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Stress Orientations Found in NE Germany Differ from the West European Trend

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ABSTRACT

Knowledge about the acting stresses is of crucial importance for understanding the tectonics of a region. Data about the stress field in north-eastern Germany used to be very rare. In general, it was assumed that the orientation of the larger horizontal principal stress (S_H) is similar to that found for western Germany and central West-Europe, i.e. NW-SE. To check this, several borehole logs of the late 1980s were analysed for information on the principal horizontal stress orientations: They include Four-Arm-Dipmeter and borehole televiewer data from 15 boreholes. The depth range of our stress results reaches from 1500 to 6700 m. They were compared to a few other data, especially from hydraulic fracturing, and to recent findings on the stresses in the Northwest German basin. In contrast to the expectations, S_H derived from breakout orientations below the salt layers displayed N to NE orientation. The latter was found at 10 locations spread over the NE-German basin from Berlin to the Baltic sea, from the Polish border to the former border between East and West Germany. Moreover, this stress rotation in the sub-saline formations seems to be the continuation of a trend found in the NW German basin.

Introduction

The knowledge of orientation and strength of the main tectonic stress is the basis for understanding many geodynamic processes like orogeny, subduction, intra-plate deformation, earthquakes, etc. The patterns of orientation and magnitude of the tectonic stress field can provide information about the active forces.

Moreover, the knowledge of tectonic stress is also of economic interest. On one hand, it contributes to solve problems concerning rock stability in planning big constructions like tunnels or water reservoirs, for mining as well as during drilling. On the other hand, the permeability of porous rocks and of fractures is influenced by stress. Permeability is one of the key issues in characterising the quality of reservoirs. Moreover, for the extraction of hot water for geothermal energy as well as in hydrocarbon-exploitation, often hydraulic fracturing is carried out to increase production. To prepare these operations knowledge about the direction of existing open fractures and about the orientation of tectonic stress is necessary in order to foresee the trend of the newly generated fractures (c.f. e.g. Bell, 1990).

The tectonic setting

The Northeast-German basin (NEGB) is part of the southern Permian basin, following Ziegler (1990). It is situated between the Transeuropean Suture zone (TESZ) in the North and the

Elbe fault system in the South. It connects the Polish trough in the East and the North German basin in the West, see Fig. 1. Presently, one would expect that the force system acting on the basin is dominated by the ridge push from the North Atlantic and the northward drift of Africa, resulting in a NW-SE to NNW-SSE orientation of the larger (compressive) horizontal principal stress, as is generally found in central western Europe.

In addition, Scheck and Bayer (1999) state a decoupling of the post-Zechstein succession due on a basin-wide salt layer, continuous through to areas close to the basin borders, and intense halokinesis, that led to a strong deformation of the post-Zechstein layers. The thickness of the salt layer, usually between 500 and 1000 m, reaches locally 4000 m (cf. Scheck and Bayer, 1999, Fig. 8a); its bottom depth, very shallow at the Elbe fault system reaches down to 4,600 m in the basin centre (cf. Tab. 1 and Scheck and Bayer, 1999, Fig. 12b).

The data

Logs measured between 1986 and 1990 in 19 wells in NE-Germany, now owned by Erdöl-Erdgas-Gommern GmbH", were checked for stress orientations by detecting tectonically induced borehole breakouts. The tools used for these measurements were Four-Arm-Dipmeters (FED) and a type of borehole televiewer (BHTV) called "Akustischer Bohrloch-Fernseher" (ABF) with optical registration on black-and-white films. These data were compared with stress data found by hydraulic fracturing experiments (Groß, 1989; Palmer and Groß, 1999).

Dipmeter-logs from 14 boreholes were analysed. In our search for breakouts, we followed the quality criteria set-up by Plumb and Hickman (1985) concerning the minimum length of breakouts, their minimum depth etc. In particular, we checked for correlations between the orientation of breakouts and the inclination of the borehole. We excluded from our breakout summary all sections where we found such a correlation to avoid a misinterpretation of key-seats as breakouts. The quality ranging in table 5, mainly dependent on the total length of breakouts and the standard deviation of their orientation, follows the criteria stated in Zoback (1992). Most of the breakouts found, are present in different formations with similar orientation, indicating independence of material properties. The lithology of some of the wells (FEG 1/87, KAA 1/87, and PUD 1/86, cf. Fig. 3) is publicly available in Hoth et al. (1993). Table 1 gives an overview about the depth range of the salt structures. Systematic deviations are discussed below.

Among the logs analysed, those from 9 wells showed breakouts - 1 above and 8 below the Zechstein salt layers (Fig. 2 shows an example). In addition, one ABF-log showed breakouts in the sub-saline formations. The results are summarised in tables 2, and 3.

Table 1: Depth and thickness of salt layers in comparison to the depth of breakouts and hydro-fracs at the boreholes considered here

Well	Long.	Latit.	Salt layer(s)	Sections with
	°E	°N	depth	breakouts or
			below ground	hydro-frac depth
			[m]	[m]
BINDE 1/86	11.425	52.859	2977-3540	3540-4130
FEG 1/87	13.417	53.339	3083-4293	4780-4830

FU 1/88	14.047	52.398	2294-3013	2240-2280
GZO 2/87	14.062	53.246	3211-4044	4030-4260
KAA 1/87	11.064	53.263	3459-4540	4600-5100
3/Dp MAH SW 2/84	11.238	52.863	below 1680	1565-1582
1/E ML 6/71	10.935	52.678	2424-3261	3262-3290
1/E ML 20/79	10.961	52.661	2608-3094*	2332
3/E ML 20/79	10.961	52.661	2608-3094*	3135
4/E ML 20/79	10.961	52.661	2608-3094*	3219
NLN 1/89	11.532	52.879	2898-3786	4000-4160
PES 153A/82	10.967	52.824	900-3209*	3190-4160 [†]
2/E PES 166/79	11.114	52.811	2552-3318*	2144
1/E PES 233/82	11.075	52.827	2626-3282*	2567
3/E PES 233/82	11.075	52.827	2626-3282*	2458
4/E PES 166/79	11.114	52.811	2552-3318*	3291 [‡]
2/E PES 233/82	11.075	52.827	2626-3282*	3275 [‡]
PUD 1/1H86	14.128	53.965	2321-2995	4500-4860
PUD 1/1H86	14.128	53.965		5590-6690
SMO 1/88	10.772	52.817	3129-3811	4100-4210
WRIZ 3/88	13.926	52.765	3075-3871	4310-4320

Remarks: The thickness of the salt layers indicates the area from the top of the uppermost salt layer to the bottom of the lowermost one. Simplified after JHoth93 and unpublished information of EEG - Erdgas Erdöl GmbH, Berlin. (*) Thickness of the entire Zechstein formation; (†) breakouts in subsaline Zechstein and Rotliegendes (cf. Palmer and Groß (1999)); (‡) hydro-fracs in subsaline Zechstein (cf. Groß, 1989; Palmer and Groß, 1999).

Table 2: Stress orientations from breakouts (BO): supra-saline formations

Well	Longitude	Latitude	Sections with	Breakout length	Azimuth
	°E	°N	BO(s) [m] (number)	total [m]	$S_H \pm \sigma$
FU 1/88	14.047	52.398	2240 - 2280 (2)	11.0	$148^\circ \pm 7^\circ$

Table 3: Stress orientations from breakouts (BO): sub-saline formations

Well	Longitude	Latitude	Sections with	Breakout	Azimuth
	°E	°N	breakouts	length, total	
			[m] quantity	[m]	$S_H \pm \sigma$
BINDE 1/86	11.425	52.859	3540-4130 16	42.7	$24^\circ \pm 9^\circ$
FEG 1/87	13.417	53.339	4780-4830 8	20.8	$13^\circ \pm 5^\circ$

GZO 2/87	14.062	53.246	4030-4260	7	31.5	$41^\circ \pm 14^\circ$
KAA 1/87	11.064	53.263	4600-5100	14	84.4	$44^\circ \pm 4^\circ$
NLN 1/89	11.532	52.879	4000-4160	5	8.2	$110^\circ \pm 10^\circ$
PES 153A/82	10.967	52.824	3190-4160	11	53.0	$8^\circ \pm 5^\circ$
PUD 1/1H86	14.128	53.965	4500-4860	17	129.0	$5^\circ \pm 4^\circ$
PUD 1/1H86	14.128	53.965	5590-6690	9	26.0	$151^\circ \pm 11^\circ$
SMO 1/88	10.772	52.817	4100-4210	10	34.4	$3^\circ \pm 6^\circ$
WRIZ 3/88	13.926	52.765	4310-4320	1	1.7	$45^\circ \pm 4^\circ$

Remark: Results from PES 153A/82 from ABF(BHTV)-data, from all other wells FED-data

Three data points of stress orientation resulted from hydro-frac experiments above the salt and two from hydro-frac experiments below the salt, that were carried out in 5 wells. Table 4 lists the stress orientations found.

Table 4: Stress orientations from hydro-frac measurements (hf)

Well	Formation	Longit.	Latit.	Depth	Azimuth
		$^\circ$ E	$^\circ$ N	[m]	$S_H [^\circ]$
MAH SW 2/84	supra-saline	11.238	52.863	1565-82	90
ML 20/79		10.961	52.661	2332	90
PES 166/79		11.114	52.811	2144	116
PES 233/82		11.075	52.827	2567	90
PES 233/82		11.075	52.827	2458	120
ML 6/71	sub-saline	10.935	52.678	3237	15-35
ML 20/79		10.961	52.661	3135	15
ML 20/79		10.961	52.661	3219	15
PES 166/79		11.114	52.811	3291	0
PES 233/82		11.075	52.827	3275	0

The hydro-frac data show an orientation of S_H of W to WNW in the supra-saline formations, and an orientation of S_H of N to NE in the sub-saline formations. The data of our breakout analysis also show this difference in the orientation of S_H between the sub-saline and the supra-saline formations. The orientation of S_H in the supra-saline formations is NW, but orientation of S_H in the sub-saline formations is, with two exceptions, N to NE. In general, the data from hydraulic fracturing and from borehole breakouts correlate very well. Table 5 gives an overview. Here, the breakout result from well PES 153A/82 was combined with those from the hydro-frac experiments 2/E PES 233/82 and 4/E PES 166/79 to one value; so were the hydro-fracturing results from PES 233/82 and PES 166/79 as well as ML 20/79 and ML 6/71, respectively.

We compared our results to those of Lempp and Röckel (1999), who analysed drill cores and drilling reports for drilling induced fractures, i.e. unintentional hydraulic fracturing. Several of the boreholes they investigated are near or identical to those from which we considered independent information (cf. the area between 10.5 and 12 °E, 52.5 and 53 °N). Their results indicate:

- a separation of the upper crustal layers into three parts: supra-saline, saline, and sub-saline concerning stress orientation,
- varying stress orientations in the supra-saline layers, trending W to NW in the area of our investigations (cf. their data points 13 - 15),
- no strong differential stresses and no clear stress directions inside the salt layers,
- relatively constant orientations below the salt pointing N to NNE (see their data points 20 - 27).

Our results fully agree with these independent findings.

Table 5: Synopsis of all stress from breakouts (BO) and hydro-fracs (HF)

Formation	Well	Longitude	Latitude	Type	Azimuth	Quality
		°E	°N		S _H	
supra-saline	FU 1/88	14.047	52.398	BO	48°	D
	MAH SW 2/84	11.238	52.863	HF	90°	C
	ML 20/79	10.961	52.661	HF	90°	C
	PES 166/79 &					
	PES 233/82	11.1	52.8	HF	109°	C
sub-saline	BINDE 1/86	11.425	52.859	BO	24°	C
	FEG 1/87	13.417	53.339	BO	13°	D
	GZO 2/87	14.062	53.246	BO	41°	C
	KAA 1/87	11.064	53.263	BO	44°	C
	ML20/79, 6/71	10.95	52.67	HF	15°	C
	NLN 1/89	11.532	52.879	BO	110°	D
	PES 166/79,					
	PES 153A/82 &					
	PES 233/82	11.1	52.8	HF/BO	4°	B
	SMO 1/88	10.772	52.817	BO	3°	C
	WRIZ 3/88	13.926	52.765	BO	45°	D
sub-s., upper						
Carboniferous	PUD 1/1H86	14.128	53.965	BO	5°	B
sub-s., lower						
Carboniferous	PUD 1/1H86	14.128	53.965	BO	151°	D

Remark: Quality range is A-D; A is highest.

Interpretation of the data

In Western Europe, an orientation for the maximum horizontal tectonic stress (S_H) from NW to NNW was found (Grünthal and Stromeyer, 1992; Müller et al., 1992; Gölke and Coblenz, 1996). As the stress orientation often is stable across a tectonic plate, it was assumed that this orientation of S_H should also be found in NE-Germany.

However, our new results do not show this. Instead, the orientation of S_H in the sub-saline formations, which we assume to represent the regional tectonic field, is totally different. In sub-saline formations, we obtained - with 2 low quality (D) exceptions - an orientation of N to NE (Fig. 3 shows the data without the result from the deepest part of well PUD).

The data from above the salt - only 4 data points, clustered in the Altmark - display W to NW orientation (see Fig. 4). In our opinion, their number and distribution give not yet a basis for an interpretation in the regional scale. In contrast to this, our results for the sub-saline formations consist of 11 data points with very homogeneous orientations. Their locations are spread over the whole NEGB. They obviously represent the regional stress field in the area.

The visible differences in orientation above and below the salt can be explained by decoupling of the stress field due to the continuous Zechstein salt layers in NE-Germany. Moreover, as the salt tends to form domes, stress measurements beside or above domes may be significantly influenced by these soft salt inclusions around which S_H tends to rotate (cf. Brereton and Müller, 1991). The cause for the difference in stress field between the NE and the NW German basin (cf. Fig. 5) might be due to changes in tectonic forces at collision zones or the proximity to inhomogeneities in lithospheric structure (cf. Bada et al., 1998), as discussed below. In any case, a change in the orientation of S_H in sub-saline formations was also found by Grote (1997) and Grote (1998), when she reanalysed stress data from the Northwest and North German basin for differences between orientations above and below the salt. For sub-saline formations, she shows that the orientation of S_H rotates from NW in the western part to N and NNE in the northern part of the basin. Obviously, this trend continues in the adjacent area investigated by us.

Furthermore, during the seismic experiment BASIN'96 within the programme DEKORP2000 (German Continental Reflection Seismic Programme) hints for an updoming of the Moho discontinuity were found, that could be explained by crustal buckling due to forces roughly in N-S direction (cf. Bayer et al., 1999). This is supported by models on the NEGB in Marotta et al. (2001a).

Discussion

What might be the explanation for S_H acting approximately NNE-SSW, leading to the rotation in the stress field in the NEGB? These have to dominate the forces from the Eurasian-African

collision in the Mediterranean and from the mid-Atlantic ridge that are commonly assumed to determine the NW orientation of the stress field in central western Europe.

Hypothesis I - Influence of the TESZ: This ancient suture zone is quite close to the area under investigation, trending NW-SE through the southern Baltic sea towards central Poland. An active fault could release by strike-slip motion the stress component parallel to it so that only perpendicular components (oriented NE in this case) would remain. However, there is no indication neither for recent seismic moment release nor for any kind of crustal deformation detectable by geodetic means (Gregersen et al., 1995).

Hypothesis II - Dominance of local stresses due to post-glacial lithospheric flexure: Grollmund and Zoback (2000) observed a change in the stress regime from reverse/strike-slip to strike-slip/normal faulting and a rotation of S_H in the northern North Sea from 100° west of the Viking Graben to about 80° closer to the coast. For stress calculations, they use a model with a layered elastic/viscoelastic lithosphere above a viscous asthenosphere subject to ice load cycles (for a thickness of 1 km and an average lateral extension). The model is two-dimensional rather perpendicular to the front of the ice load. They find an increase in compressive stress just outside the ice sheet and a decrease below the edge of the ice shield, which match the changes in stress magnitude in their observations, while the stress magnitude of the regional stress field (from ridge push at the North Atlantic) is assumed to be constant and homogeneous throughout the area. - Applying this to the NEGB would be like the following: The boundary of the ice load was about $N100^\circ E$, the maximum extension of the ice cover in eastern Germany reached as far south as $51^\circ N$ (Cepek, 1973; cf. Fig. 1 here), whereas the ice thickness is very uncertain. If we assume that the 1000 m isoline of ice thickness was at the Baltic Sea coast in this region, the Northeast German Basin would have been under increased compressional stress compared with the North German Basin further West, as there the distance to Scandinavia is larger (cf. Fig. 1). As this compressive stress would be $N100^\circ E$, it would strongly deviate from the regional NW-SE orientation of S_H , leading to N-S to NE-SW orientations fitting to our observations. Further north, formerly below the ice sheet, this additional local stress would diminish so that the regional stress would prevail. This would match the observations of a more or less NW-SE oriented S_H by Ask et al. (1996). In face of the uncertainties about the shape of the glacial ice load these qualitative arguments need to be checked with 2- or even 3-D model calculations, varying the extent and thickness of the ice load.

Hypothesis III - Strong lithospheric barrier below the northern margin of the NEGB: Investigations on the rheology/depth profile to infer the strength of the lithosphere below the NEGB (Marotta et al., 2001b) found a northward increase in lithospheric strength below the NEGB. Values there might be higher than under the Baltic shield, cf. for instance Cloetingh and Burov (1996). Therefore, they assume a barrier below the northern NEGB in a two-dimensional viscous thin-sheet model of the stress field (Marotta et al., 2001a). Such a hard inclusion acts like an optical lens or pillar in underground cavities, in focussing the stress trajectories inside and releasing them in an fan-like pattern. Indeed, their result shows a rotation of the S_H orientations, similar to our data.

Conclusions

The analysis of borehole breakouts and hydrofrac-data from the Northeast German basin with respect to the orientation of the larger horizontal principle stress indicate:

- There is a distinct difference between the supra-saline and the sub-saline layers concerning stress orientation.
- The orientation below the salt points N to NE in almost all (9 out of 11) wells.
- The large depth of the data (1500 to 6700 m; especially their location below the salt detachment surface), their number and consistency in orientation, and last not least their spatial distribution across the NEGB, are strong indicators that they represent the regional stress field in the NEGB.
- Comparing the S_H orientation in the Northwest and the North German basin with the one in the NEGB, we find a rotation from Northwest via North to Northeast.
- As there is no indication for difference in the plate boundary forces producing this stress rotation, we assume that the rigidity contrast between the NEGB and Scandinavia is responsible for this effect.

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Figure captions:

Figure 1: Regional tectonic framework of the Northeast German Basin after Scheck and Bayer (1999).

Figure 2: Four-Electrode-Dipmeter data example from well SMO with a distinct breakout in the depth interval from 4158.5 m to 4166 m (the diameters from Caliper 1 (pad 1 and 3) and Caliper 2 (pad 2 and 4) show a distinct difference, while the rotation of pad 1 (see azimuth P1) has stopped and the diameter given by Caliper 2 shows drill bit size).

Figure 3: Map showing the new data on S_H (sub-saline formations).

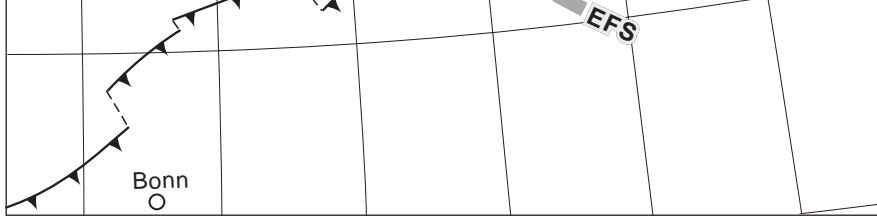
Figure 4: Map showing the new data on S_H (supra-saline formations).

Figure 5: Part of the World Stress Map (North Germany) including the new sub-saline data of this study, not yet regarding the results from (Grote, 1998).

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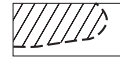
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VDF



CDF



Permo-tri
Basins

CDF: Caledonian Deformation Front

VDF: Variscan Deformation Front

DB: Danish Basin

PT: Polish Trough

NGB: North German Basin

NEGB: Northeast German Basin

NWGB: Northwest German Basin

HG: Horn Graben

RFH: Ringkobing-Fyn-H

MAH: Mon-Arkona-High

BS: Baltic Shield

EEP: East-European PL

TTZ: Tornquist-Teisseyr

STZ: Sorgenfrei-Tornqu

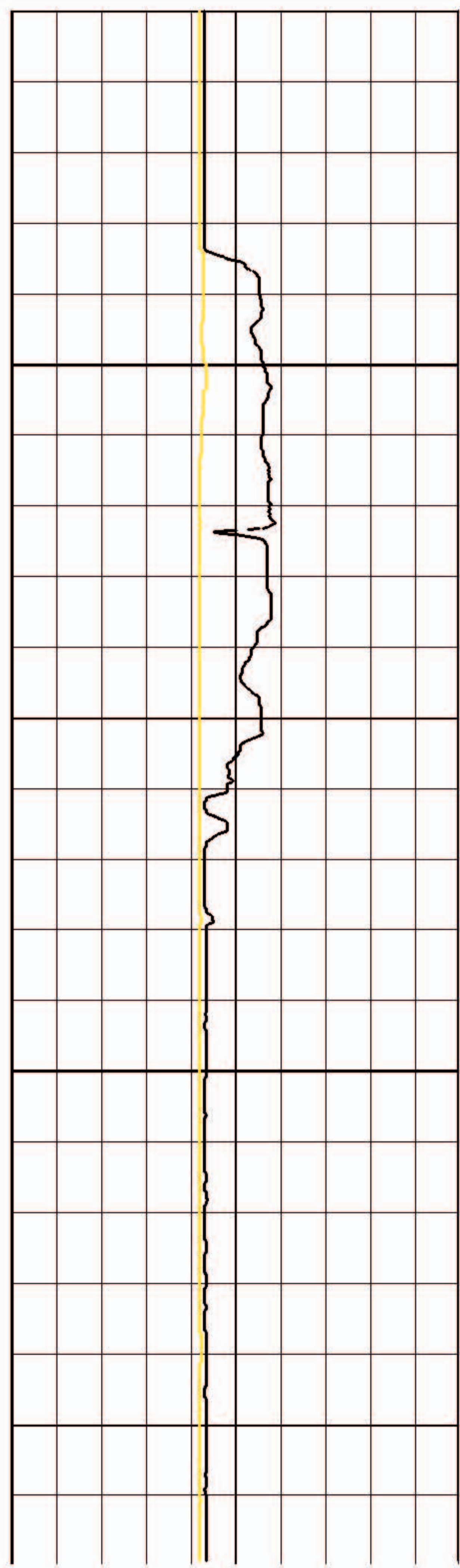
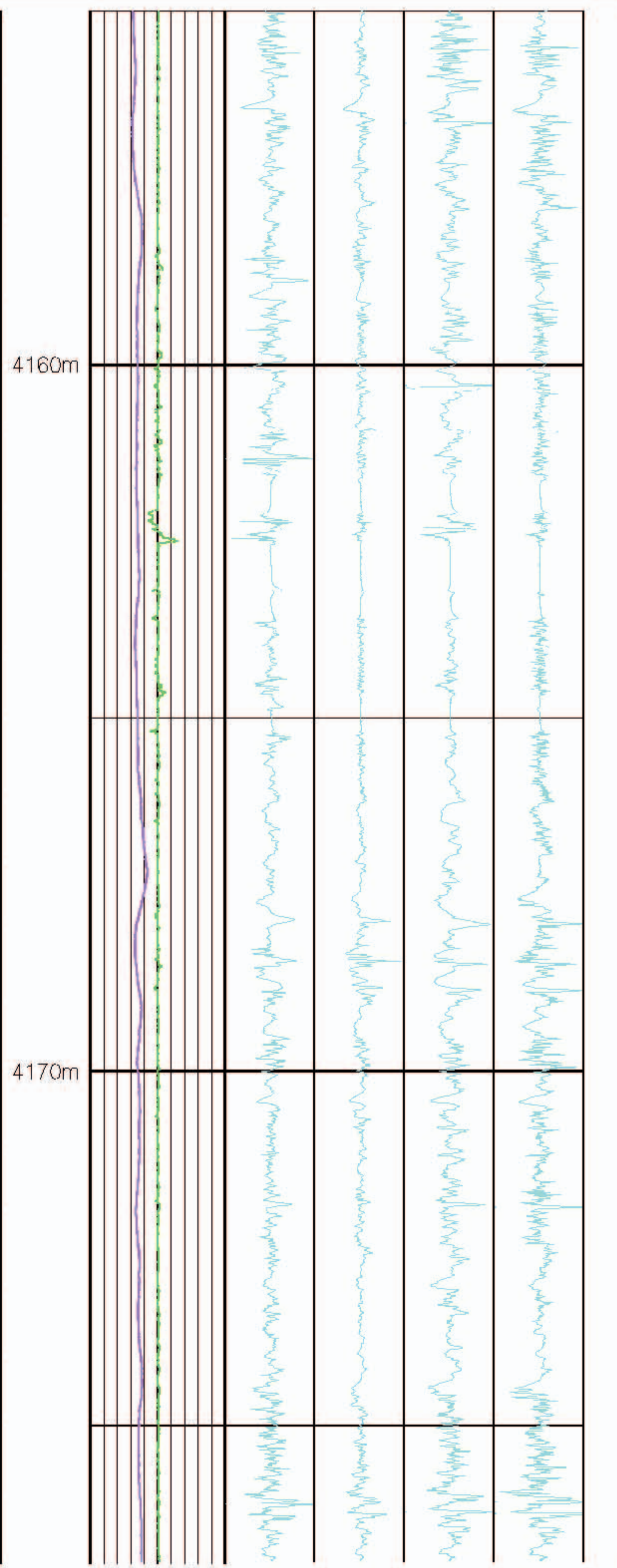
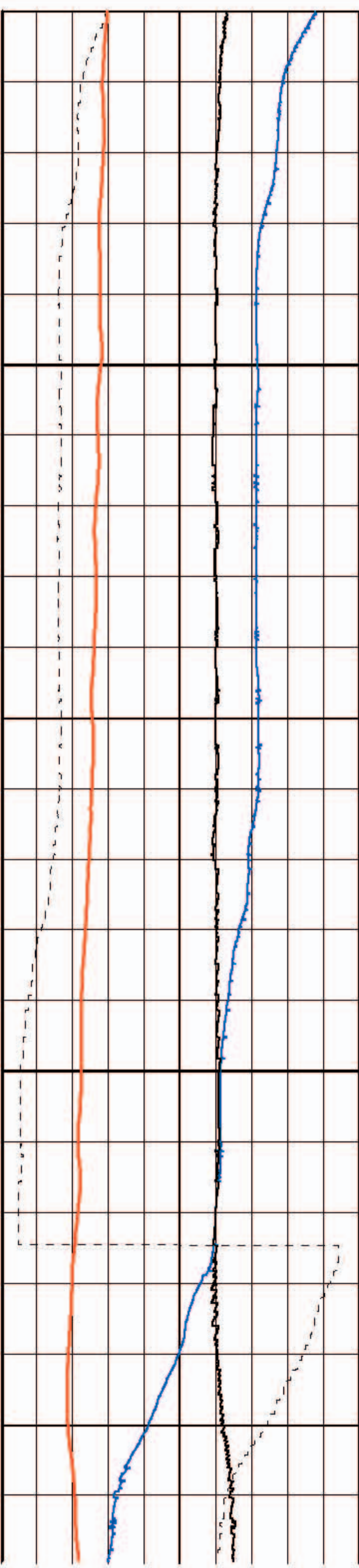
EFS: Elbe Fault System

TEF: Trans-European F

AZIMUT P1		
-20	DEG	380
INCL		
0	DEG	10
RB		
-20	DEG	380
HDIR		
-20	DEG	380

ACCE/CPS		P1/MV		P2/MV		P3/MV		P4/MV	
-50	50	0	1000	0	1000	0	1000	0	1000
GAMMA/API									
-100	400								

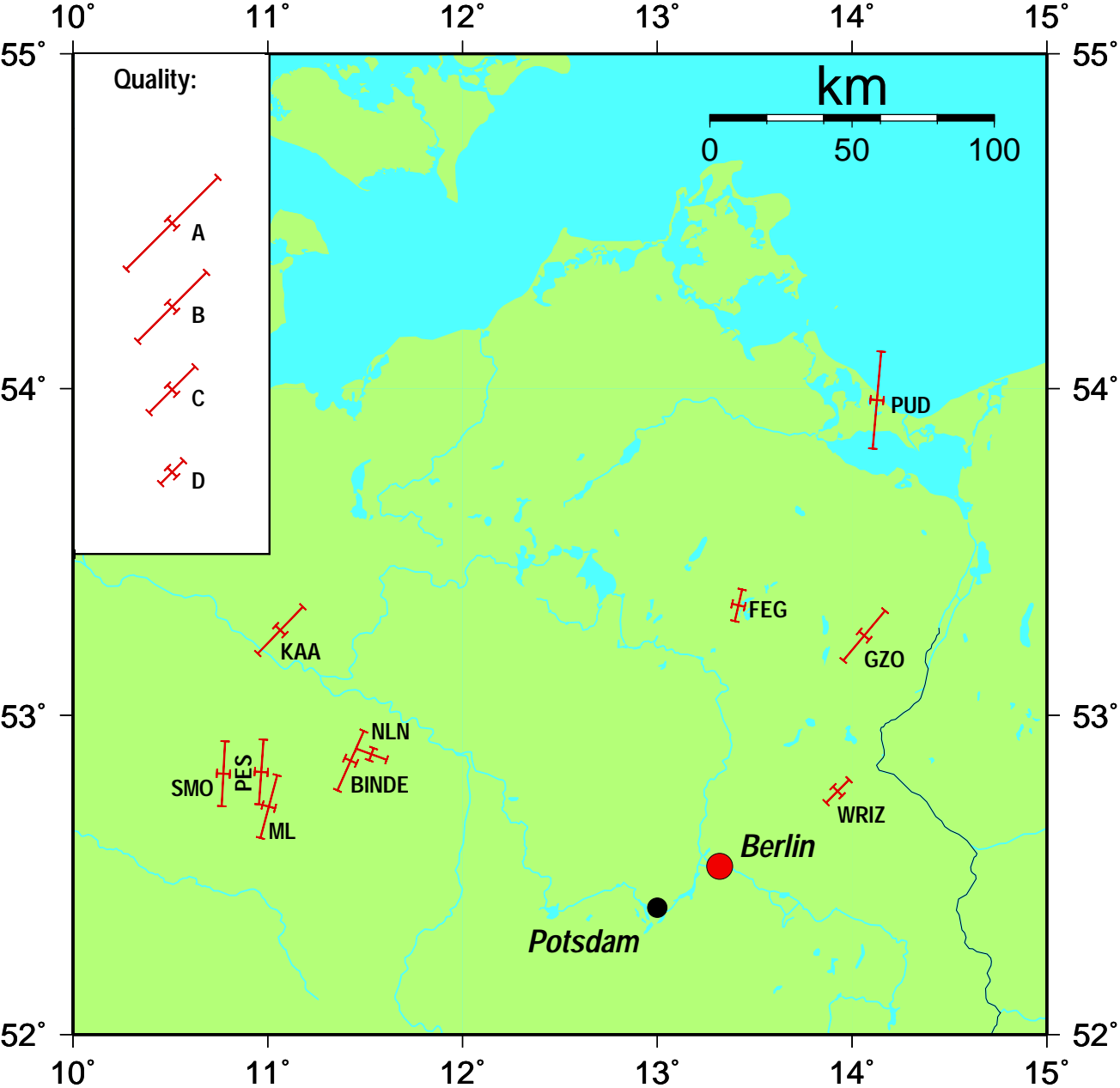
CALIPER 1		
2	INCH	12
CALIPER 2		
2	INCH	12



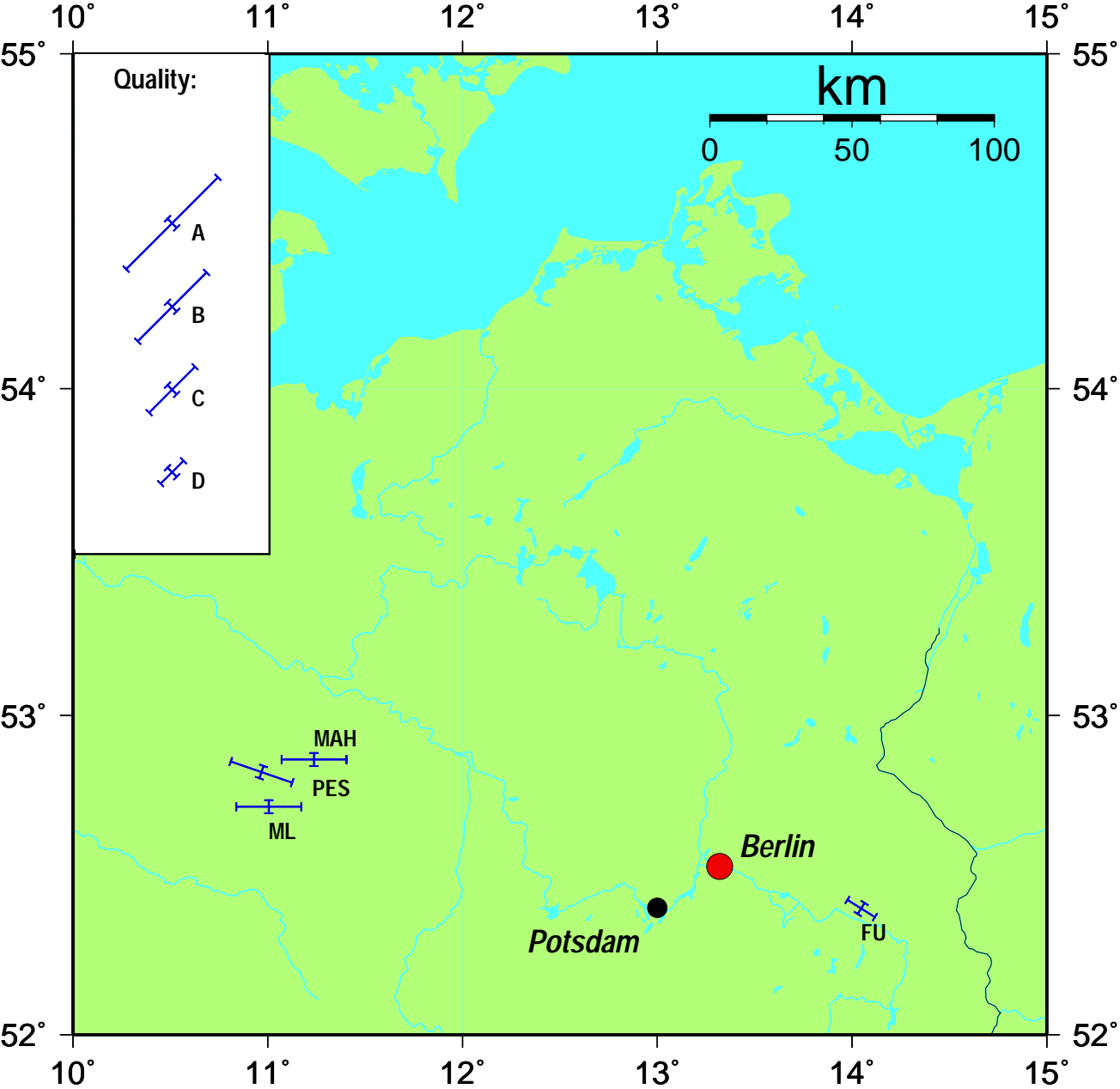
HDIR		
-20	DEG	380
RB		
-20	DEG	380
INCL		
0	DEG	10
AZIMUT P1		
-20	DEG	380

GAMMA/API									
-100	400								
ACCE/CPS		P1/MV		P2/MV		P3/MV		P4/MV	
-50	50	0	1000	0	1000	0	1000	0	1000

2	INCH	12
CALIPER 2		
2	INCH	12
CALIPER 1		
2	INCH	12



Orientation of maximum horizontal principal stress in the sub-saline formations



Orientation of maximum horizontal principal stress in the supra-saline formations

