Challenges faced in drilling high-temperature geothermal wells in Iceland

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Iceland GeoSurvey
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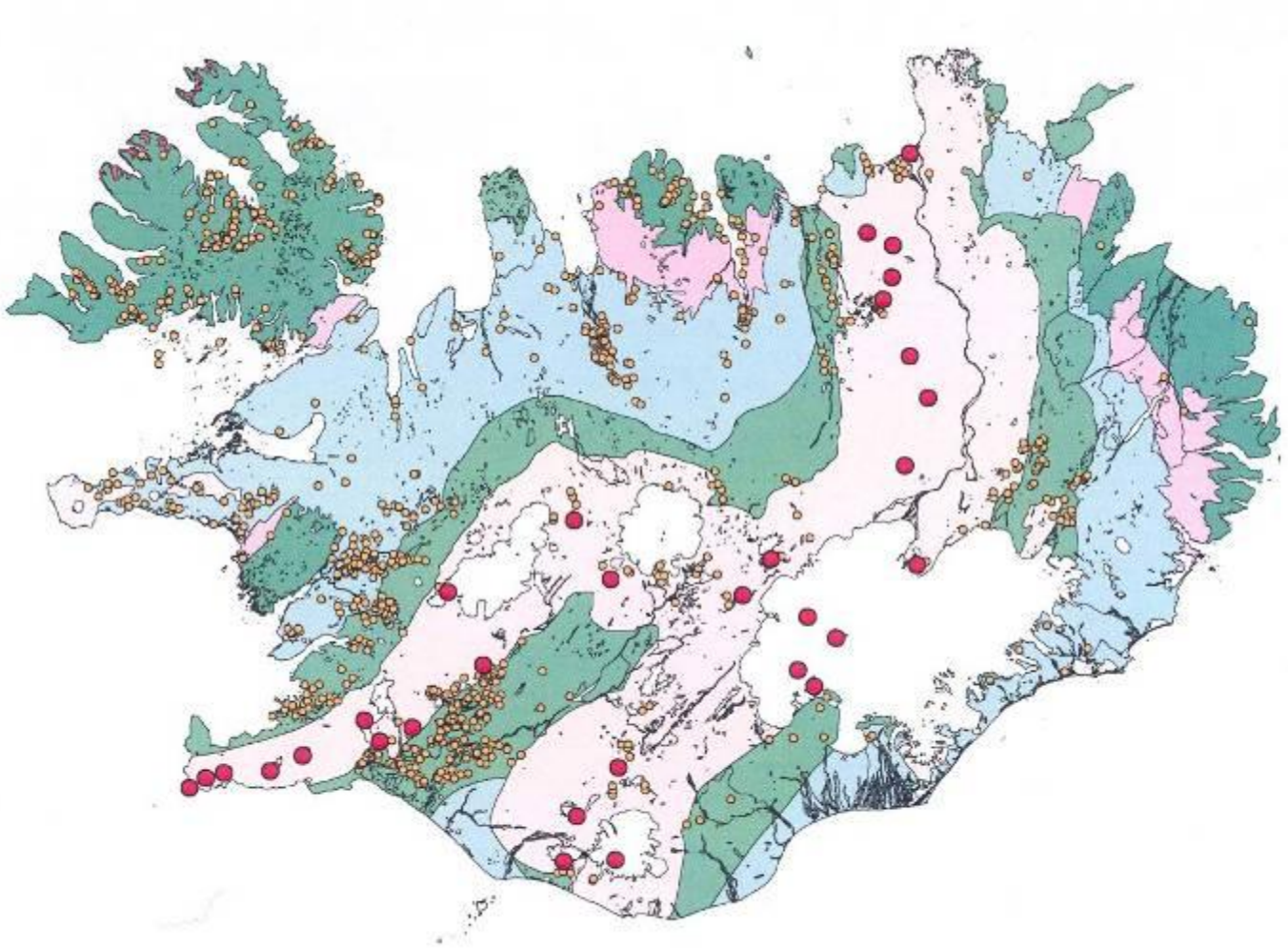
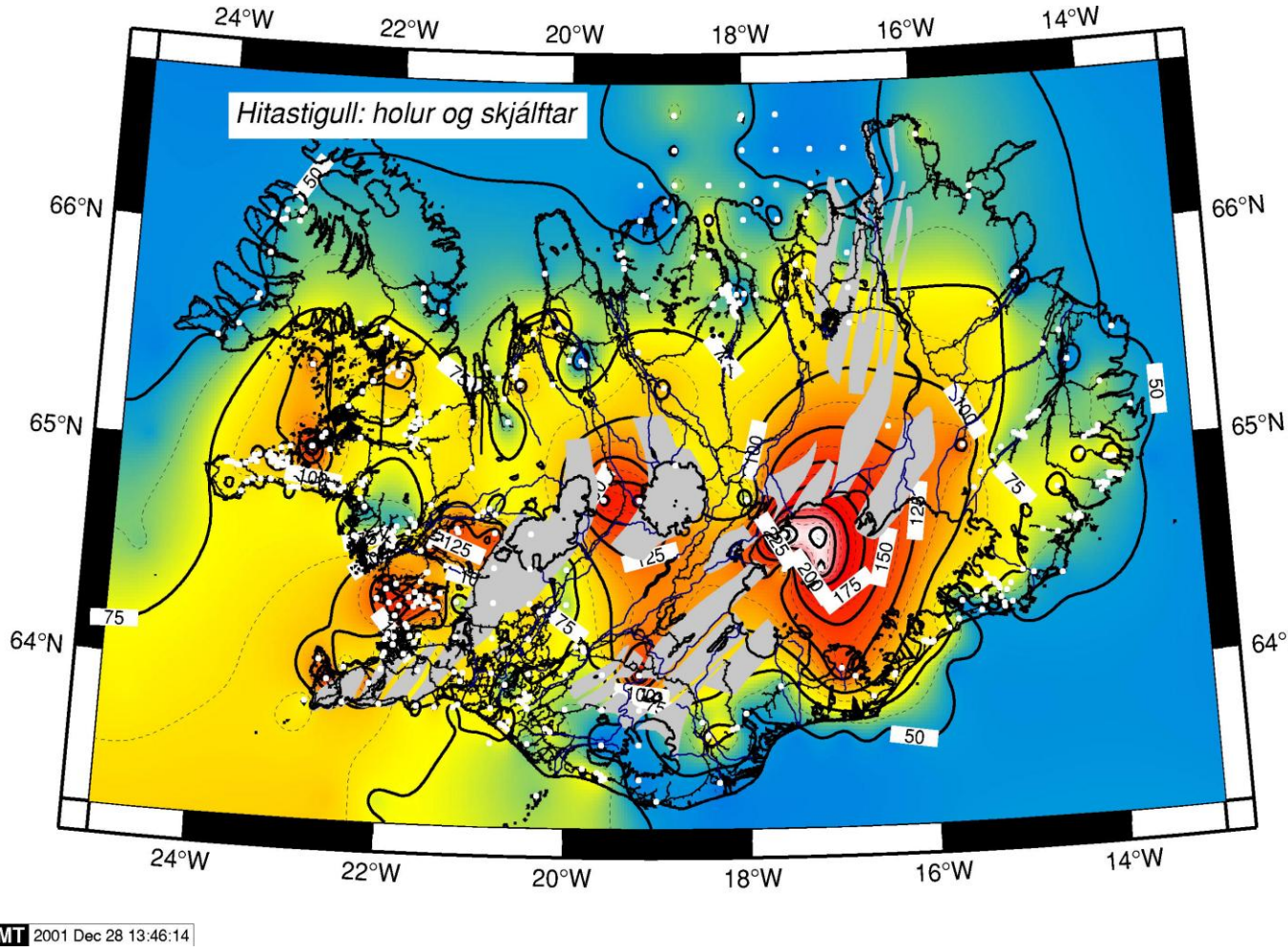
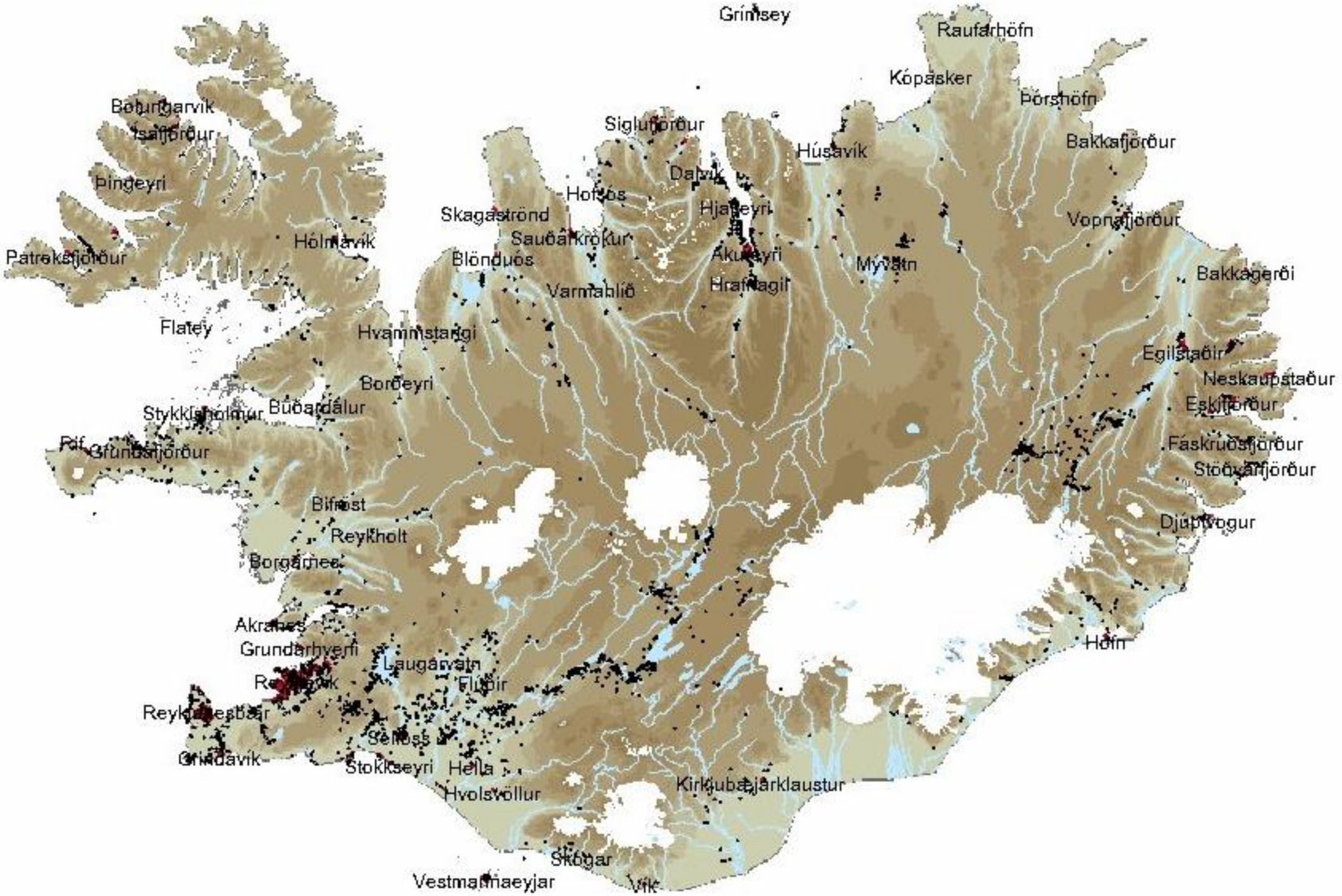
ÍSOR geothermal map of Iceland



ÍSOR thermal gradient map

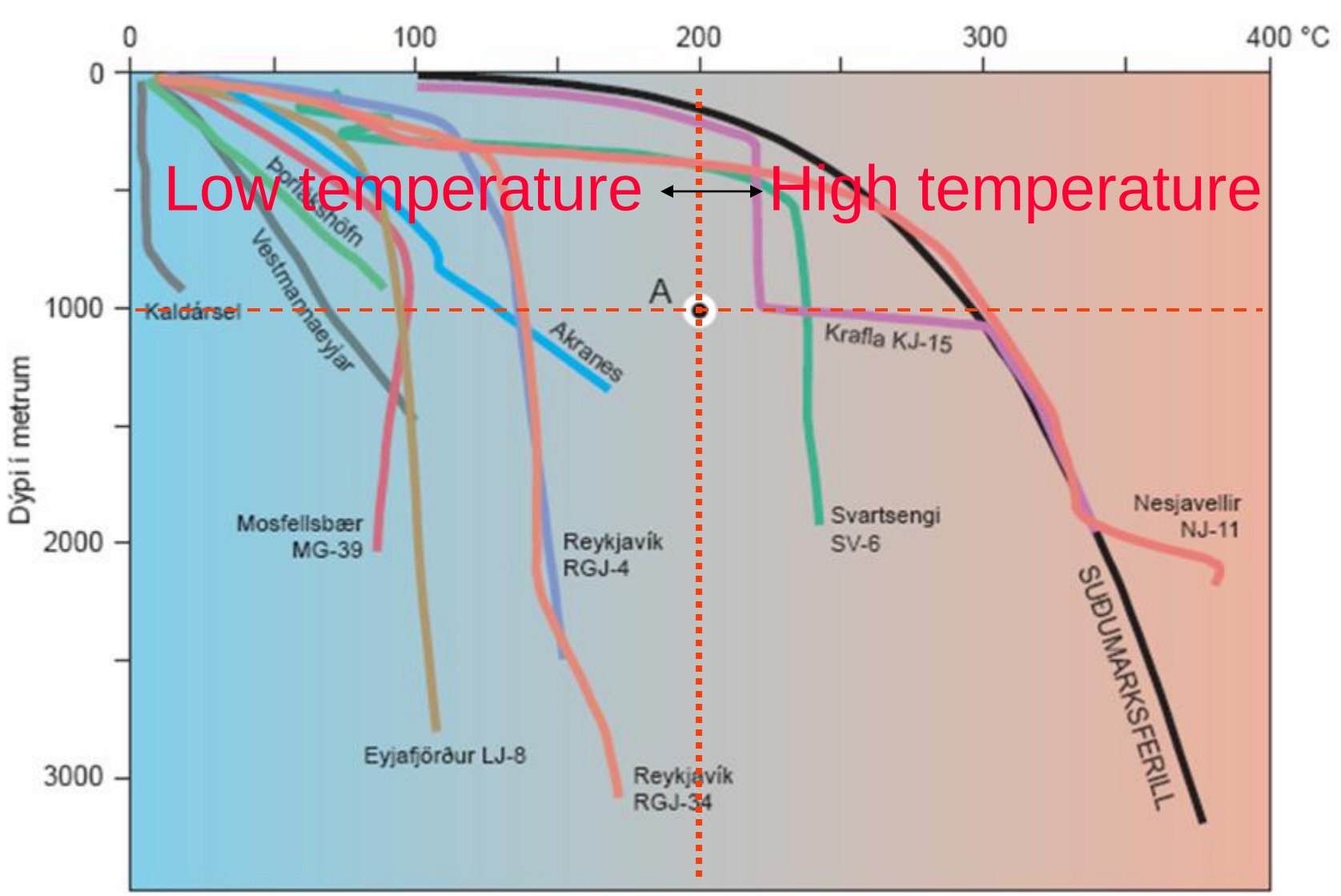
The thermal gradient reflects the heat flow in the earths crust. Outside the geothermal areas the gradient is from 50°C/km in the oldest crust up to 170°C/km in the youngest.





Location of wells in Iceland: www.gagnavefsja.is

Temp. profiles - def. of LT and HT



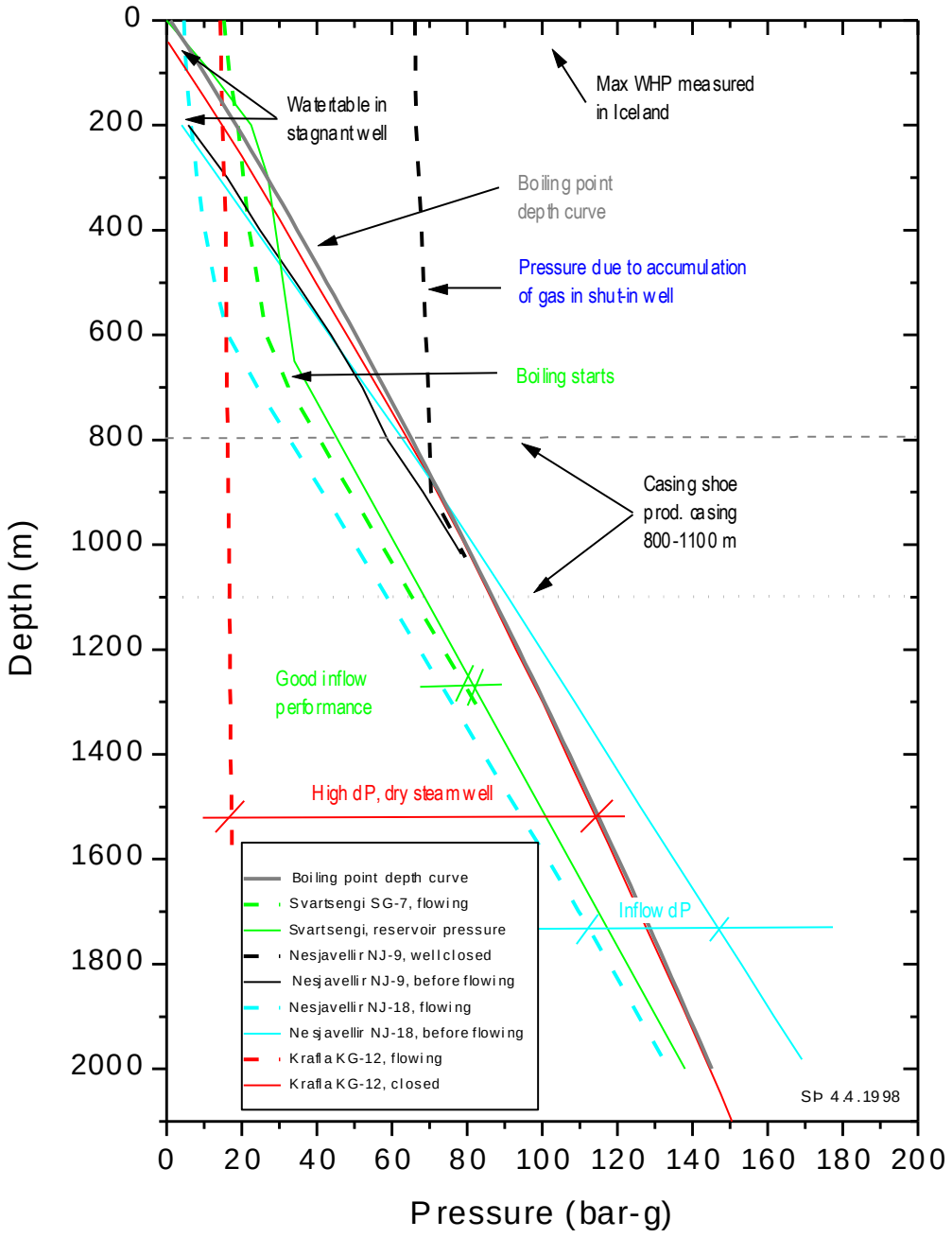
Ref.: Guðmundur Pálmason

Well Pressures

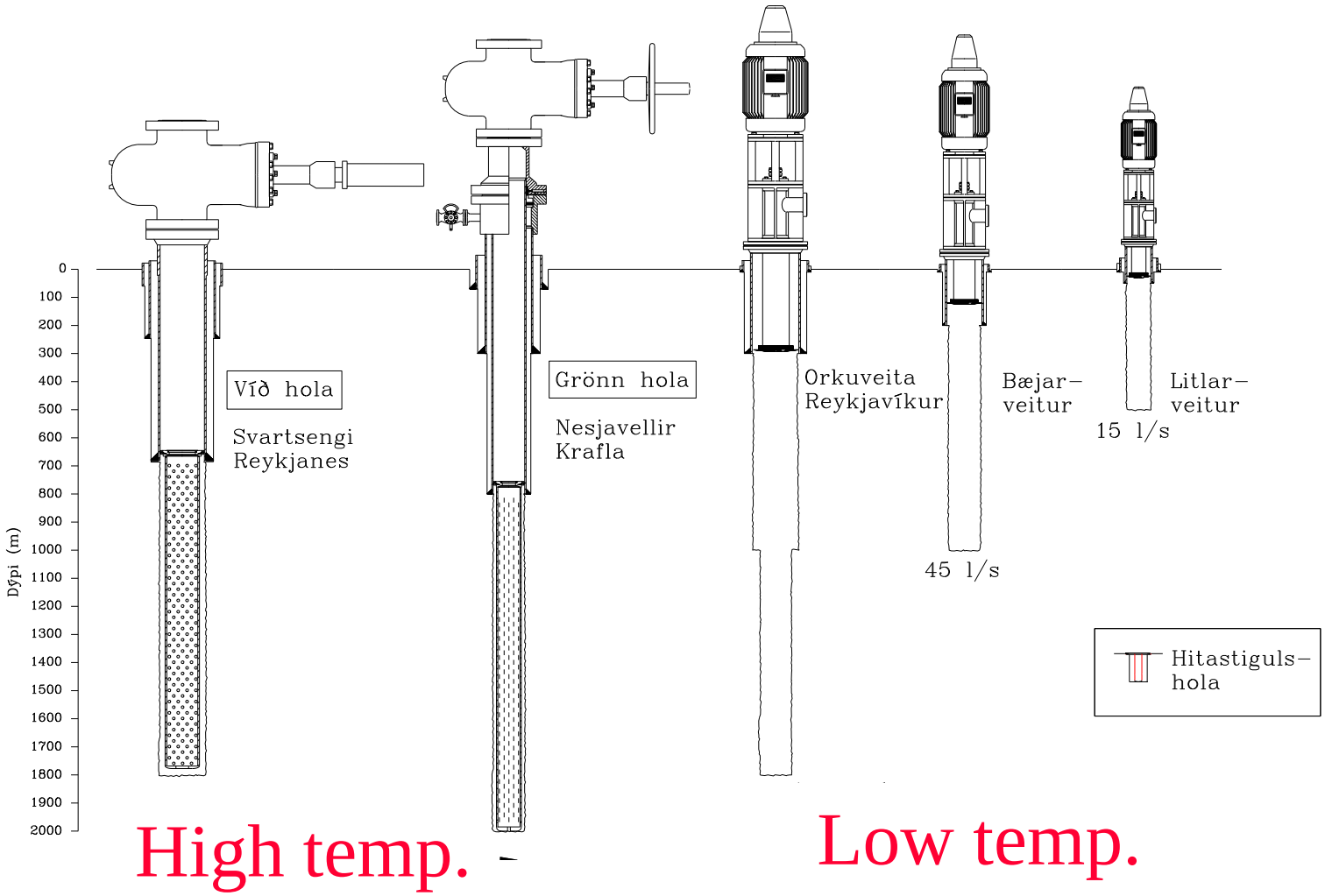
The figure shows pressure profiles that have been logged in HT geothermal wells in Iceland.

-Static (solid lines): well closed

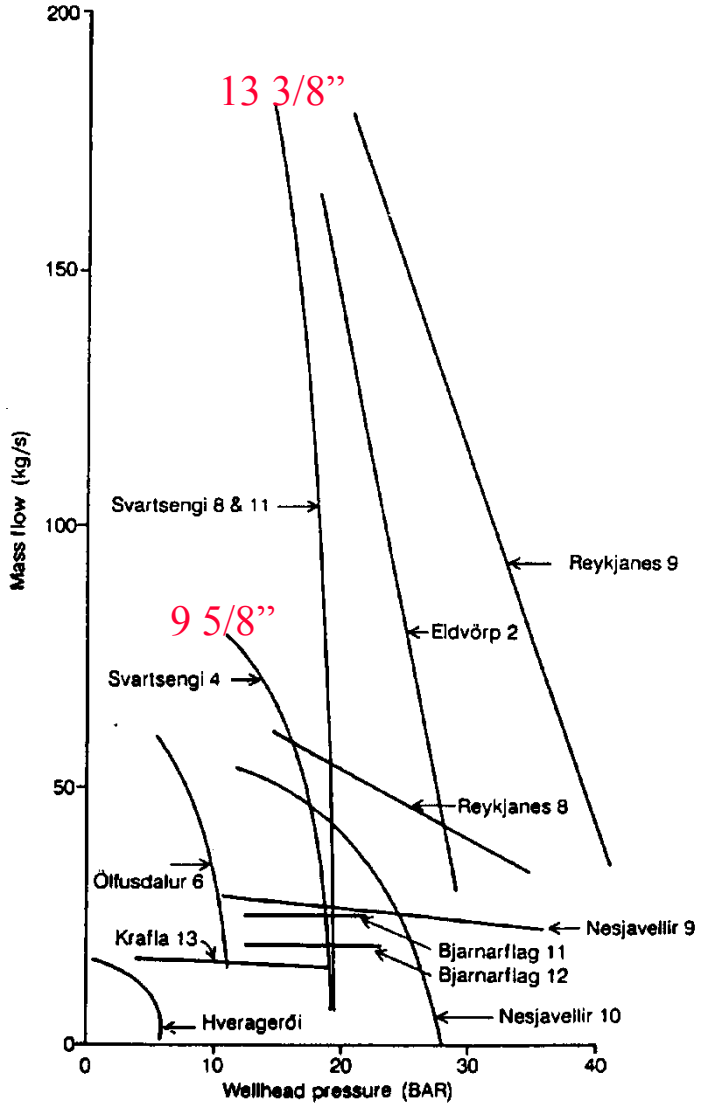
-Dynamic (dotted lines): well flowing



Icelandic geothermal wells

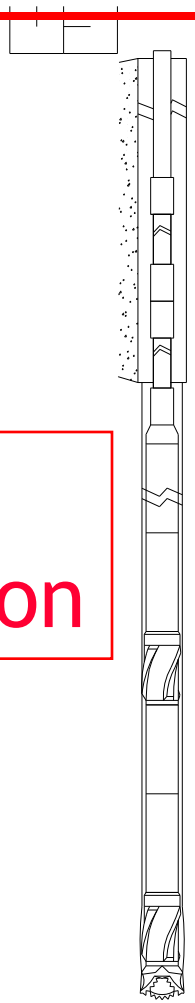


Output curves for wells in Iceland

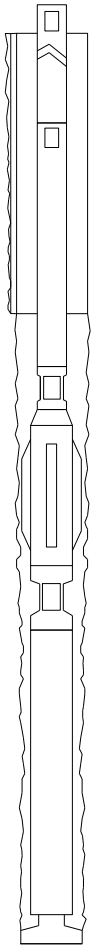


Drilling methods used in Iceland

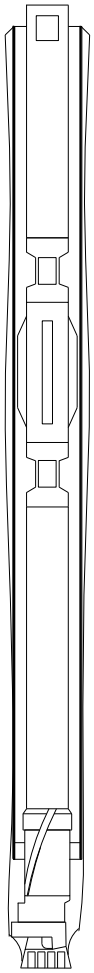
Most common



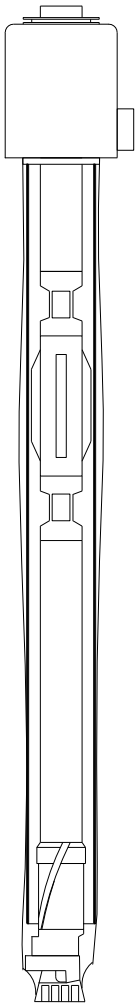
Rotary



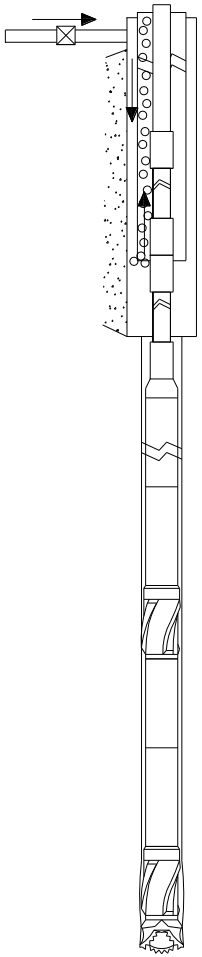
Air hammer



Odex

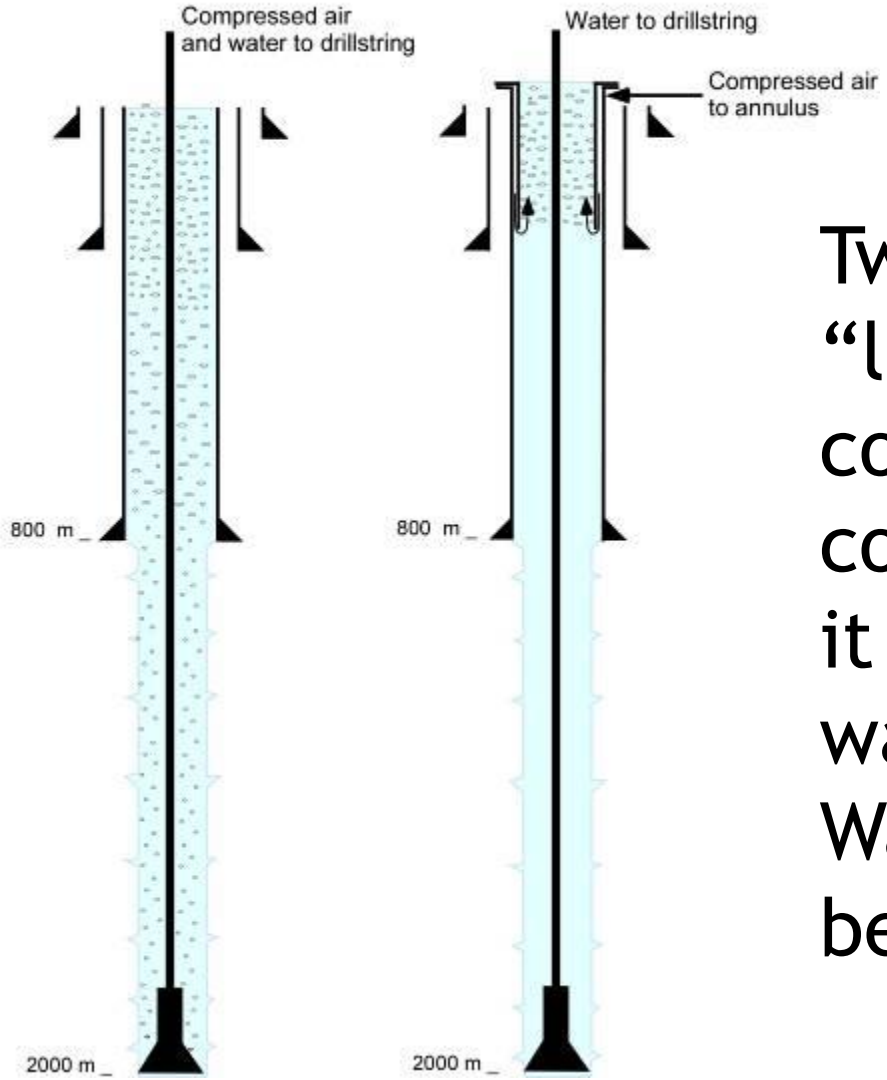


Holte



Pressure bal.

Underbalanced or balanced drilling



Two methods used to "lighten" the water column by entering compressed air – mixing it with the mud or water.
Water flow similar as before but air is extra.

Drilling rigs in Iceland 2007

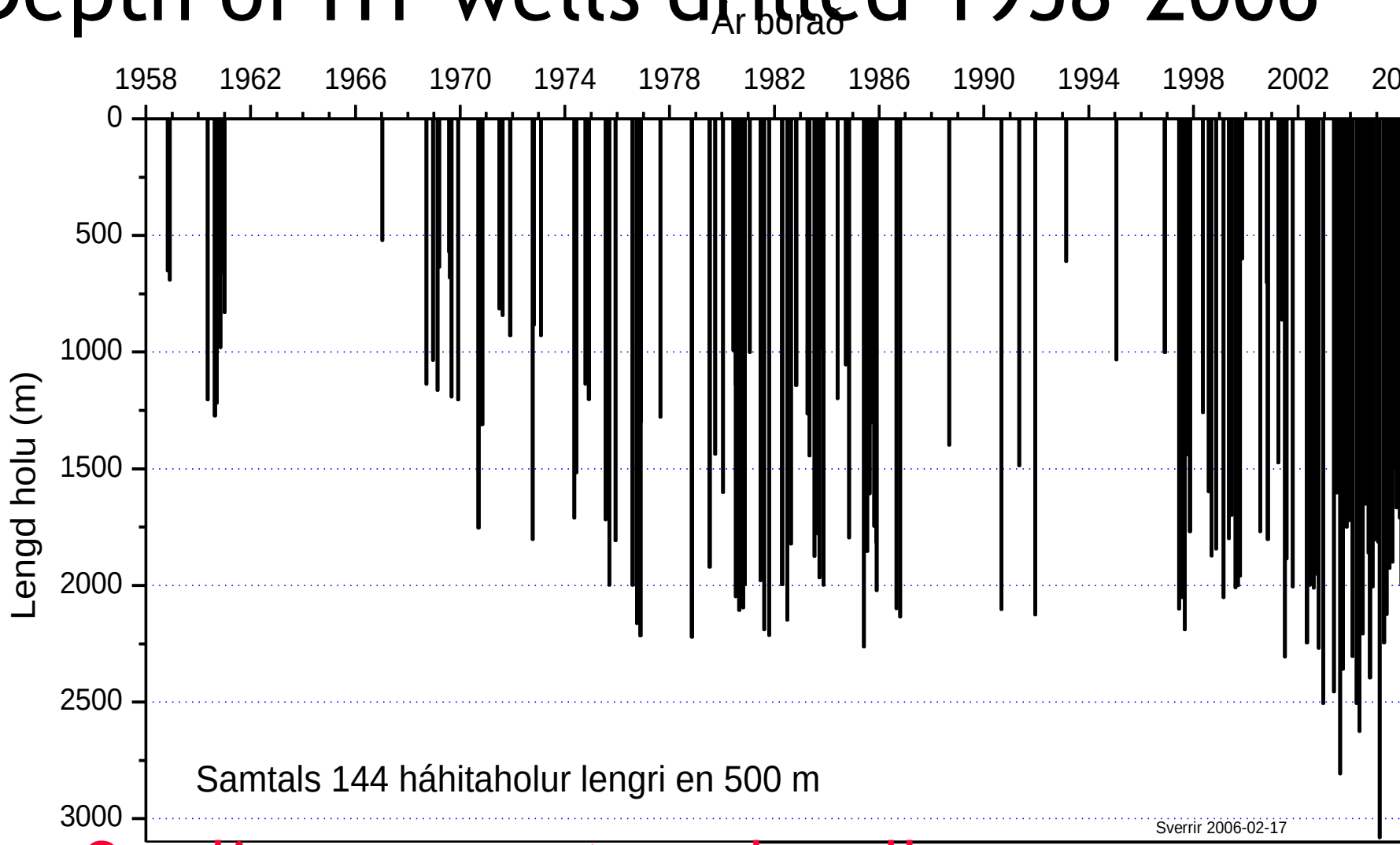
Óðinn JB	4000 m
Geysir JB	4000 m
Jötunn JB	3300 m
Sleipnir JB	2400 m
RFS new	1600 m
Saga JB	1350 m
Trölli RFS	1100 m
Ýmir JB	1000 m
Langþr. RFS	600 m
Glámur RFS	600 m
Einráður RFS	500 m
Hrímnir JB	300 m
Alvarr	300 m
Trítill RFS	120 m

1940

43 HT wells were drilled to less than 250 m from 1940-1958 at:
Hveragerði
Krýsuvík
Hengill
Námaskarð

After the arrival of “Gufubors” (The Steam Rig) in 1958 HT deep drilling started.

Depth of HT wells drilled 1958-2006



One line represents each well

180 production wells at “hitaveitas”

Hitaveita	Fjöldi virkjaðra borholna	Fjöldi virkjaðra hvera/lauga	Heildarafköst virkjaðra borholna l/s	MW1)	Vatnshiti á holutoppi °C	Lengd safn- og aðveituæða Stál km	Asbest km	Plast km	Alls km	Afl rafskautsketils MW	Afl olíuketils MW
Alls	180	12	6397,38	1562,65	.	490,6	115,1	54	659,6	60	170,5
Orkuveita Reykjavíkur	70	-	3502,83	767	88,8	160	-	-	160	-	96
Hitaveita Seltjarnarness	4	-	127,4	37,8	107,9	2,05	-	-	2,05	-	-
Hitaveita Mosfellsbæjar	-	-	.	.	.	4,74	-	-	4,74	-	-
Hitaveita Suðurnesja	10	-	216,794	150	205	67	-	-	67	-	-
Hitaveita Suðurnesja – Krýsuvík	1	-	50	34,595	205	...	...	...	...	-	-
Hitaveita Akraness og Borgarfjarðar	2	1	237	59,8046	97	8,951	66,61	-	75,56	-	-
OR – Akranes	-	-	.	.	-	-	-	-	-	-	-
OR – Borgarnes	-	-	.	.	-	-	-	-	-	-	-
OR – Munaðarnes	1	-	10	2,035	85	2,12	-	-	2,12	-	-
OR – Bifröst og Norðurárdalur	2	-	46,4516	5,8608	66	3	-	-	3	-	-
Hitaveita Stykkishólms	1	-	33,5	7,08994	87	5,134	-	-	5,134	-	2,5
Rarik – Dalabyggð	2	-	12,7	2,42938	82	23,3	-	-	23,3	-	-
OV – Reykhólar	3	-	26,39	6,44444	95	...	...	...	...	-	-
OV – Suðureyri	2	-	15	1,5873	61	3,6	-	-	3,6	1	3
OV – Ísafjörður – Eyrin	-	-	-	-	-	...	...	...	...	10	10
OV – Ísafjörður – Holtahverfð	-	-	-	-	-	...	...	...	...	1	3
OV – Patreksfjörður	-	-	-	-	-	...	...	...	...	3	3
OV – Flateyri	-	-	-	-	-	...	...	...	...	1	2
OV – Bolungarvík	-	-	-	-	-	...	...	...	...	3	3
Hitaveita Drangsness	2	-	25	2,6455	61	0,01	-	-	0,01	-	-
Hitaveita Húnaþings vestra – Laugarbakki	2	-	28,665	7	95	0,3	-	-	0,3	-	-
Hitaveita Húnaþings vestra – Hvammstangi	-	-	.	.	.	7,5	-	-	7,5	-	-
Hitaveita Húnaþings vestra – Reykir í Hrútafirði	1	-	4,02787	1	96	...	...	...	...	-	-
Hitaveita Blönduóss	2	-	70,0246	11,4	75	2	13	-	15	-	-
Skagafjarðarveitur – Sauðárkrókur	4	-	140	19,943	70	2,5	0,5	-	3	-	-
Skagafjarðarveitur – Varmahlíð	2	-	21,5	4,81278	90	0,03	-	-	0,03	-	-
Skagafjarðarveitur – Steinsstaðabyggð	1	2	24	2,442	60	...	...	...	...	-	-
Skagafjarðarveitur – Barð í Fljótum	1	-	3,5	0,42735	65	...	...	...	...	-	-
Rarik – Siglufjörður	3	-	42,8	6,61945	73	4,68	-	-	4,68	-	2,5
Hitaveita Ólafsfjarðar	3	-	49,14	5,4	62	7,2	-	-	7,2	-	-
Hitaveita Dalvíkur – Dalvík	2	-	120,273	14	63,6	2,5	-	-	2,5	-	-
Hitaveita Dalvíkur – Árskógsströnd	1	-	20,3721	3,3	74,8	5	-	-	5	-	-
Norðurorka – Hrísey	1	-	8	1,39357	77,8	-	1,1	0,3	1,4	-	-
Norðurorka – Akureyri	14	-	332,15	73	89	51,87	-	11,8	63,67	9	12
Norðurorka – Svalbarðsströnd	1	-	4	0,34188	56					-	-
Orkuveita Húsavíkur	3	3	119,75	43,8644	125	16	31,5	-	47,5	-	-
Hitaveita Reykjahlíðar	1	-	...	...	99	2	2	-	4	-	-
Hitaveita Öxarfjarðarhéraðs hf.	1	-	47	11,6687	96	-	-	34	34	-	-
Hitaveita Egilsstaða og Fella	4	-	68,5	11,2912	75,5	6	-	3	9	-	2,4
Rarik – Seyðisfjörður	-	-	.	.	.	-	-	-	-	5	2,5

Municipal district heating services tap heat from **180 wells with a cumulative flow of** 6397 l/s corresponding to 1.562 MWt.

Average flow er well is thus = **35,5 l/s**.

Ave. power **8,7 MW_t**

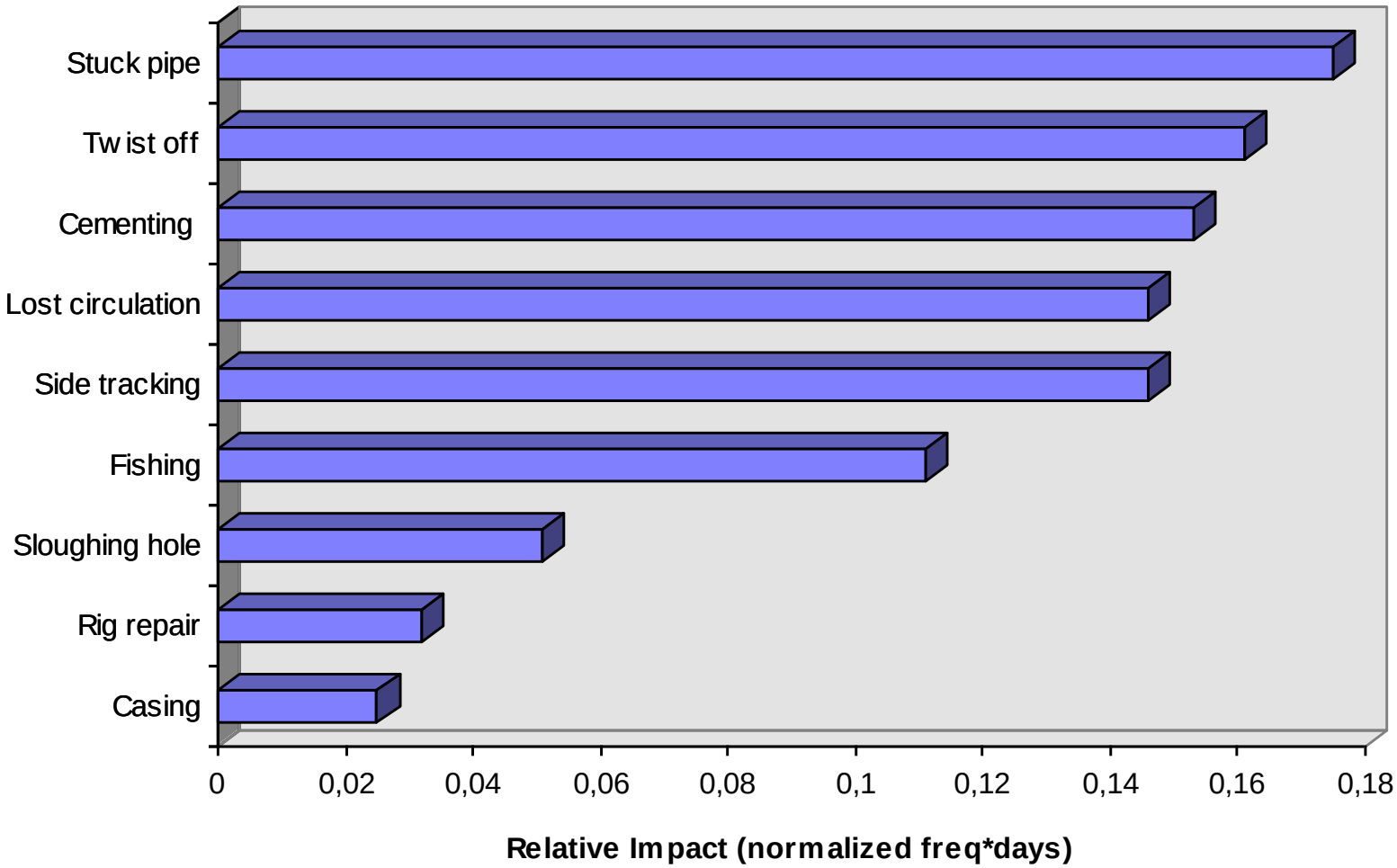
In addition there are **200 private wells**.

Ref: Þorgils Jónasson 2004
www.orkutolur.is/mm/efni/toflur.html

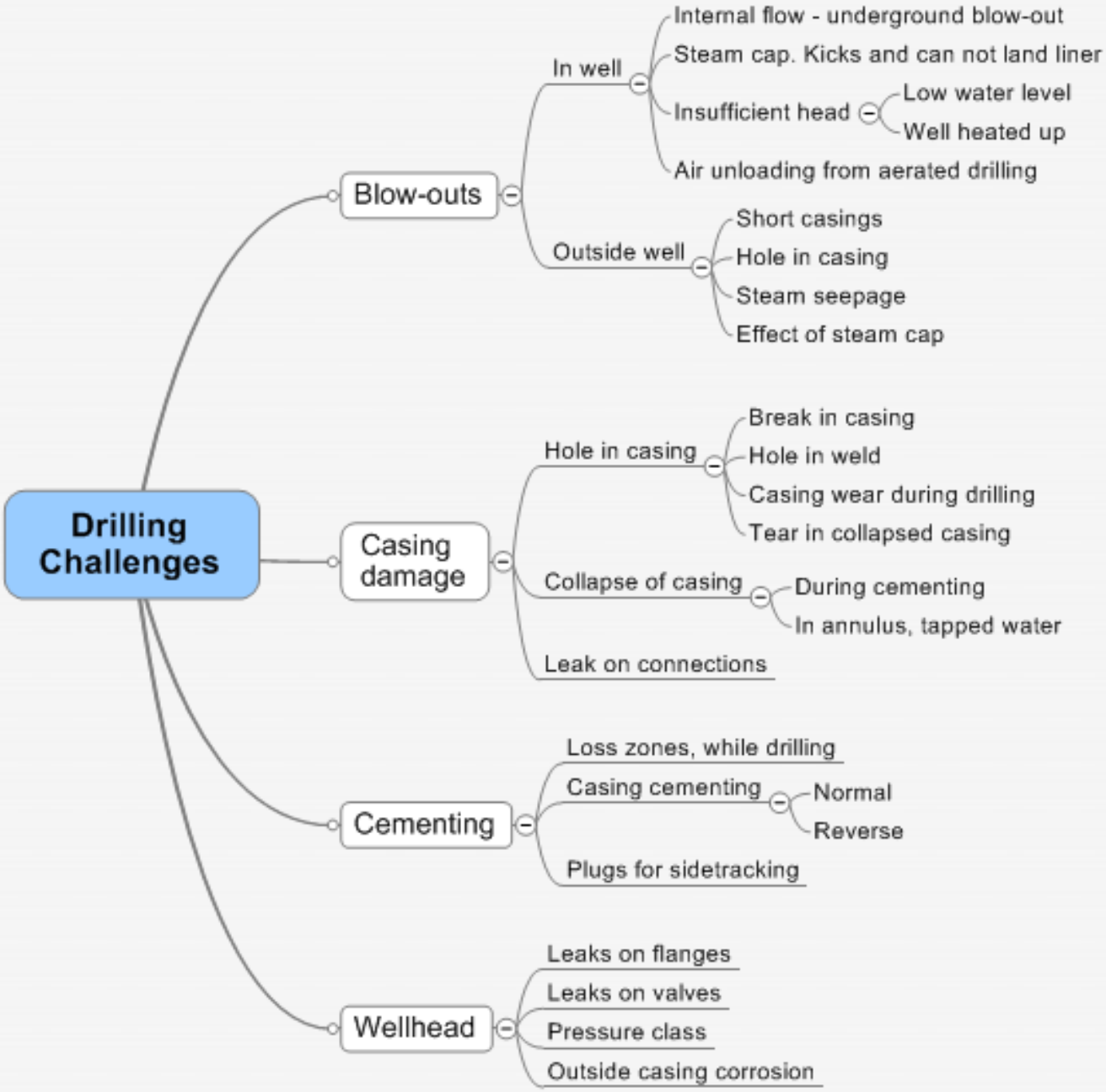
HT Drilling

1. Developers/owners: HS, LV, OR
2. Drilling works:
   - Jarðboranir hf.: drilling, casing, cementing, fishing etc.
   - ÍSOR: geoscientific and logging services.
   - VGK-Hönnun: design and supervision.
   - Foreign service companies:
     for directional drilling and aerated drilling.
   - Competitive bidding.
3. Summer of 2007 4 drilling rigs are drilling HT wells at:
   - Hellisheiði (OR)
   - Reykjanes (HS)
   - Krafla (LV)
   - Þeistareykir (LV)

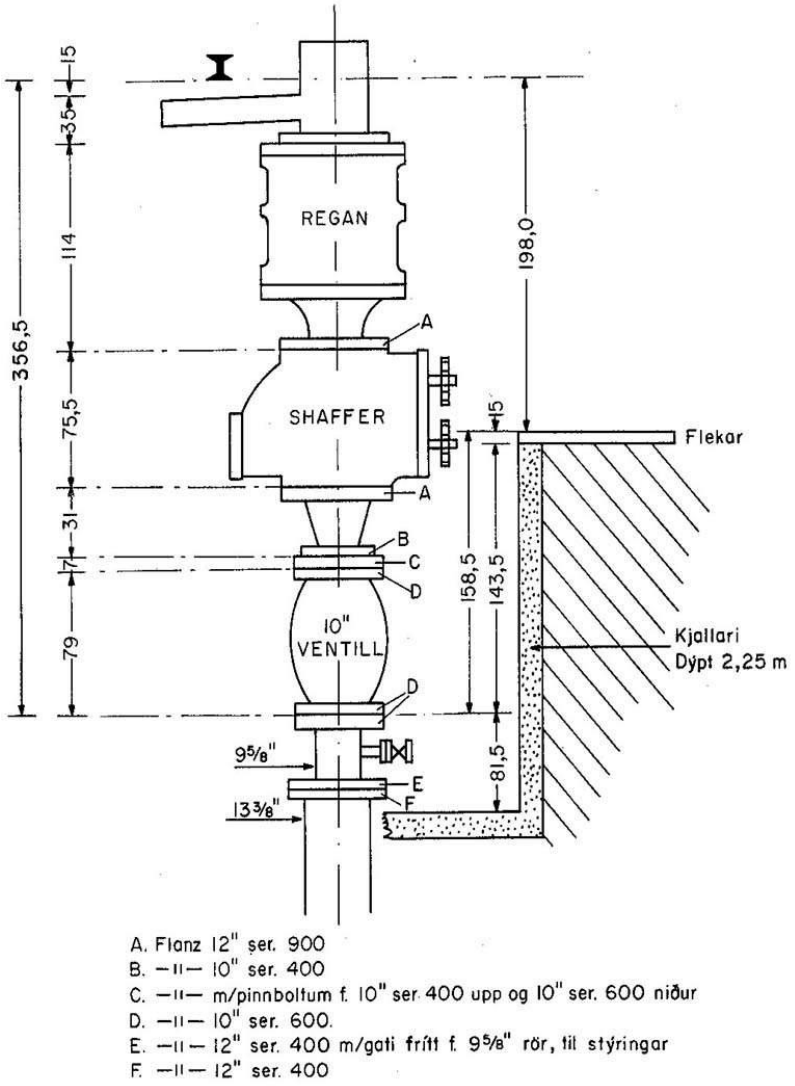
Geothermal Drilling Problems (USA)



Ref.: Pers. comm. J. Rawley (1990)

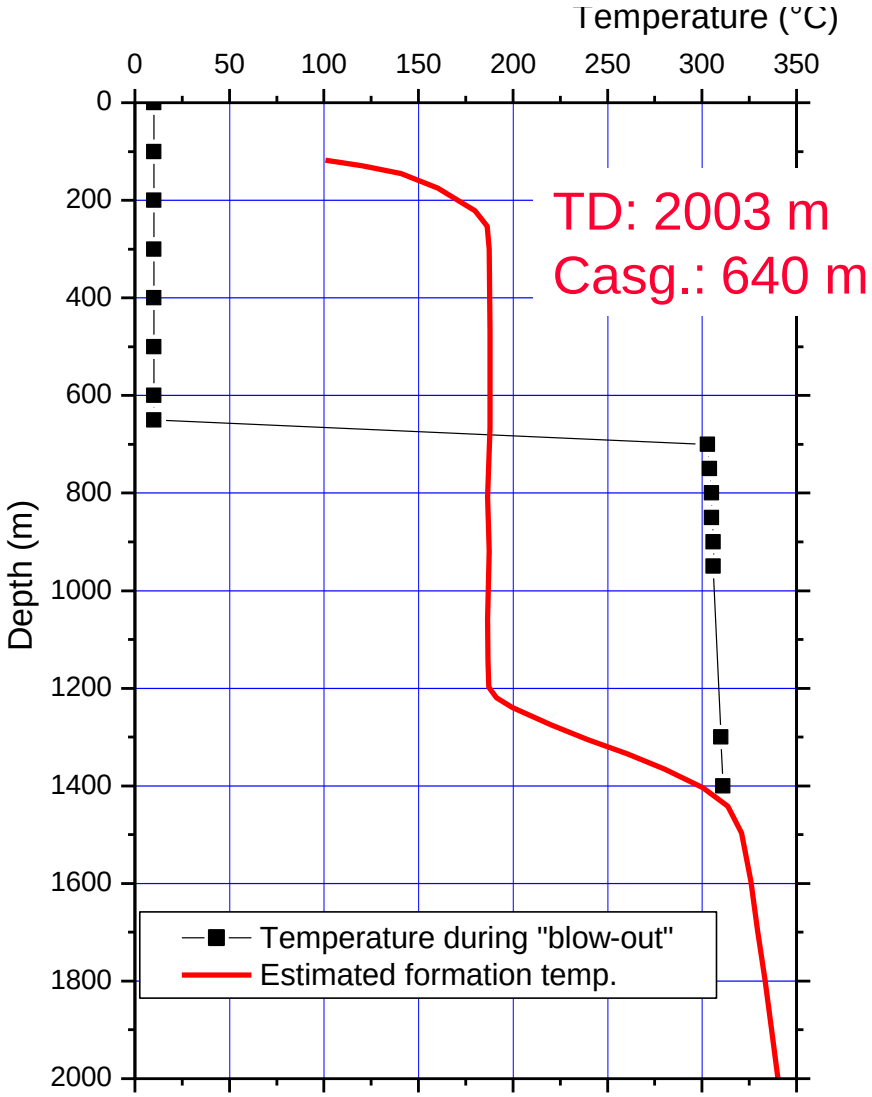

Drilling Challenges
Blow-outs
In well
Internal flow - underground blow-out
Steam cap. Kicks and can not land liner
Insufficient head
Low water level
Well heated up
Air unloading from aerated drilling
Outside well
Short casings
Hole in casing
Steam seepage
Effect of steam cap
Casing damage
Hole in casing
Break in casing
Hole in weld
Casing wear during drilling
Tear in collapsed casing
Collapse of casing
During cementing
In annulus, tapped water
Leak on connections
Cementing
Loss zones, while drilling
Casing cementing
Normal
Reverse
Plugs for sidetracking
Wellhead
Leaks on flanges
Leaks on valves
Pressure class
Outside casing corrosion

Control lost KR-4

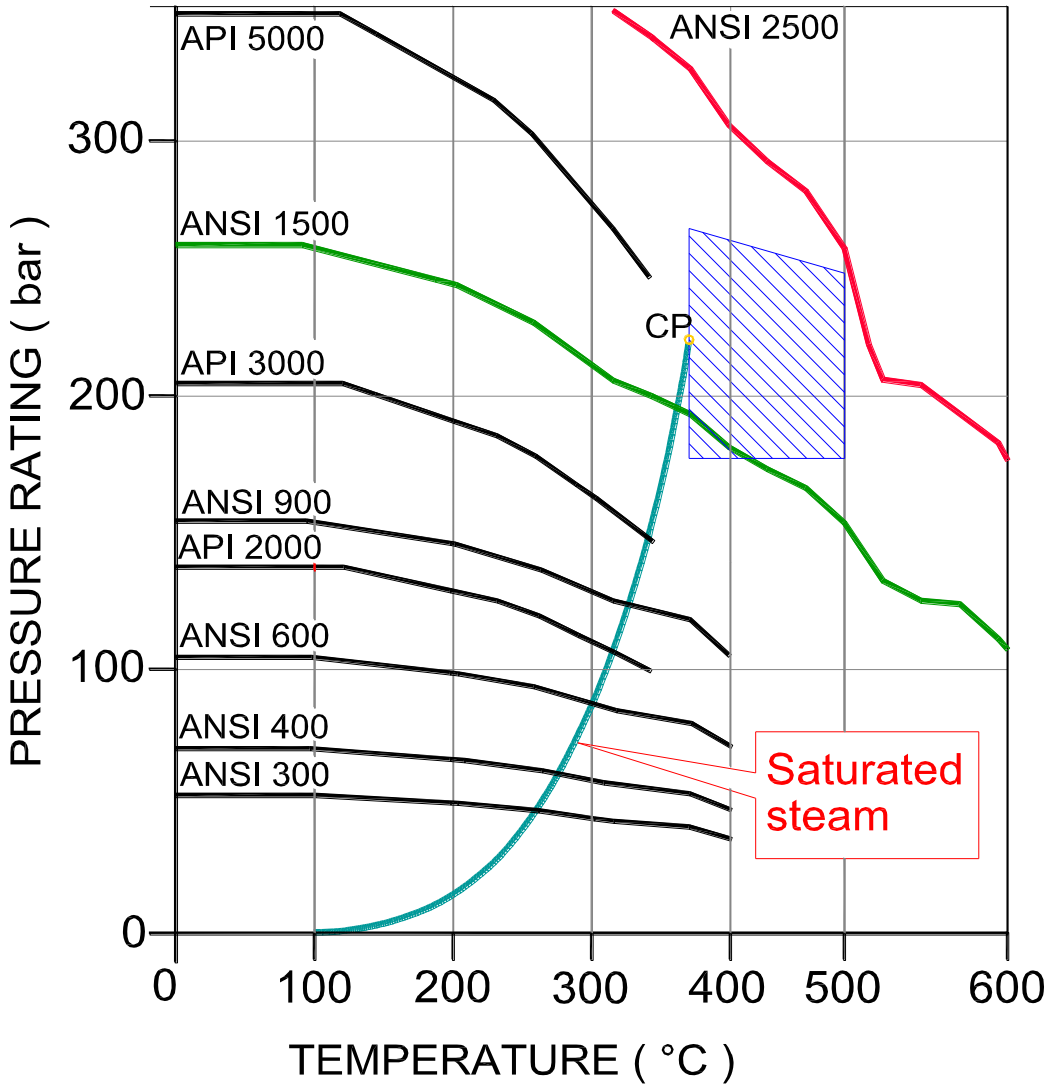


- Heavy mud mixed and pumped into well. (ρ= 1.8 g/cm^3; eq. 450 m in well)
- Po fell from 38 bar to 0 bar.
- BOP opened.
- 10-20 minutes later the well starts to flow.
- Drill pipe “blown out” of the well.
- BOP´s fail to close the well.
- Master valve can not be closed completely (3 cm missing).
- Well out of control. Decided to move the rig off the well.

Blowout at Krafla KR-4

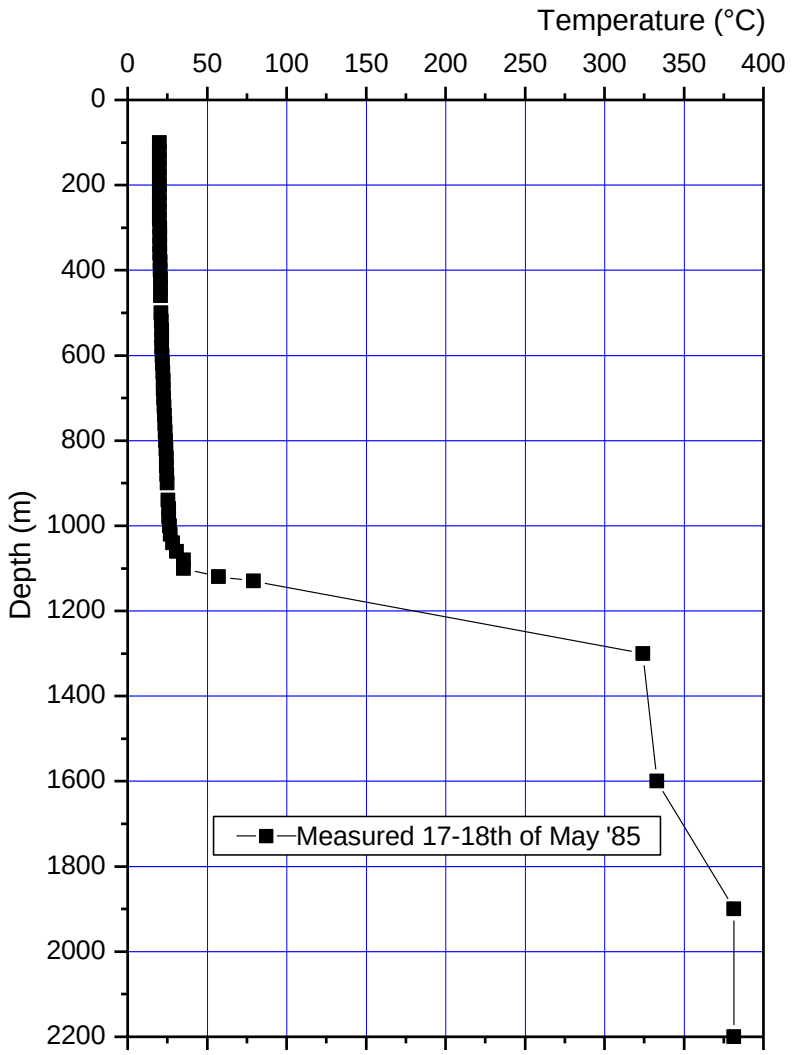


Pressure rating of wellhead




Krafla KR-4
Blow-out crater

Underground blow-out NJ-11



Temperature measured inside drill string.
To quench 44-59 l/s pumped down the well. Residual pressure WHP =6.5-6.8 bar

In 1900 m and 2200 m full deflection on the Amerada temperature gauge T>381°C

Upflow of fluid hotter than 380°C from the bottom region (2190 m aquifer ?) to the main feed zone at 1226 m, which also swallows the injection.

BOP stack

← Drilling for production casing.

Drilling production interval. →

Master valve on well.


Well.
Drilled 1949
Steam eruption 1999
Krýsuvík 1952


Krýsuvík
1987 before
Photo : GÓF


Krýsuvík
1999 after
Photo : GÓF

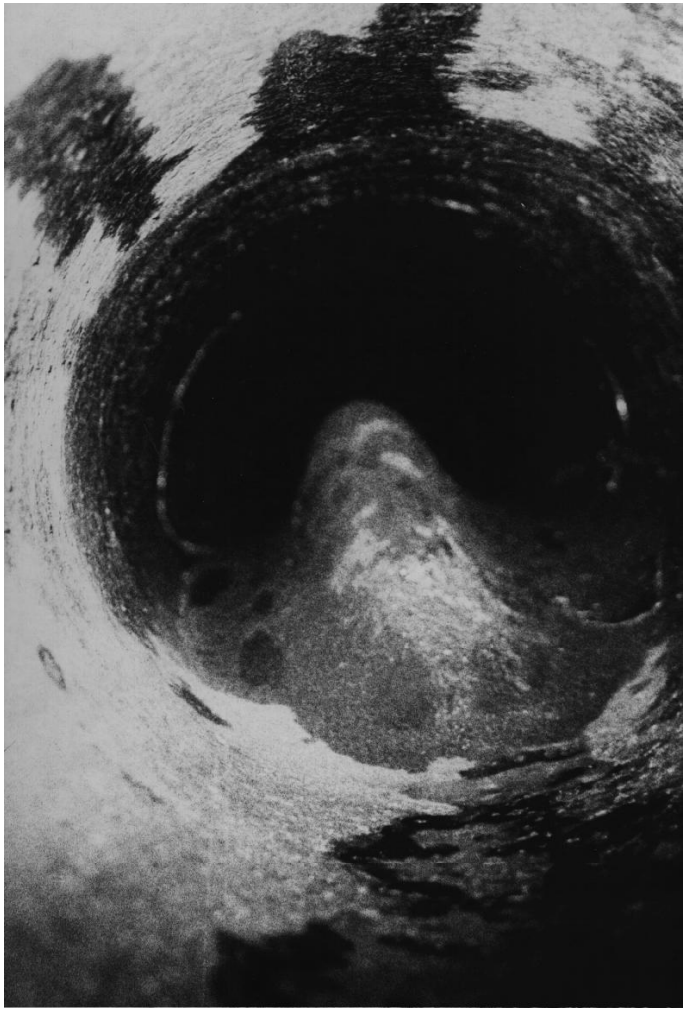

Krýsuvík steam eruption 1999
Rocks and mud thrown 300 m

Krýsuvík
Steam eruption of 1999

Hole where flying rock came down

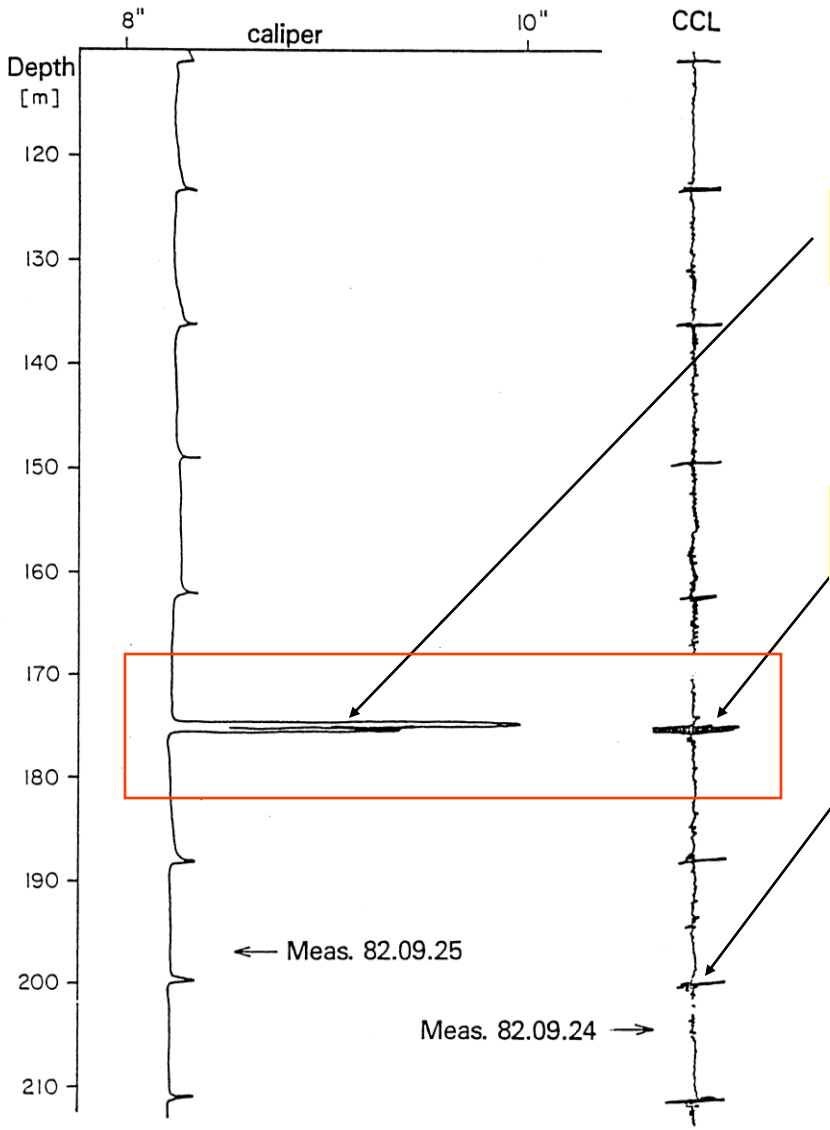
Bjarnaflag after producing lava

Casing collapse – trapped water



A casing collapse in 9 5/8" prod. cas. at 73.5 m depth in well SG-5.
It was removed with a drop-chisel and the well used for another 5 yrs.

Detection by calliper and CCL

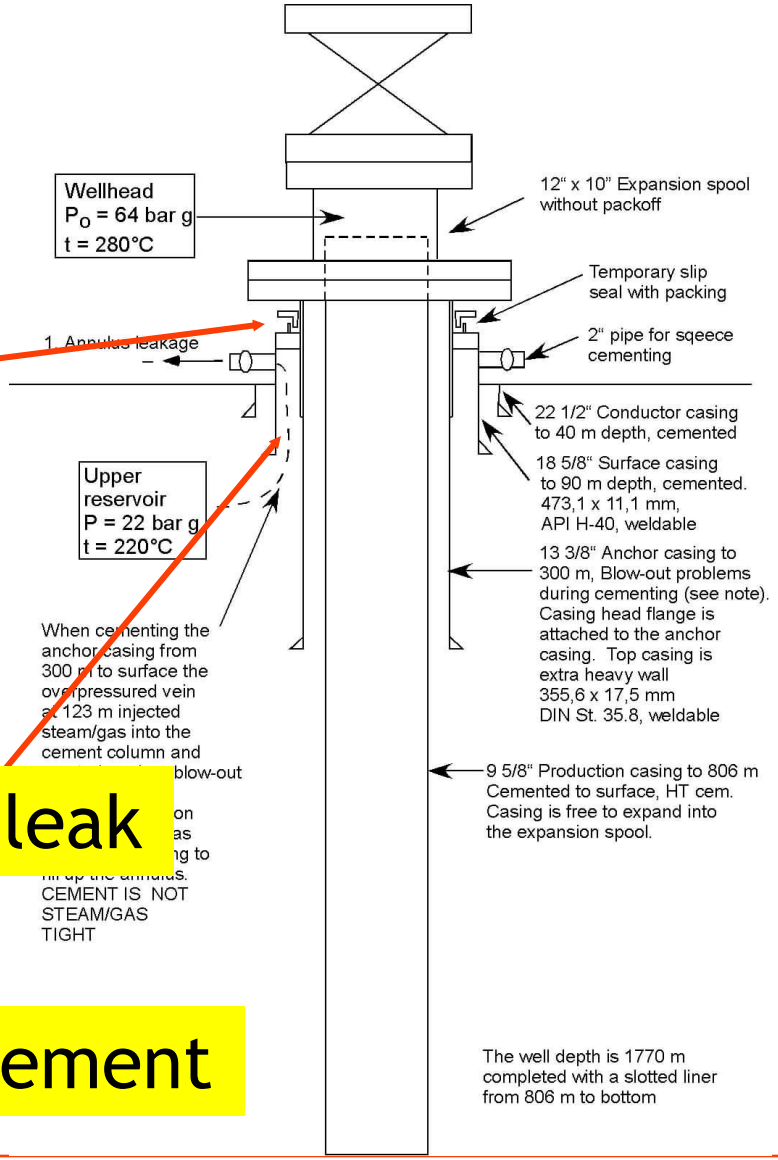


Gap detected by a calliper log

Bad casing connection (coupling)

Normal casing coupling as shown by CCL

Leak through a cemented annulus

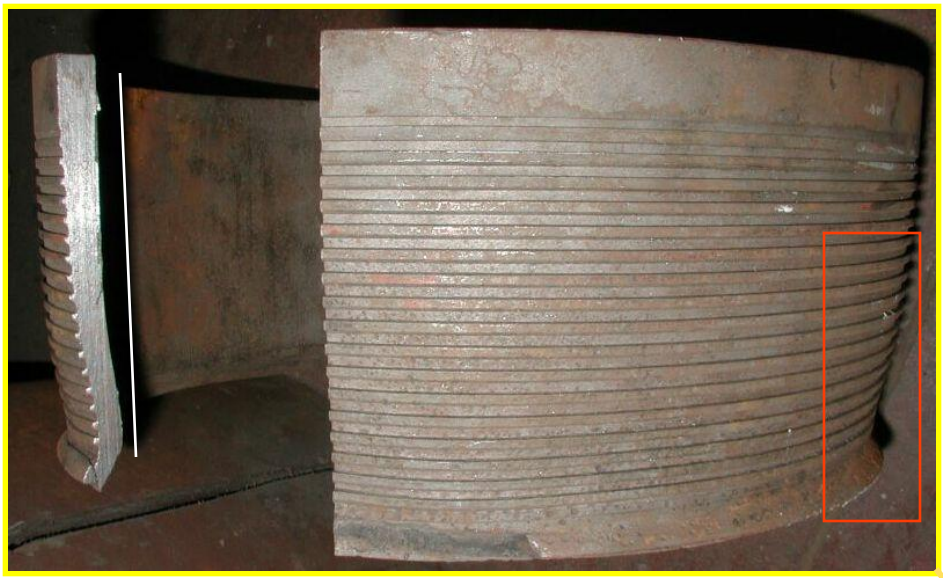


Temporary gland to stop the leak

Path of steam leak through cement

Temporary repair of leak on casing connection @ 11 m

Failed connection

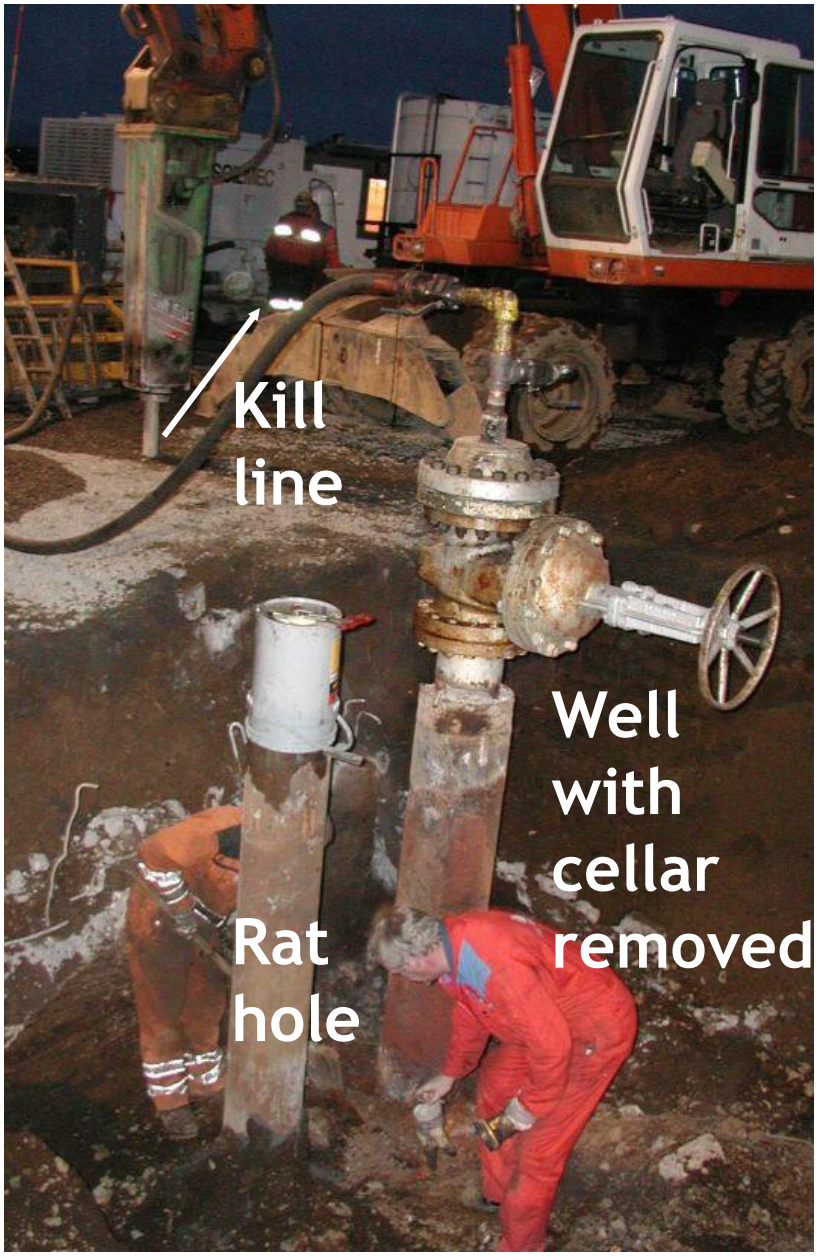


Above:
Buckling of a threaded casing joint.

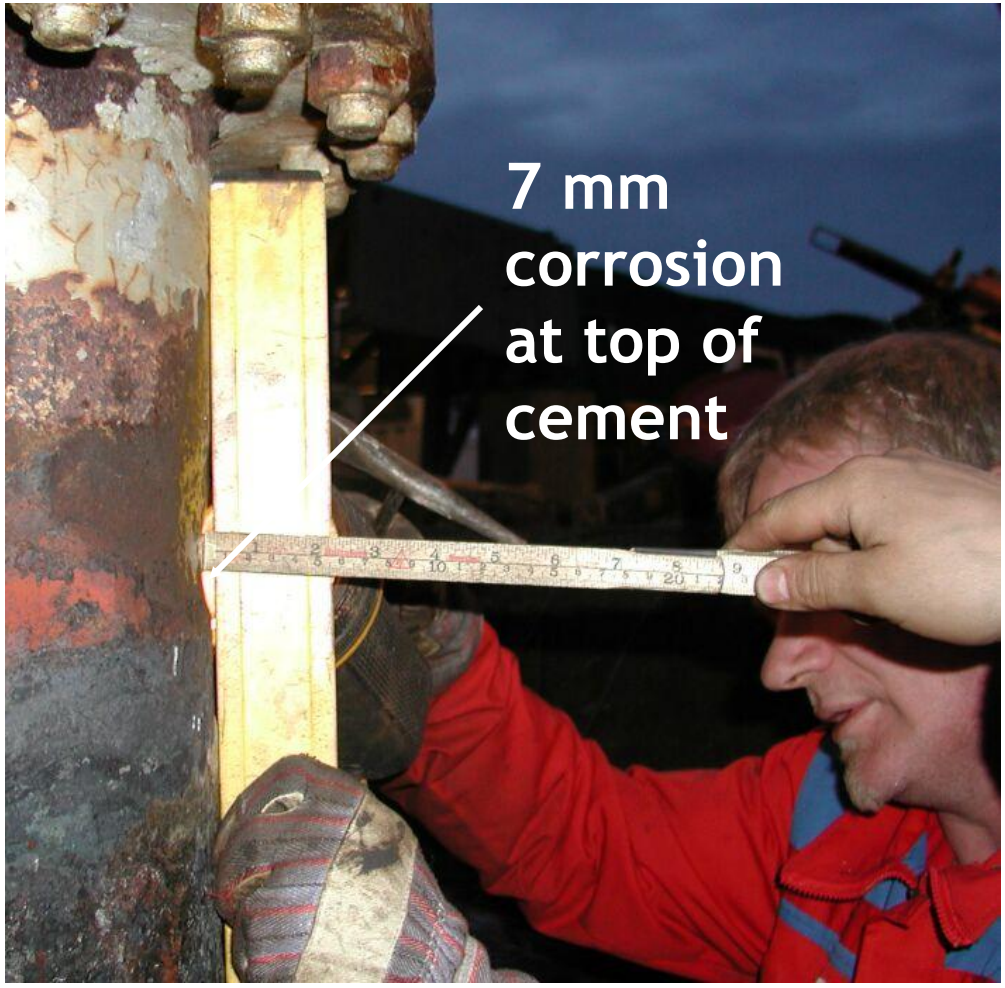
Right:
Excavation to replace the top 11 m of casing to the first coupling.

HT Wellheads

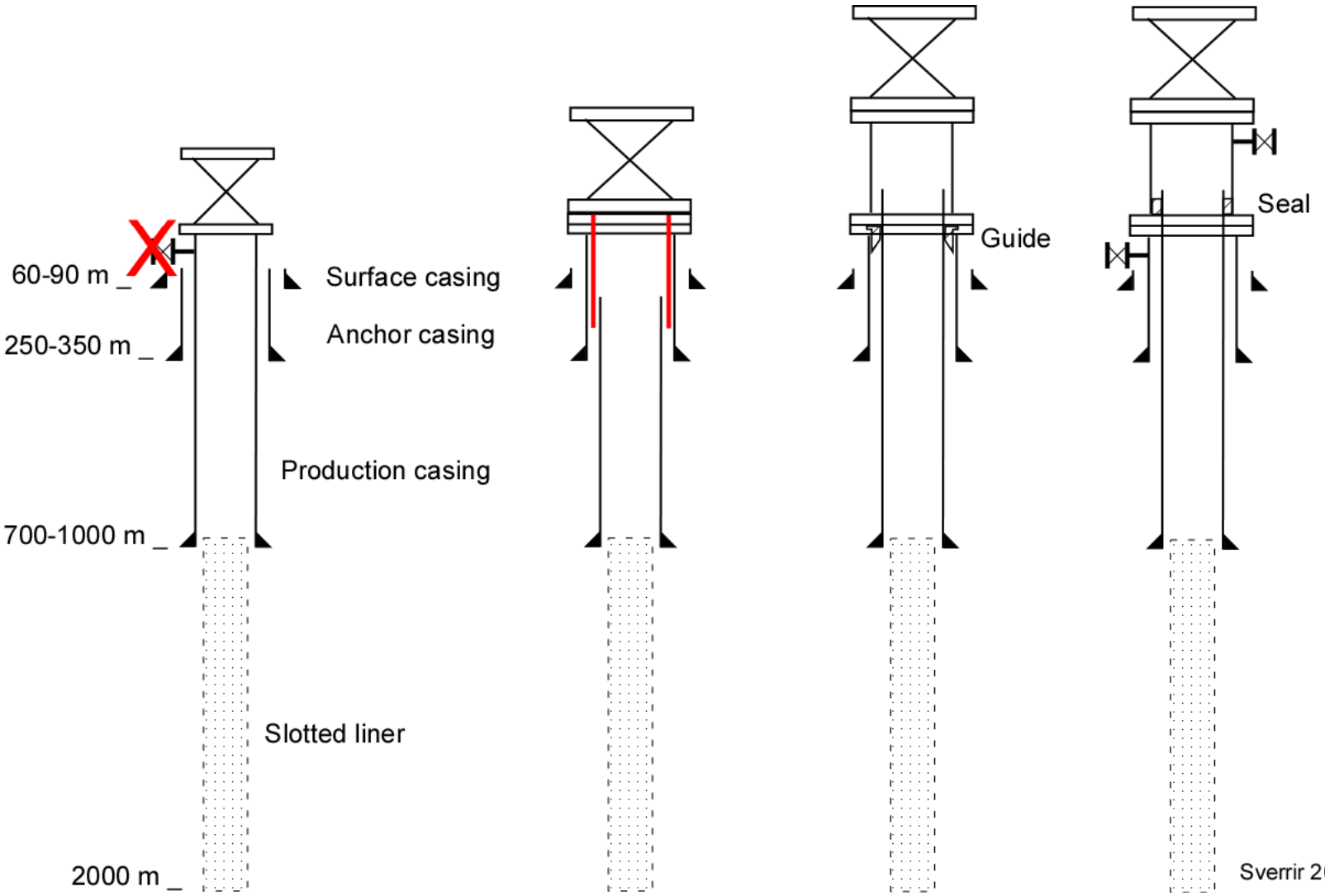
Casing corrosion



Outside corrosion of casing near surface



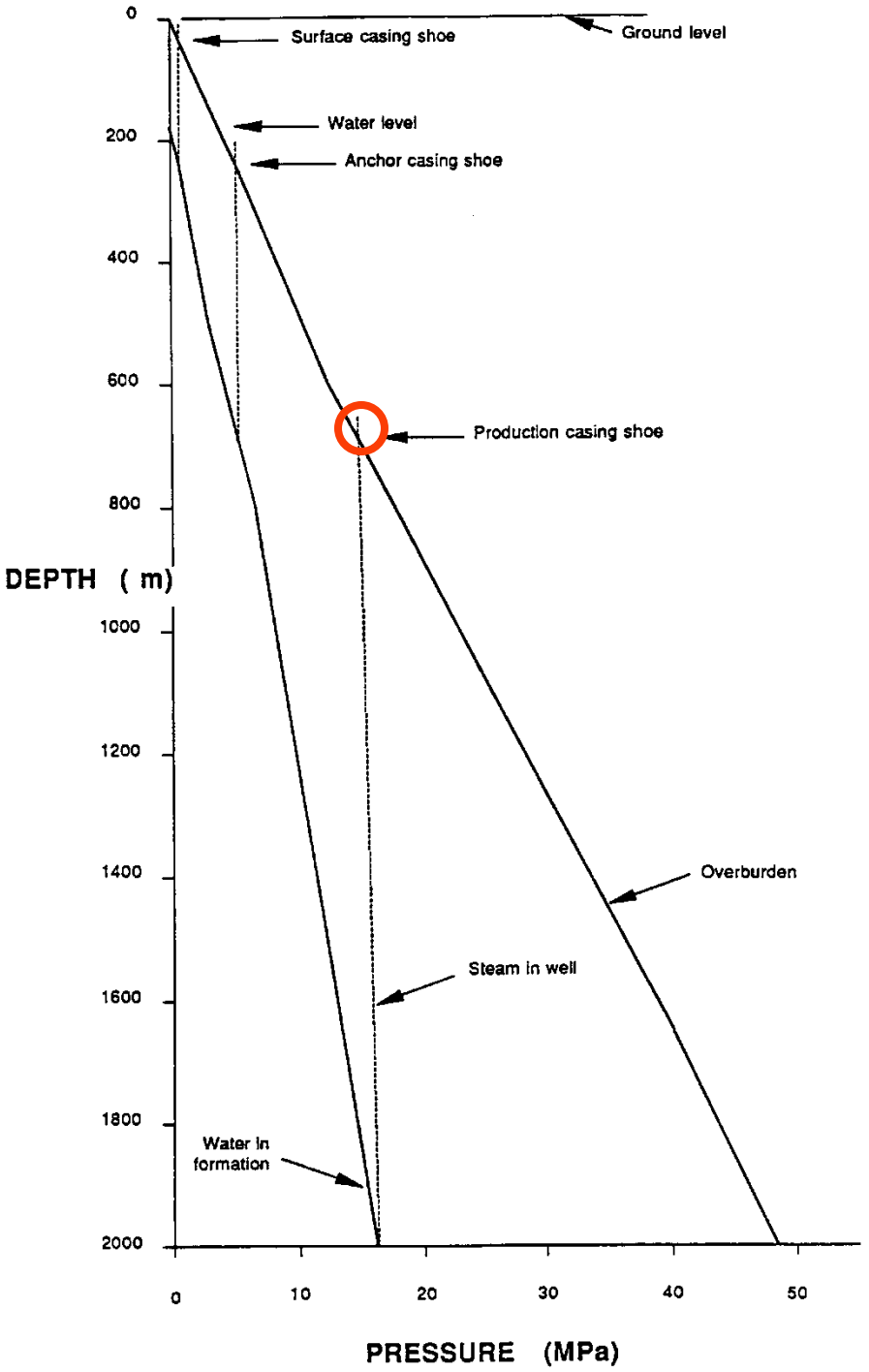
Wellhead evolution in Iceland



Min. cas. depth

Assume boiling point depth curve (BPD). The reservoir pressure is shown as “Water in formation”, and also the “Overburden” pressure.

- Draw a near vertical line from well bottom representing the density profile for saturated steam (“Steam in well”).
- The minimum casing depth is where the steam pressure intersects the “Overburden” pressure.



Conclusions

- Lessons have been learned from past failures
- Still not completely resolved is:
  - Integrity of the casing
  - Cementing procedures and materials
  - How to cope with a steam-cap induced by drawdown
  - Problems of underground blow-outs
  - Sealing of BOP´s during prolonged HT exposure
- In spite of this most HT wells are completed successfully