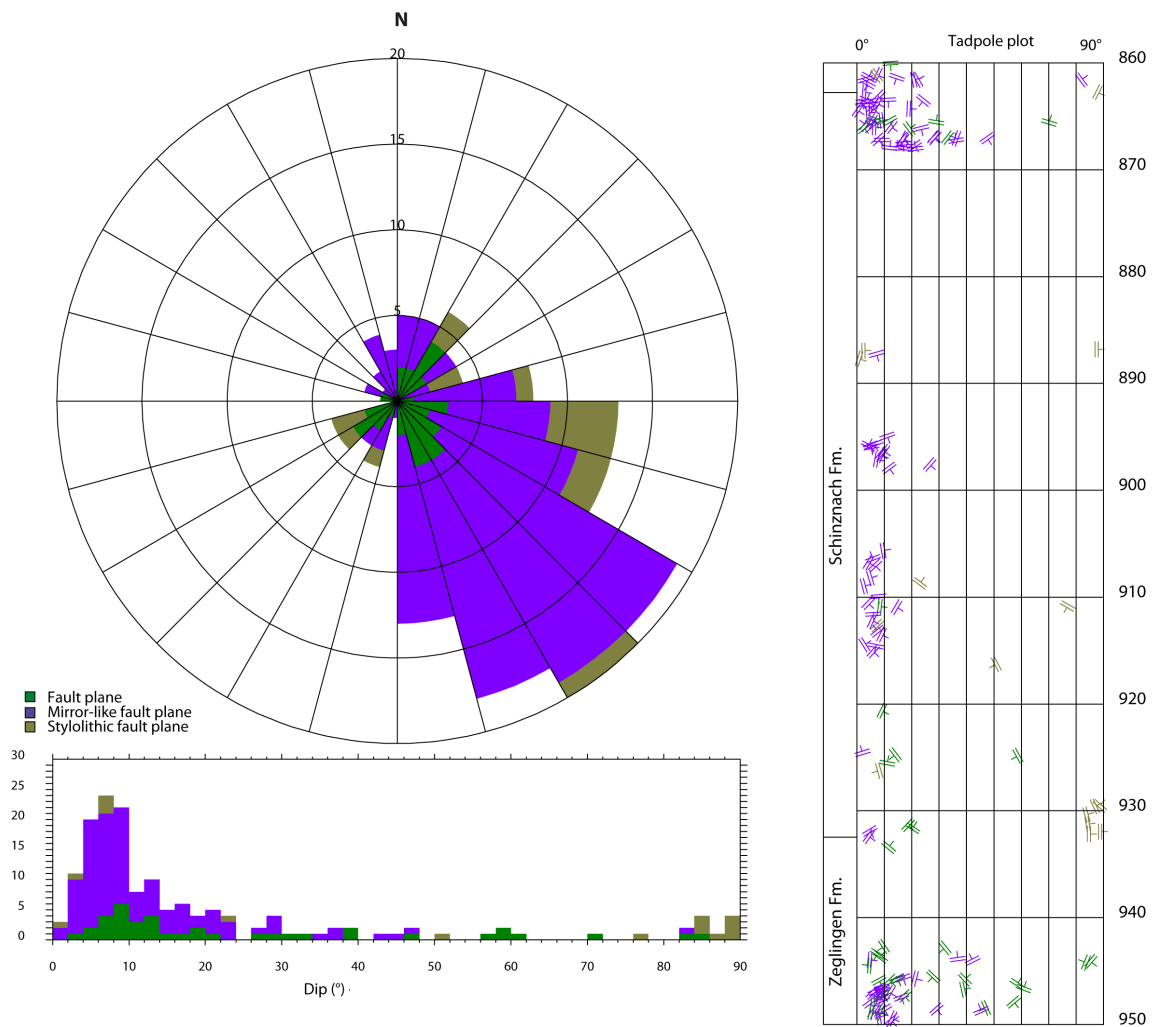


Fig. 5-14: Azimuth rose diagram, dip histogram and depth plot of fault planes from the depth interval between 860 m to 950 m MD (log depth)

Fault planes ($n = 39$), mirror-like fault planes ($n = 102$) and stylolitic fault planes ($n = 16$). Note that only oriented planes are shown.

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