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Update of structural models at SFR nuclear waste repository, Forsmark, Sweden

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SUMMARY

The final repository for radioactive waste, SFR, is located below the Baltic, off Forsmark. Site investigations commenced in 1980, and the repository was constructed 1983-1986. During this period a number of various geo-scientific investigations, were performed and used to design a conceptual model of the fracture system, to be used in hydraulic modeling for a performance assessment study of the SFR facility in 1987. Permit was granted with some restrictions, such as a monitoring program, and SFR was taken into operation in 1988. An updated study was reported in 1993. No formal basic revision of the original conceptual model of the fracture system around SFR has so far been made. During review, uncertainties in the model of the fracture system were found.

The previous local structure model comprises four zones: H2, 3, 6, 8 and 9. The evidence for this model as given by Carlsson et al (1986) and Christiansson (1986) is reviewed.

An alternative model is presented, together with evidence for the new interpretation. The model is based on review of geophysical data, geological mapping, corelogs, hydraulic testing, water inflow, etc. The main features of the alternative model are:

- Extension of H2 beyond Zones 3, 6, 8 and 9, and outcropping between U=2300 and 2400
- Extension of Zone 9 to Zone 3 in DT
- Termination of Zone 6 between DT and BT
- Reduction of Zone 8 to a 3rd order zone

The main features of the reviewed regional model are:

- Zone H2 extending beyond the Singö Zone
- Shortening of Zone 6 in accordance with tunnel mapping
- Longer Zone 9 in accordance with tunnel mapping
- Reduction of Zone 8, which is assessed not to be a main zone
- Zone 3 is identical in both models

The fact that two different models can result from the same data represent an interpretation uncertainty which cannot be resolved without more data and basic interpretations of such data. Even if the re-analysis of the data give more support for the updated model it is still recommended to consider both models as alternatives in the subsequent consequence analyses. Further refinement of the structure model could only be motivated in case the two different models discussed here would lead to significantly different consequences.

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APPENDICES

1 BACKGROUND

The final repository for low and intermediate radioactive waste, SFR, is located below the Baltic offshore of the nuclear power plant at Forsmark. Pre-investigations from platforms at sea for the siting of the facility was started in 1980, and the actual construction work was ongoing from the autumn 1983 until June 1986. During this period a number of various geo-scientific investigations, like seismic surveys, core logging and hydraulic testing were performed and used to build a conceptual model of the fracture system around SFR. The conceptual model formed the basis for hydraulic modeling that gave input to a performance assessment study of the SFR facility, which was reported by SKB in September 1987 (SBK, 1987). The application for a permit was accepted by the authorities with some restrictions, as for instance the incorporation of a control program, and the facility was taken in operation in April 1988. An updated performance assessment study was reported by SKB in May 1993 (SKB, 1993). No formal basic revision of the original conceptual model of the fracture system around SFR has so far been made. Though, a brief review of the conceptual model and the control program was performed by Axelsson et. al. (1995). One of the findings was that there were uncertainties in the official conceptual model of the fracture system and that there existed other possible interpretations.

2 SCOPE OF WORK AND EXECUTION

The scope of work for the present study is to critically review the official regional and local structural models at the SFR facility presented by SKB (1993), and to present alternative possible interpretations.

The work is based on the findings of the former review by Axelsson et al. (1995). The official structures of the local model given by SKB (1993) is critically reviewed by examining for each structure the geophysical, geological and hydrological evidence found in seismic surveys, tunnels and boreholes. Hereby, the ambition has been to "go to the source" and not to use interpretations. The basic reports for geophysical and geological investigations are:

- Hagconsult, 1981 (SFR 81-13)
- Christiansson and Magnusson, 1985 (SFR 85-07)
- Christiansson, 1986 (SFR 86-02)
- Christiansson and Bolvede, 1987 (SFR 87-03)
- Carlsson et al., 1986 (SFR 86-03)
- Tirén, 1989 (SKB TR 89-19)

Concerning the hydrological properties of the fracture zones, the scope was not to perform any reinterpretations. Therefore, the hydrology, width and location of the fracture zones was taken from the interpretations made by Carlsson et al. (1986). The connections in and between different interpreted fracture zones is based on the analysis of interference tests and the response from the breakthrough of the sub-horizontal zone H2 when drilling 10 bottom-holes for blasting of the tunnel NBT in 1985-08-05. The disturbance of the interference tests is minor compared with the breakthrough of zone H2 when blasting the tunnel NBT. The flow rate for the interference tests varies between about 0.5 and 25 l/min with a test length between 2 and 19 days. The inflow through the 10 boreholes drilled from the tunnel NBT through zone H2 was 182 l/min. The first injection was made after about 3 days. New holes were drilled followed by injection in sequences of about 5-6 days.

The basic reports for hydrology are:

- Carlsson et al., 1986 (SFR 86-03)
- Arnefors and Carlsson, 1985
- Andersson et al., 1986
- Danielsson, 1985, 1986
- Danielsson and Larsson, 1988

However, the report on interference tests made by Arnefors and Carlsson (1985) has not been possible to retrieve.

The regional model is only briefly reviewed by giving examples of different interpretations by various authors and also by discussing inconsistencies with the revised interpretation of the local model. It is also based on information on regional sub-horizontal fracture zones.

3 PREVIOUS STRUCTURAL MODEL

The previous local structure model can be seen in Figure 3-1, and comprises Zones H2 (not outcropping), 3, 6, 8 and 9. The zones of the structure model are described by Carlsson et al. (1986), some of them more detailed by Christiansson (1986). In the following, only zones which divert from the alternative model presented in this work, are described in detail.

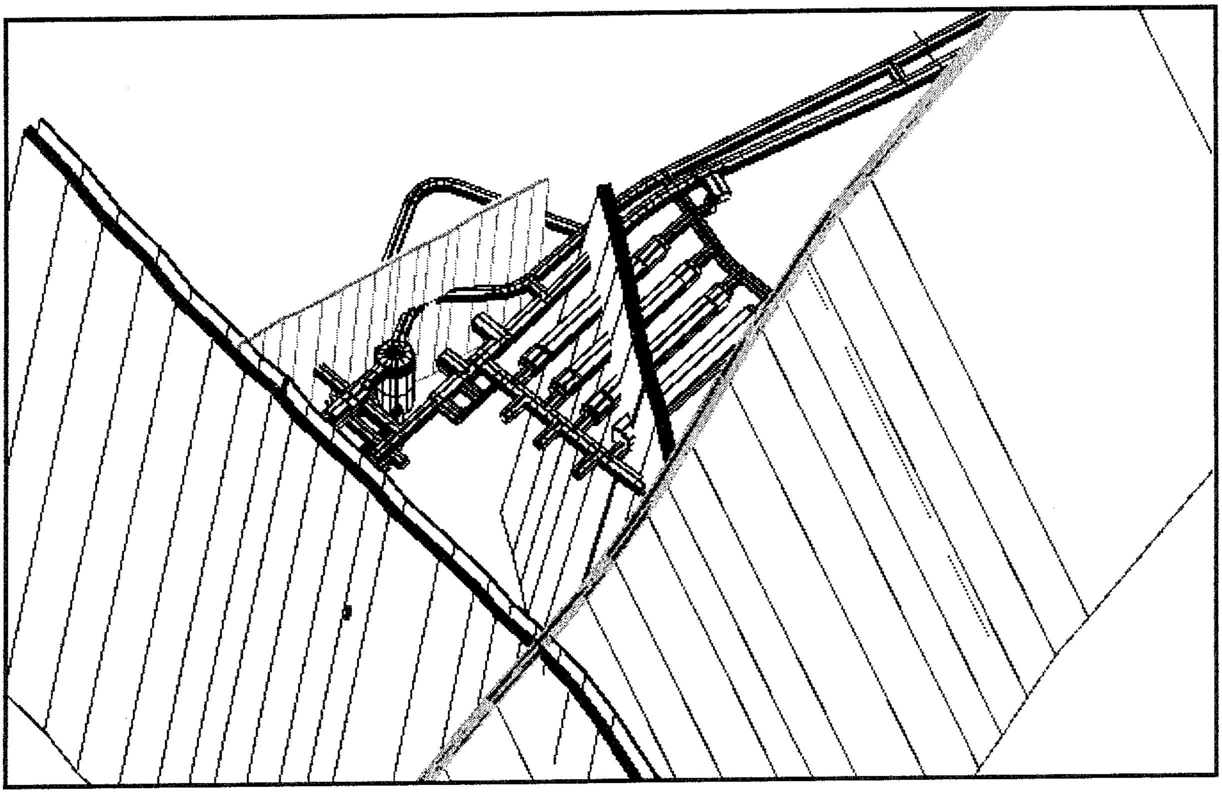

Figure 3-1. *Previous local model (SKB 1993).*

3.1 ZONE H2

H2 is regarded as being limited by Zones 3, 6, 8, and 9. Encounters and characteristics of Zone H2 are listed in Table 3-1.

The following evidence is given (Christiansson 1986) for the interpretation that Zone H2 does not extend beyond these zones.

1. No characteristic H2 indications in HK2 South of Zone 6. No hydraulic connection during flow tests.

2. Subhorizontal joints in HK13 East of Zone 9. No other characteristic H2 indications.
3. Rock stress fields and joints within the block bordered by the four zones are twisted clockwise.
4. Influence on HK 10 by flow test in SH3, are regarded as passing via Zone 3

Table 3-1. Encounters and characteristics of Zone H2 (Hagconsult 1981, Carlsson et al 1986, Christiansson 1986).

Site	Top	Bottom	Width [m]	K (m/s)	fract/m	Other characteristics
Kb1	384.0	378.0	6.0	3.E-06	>10	Alteration, horiz. joints
Kb2	371.9	363.2	8.7	1.E-06	>10	Flushwater loss, horiz. joints
Kb4	377.0	372.0	5.0	**4.E-08**	>10	Flushwater loss, horiz. joints. **Grout before test!!**
Kb5	403.0	390.7	12.3	3.E-06	>10	Horiz. Joints, core loss, grouting
Kb11	348.9	346.2	2.7	no data	>10	Alteration, clay, crushed rock
Kb12	386.8	370.1	16.7	5.E-06	>10	Flushwater loss, core loss
Kb17	343.0	332.3	10.7	2.E-05	>10	Flushwater loss, clay, crushed rock
Kb18	354.2	350.8	3.4	1.E-05	>10	Flushwater loss, clay, crushed rock
Kb27	396.4	390.4	6.0	1.E-05	>10	Alteration, clay, horiz. Joints
HK3	330.5	321.5	9.0	1.E-09	>10	Alteration, clay, **no horiz. joints recorded**
Hk5	342.7	339.9	2.8	no data	25	High fracture frequency
Hk7A	365.3	364.0	1.3	5.E-06	25	High fracture frequency
Hk7B	354.6	350.6	4.0	2.E-06	15	High fracture frequency, horiz. Joints
Hk7C	359.0	345.9	13.1	3.E-08	20	High fracture frequency
Hk12	390.6	379.6	11.0	2.E-07	25	Alteration, clay, horiz. Joints
NBT (tunnel)	363.6		6.0			Large inflow

Note: Holes Kb11, 12, 17, 18, HK5, 7A & 7C are all inclined with no core orientation. For this reason, horizontal joints cannot be detected. All these indications, except Kb 4 are within the block limited by Zones 3, 6, 8, and 9.

Carlsson et al (1986), remark that the occurrence in Kb 4 is outside Zone 8, but that other interpretations than H2 may exist. They also remark that the Zone 3 interpretation in HK 10 may as well be interpreted as H2.

Table 3-2. Encounters of Zone 8 (Carlsson et al 1986; Christiansson 1986).

Site	Strike/ dip	Appr Level, m	Width, m	fract/m	T (m2/s)	K (m/s)
Kb 4	NW/80 NE	385	2.1	10	7.5E-08	3.6E-08
Kb 5		375	4.9	10	6.8E-06	1.4E-06
Kb 26		445	-	5-25	2.3E-06	-
Hk 8		410	18.9	15	1.1E-05	6.0E-07
Hk 8		407	16.2	25	5.8E-06	3.6E-07
Hk 11		400	13.9	25	4.6E-05	3.3E-06

3.2 ZONE 8

According to Carlsson et al. (1986) and Christiansson (1986), Zone 8 is identified by seismic investigations and found in core drillings Kb 4, Kb 5, HK 8 and HK11, as shown in Table 3-2. The zone strikes NW and has an almost vertical dip. The width of the zone is 5-15 m and is flanked by rim zones. Totally the width is 10 to 45 m. It is characterised by mylonitisation, fractured rock, alteration and core loss. It is classified as a 2nd order zone, and is interpreted to continue both to the SE until it reaches the Singö Zone and to the NW.

3.3 ZONE 9

Zone 9 (Mylonite Zone, Christiansson 1985) is classified as a 4th order zone. It is identified by seismic investigations (Carlsson et al. 1986) and has been found in core drillings HK 4, Kb 18, Kb 23, Kb 24, and Kb 25, as well as in tunnels BT and STT, as shown in Table 3-3. The width is 1-3 m. The zone is characterized by crushed rock, mylonitization, alteration, calcite crystals, flushwater loss and water leakage in tunnels. It is interpreted to terminate towards vertical NNE striking joints (Christiansson 1985).

Table 3-3.

Hole No	Appr Level, m	fract per m	Width, m	T, m2/s	K, m/s
Hk 4	400	10-15	1.4	5.0E-08	3.6E-08
Kb 23	405	25	3.2	2.3E-08	7.2E-09
Kb 24	390	16	3.3	3.0E-09	9.1E-10
Kb 25	365	16	3.7	1.5E-07	3.9E-08

Tunnel	Chainage	Characteristics
BT	6/020-050	Fault gouge, water leakage
STT	6/810-820	Fault gouge, water leakage

4 REVIEW OF STRUCTURE INTERPRETATION

4.1 ZONE H2 AND OTHER HORIZONTAL STRUCTURES

4.1.1 Indications and observations

A summary of observed data is shown in Table 4-1.

Table 4-1 Zone H2. Indications

Site	Type	Strike/ dip	Geology (Reference 1 & 3) Upper surface Level [m]	Lower surface Level [m]	fract/m (approx)	Hydrology (Reference 2) Width [m]	T [m^2/s]	K [m/s]	Other characteristics
NBT, 8/405-8/435	Tunnel	WSW/20°S	368	362		6.0			
Kb1	Core drilling	sub-horiz	384	378	10	5.7	1.1E-05	2.0E-06	Alteration
Kb2	Core drilling	sub-horiz	372	363	10	7.3	5.1E-06	7.0E-07	Flushwater loss
Kb4	Core drilling	sub-horiz	377	372	10	5.2	1.6E-05	3.0E-06	Flushwater loss. Grout before test!!
Kb5	Core drilling	no data	404	391	10	16.0	8.3E-06	5.2E-07	no data
Kb11	Core drilling	no data	349	346	10	2.4	<1.2E-07	<5.0E-08	Alteration, clay, crushed rock
Kb12	Core drilling	no data	387	370	10	19.3	3.2E-05	1.7E-06	Flushwater loss
Kb17	Core drilling	no data	343	332	10	8.7	4.2E-05	4.9E-06	Flushwater loss, clay, crushed rock
Kb18	Core drilling	no data	354	351	10	2.9	2.5E-05	8.7E-06	Flushwater loss, clay, crushed rock
Kb27	Core drilling	no data	396	390	10-15	6.0	1.0E-05	1.7E-06	Alteration, clay
HK5	Core drilling	no data	343	340	25	3.0	4.4E-07	1.5E-07	High fracture frequency
HK7A	Core drilling	no data	365	364	25			9.2E-06	High fracture frequency
HK7B	Core drilling	no data	355	351	15	6.5	1.3E-05	2.0E-06	High fracture frequency
HK7C	Core drilling	no data	359	346	20	7.8	1.9E-07	2.4E-08	High fracture frequency
HK12	Core drilling	no data	391	380	25	11.4	2.3E-06	2.0E-07	Alteration, clay
*HK2	Core drilling	sub-horiz	300	290	10	10.0	1.0E-07	1.0E-08	Many horizontal joints
HK3	Core drilling	no data	331	322	10	9.0	2.0E-08	2.2E-09	Alteration, clay
HK4	Core drilling	sub-horiz	335	326	8	9.0	2.1E-07	2.3E-08	Many horizontal joints
HK13	Core drilling	sub-horiz	335	333	15	2.0	3.2E-08	1.6E-08	Many horizontal joints
HK13	Core drilling	sub-horiz	316	314	8	2.0	1.4E-06	7.0E-07	Many horizontal joints

Author's comments:
Hk2: Increased k at level 290-310 and horizontal joints at 290 indicate presence of H2
Transmissivity (T) values for HK2, HK3, HK4, HK13 interpreted from SFR 86-03, Appendix 4
References: 1) SFR 86-03, Table 4.2; 2) SFR 86-03, Table 6.4.18; 3) SFR 87-03, dwg 17

Geophysics and topography

A profile along the dip of Zone H2 is shown in Figure 4-1.With the interpreted average dip, Zone H2 appears to outcrop some 400 m NNE of the silo. At this place, there is a depression aligned along the strike of Zone H2. Although there are some seismic refraction anomalies there, they cannot be related to any single structure.

However, 300 metres further NNW there are seismic anomalies (previously not interpreted) aligned fairly well along the strike of H2 on all profiles crossed (SFR 81–13, dwg No. F4). Also, a topographic lineament is present there (Axelsson, unpublished data). As can be seen in the figure, only a very small change in dip will be sufficient for H2 to outcrop there. Such variations in dip of a tectonic structure can be regarded as more common than not.

- Hence, there are seismic refraction anomalies and a topographic lineament which fit with an outcrop of H2, some 700 m NNW of the silo.

Tunnels

Zone H2 has been encountered in NBT at chainage 8/405-435 and in INDB.

In IB, a set of sub-horizontal joints have been recorded. Its position fit with sub-horizontal joints in Kb4 and Kb5.

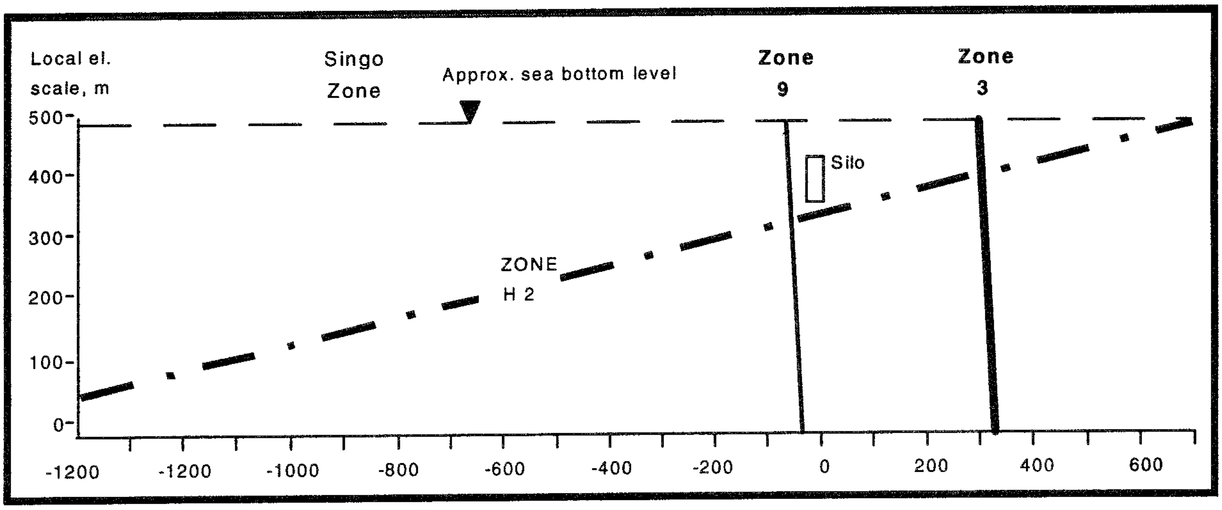

Figure 4-1. *Profile along dip direction of Zone H2.*

Core drillings

Zone H2 has been encountered in a number of holes, as demonstrated in Table 4-1. Common characteristics for the intercepts are increased hydraulic conductivity, flush water loss, high joint frequency and occurrence of sub-horizontal joints. In some holes, also alteration and crushed rock occur. Some holes which in earlier works were regarded as not penetrating Zone H2 are listed below with comments:

- HK2. Sub-horizontal joints are found at about levels 300 and 250, both zones associated with increase in K-value. Both can be fit with H2. Water pressure reacted during excavation through H2 in NBT tunnel (Appendix A).
- HK3 was expected to penetrate Zone H2 at about level 330. At about 320, jointing is high, but K-values are low, and there are no records of horisontal joints. However, water pressure reacted during excavation through H2 in NBT tunnel (Appendix A). The fracture peak at elevation 365, appears to fit with Zone 9.
- HK4 penetrates Zone 9 (a number of gouge filled joints), and should penetrate Zone H2 at about level 330. At this level, the core show increased jointing, but no difference in K-value. However, grout has been found in the core, at the intercept of Zone 9, and the K-values cannot be regarded as being virgin values. The pressure in HK4:P1 is in an increasing trend and could have reacted on the excavation through H2 in NBT tunnel (Appendix A). However there was a distinct drop in pressure when leakage occurred in the packer in borehole HK7C penetrating zone H2 (Table 4-2.). No horizontal joints have been recorded in this hole.
- HK13. Sub-horizontal joints are encountered at the expected level (330), but not associated with high K-value. At level 315-20, increased K occurs with sub-horizontal joints, a typical H2 feature. Borehole HK13 was not drilled when the excavation through H2 in NBT tunnel took place. However there was a distinct drop in pressure when leakage occurred in the packer in borehole HK7C penetrating zone H2 (Table 4-2.). Interference testing in HK13 also gives direct responses in boreholes located in zone H2.

4.1.2 Hydraulic conditions

The hydraulic width, transmissivity and hydraulic conductivity has been interpreted from a number of water injection and pressure build-up tests in boreholes penetrating Zone H2. Three interference tests were conducted in two boreholes, HK7B:1 and HK13:1, to establish the connection along the zone and the hydraulic properties of the zone. The interpretations are given in SFR 86-03 (Tables 6.4.18 and 6.4.19) and shown in Table 4-2. The interpreted hydraulic conductivity from single hole tests varies mostly between $2 \cdot 10^{-7}$ and $9 \cdot 10^{-6}$ m/s, while the interference tests gives values between $2\text{-}9 \cdot 10^{-6}$ m/s. Worth noticing is that the single hole hydraulic conductivity for HK7C:1 is $2.4 \cdot 10^{-8}$ m/s, while the interference tests give conductivities of $1.1\text{-}1.9 \cdot 10^{-6}$ m/s. The interference tests for holes HK5 and HK12 gives about 10 times higher conductivity values than the single hole tests.

The interference tests show a connection within Zone H2 with a high hydraulic conductivity between the flowing section HK7B:1 and the sections HK7A:1, HK7C:1, HK5:2 and HK12:2 (Carlsson et al., 1986, Table 6.4.19). The flowing section HK7B:1 also has a connection with sections HK8:1 and HK11:1 with a hydraulic conductivity of $6\text{-}7 \cdot 10^{-7}$ m/s (Andersson et al., 1986, Table 5.11). The boreholes HK4, HK13 and Kb25 also responds to flowing in section HK7B:1 (Andersson et al., 1986, Table 5.10).

The interference test with the flowing section HK13:1 also show a good connection within Zone H2 with a direct response in HK3:P1 and P2, HK4:1, HK5:2, HK7B, HK7C, HK8:P1 and Kb25:3 (Andersson et al., 1986, Table 5.12). Hydraulic transmissivities are calculated from Andersson et al., (1986, Table 5.13) and given in Table 4-2.

When a leakage occurred in HK7C penetrating Zone H2, the following holes reacted; HK3, HK4, HK5, HK7A, HK7B, HK13, and Kb25.

The largest disturbance in Zone H2 was during excavation of the tunnel NBT when Zone H2 was encountered by 10 drillholes with a total discharge of 182 l/min. A number of holes responded; HK1 (Singö Zone), HK2, HK3, HK4, HK5, Kb19, Kb20 and Kb25 (Table 4-2. and Appendix A).

4.1.3 Character

Zone H2 can be characterised as a complex zone with varying geological and hydraulic properties. Characteristic features are horizons with high frequency of horizontal and vertical joints with increased hydraulic conductivity, separated by ordinarily fractured rock. Alteration occur in some of the cores. Subhorizontal joints and increased hydraulic conductivity are indicative features (SFR 81-13, pp 47-48).

Table 4-2. Zone H2. Hydraulic connections - interference tests

Flow Site (Test)	Flow (l/min)	Test length (hours)	Zones in FS	Obs. hole (OH)	Zones in OH	Hydr path [m]	Draw down [m]	T (m^2/s)	K (m/s)	Indirect response	No response	Ref.
HK7B:1	19.2	95	H2	HK5:2	H2	65	Direct	9.6E-06	3.2E-06	HK3,HK4,HK5:1	HK2,HK10?	1, 2
(A)				HK7C:1	H2	25	Direct	8.2E-06	1.1E-06	HK5:3,HK5:4		1, 2
				HK7C:2	H2 ?	25	Direct	6.0E-06	?	HK7A,Kb25		2
HK7B:1	18.4	111	H2	HK5:2	H2	65	Direct	1.2E-05	4.1E-06	HK4:1-3	HK1,HK2,HK3	1, 2
(E)				HK7A:1	H2,8 ?	50	Indirect	6.4E-05	9.2E-06	HK5:1,3,4	HK4:4,HK9	1
				HK7C:1	H2	25	Direct	1.5E-05	1.9E-06	HK7A,HK7B:2	HK10,HK12:3	1, 2
				HK7C:2	H2 ?	25	Direct	1.1E-05	?	HK8:2,3	Kb19,Kb20	2
				HK8:1	H1,8 ?	105	Direct	2.8E-05	?	HK11:2-4,HK12:1	SH3:1	2
				HK11:1	H1,8 ?	75	Direct	2.4E-05	?	HK13,Kb25:2-4		2
				HK12:2	H2	215	Direct	1.9E-05	1.6E-06	Kb26:1		1, 2
HK13:1	10.5	92	H2 ?	HK3:2	9 ?		Direct	8.3E-06		HK3:1,4	HK1,HK2	4
(F)				HK3:3	9 ?		Direct	1.3E-05		HK4:2,3	HK4:4	4
				HK4:1	H2 ?		Direct	2.0E-06		HK5:1,3,4	HK7A:1,3	4
				HK5:2	H2		Direct	8.2E-06		HK7A:2	HK9,HK10	4
				HK7B:1	H2		Direct	6.9E-05		HK8:2,3	Kb19,Kb20	4
				HK7B:2	H2 ?		Direct	3.0E-05		HK11,HK12	SH3:1	4
				HK7C:1	H2		Direct	8.1E-06		HK13:2,3		4
				HK7C:2	H2 ?		Direct	9.2E-06		Kb25:2,4		4
				HK8:1	H1,8 ?		Direct	1.4E-05		Kb26:1		4
				Kb25:3	9 ?		Direct	3.4E-06				4
NBT	182.0	48 ?	H2	HK1	Singö	950	0.1				HK2:4,HK4:1	5,6,7
				HK2:1	H2 ?	350	1				Kb19:3,4	5,6,7
				HK2:2,3		350	0.5				Kb25:1,2	5,6,7
				HK3:1	H2 ?	150	20					5,6,7
				HK3:2	9 ?	150	10					5,6,7
				HK3:3,4		150	5					5,6,7
				HK4:2		100	2					5,6,7
				HK4:3	9	100	4					5,6,7
				HK4:4		100	6					5,6,7
				HK5:1,2	H2	100	20					5,6,7
				HK5:3,4		100	10					5,6,7
				Kb19:1,2		100	0.5					5,6,7
				Kb20:1-4		100	3					5,6,7
				Kb25:3,4	9 ?	125	1-2					5,6,7
HK7C *	?	?	H2	HK3:1	H2?	150	1				HK1,HK2?,	7
				HK4:1	H2?	80	3				HK3:2	7
				HK4:2		85	1				HK3:3-4?	7
				HK4:3	9	90	1				HK4:4	7
				HK5:1		60	1				HK5:3-4?	7
				HK5:2	H2	65	6				HK7A:1	7
				HK7A:2		100	0.5				HK8?	7
				HK7A:3		90	1				Kb19	7
				HK7B:1	H2	30	0.5				Kb25:1,4	7
				HK7B:2		30	1				Kb26	7
				HK13:1	H2?	100	4					7
				HK13:2,3		100	2					7
				Kb25:2	9?	50	2					7
				Kb25:3	9?	50	5					7

* Leakage i packer i HK7C, Dec. 1987 to April 1988

References: 1) SFR 86-03, Table 6.4.19; 2) IRAP 86403, Table 5.5; 3) IRAP 86403, Table 5.11; 4) IRAP 86403, Table 5.13
5) Appendix A, 6) IRAP 85244, 86314; 7) IRAP 88289

4.1.4 Extension

The main difference between the previous model and the model presented in this work, concerns the extension of Zone H2. The arguments for an interpretation of H2 bordered by Zones 3, 6, 8, and 9 are commented below.

It may be noticed that, within the block bordered by the four zones, there are many holes penetrating H2. Only three holes are drilled outside this block to a relevant depth. These three holes feature increased K at levels corresponding to H2.

Furthermore, HK2 and HK13 feature horizontal fractures, and HK10 feature a fracture zone, all fitting with H2.

Christiansson (1986)	Authors' comment
No characteristic H2 indications in HK2, South of Zone 6.	Horizontal joints are present at elevation 290-300. Increased K 290-310
No hydraulic response in HK 2 during flow tests.	Responding to breakthrough in NBT
Subhorizontal joints in HK13 East of Zone 9. No other characteristic H2 indications	Subhoriz joints coincide with increased K. Many holes respond to flow in HK13. Horiz. joints together with increased K has been regarded as sufficient H2 indicators in Kb2, Kb4 and HK7B.
Rock stress fields and joints within the block bordered by the four zones are twisted clockwise.	This indicates a block. It does not support any limitation of H2.
Influence on HK 10 by flow test in SH3, are regarded as passing via Zone 3	During the excavation of NBT, Zone H2 has turned out as the largest hydraulic zone in the project area, after the Singoe Zone. The end of SH3 is only a few metres from H2 and is most likely in hydraulic contact with it through vertical joints, which are frequent in the vicinity. It seems odd to favor Zone 3 for the connection between SH3 and HK10, instead of H2. The large zone in HK 10 fit with H2 as good as with Zone 3

The following supports that Zone H2 can be regarded as extending wider.

- Large subhorizontal zones exist in the area (Tirén 1989)
- Subhorizontal zones has been encountered in two boreholes, at depths fitting with an extension of H2 (c.f. Section 6.1)
- Response in HK2 to excavation in NBT
- Response in HK 10 to flow in SH3
- Seismic refraction anomalies which could be explained by the outcrop of H2 into the rock surface.

The observation in HK13 indicate that zone H2 has a lower elevation East of Zone 9. If this is the case, HK 3 and HK 4 do not reach down to H2, which can explain the absence of horizontal joints in HK3. The horizontal joints in HK4 fit with the upper set of horizontal joints in HK13.

4.1.5 Other sub-horizontal zones

Another, sub-horizontal zone appears to be present below H2. This would satisfy indications below H2 in HK2, HK5, Kb1 and Kb5, the latter interpreted as Zone 8 (Carlsson et al 1986, Christiansson 1986).

In tunnel IB, and in hole Kb4, there are sub-horizontal joints above H2, at level 400. Kb4 has been grouted prior to hydraulic testing. These joints constitute a pathway between HK8 and HK11 as an alternative to Zone 8.

4.2 ZONE 3

4.2.1 Indications and observations

A summary of observed data is shown in Table 4-3.

Table 4-3. Zone 3. Indications

Site	Type	Geology (Reference 1 and 3) Width [m]	Strike/ dip	Appr Level [m]	fract per m	Hydrology (Reference 2) Width [m]	T [m^2/s]	K [m/s]
DT, 1/470-1/495	Tunnel	10	NNE/ steep W					
BT, 5/390-5/420	Tunnel	10	NNE/ steep W					
Kb 16	Core drilling			430	10	8.2	1.3E-05	1.5E-06
HK 9:2	Core drilling			415	10-20	4.7	3.4E-05	7.2E-06
HK 10:1	Core drilling			350	10-25	*	*	2.3E-06
Seismic Refraction (Reference 4)								
Seismic Profile No	**Seismic velocity [m/s]**							
S8113	3600							
S8117	4200							
S8101	4200							
S8111	4000							
S8116	3700							
S8102	4000							
S8115	4200							
S8110	4500							
S8107	4000							

*Borehole HK10 only penetrates part of Zone 3. Mean hydraulic conductivity calculated for penetrated part.
References: 1) SFR 86-03; 2) SFR 86-03, Table 6.4.4; 3) SFR 87-03, dwg 05 & 06; 4) SFR 81-13

Geophysics and topography

All seismic refraction profiles feature anomalies where crossed by Zone 3.

Tunnels

Zone 3 has been encountered in BT and in DT, fitting approximately with seismic refraction anomalies.

Core drillings

Zone 3 has been encountered in Kb16, HK9, and possibly HK10 (This encounter may as well be H2 or the intersection between the two).

4.2.2 Hydraulic conditions

In the tunnels, Zone 3 feature moisture and dripping, occasionally running water.

Hydraulic tests have been carried out in holes HK9, HK10 and Kb16, which feature hydraulic conductivities over 10^{-6} m/s (Carlsson et al., 1986, Table 6.4.4).

Interference tests are summarised in Table 4-4. Interference tests with flowing sections in HK9:2 and HK10:1 respectively indicate a poor connection between the holes. The interference test with flowing section in SH3 indicates a good connection to the holes HK9 and HK10. However, the path may be questioned. SH3 is drilled through a zone parallel to Zone 6 which probably has connection with both Zone 3 and H2. As H2 has proved to be the main water bearing zone in the repository, and as it is close to SH3, it should be favoured.

Table 4-4. Zone 3. Hydraulic connections - interference tests

Flow Site (Test)	Flow (l/min)	Test length (hours)	Zones in FS	Obs. hole (OH)	Zones in OH	Hydr path [m]	Draw down [m]	T (m^2/s)	K (m/s)	Indirect response	No response	Ref.
HK7B:1 (A)	19.2	95	H2	HK5:2	H2	65	Direct	9.6E-06	3.2E-06	HK3,HK4,HK5:1	HK2,HK10?	1, 2
				HK7C:1	H2	25	Direct	8.2E-06	1.1E-06	HK5:3,HK5:4		1, 2
				HK7C:2	H2 ?	25	Direct	6.0E-06	?	HK7A,Kb25		2
HK7B:1 (E)	18.4	111	H2	HK5:2	H2	65	Direct	1.2E-05	4.1E-06	HK4:1-3	HK1,HK2,HK3	1, 2
				HK7A:1	H2,8 ?	50	Indirect	6.4E-05	9.2E-06	HK5:1,3,4	HK4:4,HK9	1
				HK7C:1	H2	25	Direct	1.5E-05	1.9E-06	HK7A,HK7B:2	HK10,HK12:3	1, 2
				HK7C:2	H2 ?	25	Direct	1.1E-05	?	HK8:2,3	Kb19,Kb20	2
				HK8:1	H1,8 ?	105	Direct	2.8E-05	?	HK11:2-4,HK12:1	SH3:1	2
				HK11:1	H1,8 ?	75	Direct	2.4E-05	?	HK13,Kb25:2-4		2
				HK12:2	H2	215	Direct	1.9E-05	1.6E-06	Kb26:1		1, 2
HK13:1 (F)	10.5	92	H2 ?	HK3:2	9 ?		Direct	8.3E-06		HK3:1,4	HK1,HK2	4
				HK3:3	9 ?		Direct	1.3E-05		HK4:2,3	HK4:4	4
				HK4:1	H2 ?		Direct	2.0E-06		HK5:1,3,4	HK7A:1,3	4
				HK5:2	H2		Direct	8.2E-06		HK7A:2	HK9,HK10	4
				HK7B:1	H2		Direct	6.9E-05		HK8:2,3	Kb19,Kb20	4
				HK7B:2	H2 ?		Direct	3.0E-05		HK11,HK12	SH3:1	4
				HK7C:1	H2		Direct	8.1E-06		HK13:2,3		4
				HK7C:2	H2 ?		Direct	9.2E-06		Kb25:2,4		4
				HK8:1	H1,8 ?		Direct	1.4E-05		Kb26:1		4
				Kb25:3	9 ?		Direct	3.4E-06				4
NBT	182.0	48 ?	H2	HK1	Singö	950	0.1				HK2:4,HK4:1	5,6,7
				HK2:1	H2 ?	350	1				Kb19:3,4	5,6,7
				HK2:2,3		350	0.5				Kb25:1,2	5,6,7
				HK3:1	H2 ?	150	20					5,6,7
				HK3:2	9 ?	150	10					5,6,7
				HK3:3,4		150	5					5,6,7
				HK4:2		100	2					5,6,7
				HK4:3	9	100	4					5,6,7
				HK4:4		100	6					5,6,7
				HK5:1,2	H2	100	20					5,6,7
				HK5:3,4		100	10					5,6,7
				Kb19:1,2		100	0.5					5,6,7
				Kb20:1-4		100	3					5,6,7
				Kb25:3,4	9 ?	125	1-2					5,6,7
HK7C *	?	?	H2	HK3:1	H2?	150	1				HK1,HK2?,	7
				HK4:1	H2?	80	3				HK3:2	7
				HK4:2		85	1				HK3:3-4?	7
				HK4:3	9	90	1				HK4:4	7
				HK5:1		60	1				HK5:3-4?	7
				HK5:2	H2	65	6				HK7A:1	7
				HK7A:2		100	0.5				HK8?	7
				HK7A:3		90	1				Kb19	7
				HK7B:1	H2	30	0.5				Kb25:1,4	7
				HK7B:2		30	1				Kb26	7
				HK13:1	H2?	100	4					7
				HK13:2,3		100	2					7
				Kb25:2	9?	50	2					7
				Kb25:3	9?	50	5					7

* Leakage i packer i HK7C, Dec. 1987 to April 1988

References: 1) SFR 86-03, Table 6.4.19; 2) IRAP 86403, Table 5.5; 3) IRAP 86403, Table 5.11; 4) IRAP 86403, Table 5.13
5) Appendix A, 6) IRAP 85244, 86314; 7) IRAP 88289

4.2.3 Character

Zone 3 is a composite zone, consisting of several narrower zones and fractures, which diverge and converge in a complex pattern. This structure gives the zone a wide appearance and gives rise to the extended seismic anomalies.

4.2.4 Extension

Zone 3 and its extension appear to be well verified by seismic refraction survey and occurrence in tunnels and boreholes. Probably it terminates towards the Singö Zone, some 100 m South of its crossing with the tunnels. Its extension towards the NE into the sea is not surveyed, but assessed to be probable.

4.3 ZONE 6

4.3.1 Indications and observations

A summary of observed data is shown in Table 4-5.

Table 4-5 Zone 6. Indications

Site	Type	Geology (Reference 1 & 3) Width [m]	Strike/ dip	Appr Level [m]	fract per m	Hydrology (Reference 2) Width [m]	T (m^2/s)	K (m/s)
BT, No obs	Tunnel							
DT, 1/930	Tunnel	0.5	NNW/ steep W					
1 BTF, 0/100	Tunnel	0.5	NNW/ steep W					
2 BTF, 0/085	Tunnel	2	NNW/ steep W					
1 BLA, 0/060	Tunnel	0.5	NNW/ steep W					
1 BMA, 0/030	Tunnel	1	NNW/ steep W					
Kb 13	Core drilling			465	10	2.1	5.0E-08	2.4E-08
Kb 15	Core drilling			460	10	2.8	5.1E-06	1.8E-06
Kb 27	Core drilling			400	15			
Seismic refraction (Reference 4)								
Seismic Profile No	**Seismic velocity [m/s]**							
8113	4900							

Clayey water bearing gouge, partly with intensely fractured rims. In the North, it transits into a fracture zone
Terminates in the SSE between BT and DT, probably towards a gouge filled SW striking fracture
In the NNW it probably joins Zone 3. Seismics indicate that another branch of zone 3 continues towards the north
No interference tests performed in Zone 6

References: 1) SFR 86-02, Dwg 27; 2) SFR 86-03, Table 6.4.7; 3) SFR 87-03, dwg 09, 22, 23; 4) SFR 81-13

Geophysics and topography

Zone 6 only crosses 1 seismic refraction profile. No anomaly is present, probably due to that Zone 6 is narrow.

Tunnels

Zone 6 has been encountered in the four storage caverns and in DT but not in BT tunnel.

Core drillings

Zone 6 has been encountered in Kb13, Kb15 and possibly in Kb27.

4.3.2 Hydraulic conditions

In the tunnels, Zone 6 features moisture and occasionally dripping water.

Hydraulic tests have been carried out in holes Kb13 and Kb15, which feature hydraulic conductivities of $2.4 \cdot 10^{-8}$ and $1.8 \cdot 10^{-6}$ m/s respectively (Carlsson et al., 1986, Table 6.4.7).

None of the interference tests concern Zone 6.

4.3.3 Character

Zone 6 is for most of its length a slightly water bearing gouge-filled joint, occasionally with increased fracturing on one or both sides.

4.3.4 Extension

Zone 6 is well verified by mapping in the storage caverns and in boreholes. To the south, it terminates somewhere between BT and DT, towards a fault gouge filled fracture, interpreted as a branch of Zone 9. In the north, it appears to terminate towards Zone 3. In its extension beyond Zone 3, there are seismic anomalies, identified as Zone 4 (Carlsson et al 1986).

4.4 ZONE 8

4.4.1 Indications and observations.

A summary of observed data is shown in Table 4-6.

Table 4-6. Zone 8. Indications

Site	Type	Geology (Reference 1) Width [m]	Strike/ dip	Appr Level [m]	fract per m	Hydrology (Reference 2) Width [m]	T (m^2/s)	K (m/s)
Kb 4	Core drilling		NW/Steep NE	385	10	2.1	7.5E-08 *	3.6E-08
Kb 5[1]	Core drilling			375	10	4.9	6.8E-06	1.4E-06
Kb 26	Core drilling			445	5-25	?	2.3E-06 [4]	?
Hk 8[2]	Core drilling			410	15	18.9	1.1E-05	6.0E-07
Hk 8[3]	Core drilling			407	25	16.2	5.8E-06	3.6E-07
Hk 11	Core drilling			400	25	13.9	4.6E-05	3.3E-06
Seismic refraction (Reference 3)								
Seismic Profile No	**Seismic velocity [m/s]**							
S8108	3700 (Zone 9)							
S8114	5200							
S8101	4900							
S8113	4900							
S8110	5000							
S8102	4000 (Zone 3)							

* Grouting in borehole before testing

References: 1) SFR 86-03; 2) SFR 86-03, Table 6.4.10; 3) SFR 81-13

Author's comments:

[1] Sub-horisontal zone below H2?

[2] Claimed to be rim zone

[3] Claimed to be core

[4] Calculated from packer testing (SFR 86-03, Appendix 4:21)

There are no seismic indications of Zone 8 stretching from Zone 3 to the Singö Zone

Geophysics and topography

Zone 8 crosses 6 seismic refraction profiles. Only two of the profiles feature anomalies. One coincides with Zone 3, the other could be Zone 9, as well.

Tunnels

Zone 8 has not been encountered in any of the underground excavations.

Core drillings

Zone 8 has been encountered in Kb4, Kb5, HK8 and HK11. Hole HK7A terminates in what has been interpreted as the rim of Zone 8 (SFR AR 86-02).

4.4.2 Hydraulic conditions

Hydraulic tests have been carried out in holes Kb4, Kb5, Kb26, HK8 and HK11, which show hydraulic conductivities between $3.6 \cdot 10^{-7}$ and $3.3 \cdot 10^{-6}$ m/s, except for Kb4 where the conductivity is $3.6 \cdot 10^{-8}$ m/s (Carlsson et al., 1986, Table 6.4.10).

However, in Kb4 traces of gruot has been found, and the values of this hole may not be regarded as virgin values.

One interference test was made in Zone 8 with a flowing section in HK8:1. This indicates a good connection between HK8 and the boreholes HK11, HK7A and HK7B (Table 4-7). However, interference tests with flowing sections in HK7B:1 and HK13:1 have a direct response with HK8:1 but no or little response in HK7A (Table 4-2.). The water of this hole also features a different chemical composition than that of HK8 and 11 (Axelsson et al., 1995)

4.4.3 Character

In holes Kb4 and Kb5, Zone 8 is characterised by increased jointing along with the gneissic foliation of the host rock. Its earlier interpreted character with a highly crushed and conductive core, with rims on both sides may be doubted (cf. below)

Table 4-7 Zone 8. Hydraulic connections - interference tests

Flow Site (Test)	Flow (l/min)	Test length (hours)	Zones in FS	Obs. hole (OH)	Zones in OH	Hydr path [m]	Draw down [m]	T (m^2/s)	K (m/s)	Indirect response	No response	Ref.
HK8:1	14.7	76	H1,8 ?	HK7A:1	H2,8 ?			6.9E-05		HK2:1,3,4	HK1,HK2:2	1,2
(G)				HK7B:1	H2			9.3E-05		HK3:2	HK3:1,3,4	1,2
				HK11:1	H1,8 ?			3.7E-05	2.7E-06	HK7A:2,3	HK4,HK5	1,3
										HK7B:2,HK7C	HK9,HK10	1
										HK8:2,3	HK12,HK13	1
										HK11:2-4	Kb19:4,Kb20	1
										Kb19:1-3	Kb25	1

References: 1) IRAP 86403, Table 5.14; 2) IRAP 86403, Tables 5.15; 3) SFR 86-03, Table 6.4.11

4.4.4 Extension

In Carlsson et al. (1986), Zone 8 is characterised as one of the major conductive zones (classified as 2nd order) near SFR, with a width of 5-15 m (10-45 m incl rim zones), and extending to the Singö zone. This characterisation fits very badly with the seismic refraction results. A zone of this size would give rise to anomalies on all lines passed (cf. Zone 3).

Indications in boreholes, interpreted as Zone 8, can as well have other explanations as shown in table 4-8.

Table 4-8. Zone 8. Alternative indication interpolation

Hole No	Alternative indication interpretation
Kb4	Zone H2
Kb5	Horizontal zone below H2. (Fits with indications in Kb1, HK2 and HK5.
HK8 and 11	The two holes are drilled at the same level. The trend of the path between the high conductive zones in these holes does not fit with the strike of Zone 8. The holes coincide with a set of horizontal joints mapped in Kb4 and in IB tunnel. These joints could form the hydraulic path.

Interference tests have been interpreted to confirm that Zone 8 is a strongly hydraulic conductive zone connected with Zone H2 (Carlsson et al., 1986) as shown in Table 4-2. However, in interference tests A, E and F, holes 7B, 7C, HK5 and HK13 (all in Zone H2) and HK8 and HK11 (both in Zone 8) all show direct response. In section HK7A:1, which lies in the middle of the area, at the intersection between the two zones, the response is indirect or absent. Furthermore, hole HK8 has a water of Baltic type, while hole HK7A has not. This does not favour the interpretation of Zone 8 as a strongly conductive zone, as shown in Figure 4-2.a. Figure 4-2.b shows an alternative water path which explains the good connection among HK7B, HK7C, HK5, HK13, HK8 and HK11, and the poor connection with HK7A.

- Conclusively, Zone 8 may be regarded as a much smaller zone than previously anticipated, with respect to hydraulic properties.

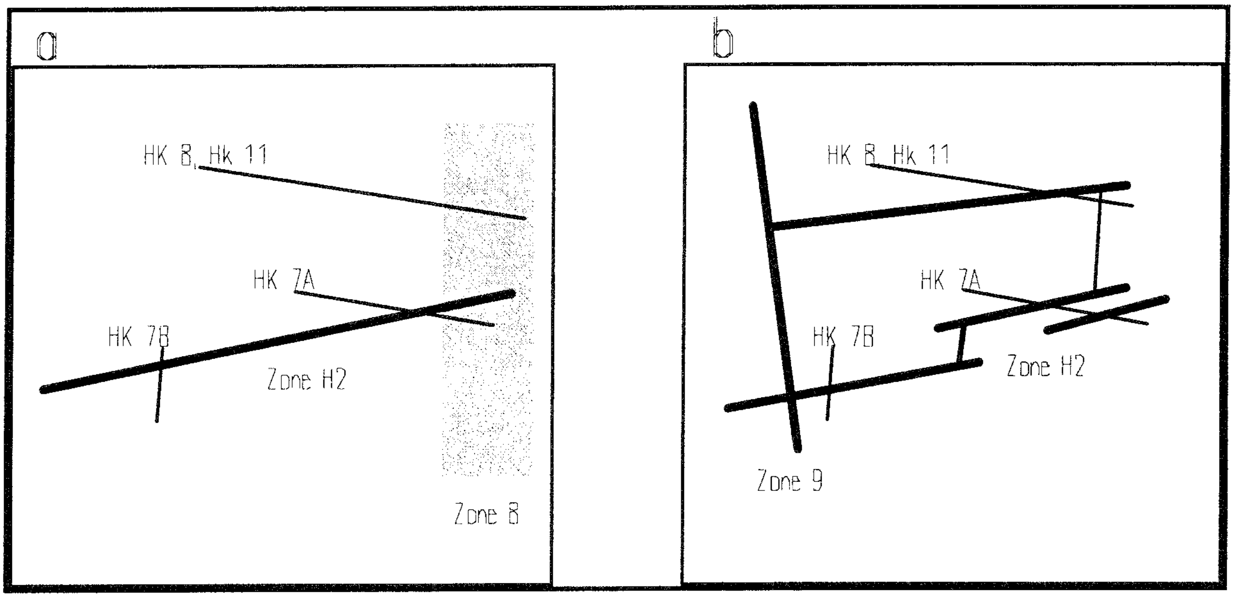

Figure 4-2. *Alternative models for hydraulic pathways in borehole interference tests including holes HK7A, 7B, 8 and 11. a) explanation model in SFR 86-03. b) explanation model in this report.*

In this context, it may be noted that the term "zone" can be used in various ways: In rock construction, it is used to describe an area with different (often inferior) rock-mechanical properties from the surrounding rock. This does not automatically mean that the zone is water conductive.

4.5 ZONE 9

4.5.1 Indications and observations.

A summary of observed data is shown in Table 4-9.

Table 4-9 Zone 9. Indications

Tunnel	Description		Remarks	Width, m	Strike/ dip	Reference
DT 1/530-70	Water bearing clayey gouge w cl, ca. Branches off from Zone 3			<1	ENE/Steep SE	1), Dwg 06
Connection at DT 1/610	Water bearing gouge			<1	ENE/Steep	1), Dwg 07
BT 5/640-5/690	Waterbearing gouge w clay & mylonite			<1	ENE/80SE	1), Dwg 07
NBT 8/025	Two branching water bearing gouges			<1	ENE/70SE	1), Dwg 15
BT 6/025-050	Waterbearing gouge w clay & mylonite			<1	ENE/Steep	1), Dwg 10
ISTT 6/800-820	Fractured zone w mylonite and clay			3	ENE/Steep	1), Dwg 10
IST 4/090	Increased jointing			3	ENE/90	1), Dwg 11
NBT 8/290-350	Water bearing gouge with clay, ca and Fe		Surrounded by increased jointing	3	ENE/80 NW-85NE	1), Dwg 17
Hole No	**Appr Level [m]**	**fract per m**	**Width [m]**	**T (m^2/s)**	**K (m/s)**	**Reference**
Hk 4	400	10-15	1.4	5.0E-08	3.6E-08	1,2
Kb 23	405	25	3.2	2.3E-08	7.2E-09	1,2
Kb 24	390	16	3.3	3.0E-09	9.1E-10	1,2
Kb 25	365	16	3.7	1.5E-07	3.9E-08	1,2
Seismic Profile No	**Seismic velocity [m/s]**					**Reference**
S8110	4700					3
S8117	4800					3
S8114*	4200					3

References: 1) SFR 87-03; 2) SFR 86-03, Table 6.4.14, Appendix 4; 3) SFR 81-13
Absence of seismic anomalies, indicates that the zone is narrow,

Geophysics and topography

Zone 9 only crosses two seismic refraction profiles. No anomaly is present, probably due to that Zone 9 is narrow.

Tunnels

In the present work, further encounters in the tunnels are interpreted as Zone 9, as shown in Table 4-9.

Core drillings

Zone 9 has been encountered in Kb23, Kb24, Kb25, and HK4. The present authors also regard the following encounters to be Zone 9:
- HK2 (elevation 380).
- HK 3 features intense jointing at elevation 365.

4.5.2 Hydraulic conditions

In the tunnels, Zone 9 feature moisture, dripping, and running water.

Hydraulic tests have been carried out in holes HK4, Kb23, Kb24 and Kb25, which feature hydraulic conductivities between $9.1 \cdot 10^{-10}$ and $3.9 \cdot 10^{-8}$ m/s (Carlsson et al., 1986, Table 6.4.14). However, in HK4 traces of grout has been found, and the values may not be regarded as virgin values.

Interference tests are summarised in Table 4-10. Test No. 1 indicates a connection between HK4:3 (flowing), Kb24:2, Kb25, HK2:4 and HK4:1-2. The response in HK2 is in accordance with the mapping in BT and NBT of the water bearing, gouge-filled joint which constitutes the main feature of Zone 9. Testing in Kb25 (flowing) gives responses in HK4 and Kb24:2.

During excavation of NBT, Zone 9 was encountered. Response was recorded in HK1 in the Singö Zone (Christiansson letter communication 1986-10-07).

Table 4-10 Zone 9. Hydraulic connections - interference tests

Flow Site (Test)	Flow (l/min)	Test length (hours)	Zones in FS	Obs. hole (OH)	Zones in OH	Hydr path [m]	Draw down [m]	T (m^2/s)	K (m/s)	Indirect response	No response	Ref.
HK4:3	0.5	98	9	HK2:1-3		250	< 1				HK1,HK3	1
(1)				HK2:4	9	250	1				HK4:4	1
				HK4:1-2			4					1
				Kb25:1			< 1					1
				Kb25:2-4	9		4					1
				Kb24:2	9			1.4E-07	4.3E-08			2
				Kb25:3	9			1.6E-07	4.3E-08			2
Kb25:2	0.2	93	9	HK2:2			< 1				HK1	1
(2)				HK4:1-3			5				HK2:1,3,4	1
				Kb25:3			< 1				HK3,HK4:4	1
				HK4:3	9			1.1E-07	7.5E-08			2
				Kb24:2	9			1.4E-07	4.3E-08			2
Kb25:3	0.8	71	9	HK3:1-4			1				HK1,HK2	1
(3)				HK4:1			20				HK4:4	1
				HK4:2-3			5					1
				Kb25:2,4			3-8					1
				Kb24:2	9			2.9E-07	8.7E-08			2

References: 1) IRAP 85244, Appendix 2:2, 2:3a, 2:4a, 2:8a; 2) SFR 86-03, Table 6.4.15

4.5.3 Character

Zone 9 is for most of its length a water bearing gouge-filled joint, occasionally with increased fracturing on one or both sides. The gouge fill indicates that Zone 9 may be a fault.

4.5.4 Extension

Zone 9 is well verified by mapping in the tunnels and in boreholes. To the South-west, in DT, it terminates towards a branch of Zone 3. In the North-east, it probably continues.

4.6 ROCK MASS PROPERTIES

A characteristic feature of the upper part of the bedrock within the construction area of Forsmark Power Station is the occurence of horizontal and subhorizontal fractures (Carlsson, 1979). Each individual horizontal fracture is reported to have a maximum length of 170 m. The fractures are usually displaced and overlaid, thus forming a continuity in the rock. These horizontal fractures form more or less distinct horizontal zones in the upper part of the rock. However, it is not possible to identify each zone in the upper part of the bedrock as an individual hydraulic unit when considering the scale of kilometres (Carlsson et al., 1986). Instead the upper part might be defined as a separate unit containing these horizontal and subhorizontal zones.

The horizontal zones are usually identified as having a high hydraulic conductivity compared with the surrounding rock mass. Horizontal and subhorizontal zones of the same type as at Forsmark may be recognized at SFR in boreholes drilled from the ground surface or from platforms in the Baltic (Carlsson et al., 1986). Since these zones are assumed to contribute to a high hydraulic conductivity in the rock mass, the upper more conductive parts of the boreholes are identified as containing these zones. The rock mass in the area enclosing the boreholes Kb1 to Kb5 and Kb17 to Kb18 has an average hydraulic conductivity exceeding $1 \cdot 10^{-7}$ m/s in the upper 40 m of rock (Table 4-11). Further towards south west, the area enclosing the boreholes Kb11 to Kb15 have an average hydraulic conductivity in the upper 40 m of rock of less than $1 \cdot 10^{-7}$ m/s.

Table 4-11 Average hydraulic conductivity and transmissivity in the upper 40 m of the rock mass at SFR determined from hydraulic testing in boreholes drilled from platforms in the Baltic (Carlsson et al., 1986).

Bore hole	Elevation (m a.s.l.) From	To	Average hydraulic conductivity (m/s)	Transmissivity (m^2/s)
Kb1	492.5	454.0	$3.2 \cdot 10^{-7}$	$1.2 \cdot 10^{-5}$
Kb2	491.0	460.2	$9.1 \cdot 10^{-8}$	$2.8 \cdot 10^{-6}$
Kb3	492.8	457.6	$2.4 \cdot 10^{-6}$	$8.4 \cdot 10^{-5}$
Kb4	492.8	461.0	$3.1 \cdot 10^{-7}$	$9.9 \cdot 10^{-6}$
Kb5	494.3	460.4	$6.4 \cdot 10^{-7}$	$2.2 \cdot 10^{-5}$
Kb11	493.2	463.9	$6.0 \cdot 10^{-8}$	$1.8 \cdot 10^{-6}$
Kb12	492.3	465.1	$5.4 \cdot 10^{-8}$	$1.5 \cdot 10^{-6}$
Kb13	490.2	463.6	$4.4 \cdot 10^{-8}$	$1.2 \cdot 10^{-6}$
Kb14	494.4	466.5	$5.4 \cdot 10^{-8}$	$1.5 \cdot 10^{-6}$
Kb15	491.8	465.2	$8.7 \cdot 10^{-8}$	$2.3 \cdot 10^{-6}$
Kb16	493.6	461.8	$5.4 \cdot 10^{-7}$	$1.7 \cdot 10^{-5}$
Kb17	493.6	464.5	$1.8 \cdot 10^{-7}$	$5.2 \cdot 10^{-6}$
Kb18	493.6	464.0	$6.5 \cdot 10^{-7}$	$1.9 \cdot 10^{-5}$

The rock mass at SFR can be treated in two different ways (Carlsson et al., 1986):

1. Rock mass as a homogeneous body with the hydraulic conductivity changing with depth (Z) according to the following equations.

$$K = 5.65 \cdot 10^{-6} \cdot Z^{-1.30} \quad \text{(2-D flow)}$$
$$K = 8.87 \cdot 10^{-6} \cdot Z^{-1.30} \quad \text{(3-D flow)}$$

2. Rock mass as one upper hydraulic conductive part and one lower part having a lower hydraulic conductivity which also changes with depth.
   The upper 40 m of the bedrock is divided into two areas: Area A bounded by the fracture zones 3, 6, 8 and 9 (comprising the boreholes Kb1 to Kb5 and Kb17 to Kb18) and Area B outside these fracture zones. Measured data in boreholes within these areas (Table 4-11) give the following hydraulic conductivities (Table 4.12):

Table 4-12.

Area	Lowest value	Arithmetic mean	Geometric mean	Highest value
A	$9.1 \cdot 10^{-8}$	$6.8 \cdot 10^{-7}$	$4.0 \cdot 10^{-7}$	$2.4 \cdot 10^{-6}$
B	$5.4 \cdot 10^{-8}$	$1.5 \cdot 10^{-7}$	$8.4 \cdot 10^{-8}$	$5.4 \cdot 10^{-7}$

The rock mass below 40 m depth is assumed to be a homogeneous body with the hydraulic conductivity changing with depth (Z) according to the following equations

$$K = 5.69 \cdot 10^{-5} \cdot Z^{-1.80} \quad \text{(2-D flow)}$$
$$K = 9.30 \cdot 10^{-5} \cdot Z^{-1.80} \quad \text{(3-D flow)}$$

However, one should note that the depth decrease relations are highly questionable. By reinterpreting hydraulic data from some SKB study areas Walker et al. (1997) find that there is no statistical support for a depth decrease below a certain depth. Reinterpretation of the SFR hydraulic data would possible result in a similar result.

A band of schistosity is found running through the silo. This feature may be conceptualised as a discrete feature existing from Zone 8 through the silo and up to borehole HK2 and the crossing with the access tunnels (Carlsson et al., 1986). The width of this almost vertical feature is assumed to be 5 - 20 m. However, the band may continue as an infilled break crossing the access tunnels and running almost parallell to these tunnels. The hydraulic conductivity of the schistosity is estimated to about $5 \cdot 10^{-7}$ m/s. The hydraulic conductivity of the infilled break calculated as a 10 m section of the access tunnel DT and BT is $4 \cdot 10^{-8}$ m/s and $3 \cdot 10^{-7}$ m/s respectively. Water yielding schistosity is also encountered in other orientations within SFR according to Christiansson and Bolvede (1986).

It is likely that a skin-zone is developed around the access tunnels, silo and caverns due to rock stress redistribution and grouting campaigns. Measurements and model calculations show that this skin-zone would have a decreased hydraulic conductivity by a factor of 0.1 - 0.5 (Carlsson et al., 1986).

5 ALTERNATIVE STRUCTURAL MODEL

An alternative local structural model is shown in Figure 5-1.The main deviations from the previous model are:

- Extension of H2 beyond Zones 3, 6, 8 and 9, and outcropping between U=2300 and 2400
- Extension of Zone 9 to Zone 3 in DT
- Downwards termination of Zone 6 towards Zone H2. Termination between BT and DT.
- Reduction of Zone 8 to a 3rd order zone, with limited depth and limited extension to the NW (Zone 3) and SE.

Coordinates for the zones are shown in Table 5-1.

Table 5-1. Coordinates for zones in the alternative local model

Zone	Location character	T-coord	U-coord	Z-coord
H2	upper West corner	4412	2109	486
	upper East corner	2356	2190	480
	lower West corner	4374	1116	210
	lower East corner	2317	1197	204
3	upper termination to Singoe Zone	3835	1599	480
	upper East corner	2359	2470	480
	lower termination to Singoe Zone	3835	1598	0
	lower East corner	2359	2470	0
6	upper termination to Zone 3	3197	1978	429
	upper South corner	3286	1660	429
	termination to Zone 3 and H2	3197	1978	429
	South termination to Zone H2	3286	1660	347
8	upper termination to Zone 3	3030	2074	429
	upper South corner	2874	1379	429
	lower termination to Zone 3	3030	2074	300
	lower South corner	2874	1379	300
9	upper termination to Zone 3	3736	1658	429
	upper vertex	3330	1622	429
	upper East corner	2325	1718	429
	lower termination to Zone 3	3726	1663	300
	lower vertex	3329	1628	300
	lower East corner	2325	1718	300

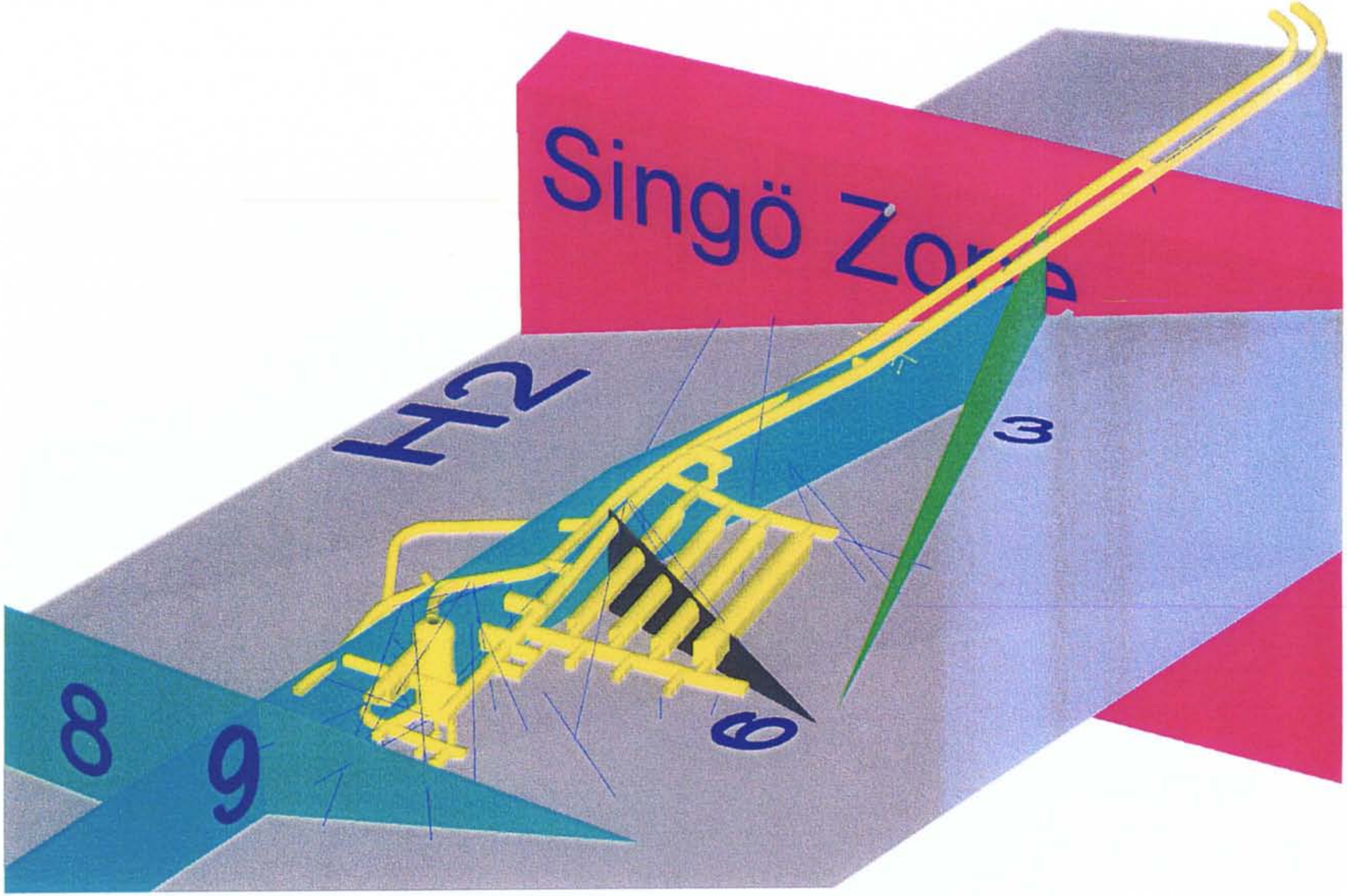

Figure 5-1. *Alternative local structural model.*

6 REVIEW OF REGIONAL MODEL

Figure 6-1 and Figure 6-2. show the development of the regional tectonic model of the Forsmark area from 1981 to 1996. All the models feature, however, some zones which have not been verified during the investigation for the SFR repository, or which do not occur at all in the repository, and which do not correspond with the local model. In the 1996 model, for instance, Zone 3 appears to be doubled. The seismic survey interpretation at surface and the tunnel and borehole interceptions at depths are shown as two zones. Zone 6 is shown as verified to continue almost to the Singö Zone, although it is documented to terminate between BT and DT (Christiansson and Bolvede 1987). It appears that earlier work need to be scrutinised further.

Figure 6-3. shows the updated regional model presented in this work and described below, in comparison with the previous model (Carlsson et al., 1986; Carlsson and Christiansson, 1987; SKB, 1993). The main features are:

- Outcrop of Zone H2, which extends at depth probably beyond the Singö Zone
- Shortening of Zone 6 in accordance with tunnel mapping
- Longer Zone 9 in accordance with tunnel mapping
- Reduction of Zone 8 to a local zone with limited depth
- Zone 3 is identical in both models

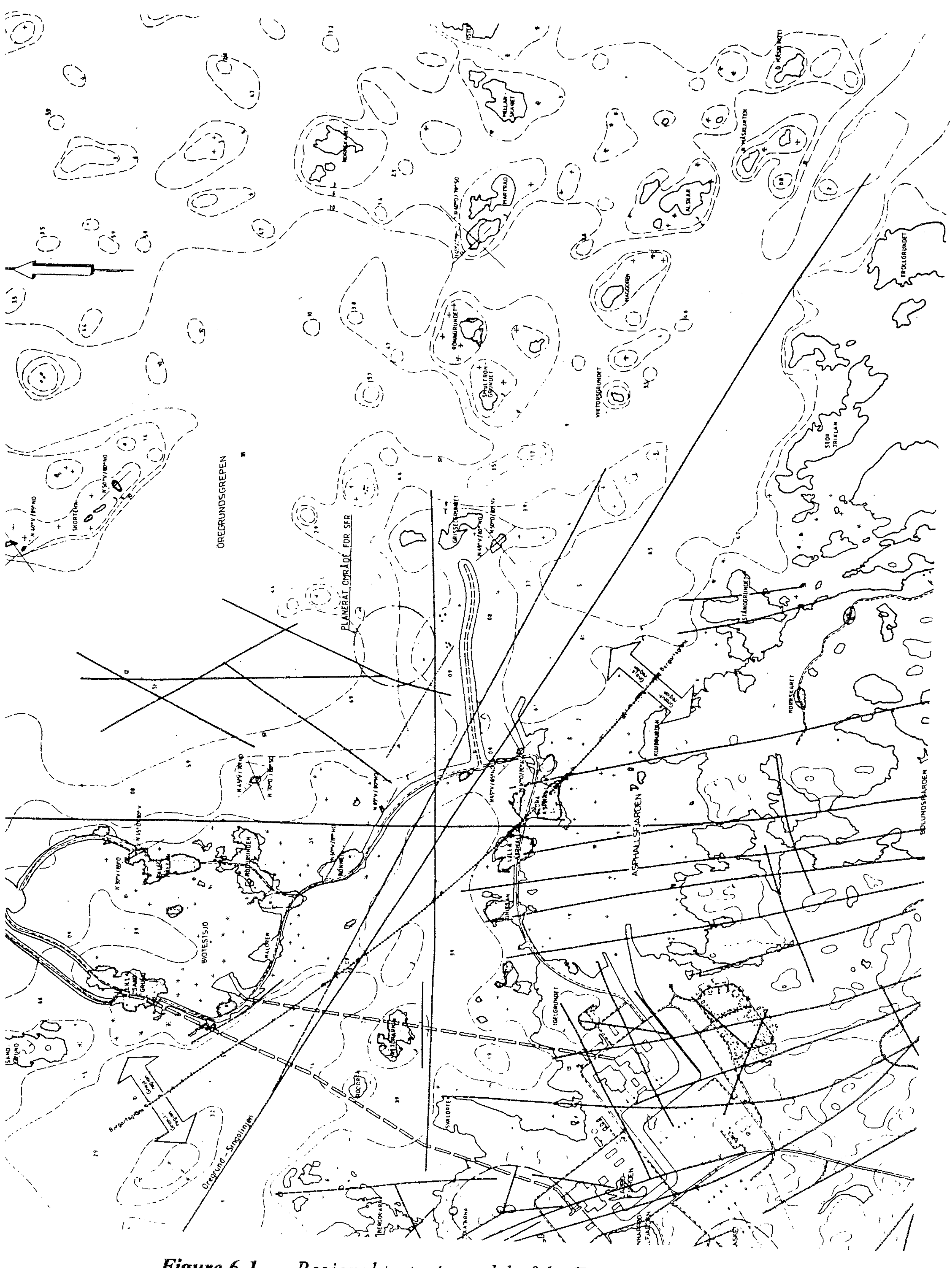

Figure 6-1. Regional tectonic model of the Forsmark Area. Hagconsult, SFR 81-13.

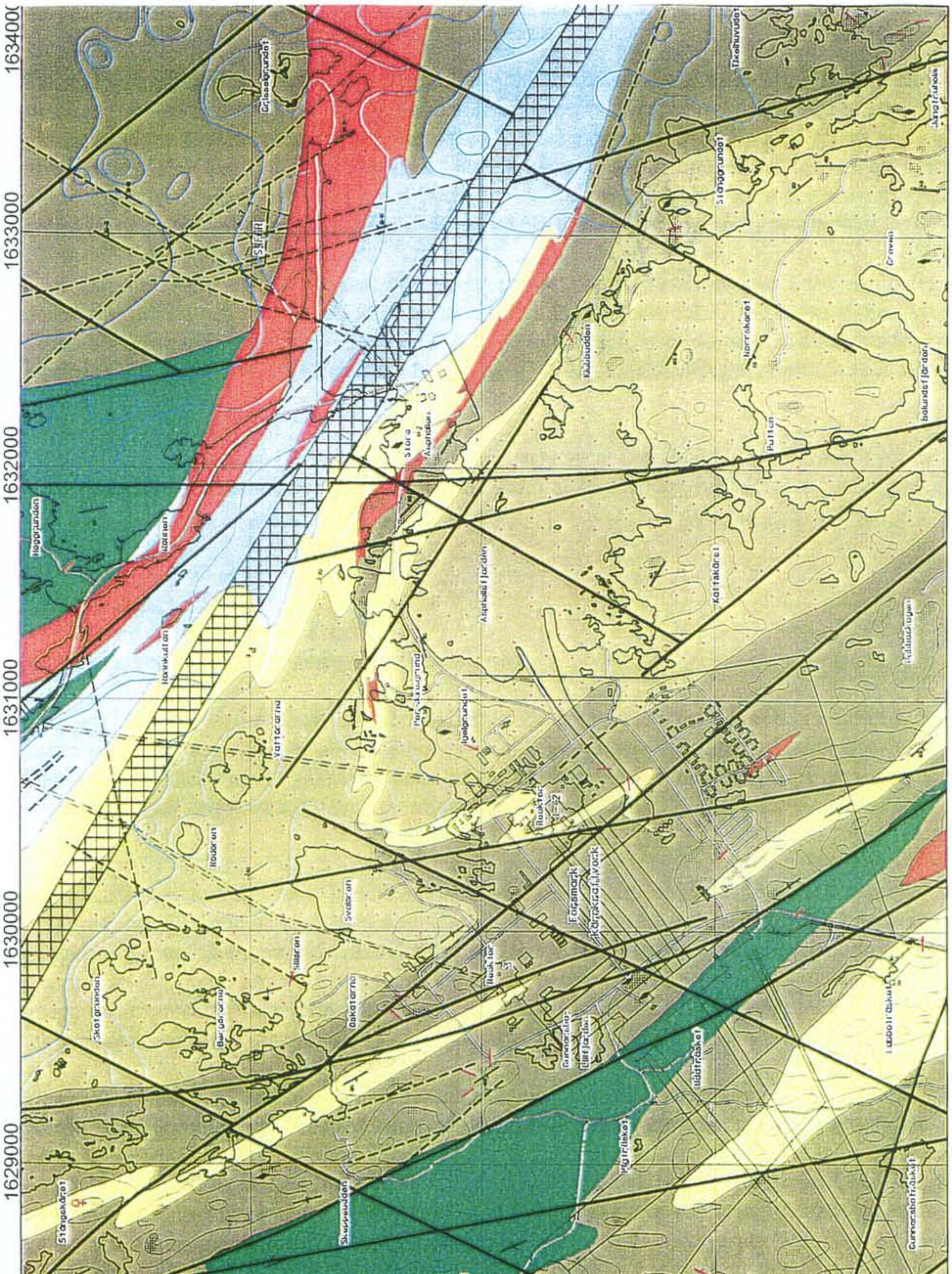

Figure 6-2. *Regional tectonic model of the Forsmark Area. Bergman et al, 1996. SKB PR D-96-025.*

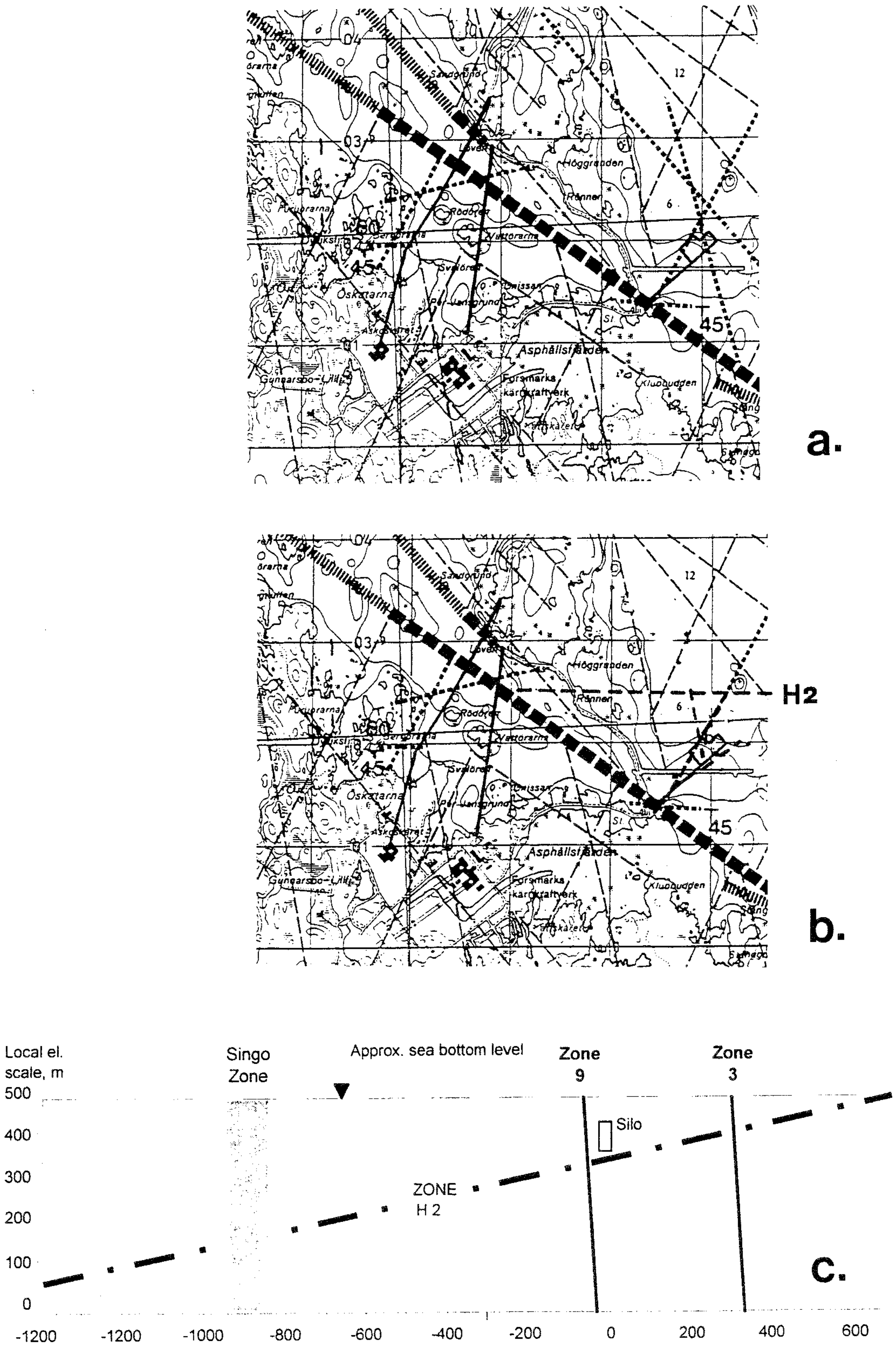

Figure 6-3. *Alternative regional tectonic model of the Forsmark Area, compared with the official model (SKB 1993). a) Official model; b) Alternative regional model, map; c) Alternative regional model, NS section.*

6.1 SUB-HORIZONTAL ZONES

Sub-horizontal zones have been reported to exist at several places in the Northern part of Upland Province: Finnsjön, SFR-Forsmark and Dannemora. The Sub-horizontal Zone 2 at Finnsjön has been traced in boreholes along 1 km with a width of some 100 m. It has been identified as part of a regional thrust fault regime, predating some of the steep faults in the area (Tirén, 1989). In Dannemora, displacement of some 400 m along a sub-horizontal fault has been reported (Lager, 1986). In two boreholes at Forsmark, Sub-horizontal fractures have been recorded with smooth (shiny) or slickensided surfaces, indicating shear (Bergman et al., 1996; Carlsson & Olsson, 1982).

These data indicate that sub-horizontal zones encountered during civil works and investigations in the area, without unreasonable conservatism can be regarded as regional features, unless very strong evidence indicate a limited spread.

- As shown in Section 4.1.4, there is no such evidence. Hence, in the present model, the sub-horizontal zone H2 is anticipated to continue at least to the Singö Zone.

In the borehole DBT 1, at Nuclear Power Unit No. 3, a 10 m wide zone with many sub-horizontal, chlorite coated joints with shiny surfaces (Hansen, personal communication) was encountered at a depth of 320 m, equal to elevation 180 m, and a zone of increased hydraulic conductivity some 30-40 m deeper (Carlsson & Olsson, 1982).

With a WSW strike, the Zone H2 elevation 150 m strike line fits fairly well with the observations in DBT 1. However, a small deviation in orientation would, off course, result in a somewhat different elevation. As for Zone 2 in Finnsjön (Tirén, 1989), Zone H2 at Forsmark may very well have been displaced by a sub-vertical fault, in this case, The Singö Zone. Hole KFo 01 (Bergman et al. 1996), 2.5 km further WSW at some 20 m a.s.l. has encountered an 8 m wide zone of sub-horizontal joints with traces of shear at 450 m of depth (elevation 70 m), which fits fairly well with an extrapolation of Zone H2.

- Thus, these holes, in the light of the results from Finnsjön, indicate a potential continuation of Zone H2 Southwest of the Singö Zone, alternatively, the existence of other sub-horizontal zones, there.

6.2 SUB-VERTICAL ZONES

With respect to the sub-vertical zones, the updated regional model, suggested in this work, features the following:

- Zone 1 has been encountered in the tunnel as an increased jointing along the foliation, but is weakly pronounced and appears to terminate against Zone 3. However, seismic anomalies indicate an extension. As no water leakage has been reported from the follow-up, it is regarded as being a not water bearing branch of the Singö Zone.
- Zone 3 is kept. It is regarded as certain, as it has been verified in the tunnels, BT and DT and gives rise to anomalies on all seismic refraction survey lines crossed by it, and also coincides with a depression in the rock surface. It is probably encountered in three boreholes.
- The NNE striking zone 4 (SFR 81-13) has been added as a branch of Zone 3.
- Zone 6 has been encountered in the SFR as a gouge-filled fracture, sometimes accompanied by parallel joints. Due to lack of seismic anomalies, Zone 6 is regarded as smaller than Zones 3 and 4. With respect to its position and orientation, it can be regarded as the "tail" of Zone 4. It has been documented that it terminates in the repository area, between DT and BT tunnels.
- Zone 9 is a fracture with the same character as Zone 6. It branches off from Zone 3, continues along BT, passes SE of the silo and crosses NBT. Topography indicates a potential extension further NE.

7 CONCLUSIONS

The previous local structure model comprises four zones: H2, 3, 6, 8 and 9. The evidence for this model as given by Carlsson et al (1986) and Christiansson (1986) is reviewed.

An alternative model is presented, together with evidence for the new interpretation. The model is based on review of geophysical data, geological mapping, corelogs, hydraulic testing, water inflow, etc.

Local model

The fracture zones in the official local model is revised according to the following.

Zone 1	No revision.
Zone 3	No revision.
Zone 6	No revision.
Zone 8	The seismic surveys do not indicate a major vertical zone. The indications of zones found in boreholes can be interpreted as a subhorizontal zone parallel to Zone H2 and outcropping at the sea bottom north of SFR. There might be a vertical connection between this zone (Zone H1) and Zone H2. A minor zone may exist.
Zone 9	The zone is more pronounced than the earlier interpretation. It runs along the construction and access tunnels, BT and DT and terminates towards a branch of Zone 3 in the southwest. In the northeast it probably continues.
Zone H2	The zone is probably more pronounced than the earlier interpretation. It probably extends at least to the Singö zone in the southwest. In the northeast it could be regarded as outcropping at the sea bottom or joining a higher elevated subhorizontal zone H1. southeast of Zone 9 it is probably found at a lower level.

Regional model

The main revisions of features of the official regional model are:

Zone 3	No revision.

Zone 6	Shortening of Zone 6 in accordance with tunnel mapping and the local model.
Zone 8	Reduction of Zone 8 to a 3rd order zone.
Zone 9	Longer Zone 9 in accordance with tunnel mapping and the updated local model.
Zone H2	Outcrop of Zone H2, which probably extends beyond the Singö Zone.

The fact that two different models can result from the same data represent an interpretation uncertainty which cannot be resolved without more data and basic interpretations of such data. Even if the re-analysis of the data give more support for the updated model it is still recommended to consider both models as alternatives in the subsequent consequence analyses. Further refinement of the structure model could only be motivated in case the two different models discussed here would lead to significantly different consequences. The previous and the alternative local models are delivered as computer files for microstation.

Finally, one should note that there has been no reinterpretation of the hydraulic properties of the fracture zones or of the rock mass. As an example, it is likely that re-interpretation of the hydraulic data of the rock mass would lead to revisions of the model for depth dependence of the hydraulic conductivity. Such re-interpretations, however, can be done jointly with an update of the hydrogeological modelling of the SFR site.

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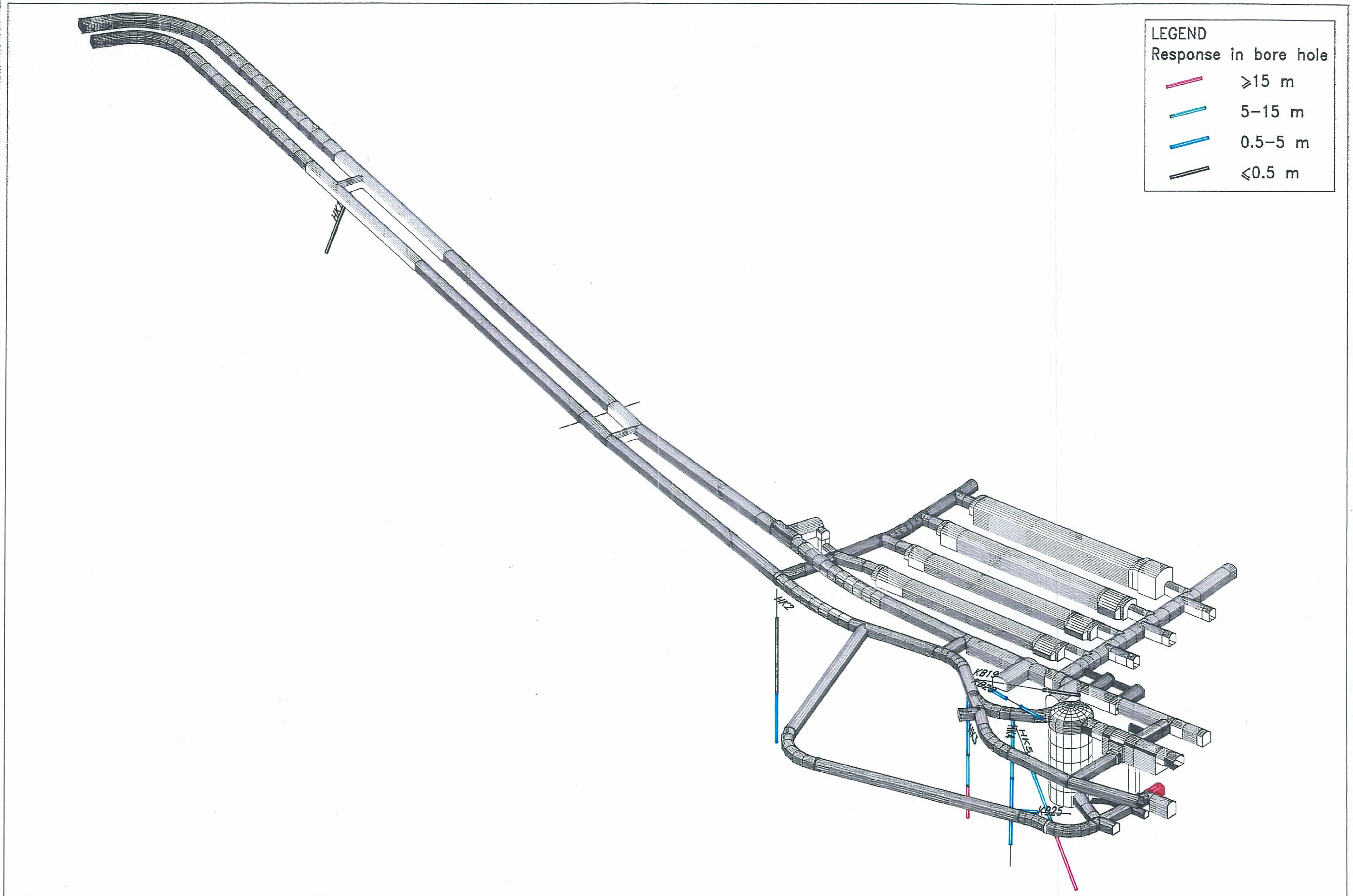
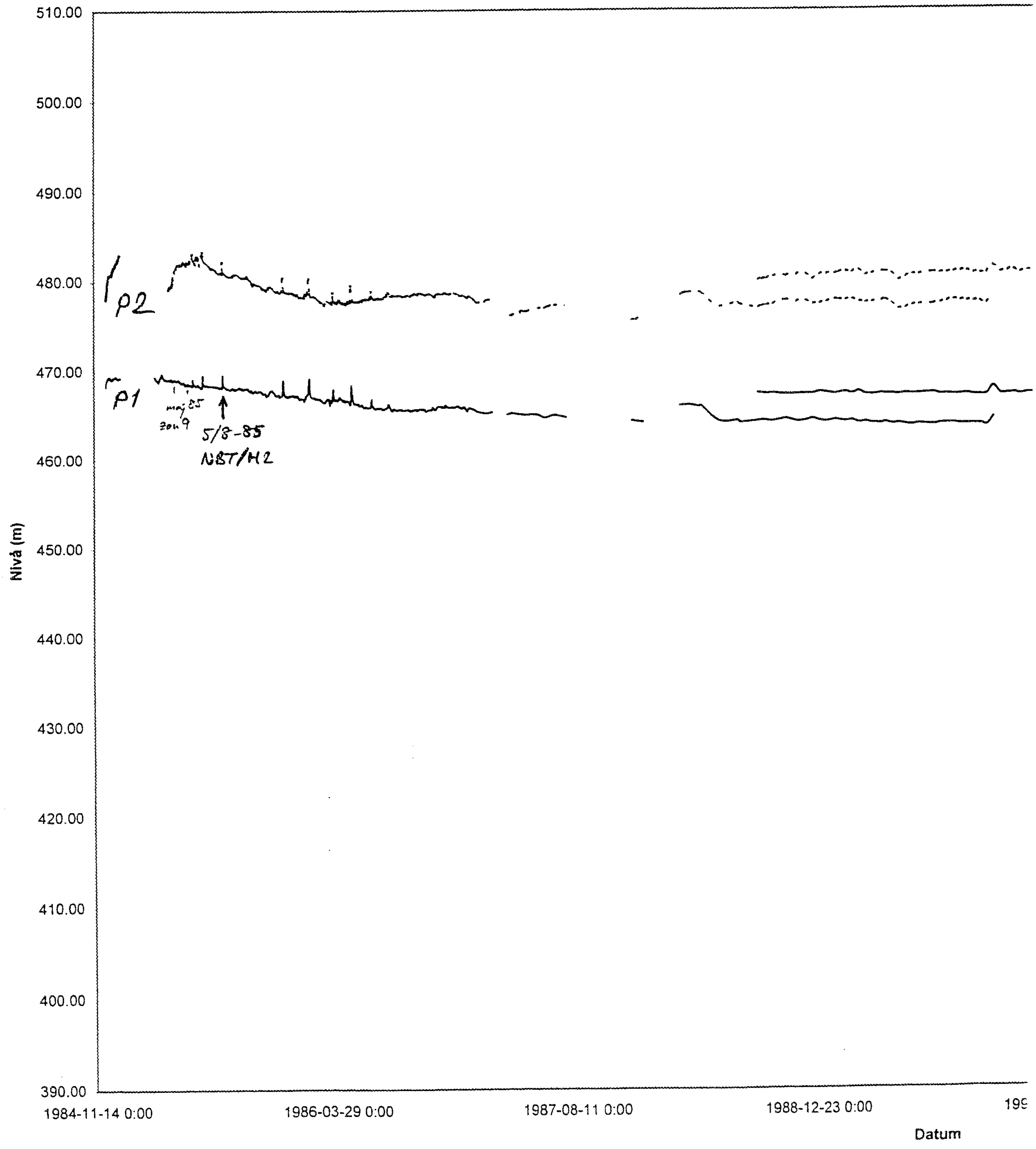
APPENDIX A

Responses in boreholes caused by drilling into Zone H2 from the tunnel NBT.



Breakthrough of zone H2 in NBT with 10 bore holes 1985-08-05. Total inflow 182 l/min
References: IRAP 85244, 86314, 88289

HK1



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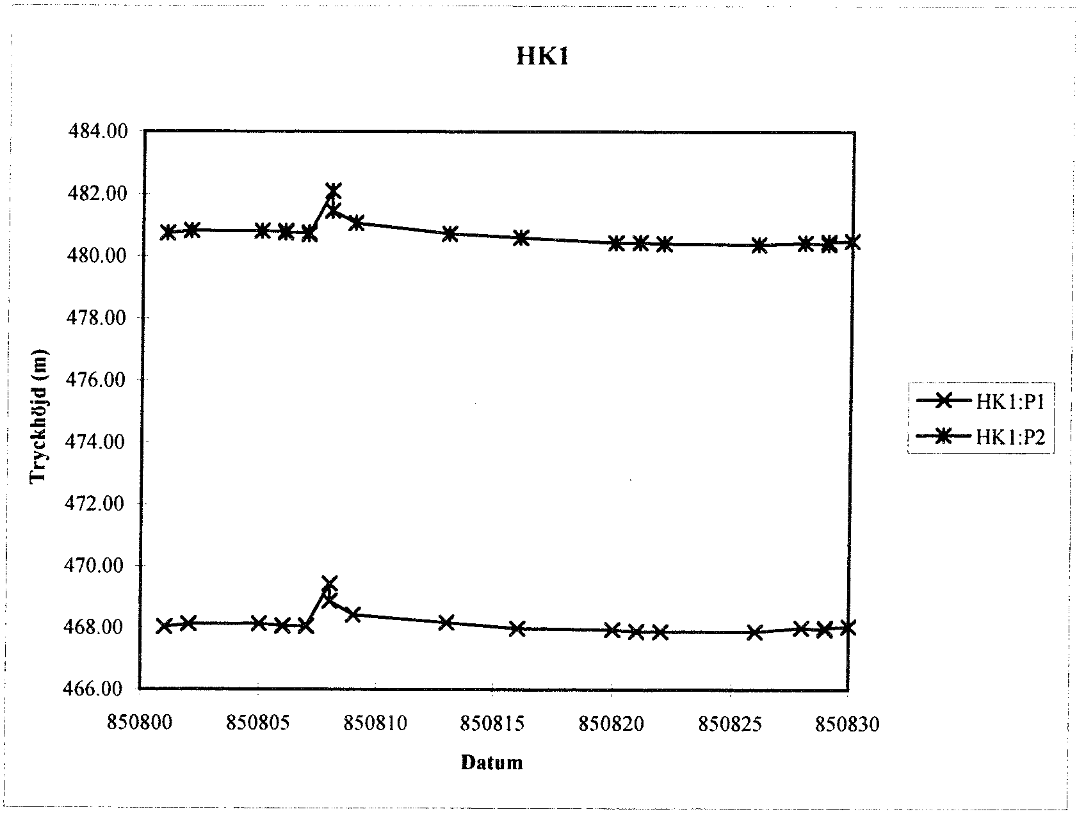
P1
maj 85
5/8-85
NBT/H2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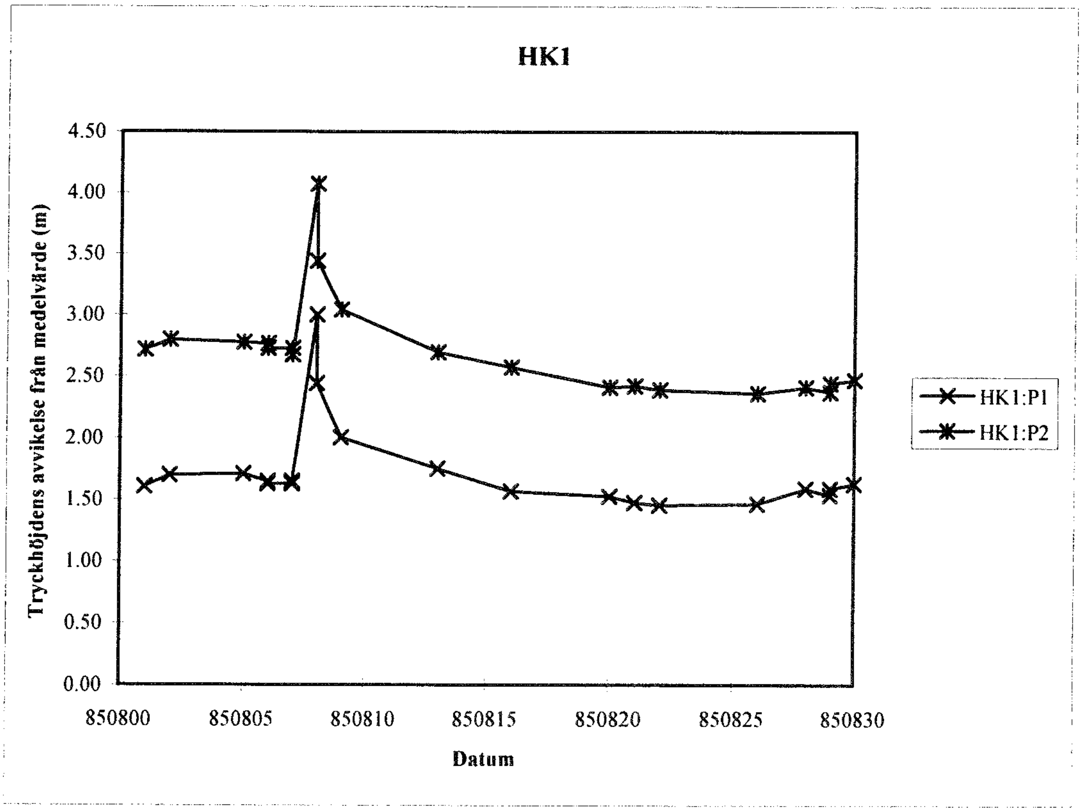
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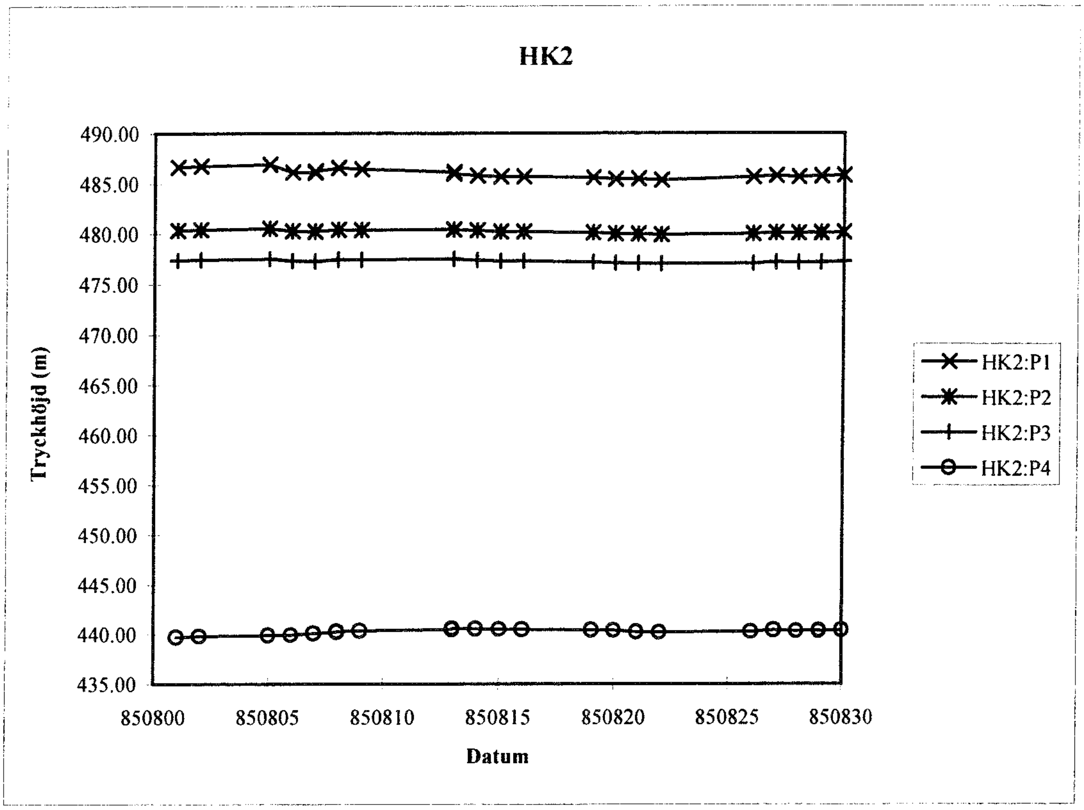
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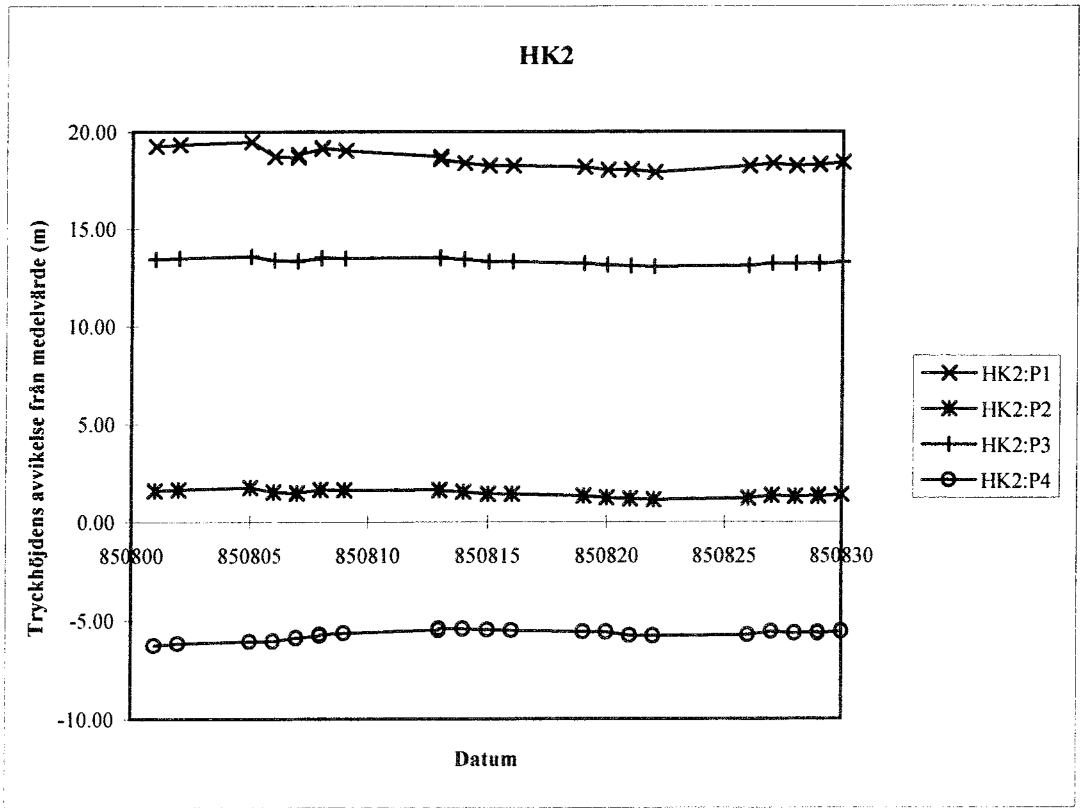
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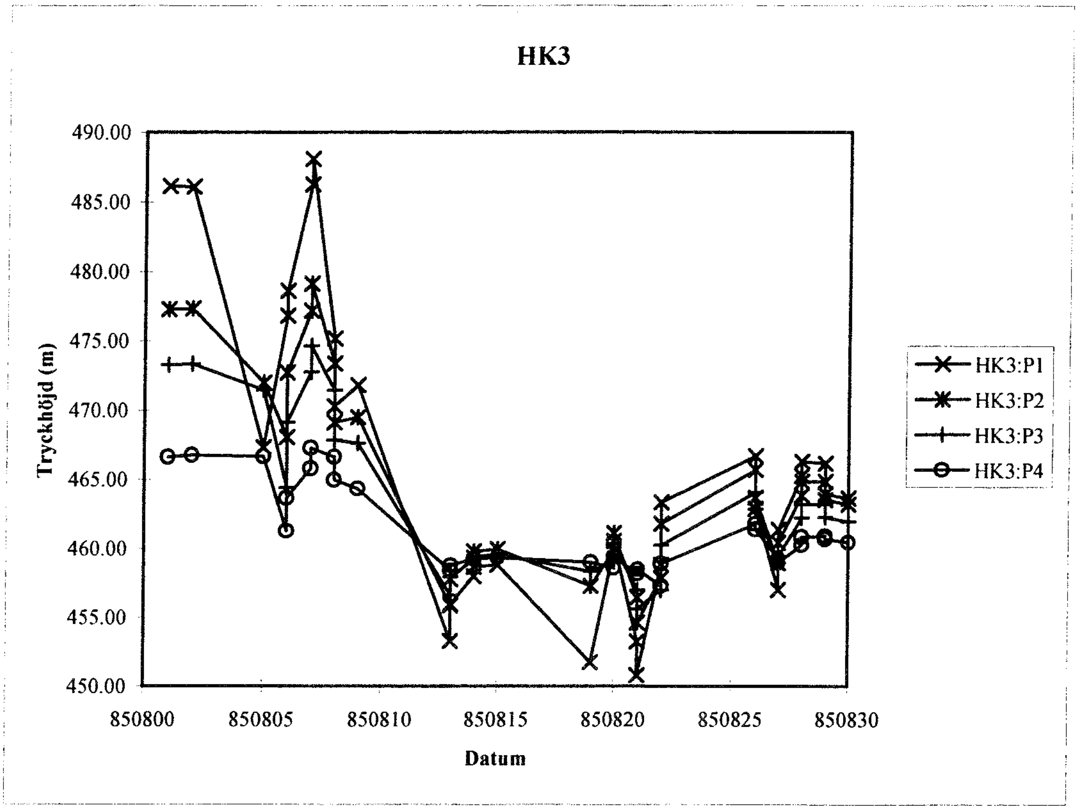
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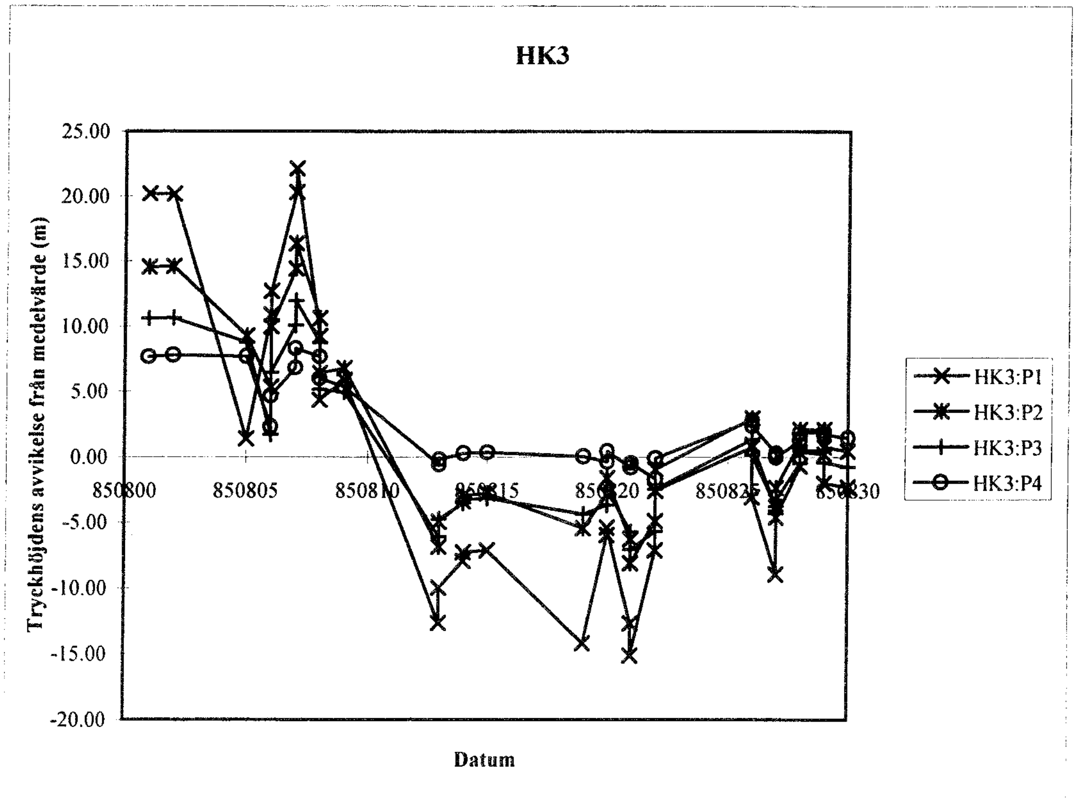
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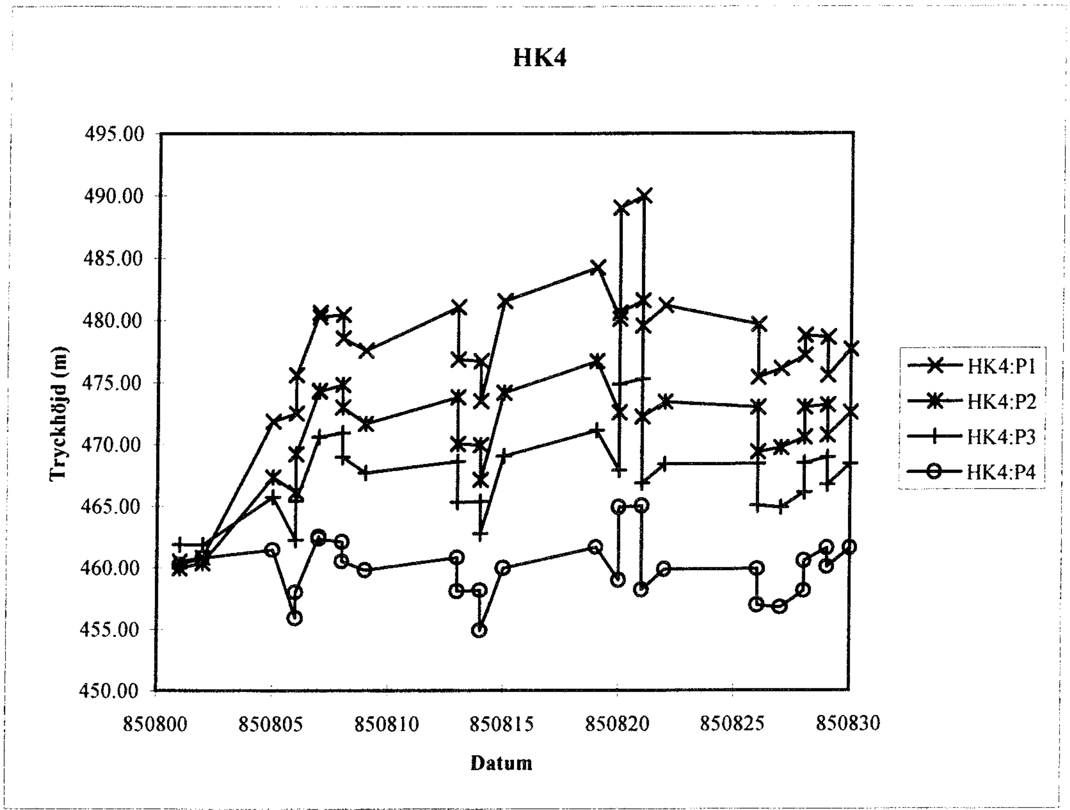
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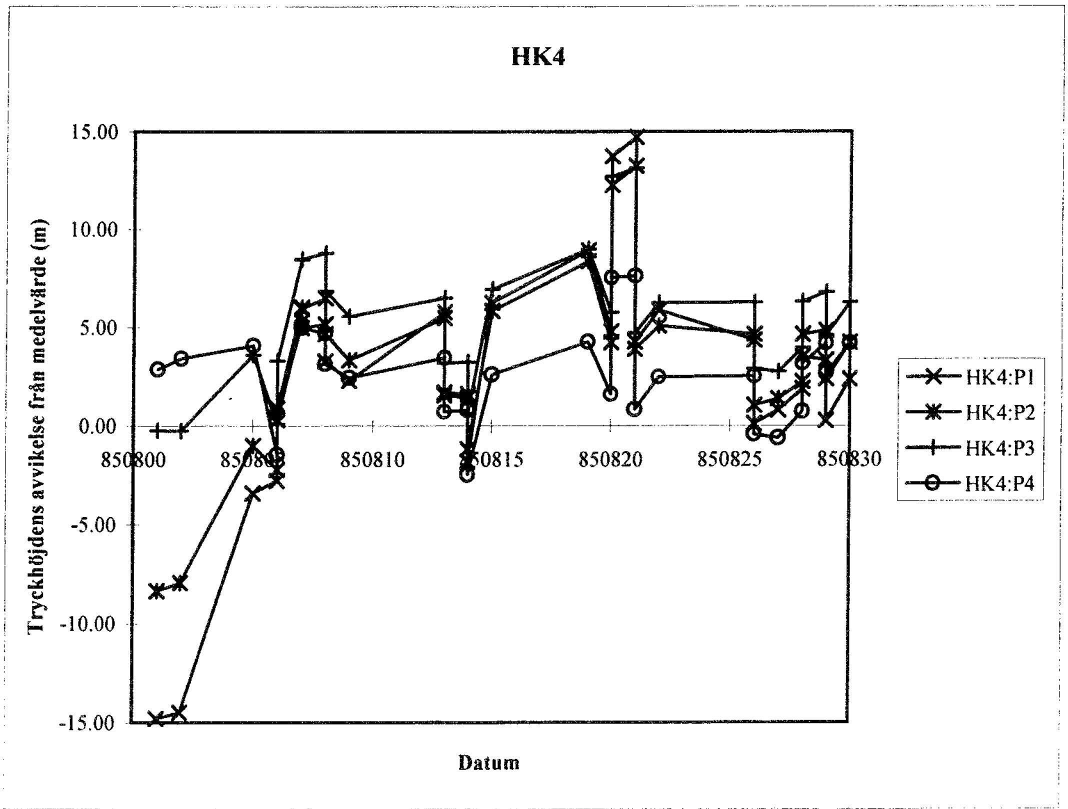
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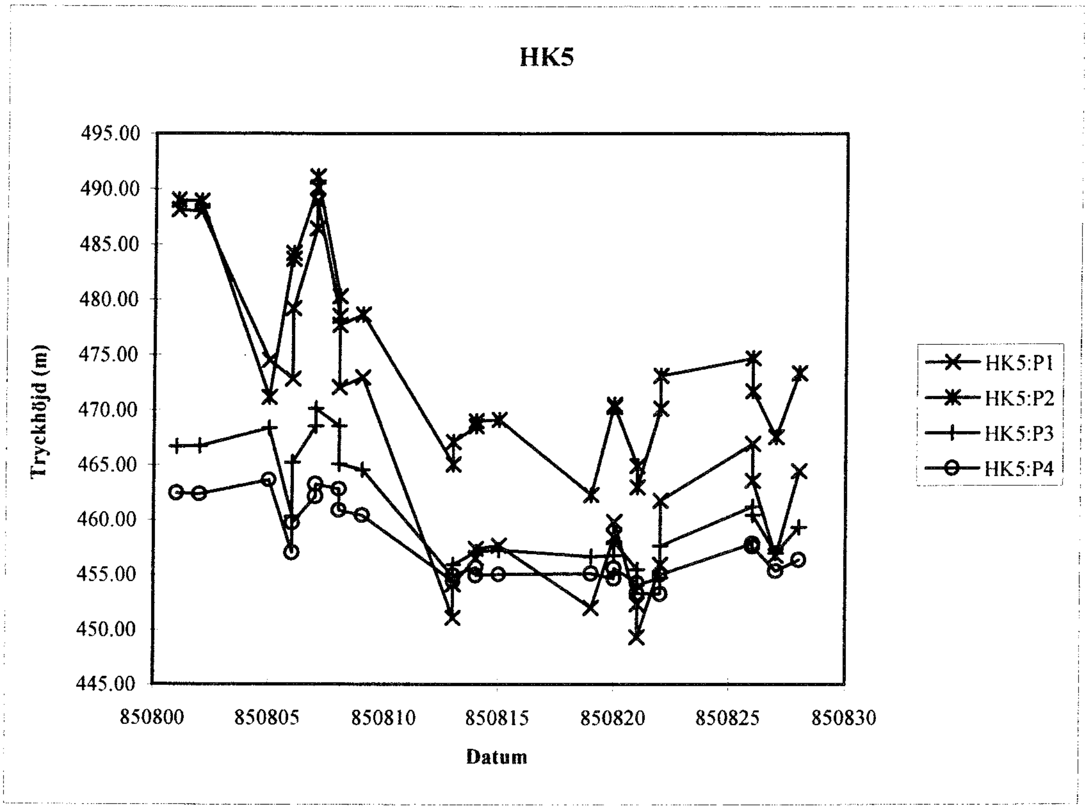
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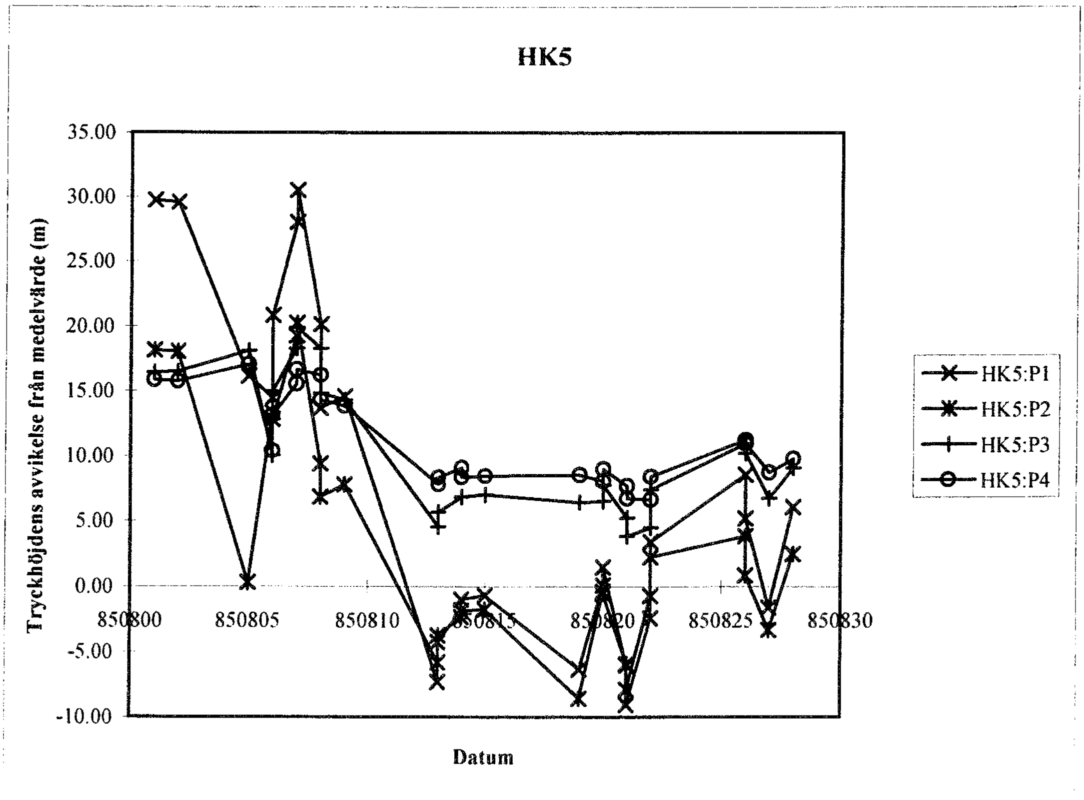
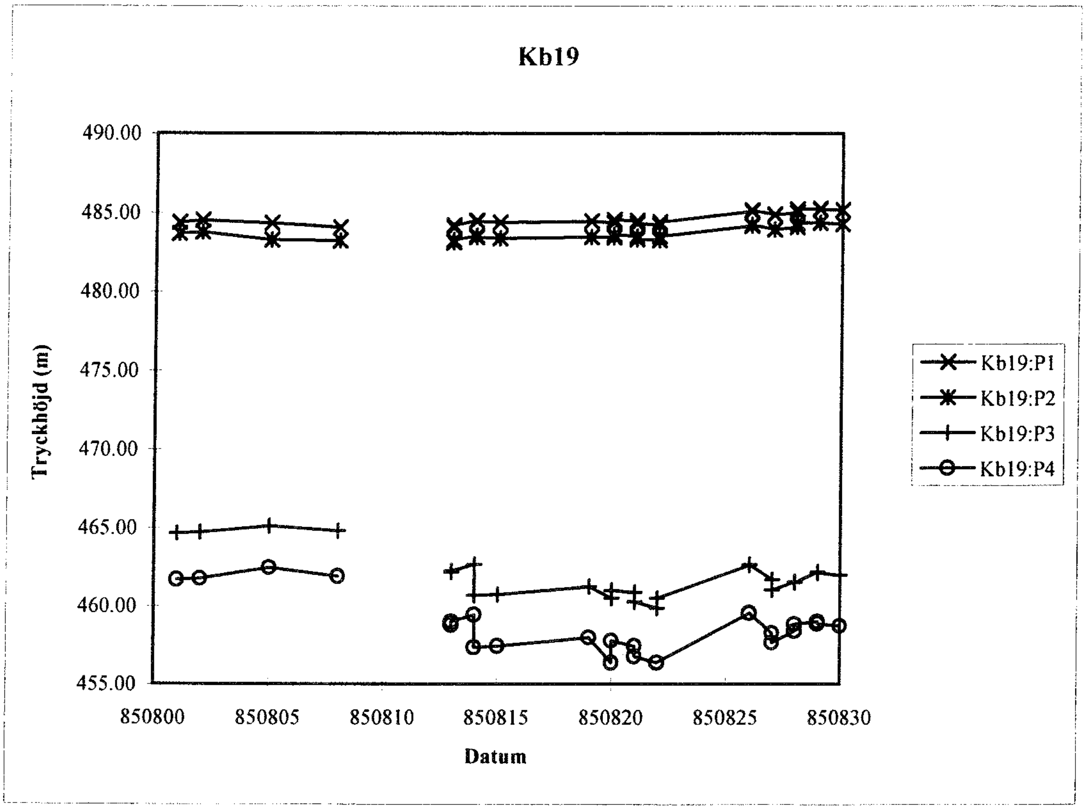
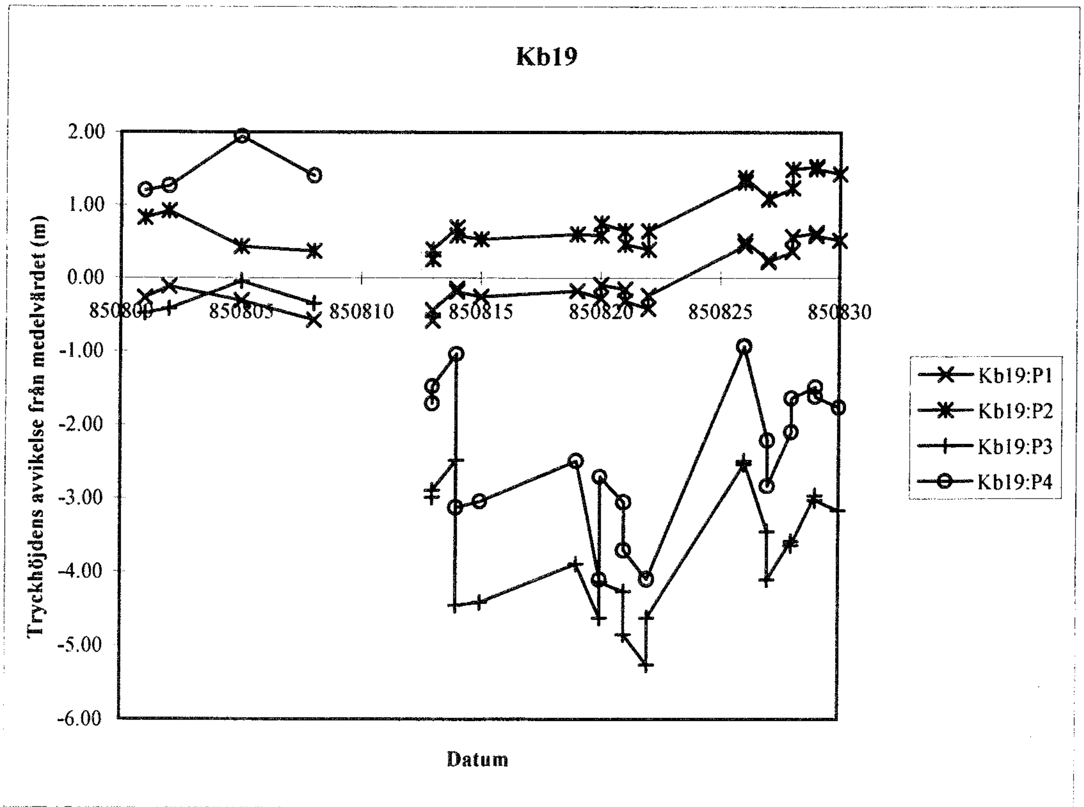
850830
Datum
HK5:P1
HK5:P2
HK5:P3
HK5:P4

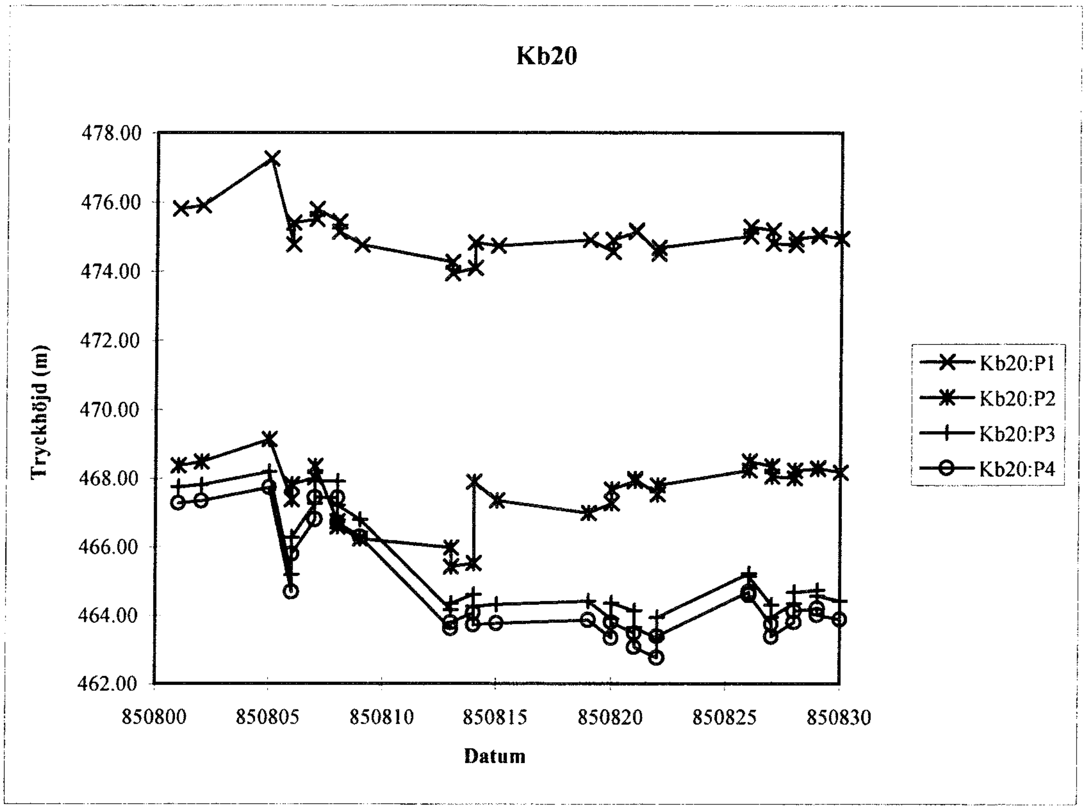

HK5
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
Tryckhöjdens avvikelse från medelvärde (m)
850800
850805
850810
850815
850820
850825
850830
Datum
HK5:P1
HK5:P2
HK5:P3
HK5:P4



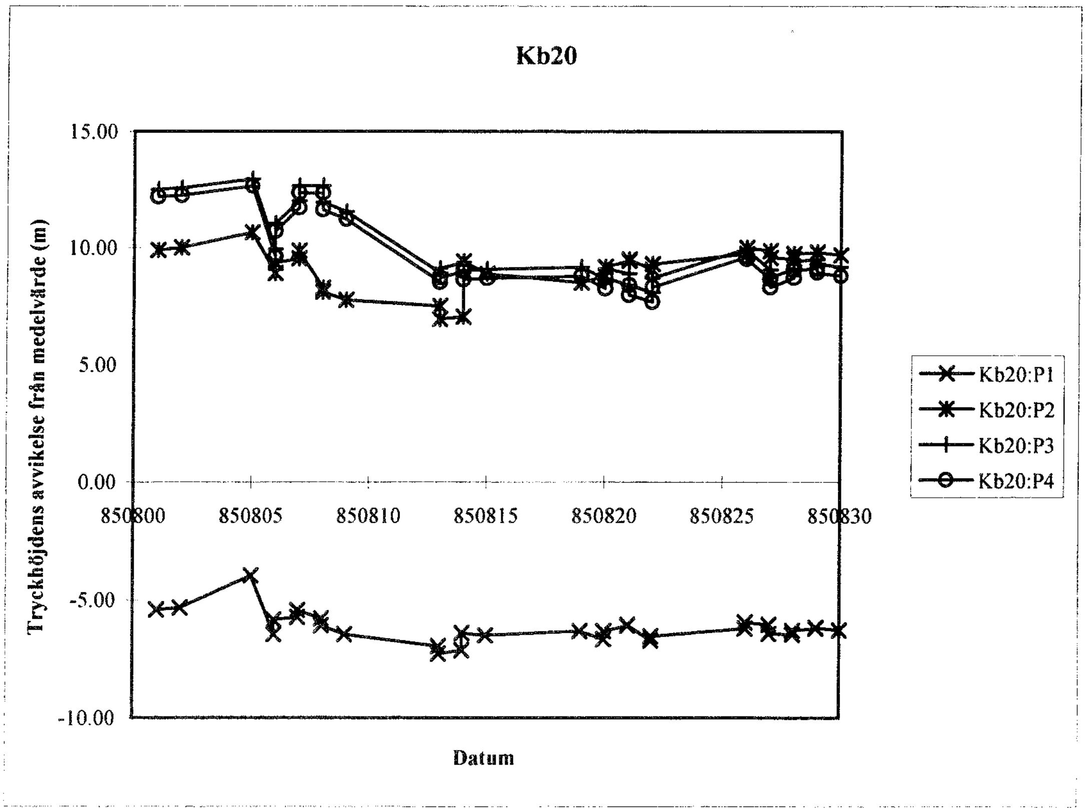
Kb19
490.00
485.00
480.00
475.00
470.00
465.00
460.00
455.00
Tryckhöjd (m)
850800
850805
850810
850815
850820
850825
850830
Datum
Kb19:P1
Kb19:P2
Kb19:P3
Kb19:P4



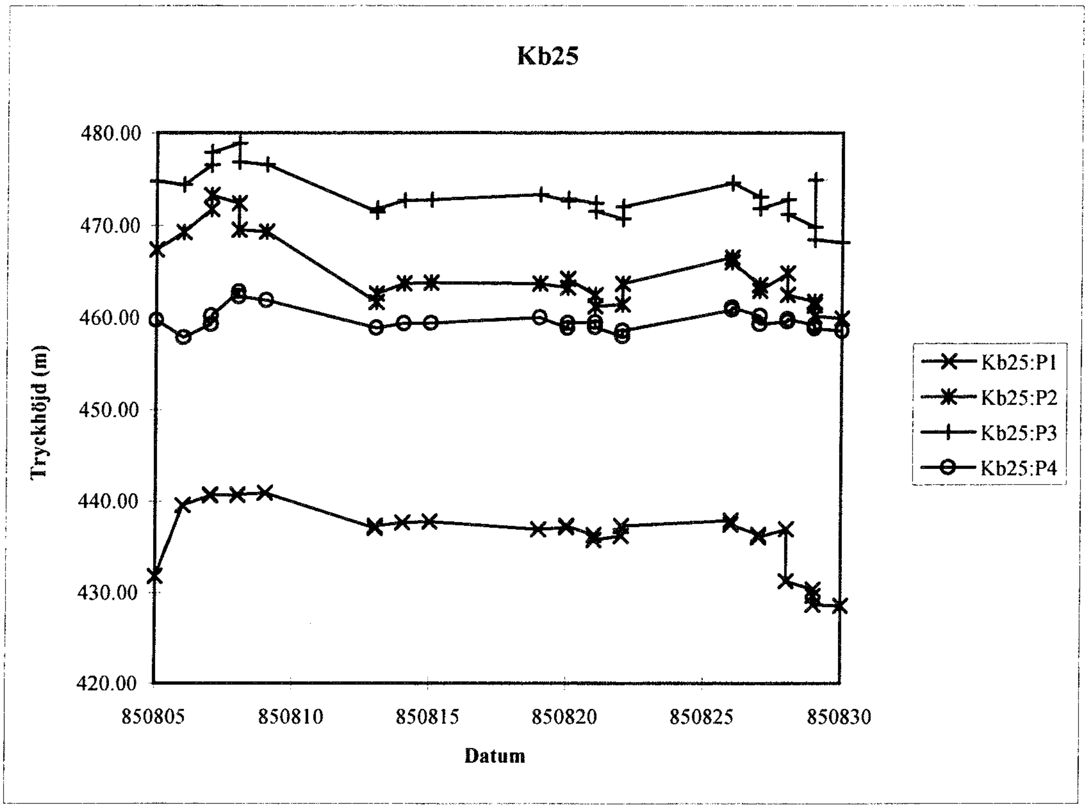
Kb19
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
Tryckhöjdens avvikelse från medelvärdet (m)
850800
850805
850810
850815
850820
850825
850830
Datum
Kb19:P1
Kb19:P2
Kb19:P3
Kb19:P4

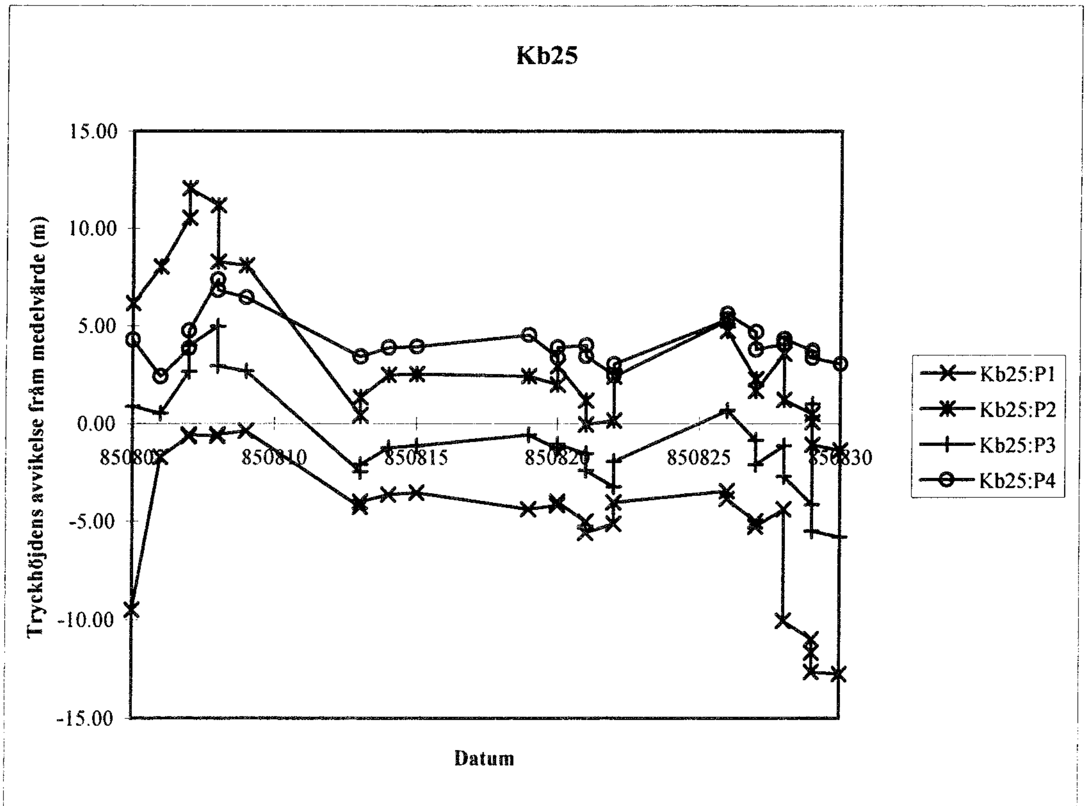


Kb20
478.00
476.00
474.00
472.00
470.00
468.00
466.00
464.00
462.00
Tryckhöjd (m)
850800
850805
850810
850815
850820
850825
850830
Datum
Kb20:P1
Kb20:P2
Kb20:P3
Kb20:P4



Kb20
15.00
10.00
5.00
0.00
-5.00
-10.00
Tryckhöjdens avvikelse från medelvärde (m)
850800
850805
850810
850815
850820
850825
850830
Datum
Kb20:P1
Kb20:P2
Kb20:P3
Kb20:P4


Kb25
480.00
470.00
460.00
450.00
440.00
430.00
420.00
Tryckhöjd (m)
850805
850810
850815
850820
850825
850830
Datum
Kb25:P1
Kb25:P2
Kb25:P3
Kb25:P4


Kb25
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Tryckhöjdens avvikelse fråm medelvärde (m)
850810
850815
850825
Datum
Kb25:P1
Kb25:P2
Kb25:P3
Kb25:P4

APPENDIX B

Explanations of abbreviation of tunnel names

DT	=	Drifttunnel
BT	=	Byggtunnel
CT	=	Centraltunnel
NBT	=	Nedre byggtunnel
1TT	=	Tvärtunnel 1
BST	=	Bergsalstunnel
1STT	=	Silotaktunnel1
1ST	=	Silotunnel1
2GS	=	Genomstick 2
3GS	=	Genomstick 3
1SBT	=	Silobottentunnel 1
1SDT	=	Silodränagetunnel 1
1NDB	=	Nedre dränagebassäng 1
FS	=	Förbindelseschakt

APPENDIX C

Definition of local co-ordinate system

The translation between the regional co-ordinate system, RT 38, and the local co-ordinate system at Forsmark is defined by

$$T = 16130.736 + (X - 6690000) \cdot \cos(258.385^g) + Y \cdot \sin(258.385^g)$$
$$U = -361.177 - (X - 6690000) \cdot \sin(258.385^g) + Y \cdot \cos(258.385^g)$$

Where

T = Local co-ordinate
U = Local co-ordinate
X = Regional co-ordinate according to RT38
Y = Regional co-ordinate according to RT38