BOREHOLE   TESTING

HYDROFRACTURING

STRESS MEASUREMENTS

System Design · Planning
Lab + Field Measurements

CBM - Project Sigillaria License Area

CASED - HOLE PERMEABILITY AND HYDROFRAC STRESS MEASUREMENTS IN BOREHOLE NATARP - 1

Final Report

Client	:	CONOCO Mineralöl GmbH, Essen
Contract	:	Ref. - No. GCBM-04, Variation Order 001
		dated 09.05.1995
MeSy - Quotation	:	113.05.95 dated 04.05.1995
MeSy - Reporter	:	Dipl. Geophys. G. Klee
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Report - Date	:	09.11.1995
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CONTENT

APPENDIX

SUMMARY

The present report summarizes an extensive hydraulic test program carried out in the cased - hole section of borehole Natarp-1 on 11 coal seams between 1380 m to 1949 m depth. The test program was part of the geotechnical site investigation for the CBM - project Sigillaria License Area within the Ruhr - Carboniferous.

In - situ testing was carried out with the MeSy wireline technique which consists of a straddle packer tool tripped on a standard logging cable in the borehole. The test procedure followed the recommendations prepared by Conoco and can be divided into (i) short - time pressure pulse tests, (ii) subsequent long - time injection / pressure fall - off tests for permeability determination, and (iii) hydrofrac tests for stress - evaluation. The in - situ test results can be summarized as follows:

(i)   The injection / pressure fall - off tests yield permeability values for the coal seam test sections ranging between 0.04 mD and 0.12 mD with a mean value off app. 0.1 mD. In comparison, most of the short - time pressure pulse tests yield identical or similar permeability data for the direct vicinity around the borehole.

(ii) The results of the hydrofrac stress tests carried out in the cased borehole together with the open - hole test results demonstrate a convincing stress profile for the depth range between 1375 m and 1950 m given by the following principle stress / depth relations:

$$S_v , \text{MPa} = 0.0245 \cdot \text{TVD, m} \ (\varrho = 2.5 \ \text{g/cm}^3)$$
$$S_h , \text{MPa} = 22.0 + 0.0165 \cdot (\text{TVD, m } -1375)$$
$$S_H , \text{MPa} = 40.3 + 0.0381 \cdot (\text{TVD, m } -1375)$$

Both, permeability and stress data correspond to previous results of hydraulic and hydrofrac tests carried out in borehole Rieth-1 within the Sigillaria License Area. The stress data from the Rieth-1 and Natarp-1 boreholes also are in good agreement with stress data derived from numerous stress tests conducted in various coal - mines of the Ruhr coal area.

1. INTRODUCTION

Borehole Natarp-1, located about 20 km southeast of Münster (geographical coordinates: N 51° 53' 37" , E 7° 53' 41"), is the second borehole drilled in the Sigillaria License Area to about 1969 m depth to investigate the coal bed methane (CBM) recovery potential in the Ruhr Carboniferous. Within the open - hole section, a series of hydrofrac stress and hydraulic permeability tests were conducted between 1418 m and 1935 m depth. The results of the open - hole tests are given in the MeSy REPORT NO. 35.95 [1995] which yields first information on the permeability of both, the coal bearing formation and the coal seam sections as well as the in - situ stress regime and the in - situ frac - gradients in borehole Natarp-1.

After a casing of 5" OD / 4.283" drift ID was cemented and perforated, additional 11 pressure - pulse and injection / pressure fall - off tests for permeability estimation and hydrofrac stress measurements were carried out on coal seams between 1380 m and 1949 m depth. The present report describes the test - equipment used, the test program and procedures, and the results obtained. The final discussion compares the results with previous data.

2. TEST - EQUIPMENT

The cased - hole tests in borehole Natarp-1 were carried out using the MeSy wireline technology consisting of the following components (Fig. 2.1):

- The MeSy MKW - 5000 winch unit with app. 5500 m of 7 - conductor logging cable (CAMESA, type 7-J 46 RTZ, OD 15/32") housed in a 20 ft standard sea - container
- The straddle packer assembly type MeSy PERFRAC II equipped with nylon - reinforced inflatable packer elements type S & K TK 83 - V - 1300 with a diameter of 91 mm and an effective sealing length of app. 1 m. The length of the test interval between the two packers was app. 8.7 m.
- A downhole transducer housing with connection to the CSMA type cable head. The unit contains two strain - gauge type pressure transducers (KELLER, type PA-23, 0 - 60 MPa) to monitor packer - and interval pressure and a temperature transducer (0 - 211 °C).

- Two separate hydraulic stainless steel pressure tubing lines (OD 10 mm / ID 8 mm for interval pressurization; OD 8 mm / ID 6 mm for packer pressurization) fixed to the logging cable by special aluminum clamps in 50 m intervals.

- An air - driven pump (MAXIMATOR, type GW 100) for packer pressurization and a servo - electric driven three plunger pump (SPECK, type HP 400 / 2 - 12) with a capacity of 40 MPa / 0.17 l/min - 12 l/min for interval pressurization. The injection fluid was KCL - brine with a density of app. 1.02 g/cm^3.

- A surface pressure control unit containing an uphole strain - gauge type pressure transducer (KELLER, type PA-23, 0 - 100 MPa), a turbine - type flowmeter (UNIMESS, type QPT 04, 1.2 - 10 l/min) and several manometers.

- A special plastic tube device to measure flow - rates smaller than 1.2 l/min.

- An analogue and digital data acquisition unit consisting of a paper strip - chart recorder (BBC, type SE - 400, 4 channels) and the MeSy digital SILVI system (8 channels, 16 resolution, sampling rate: 1 Hz during permeability tests and 5 Hz during hydrofrac tests).

Figure 2.1 : Scheme of the MeSy wireline hydrofrac - system.
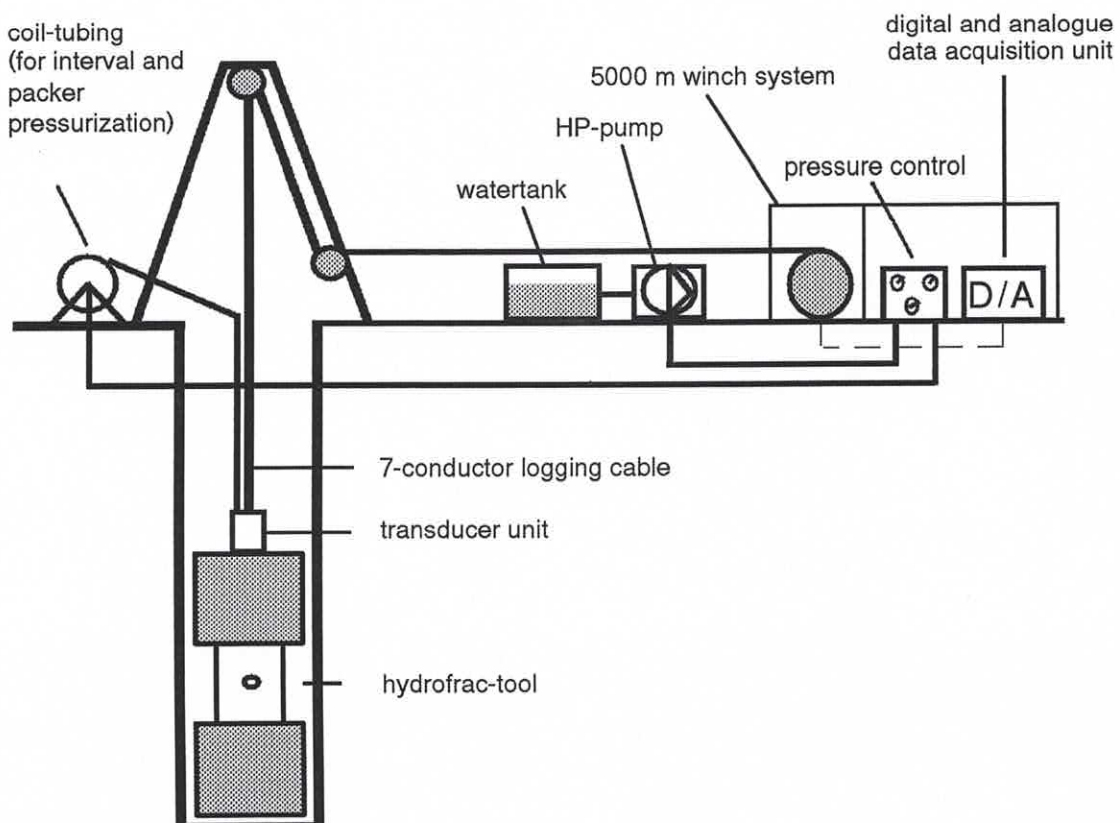
3. TEST - PROGRAM AND TEST PROCEDURE

The perforated test intervals and the cased - hole test program conducted during 22.08. to 03.09.1995 are given in Table 3.1. Further details can be taken from the MeSy Operation Report dated 12.09.1995 (APPENDIX A) or from the overview plots given in APPENDIX B, C and D.

Apart from test no. 5 at 1596.15 m and test no. 7 B at 1627.5 m depth (mid - points of the perforated test intervals), the test procedure closely followed the Conoco recommendations given as "NATARP-1 PLAN" (Conoco fax massage dated 18.8.1995) which can be divided into the following test phases:

- pressure pulse test
- injection / pressure fall - off test (injection rate: app. 0.2 l/min)
- frac test / pressure step - rate test (injection rate of some l/min)

The following major alternative test procedures were:

(i) Due to a fault - system intersecting the coal seam at 1596.15 m depth (test no. 5) and associated high permeability, the fluid injection rate during the injection / pressure fall - off sequence was stepwise increased from app. 0.2 l/min to 5 l/min. The high permeability also prevented the conduction of the frac - / step - rate test.

(ii) The injection / pressure fall - off test at 1627.5 m depth (test no. 7 A) was repeated and extended at the end of the cased - hole test campaign by a long - term injection / pressure fall - off test (test no. 7 B) to achieve a greater radius of investigation in order to study the influence of the fault system observed at 1596.15 m depth.

Table 3.1 : Cased - hole test program, borehole Natarp-1.

pp : pressure pulse test   f   : frac test
i   : injection test   pfo : pressure fall - off test

test no.	start date	perforated test interval m	test phase	test duration min	injected volume liter	remark
1	22.08.	1947.60-1950.30	pp	11		
			i	90	17.7	
			pfo	240		
			f	53		
2	23.08.	1896.70-1899.20	pp	11		
			i	390	82.8	
			pfo	549		
			f	193		
3	23.08.	1851.60-1853.00	pp	11		
			i	142	27.2	
			pfo	374		
			f	200		
4	24.08.	1759.60-1760.90	pp	20		
			i (1)	100	18.5	
			i (2)	49	-	power cut
			i (3)	4	-	dto.
			i (4)	61	13.5	
			pfo	230		
			f	49		
5	25.08.	1594.80-1597.50	pp (1)	5		low pressure build-up with 6.5 l/min
			pp (2)	10		
			i (1)	60	11.1	0.185 l/min
				30	18.0	0.6 l/min
				20	22.8	1.14 l/min
			pfo (1)	20		
			i (2)	205	429	2.09 l/min
				200	541	2.705 l/min
				170	788	4.635 l/min
			pfo (2)	600		

Table 3.1 : Continue.

test no.	start date	perforated test interval m	test phase	test duration min	injected volume liter	remark
6	26.08.	1529.85-1531.35	pp	10		
			i	300	58.8	
			pfo	420		
			f	151		
7 A	27.08.	1626.75-1628.25	pp	10		
			i	270	55.5	
			pfo	519		
			f	195		
8	28.08.	1747.65-1749.15	pp	12		
			i	377	83.5	
			pfo	539		
			f	77		
9	29.08.	1427.70-1429.20	pp	10		
			i	294	65.6	
			pfo	510		
			f	56		
10	29.08.	1402.10-1405.10	pp	11		
			i	300	64.7	
			pfo	655		
			f	56		
11	30.08.	1378.60-1381.30	pp	15		
			i	210	46.7	
			pfo	486		
			f	65		
7 B	31.08.	1626.75-1628.25	i	3180	710.2	
			pfo	2900		

4. TEST ANALYSIS AND RESULTS

4.1 INJECTION / PRESSURE FALL - OFF TESTS

The main injection / pressure fall - off tests were directly evaluated by Conoco. Therefore, MeSy only supplies the corresponding overview plots (APPENDIX B). The test results are presented in Table 4.1. Conoco's analysis of the pressure fall - off test data yields permeability values for the coal seam test sections ranging between 0.04 mD and 0.12 mD (the result of test no. 5 at 1596.15 m is not presented). It is interesting to note, that the open - hole test of the coal seam at 1760.3 m depth yielded a permeability of 0.1 mD [MeSy REPORT NO. 35.95, 1995] in comparison to 0.09 mD derived from cased - hole test no. 4.

Table 4.1 : Results of injection / pressure fall - off tests for permeability estimation.

test no.	mean depth of perforation	mean depth below surface TVD	permeability	lithology
	m	m	mD	
11	1379.95	1377.15	0.04	coal - seam
10	1403.60	1400.80	0.04	dto.
9	1428.45	1425.65	0.14	dto.
6	1530.60	1527.80	0.09	dto.
7 A	1627.50	1624.70	0.07	dto.
8	1748.40	1745.60	0.10	dto.
4	1760.25	1757.45	0.09	dto.
3	1852.30	1849.50	0.11	dto.
2	1897.95	1895.15	0.12	dto.
1	1948.95	1946.15	0.06	dto.

4.2 ANALYSIS OF PRESSURE PULSE TESTS FOR PERMEABILITY EVALUATION

Prior to the injection / pressure fall - off tests, short pressure pulse tests were carried out to determine the in - situ rock permeability of the test - sections. The analysis of the tests is based on the classical method suggested by COOPER et al. [1967] for slug - tests. For the special conditions of the wireline hydrofrac - system MeSy has developed the software code PERM, where theoretical and measured pressure decline curves are matched for a variety of input parameters such as system stiffness, storage coefficient and permeability by using an inversion procedure (master curve method). The results of the calculations are given as the mean of all successful models, which satisfy the L^1 - standard.

The permeability / transmissivity data derived from the pressure pulse tests (APPENDIX C) are summarized in Table 4.2. The analysis yields permeability data between 0.04 mD and 0.11 mD.

A comparison between the permeability values for the coal seam sections derived from both test methods is shown in Figure 4.1. The graph includes the results of the open - hole permeability measurements on coal seams [MeSy REPORT NO. 35.95, 1995]. Apart from the result of the cased - hole test no. 2 at 1897.95 m depth, the permeability data derived from the pressure pulse tests are very similar to the results of the corresponding injection / pressure fall - off test although the test results of both measurements are valid for different radii of investigation.

Figure 4.1 : Comparison between permeability values of coal seam sections de-
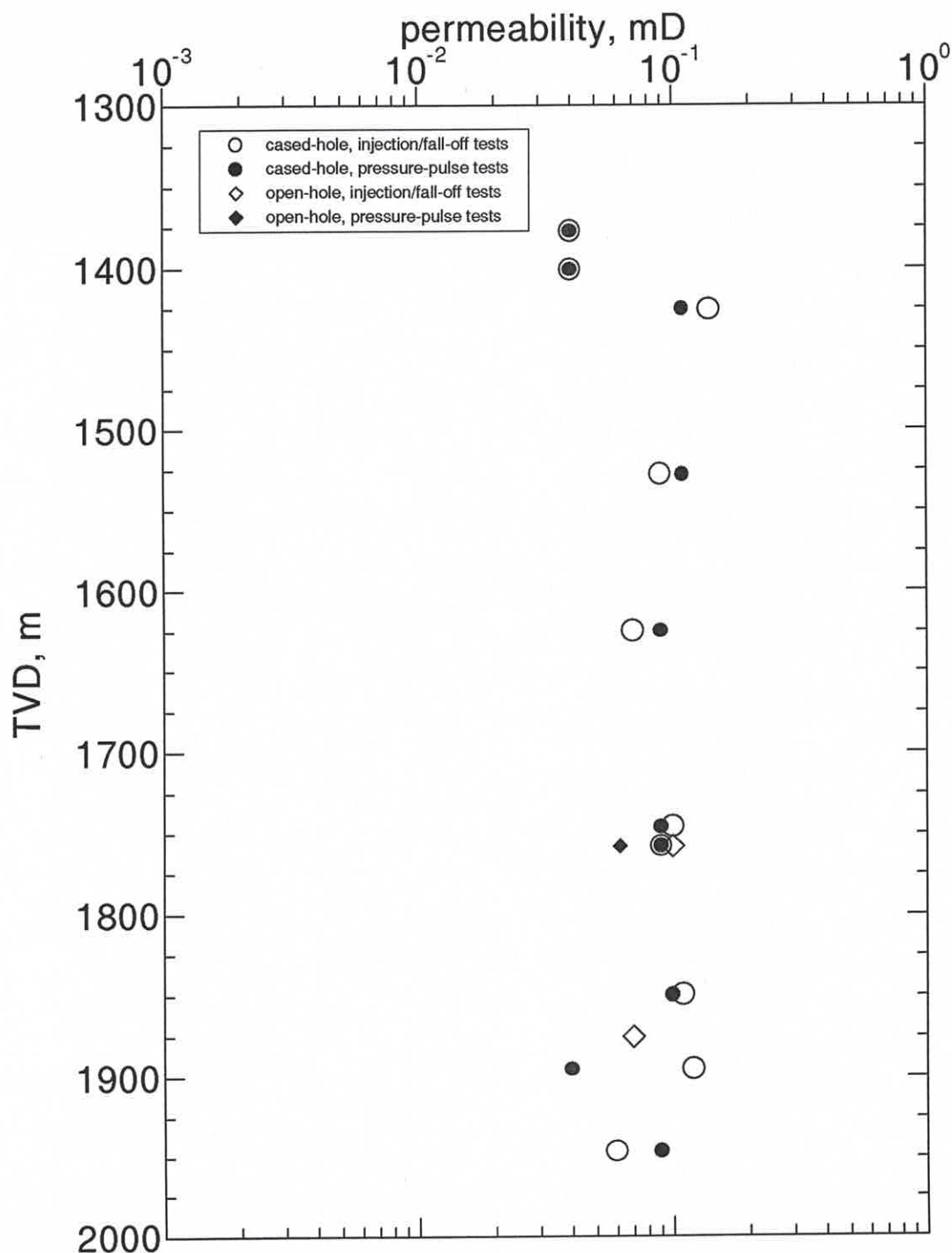rived from pressure pulse - and injection / pressure fall - off tests.

Table 4.2 : Results of pressure pulse tests for permeability / transmissivity estimation.

test no.	mean depth of perforation	mean depth below surface TVD	permeability	transmissivity	lithology
	m	m	mD	cm²/s	
11	1379.95	1377.15	0.04	0.04	coal - seam
10	1403.60	1400.80	0.04	0.04	dto.
9	1428.45	1425.65	0.11	0.04	dto.
6	1530.60	1527.80	0.11	0.06	dto.
7 A	1627.50	1624.70	0.09	0.04	dto.
8	1748.40	1745.60	0.09	0.04	dto.
4	1760.25	1757.45	0.09	0.03	dto.
3	1852.30	1849.50	0.10	0.03	dto.
2	1897.95	1895.15	0.04	0.04	dto.
1	1948.95	1946.15	0.09	0.04	dto.

4.3 HYDROFRAC STRESS TEST ANALYSIS AND RESULTS

Since fracture orientations could not be determined in the cased borehole, the analysis of the hydrofrac stress tests were conducted on the basis of the "classical" HUBBERT and WILLIS [1957] concept with the following simplified assumptions:

- the overburden stress $S_v = \varrho gz$ is a principal stress and borehole deviations from vertical are negligible;
- the rock is homogenous and isotropic;
- the fracturing fluid does not penetrate into the rock prior to fracture initiation;
- the induced vertical fracture is oriented perpendicular with respect to the minimum horizontal stress S_h.

This results in the following simple relations:

$$P_c = 3 S_h - S_H + P_{co} - P_o \tag{4.1}$$

$$P_{si} = S_h \tag{4.2}$$

$$P_{co} = P_c - P_r \tag{4.3}$$

with

P_c breakdown pressure at frac initiation
P_r fracture re-opening pressure
P_{si} shut-in pressure
P_{co} in-situ hydrofrac tensile strength
P_o pore pressure
S_h minimum horizontal stress
S_H maximum horizontal stress

Because the accuracy of hydrofrac stress measurements requires highly accurate pressure data, an extensive pressure data analysis program was carried out for the identification of the characteristic hydrofrac pressure values (APPENDIX D).

The determination of the **breakdown pressure P_c** was not relevant since breakdown events were not observed during the cased - hole tests.

The determination of the **refrac pressure P_r** considers the system stiffness (during the initial pumping cycle). Assuming a constant system stiffness, initially the pressure P linearly increases with the injected fluid volume V. Therefore, a deviation from linear in a P vs. V or P vs. system stiffness dP/dV plot indicates the opening of a fracture.

The **shut - in pressure P_{si}** is determined by a three step analysis of the pressure plots:

- in a pressure P vs. flow - rate Q plot the moment at which hydraulic flow stops (Q = 0) indicates an upper bound of P_{si};
- a Muskat - type plot yields a lower - bound of P_{si} , assuming that the linear part of the plot characterizes radial flow, i.e. the stimulated fracture is nearly closed;

- within the two limits, the P_{si} - value marks the transition from a rapid linear pressure drop to a diffusion dominated pressure decrease; the transition can be determined by the tangent method (inflection point method).

In some of the tests (test no. 2, 3, 8 and 10) the determination of P_{si} could only be derived from P vs. Q diagrams. The change of slope in such diagrams characterizes the P_{si} - value. It is interesting to mention that test no. 4, 6, 7 A and 9 yielded clear P_{si} - values independent on the evaluation method.

The characteristic pressure values P_r and P_{si} are listed in Table 4.3 and are graphically shown in Figure 4.2. A reliable determination of the refrac pressure could only be achieved for the three test sections at 1379.85 m, 1530.6 m and 1760.3 m depth since most of the stimulated fractures / fracture systems within the tested coal seams showed a diffusion dominated fracture opening behavior.

Table 4.3 : Refrac - pressure P_r and Shut - in pressure P_{si} derived from cased - hole hydrofrac testing in borehole Natarp-1.

test no.	mean depth of perforation m	mean depth below surface TVD m	P_r MPa	P_{si} MPa	P_{si} - estimation method
11	1379.95	1377.15	21.74	21.50	inflection point
10	1403.60	1400.80	-	20.9-23.3	PQ-analysis
9	1428.45	1425.65	-	24.50 (24.7)	inflection point PQ-analysis
6	1530.60	1527.80	20.50-22.24	23.36 (24.1-25.2)	inflection point PQ-analysis
7 A	1627.50	1624.70	-	25.83 (26.0)	inflection point PQ-analysis
8	1748.40	1745.60	-	27.35	PQ-analysis
4	1760.25	1757.45	25.30	28.07 (27.95)	inflection point PQ-analysis
3	1852.30	1849.50	-	28.6-31.8	PQ-analysis
2	1897.95	1895.15	-	29.6	PQ-analysis
1	1948.95	1946.15	-	(28.5-34.1)*	inflection point

* Circulation around the packers possible

Figure 4.2 : Refrac - pressure P_r and shut - in pressure P_{si} derived from cased - hole hydrofrac testing in borehole Natarp-1.
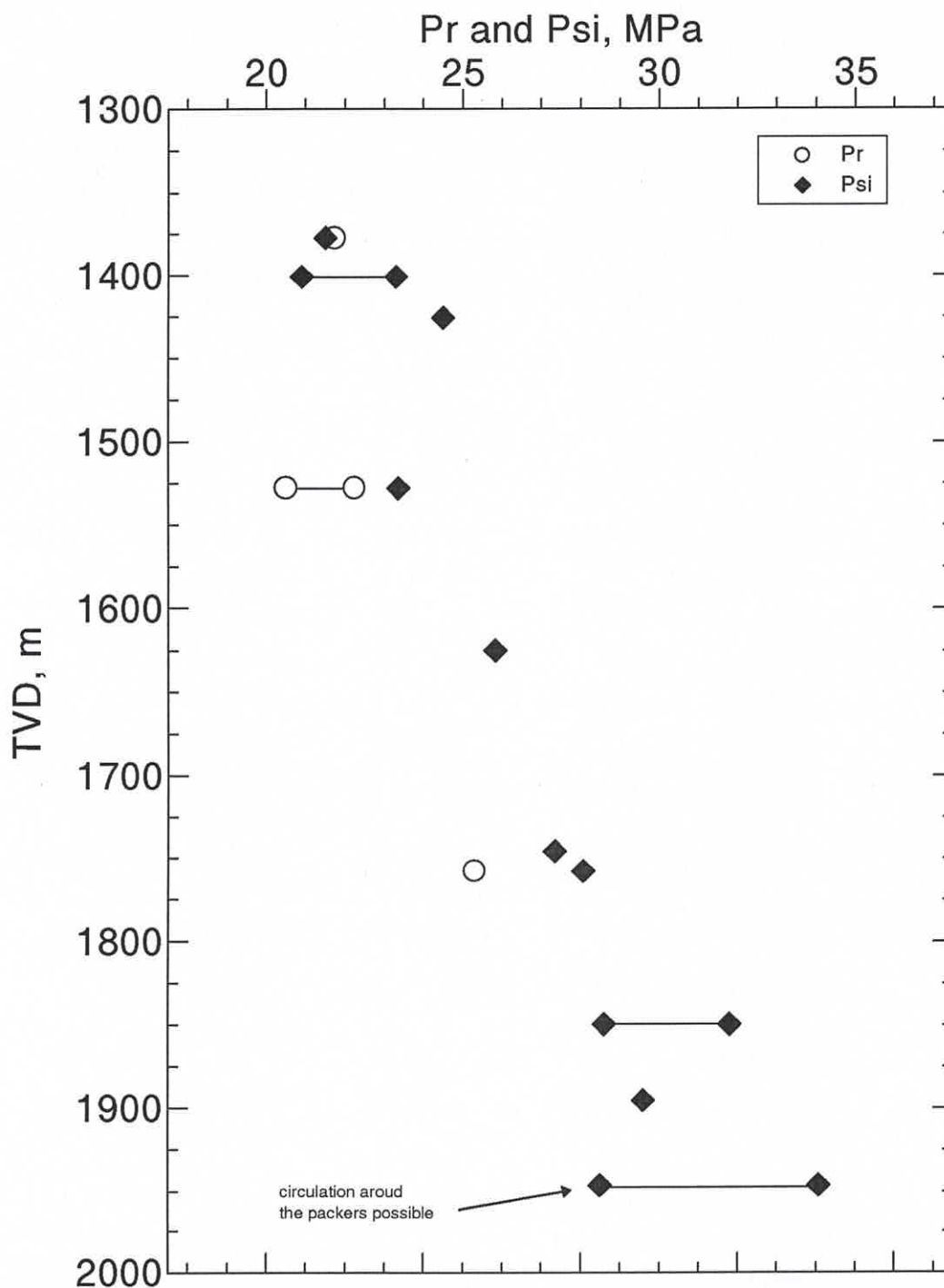
Neglecting the formation pore pressure P_o, the resulting principle horizontal stresses S_h and S_H according to eqs. 4.1 to 4.3 are listed in Table 4.4 together with the open - hole test results [MeSy REPORT NO. 35.95, 1995]. The stress gradients (with respect to depth TVD) and the stress ratios (with respect to the vertical stress S_v) are given in Table 4.5.

The minimum horizontal stress data yield a reliable depth relationship (Fig. 4.3) although some deviations (e.g. at 1428.45 m and 1882.0 m) are observed. Summarizing the stress data available for the depth range between 1375 m to 1950 m, the following stress - depth profiles can be suggested:

$$S_v \text{, MPa} = 0.0245 \cdot \text{TVD, m} \ (\varrho = 2.5 \text{ g/cm}^3)$$
$$S_h \text{, MPa} = 22.0 + 0.0165 \cdot (\text{TVD, m} - 1375)$$
$$S_H \text{, MPa} = 40.3 + 0.0381 \cdot (\text{TVD, m} - 1375)$$

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Table 4.4 : Result of stress evaluation using the HUBBERT and WILLIS approach. The vertical stress S_v is calculated for a mean overburden rock mass density of 2.5 g/cm^3.

test phase	test no.	mean depth of perforation	mean depth below surface TVD	S_v	S_h	S_H
		m	m	MPa	MPa	MPa
cased-hole	11	1379.95	1377.15	33.77	21.50	42.76
	10	1403.60	1400.80	34.35	20.9-23.3	-
	9	1428.45	1425.65	34.96	24.50	-
	6	1530.60	1527.80	37.47	23.36	47.84-49.58
	7 A	1627.50	1624.70	39.85	25.83	-
	8	1748.40	1745.60	42.81	27.35	-
	4	1760.25	1757.45	43.10	28.07	58.91
	3	1852.30	1849.50	45.36	28.6-31.8	-
	2	1897.95	1895.15	46.48	29.6	-
	1	1948.95	1946.15	47.73	(28.5-34.1)*	-
open-hole	10	1418.0	1415.2	34.71	23.13	41.50
	9	1587.0	1584.2	38.85	25.67	40.25
	8	1681.0	1678.2	41.16	25.67	49.00
	6	1755.0	1752.2	42.97	29.16	59.16
	5	1882.0	1879.2	46.02	31.74	57.54

* Circulation around the packers possible

Table 4.5: Stress gradients (with respect to depth TVD) and stress ratios (with respect to S_v).

test phase	test no.	mean depth below surface TVD m	S_h / TVD MPa / m	S_H / TVD MPa / m	S_h / S_v	S_H / S_v
cased-hole	11	1377.15	0.0156	0.0311	0.64	1.27
	10	1400.80	0.0158	-	0.64	-
	9	1425.65	0.0172	-	0.70	-
	6	1527.80	0.0153	0.0319	0.62	1.30
	7 A	1624.70	0.0159	-	0.65	-
	8	1745.60	0.0157	-	0.64	-
	4	1757.45	0.0160	0.0335	0.65	1.37
	3	1849.50	0.0163	-	0.67	-
	2	1895.15	0.0156	-	0.64	-
open-hole	10	1415.2	0.0163	0.0293	0.67	1.20
	9	1584.2	0.0162	0.0254	0.66	1.04
	8	1678.2	0.0153	0.0292	0.62	1.19
	6	1752.2	0.0166	0.0338	0.68	1.38
	5	1879.2	0.0169	0.0306	0.69	1.25
mean			0.0161	0.0306	0.066	1.25

Figure 4.3 : Principal stresses derived from cased - hole and open - hole hydrofrac stress measurements in borehole Natarp-1.

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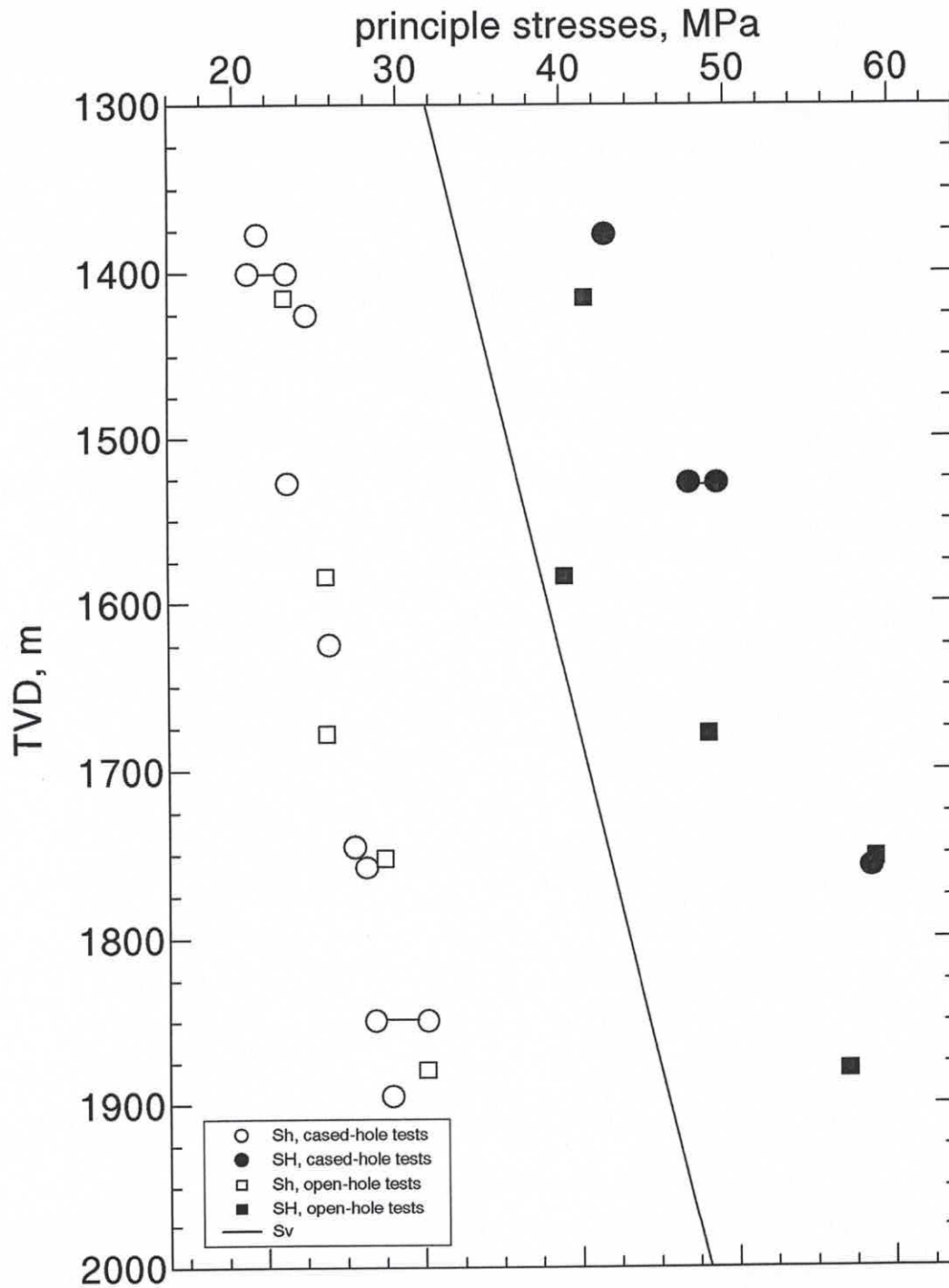
5.   DISCUSSION OF RESULTS

5.1   PERMEABILITY DATA

The permeability measurements on coal seams in borehole Natarp-1 yield valuable data to be considered for CBM - potential evaluation (independent from the test method applied). The observed mean permeability of about 0.1 mD corresponds to the data derived in borehole Rieth-1 [MeSy REPORT NO. 29.95, 1995], although some deviations (e.g. at 1570 m and 1580 m in borehole Rieth-1) are observed as shown in Figure 5.1. The coal permeability of about 0.1 mD seems to be a characteristic value for the Ruhr Carboniferous.

The pressure pulse tests conducted on the coal bearings of borehole Natarp-1 and Rieth-1 [MeSy REPORT NO. 27.95 and 29.95, 1995] yield correspondingly a mean rock mass permeability of about 0.01 mD which characterizes the tight sandstone and claystone formation. The low permeability together with the observed high in - situ tensile strength causes the observed high frac - gradients in borehole Natarp-1.

5.2   STRESS DATA

The interpretation of the cased - hole hydrofrac tests is based on the classical HUBBERT and WILLIS [1957] concept. The detailed analysis of the test records together with the open - hole test results yields a linear pressure vs. depth relationship which suggest principle stress vs. depth profiles.

Although the magnitude of the minimum horizontal stress (as well as the resulting stress gradient and stress ratio) in borehole Natarp-1 is slightly higher than in borehole Rieth-1 (Fig. 5.2), the results at both locations generally are in good agreement with stress profiles measured in boreholes drilled to a depth of about 2 km at numerous locations in Central Europe (Fig. 5.3, 5.4), if the uncertainities caused by the assumptions of the HUBBERT and WILLIS concept are considered. Similar relationships were already derived from extensive hydrofrac stress measurements in Ruhr coal - mines [MeSy REPORT NO. 28.94, 1994].

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Figure 5.1 : Comparison of permeability data in borehole Natarp-1 and Rieth-1 (permeability of coal seams derived from injection / pressure fall - off tests, permeability of the coal bearings derived from pressure pulse tests).
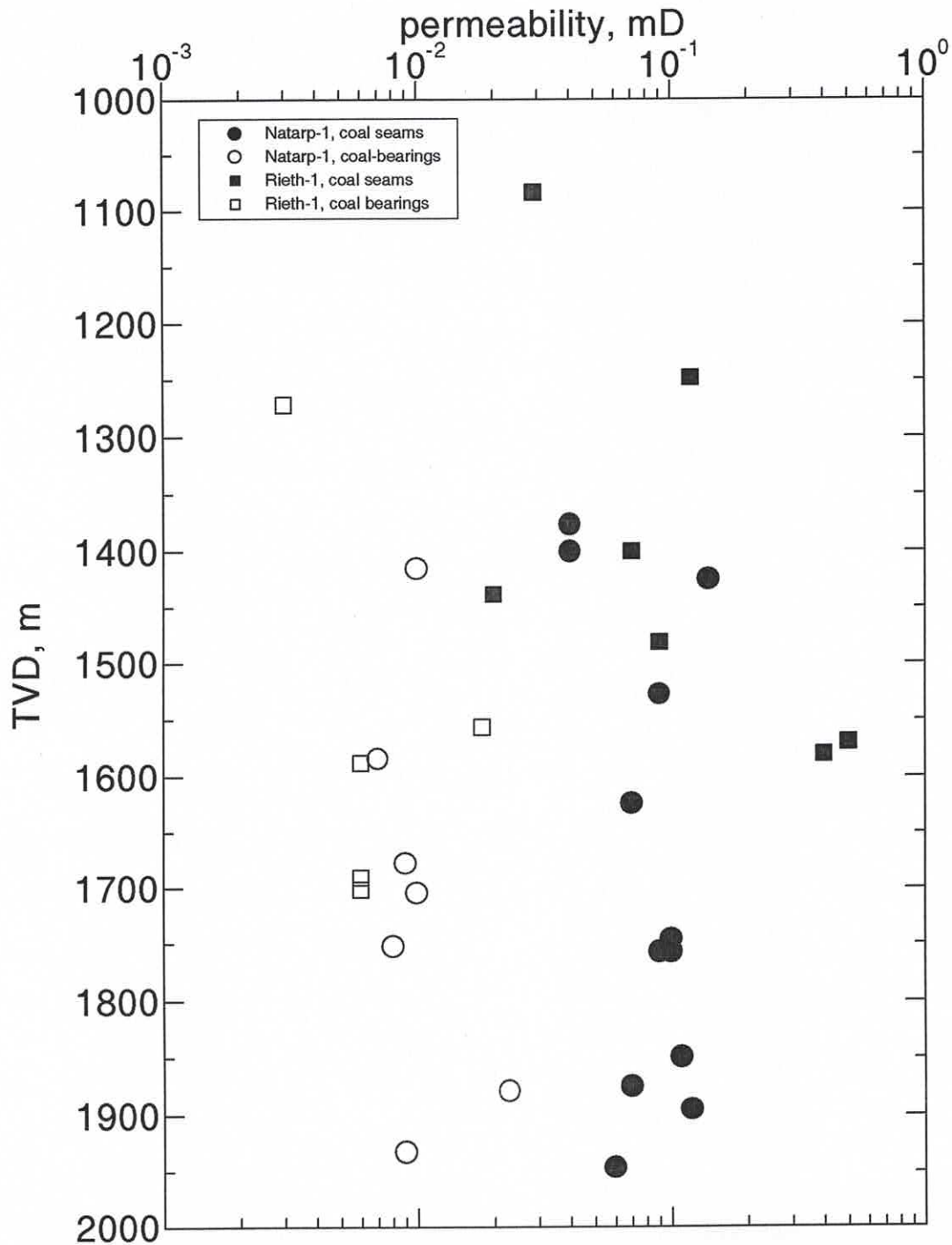
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Figure 5.2 : Comparison of stress profiles derived from hydrofrac testing in borehole Natarp-1 and Rieth-1.
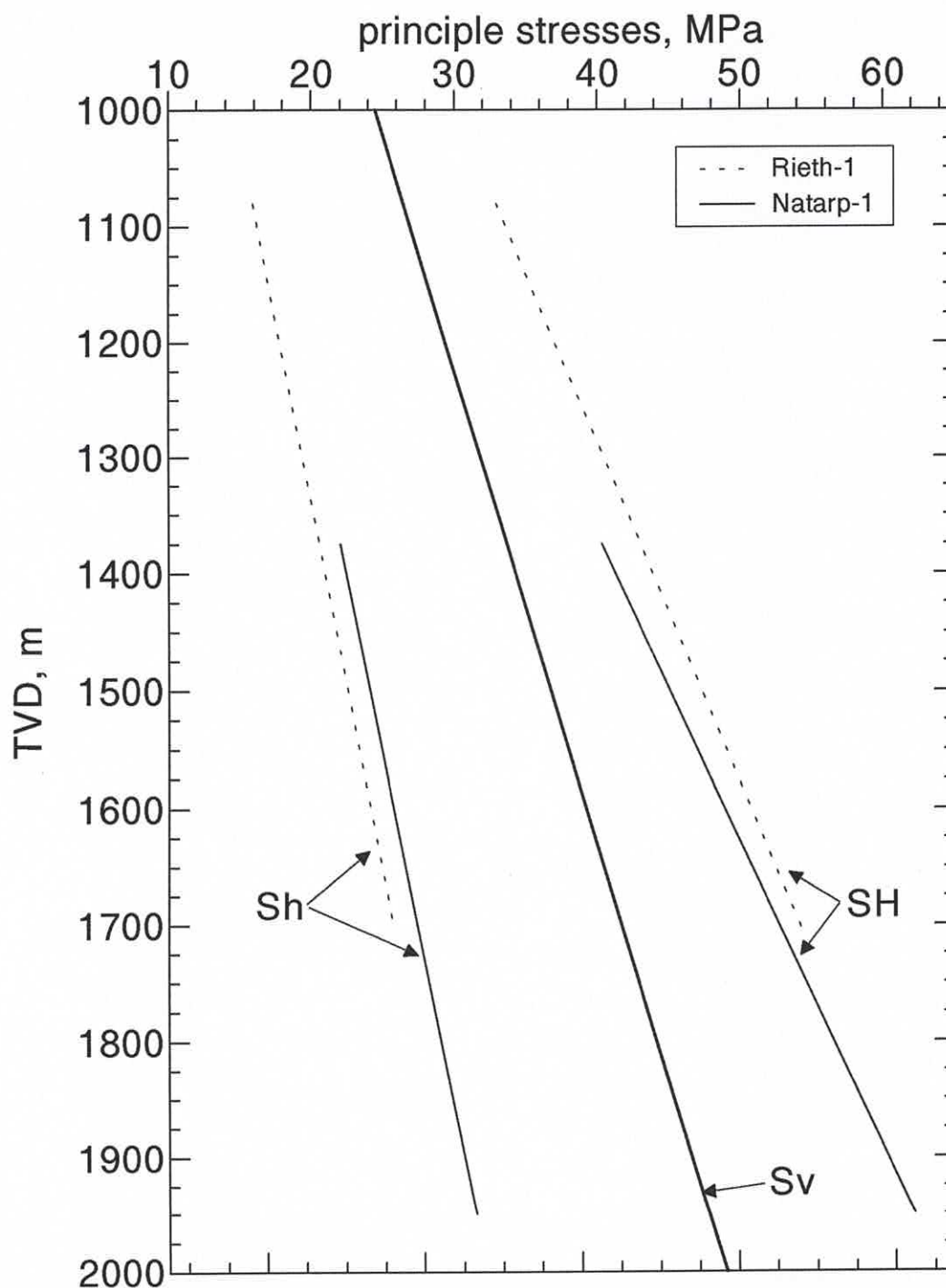
Figure 5.3 : Minimum horizontal stress S_h normalized with respect to S_v derived from numerous hydrofrac stress measurements in Central Europe.
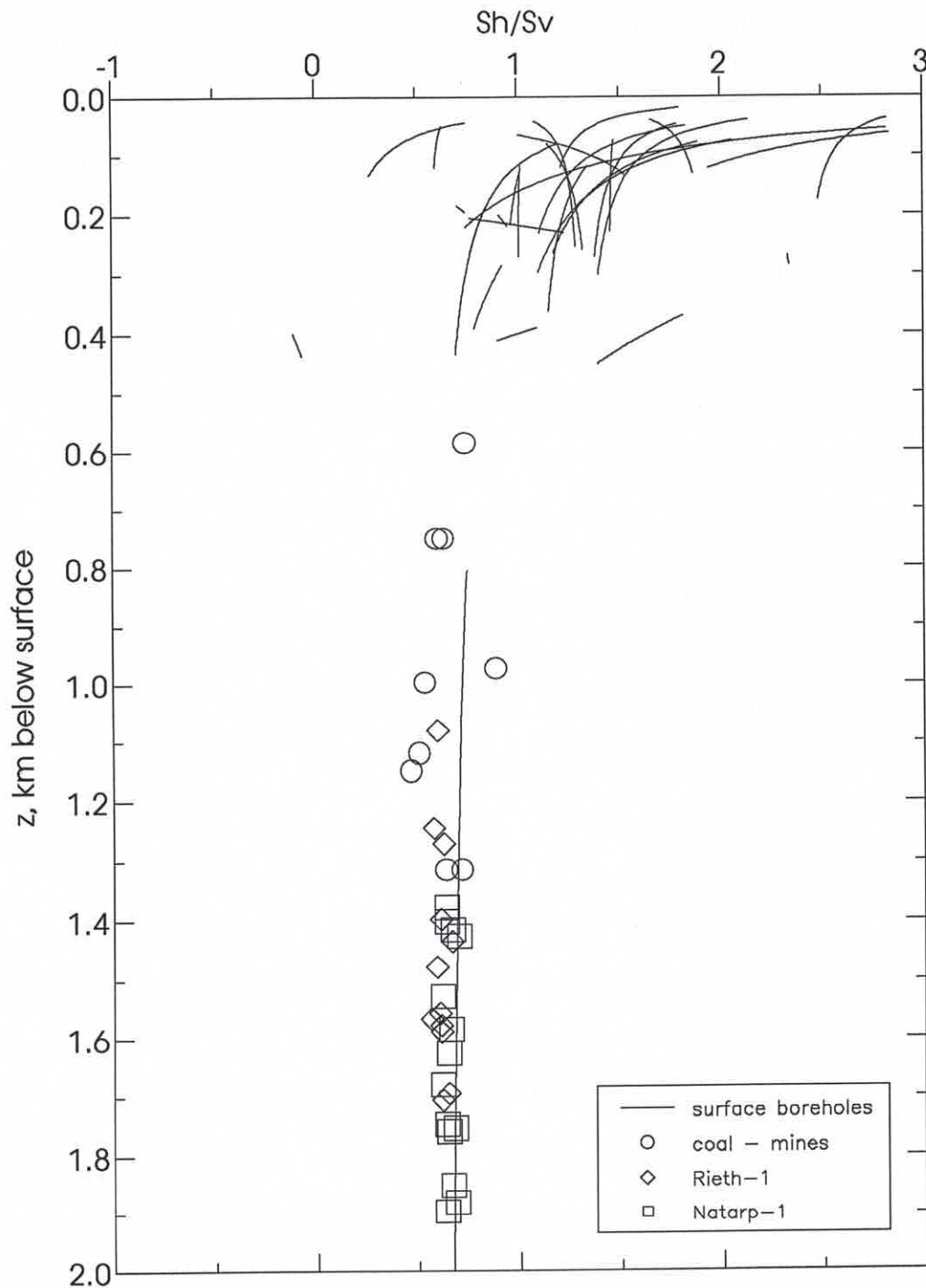
Figure 5.4 : Maximum horizontal stress S_H normalized with respect to S_v derived from numerous hydrofrac stress measurements in Central Europe.
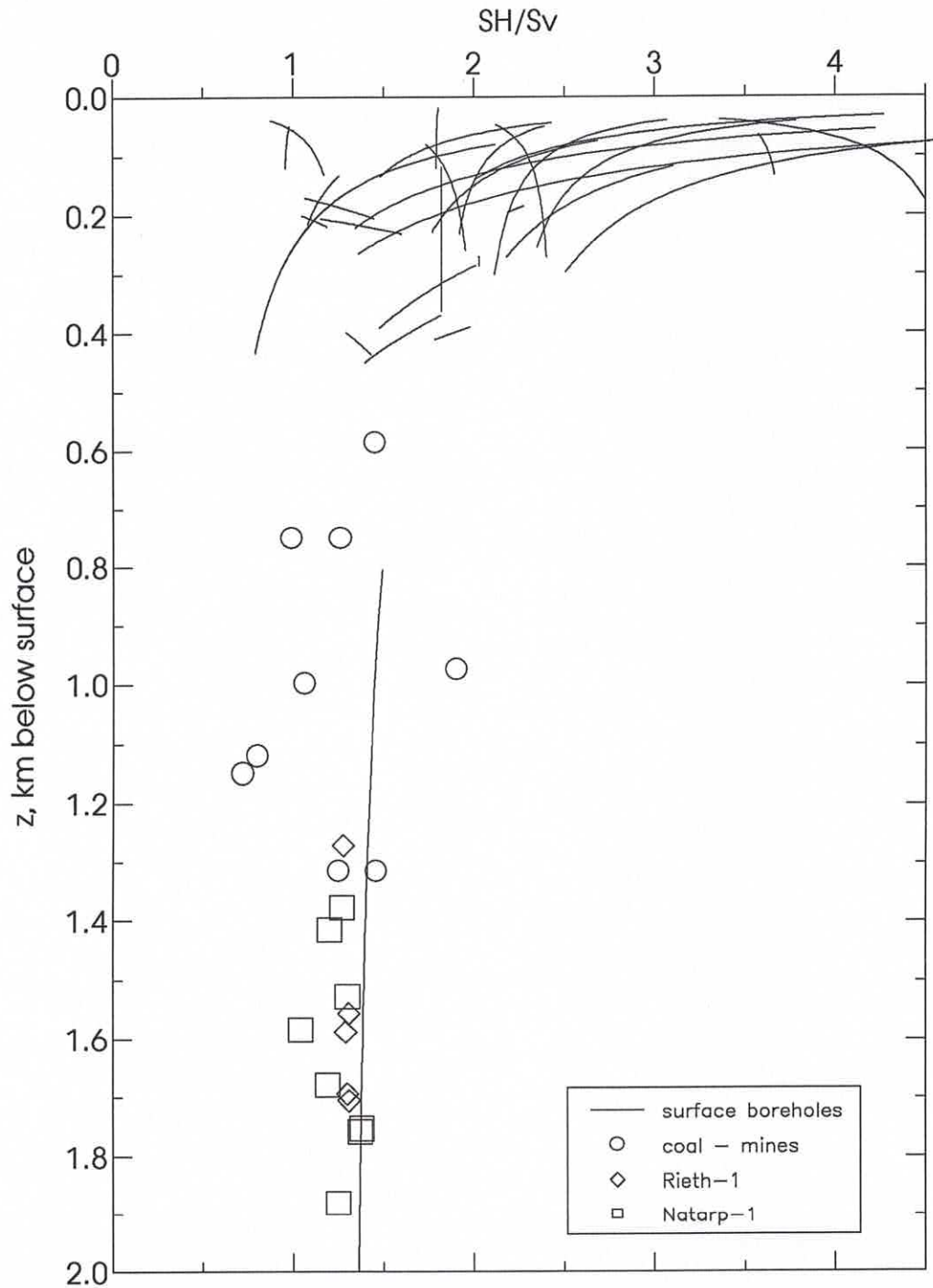
6. REFERENCES

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7. ACKNOWLEDGMENT

APPENDIX A

OPERATION REPORT DATED 12.09.95