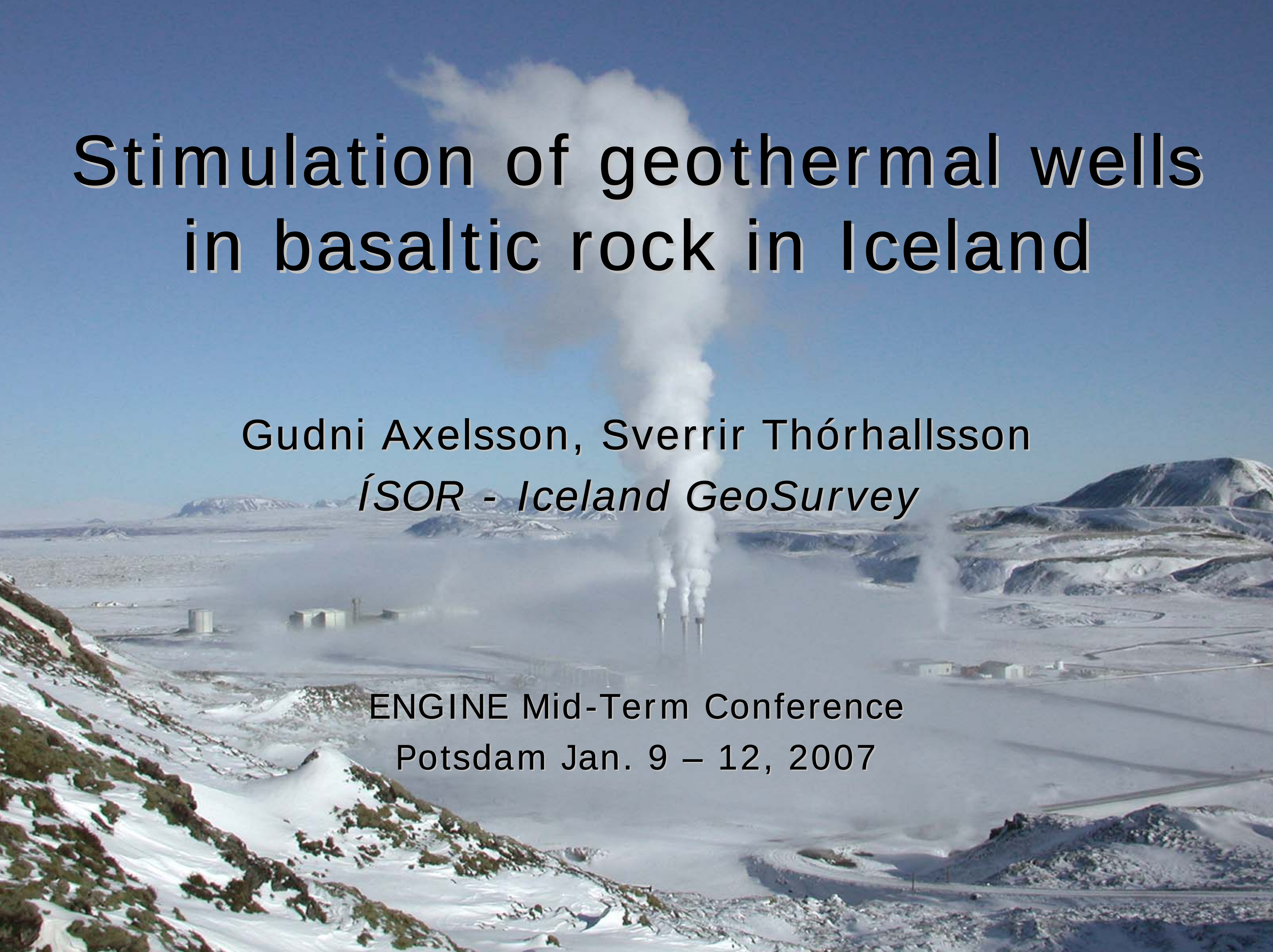

Stimulation of geothermal wells in basaltic rock in Iceland

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ÍSOR - Iceland GeoSurvey

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GEOTHERMAL ENERGY IN ICELAND

- Iceland is geologically young as well as volcanically and tectonically active.
- Abundant geothermal resources.
- High temperature systems are within volcanic zone (heat sources = cooling magma bodies), temperature exceeds 200ºC at 1 km depth. Suitable for electricity production or co-generation.
- Low temperature systems are outside volcanic zone (heat source = convective heat mining in hot fractured crust). Temperature less than 150ºC at 1 km depth. Suitable for direct uses.
- Accounts for more than half of the primary energy supply of the country.

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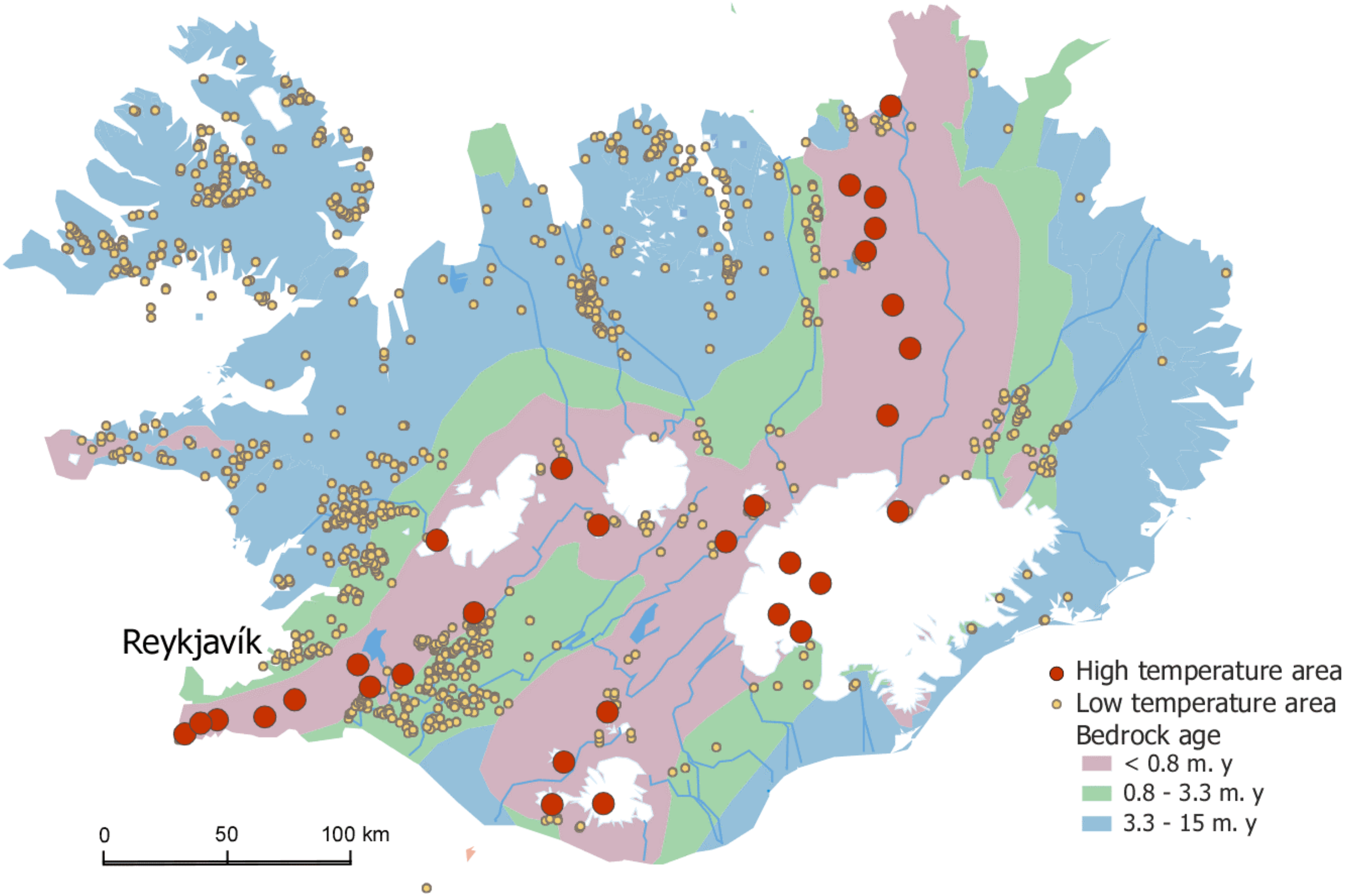
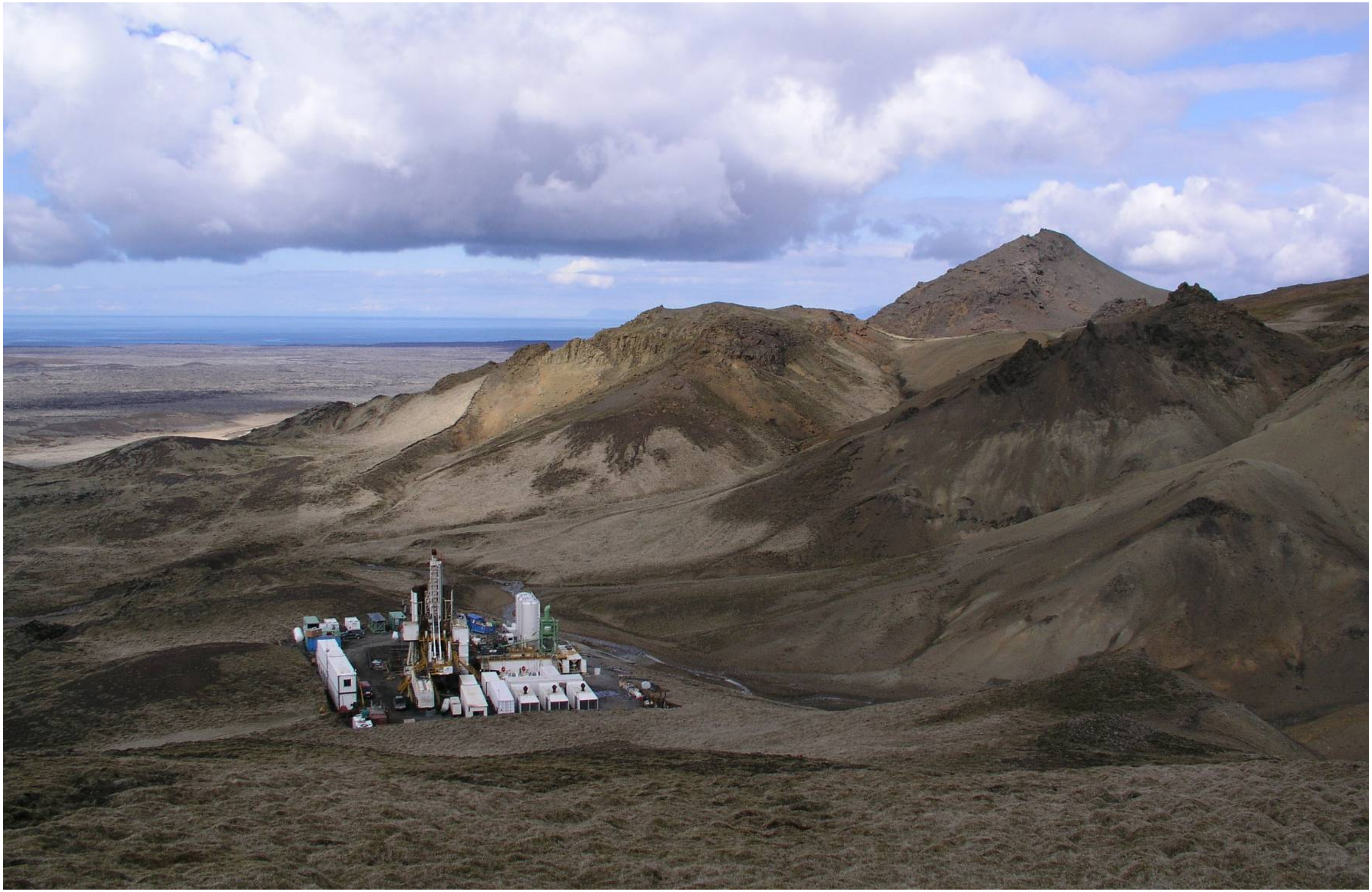


Geological map of Iceland showing low-temperature (yellow dots) and high-temperature (red dots) geothermal areas.

GEOTHERMAL DRILLING IN ICELAND

- Exploration and drilling activity started during the middle of last century.
- Intensive drilling commenced in the 1960's and 1970's.
- About 574 geothermal production wells had been drilled in Iceland at the end of 2004.
- Total combined depth of about 550 km.
- Stimulation operations are commonly an integral part of completion programs, both for high-temperature and low-temperature wells.
- Operations usually conducted at the end of drilling.



Drilling of well TR-02 in the Trölladyngja high-temperature field in SW-Iceland in the spring of 2006.

PURPOSE OF STIMULATION OPERATIONS

To enhance output/productivity of wells, either by improving near-well permeability reduced by the drilling operation itself (feed-zones clogged by drill cuttings or drilling-mud) or to open up hydrological connections to permeable zones not intersected by a well.

STIMULATION METHODS/PROCEDURES

(A) Air-lift aided drilling and air-lift cleaning.

(B) Circulation through drill-string.

(C) High-pressure well-head water injection.

(D) Water injection above, or below, inflatable open-hole packers.

(E) Water injection through double packers.

(F) Intermittent cold water injection and heating.

(G) Acidizing by well-head acid injection or acid injection through packers or coil-tubes.

STIMULATION METHODS CONT.

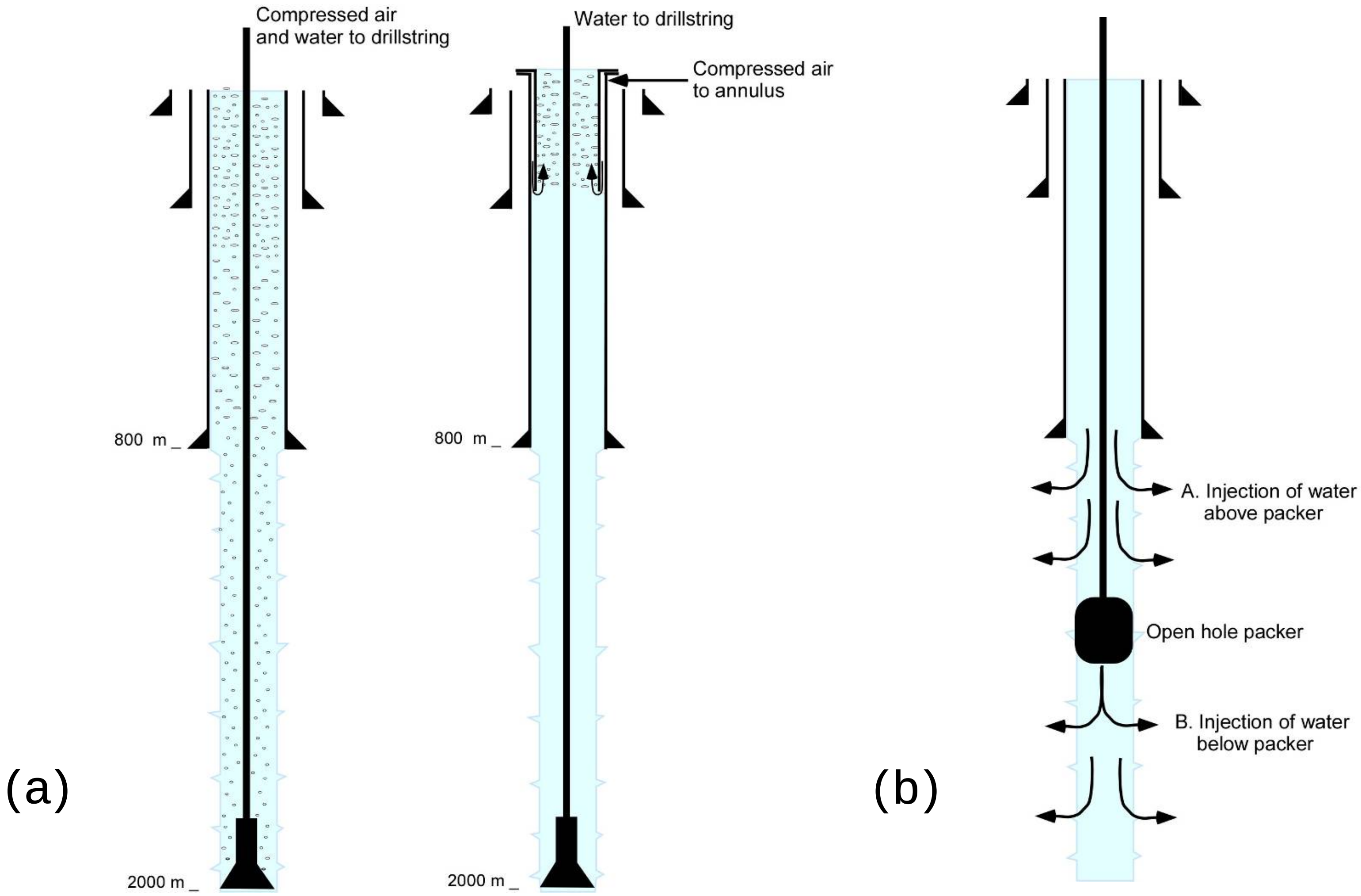
(A) Air-lift aided drilling not a stimulation method per se, but helps preventing feed-zone clogging-up during drilling.

(B) Water circulation helps restore feed-zone permeability reduced during drilling.

(E) Double packers have not been used in Iceland yet, even though they have the potential of being more powerful than single packers.

(G) Acidizing only used to remove calcite scale deposits within wells. Could be used as a stimulation tool by dissolving scaling material in fractures.

Other methods ((C), (D) and (F)) commonly used, described in more detail in the following slides.



Schematic illustration of the setup for (a) air-lift aided drilling and (b) stimulation with an inflatable packer.

Low temperature (LT) stimulation in Iceland

- Air-lift cleaning + injection of cold water at high pressures, either through the well-head or above or below a packer placed at a specific depth. By using inflatable packers the stimulation is focused on specific intervals in a well rather than the whole open part of the well.
- Pressures applied can be of the order of a few MPa, to some tens of MPa.
- Water flow-rates determined by capacity of equipment used and injectivity of well.
- Started as early as 1970.
- Usually lasts a few days.

LT-STIMULATION EXAMPLE 1 – MOSFELLSSVEIT AREA

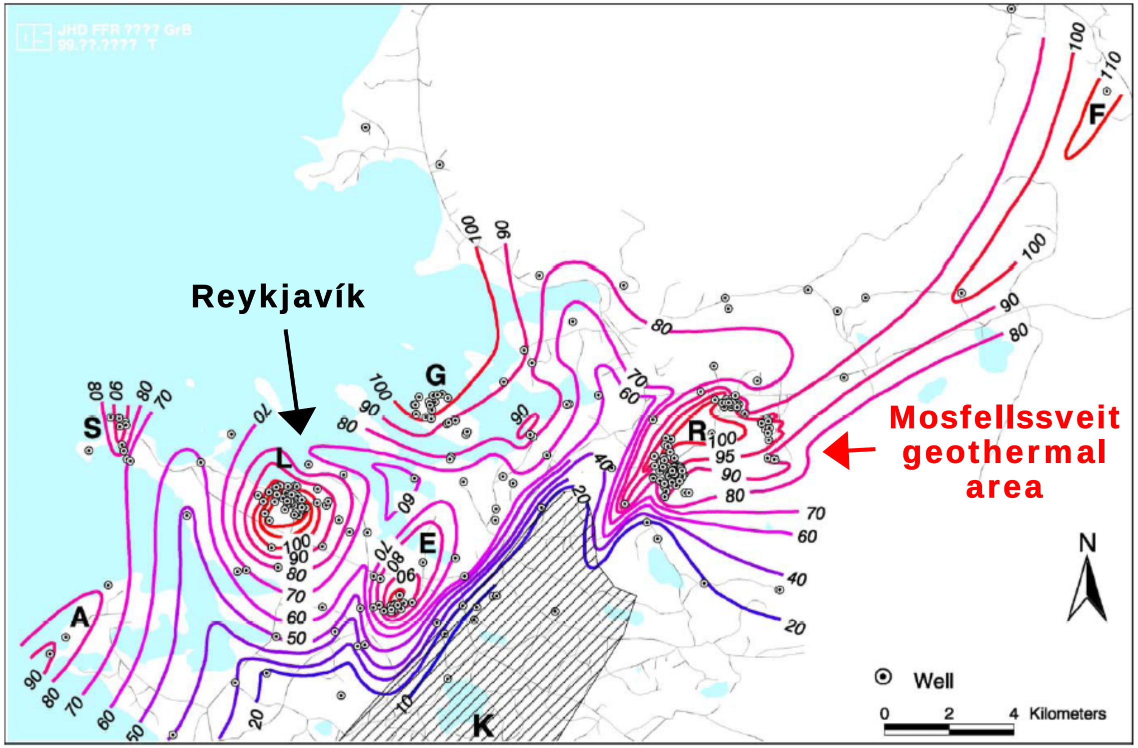
– Utilized for space heating in Reykjavík since 1944.

– Redeveloped during 1970's by drilling 37 new wells.

– All stimulated by open-hole packers.

– Injection rates 15 - 100 l/s.

– Feed-zone pressures up to 150 bar.



Temperature at 500 m depth around Reykjavík. Also shown is the location of the Mosfellssveit area.

LT-STIMULATION EXAMPLE 1 – MOSFELLSSVEIT AREA

Stimulation results:

(i) By comparing final productivity to productivity before stimulation operations started the productivity was estimated to have improved by a factor of 30-40. Mostly due to re-opening of feed-zones clogged during drilling.

(ii) By comparing final productivity to cumulative circulation losses during drilling the productivity was estimated to have increased as much as three-fold. Due to permeability enhancement (see later).

Redevelopment of the Mosfellssveit geothermal field, both drilling and stimulation, resulted in production capacity increasing from 300 l/s in 1970 to 1500 l/s in 1977.

LT-STIMULATION EXAMPLE 2 – SELTJARNARNES AREA

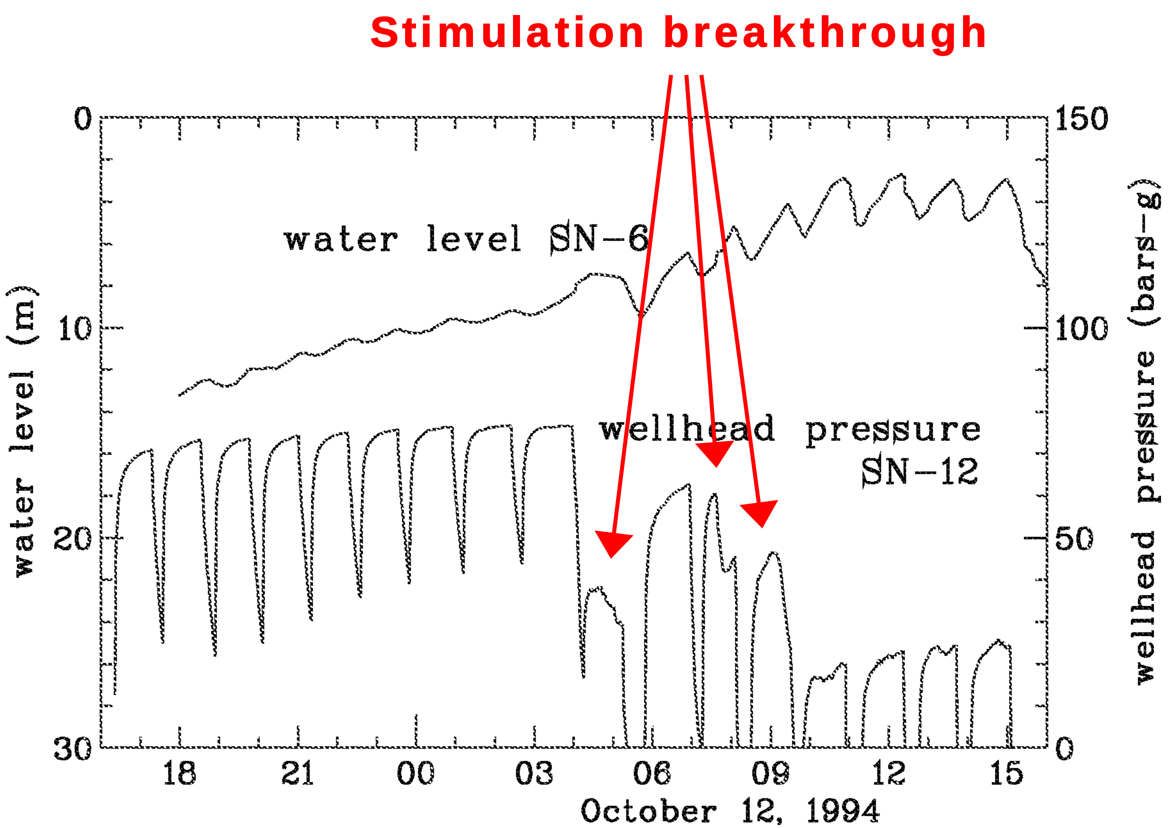
– Well SN-12 drilled to a depth of 2714 m in 1994.

–Almost non-productive at end of drilling.

–Stimulated by well-head injection and injection below a packer at 1412 m depth.

–Sudden stimulation after 12 hrs.

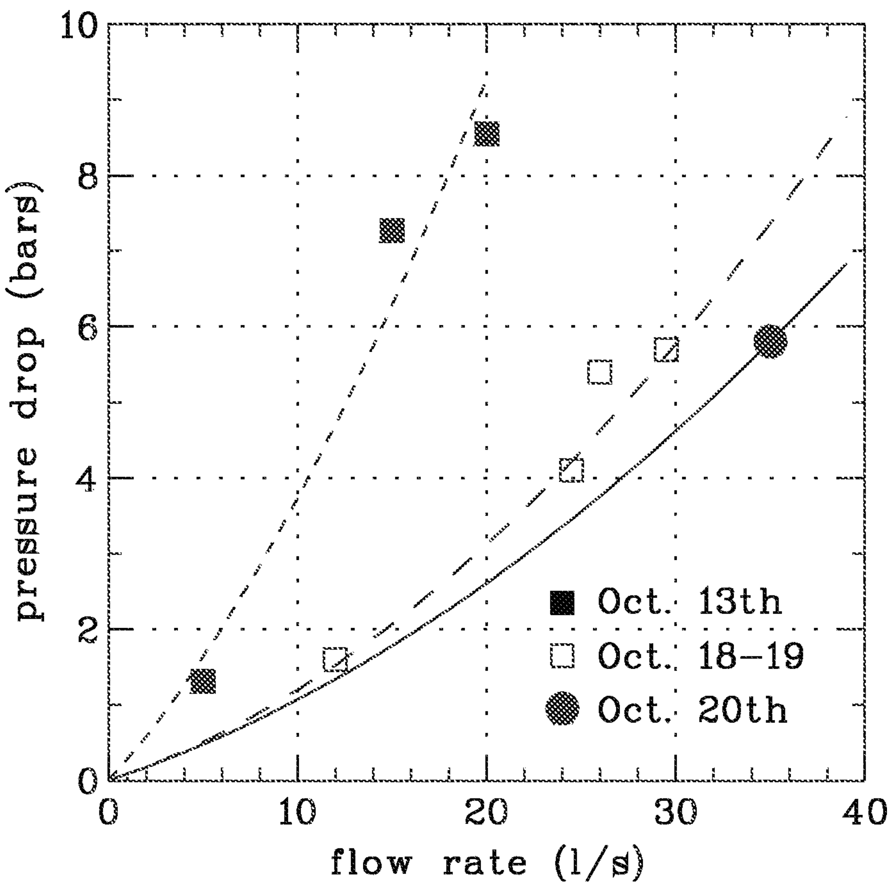
–Further stimulation as program continued.



Water level in observation well SN-6 and well-head pressure of well SN-12 during wellhead injection phase.

LT-STIMULATION EXAMPLE 2 – SELTJARNARNES AREA

- Well SN-12 eventually produced about 35 l/s at a drawdown of 60 m.
- Stimulation increased the yield of the well by a factor of nearly 60.
- Believed that some previously closed fractures, or interbed contacts, reopened connecting well SN-12 to the main fracture system of the geothermal reservoir.



Results of production testing of well SN-12 during the stimulation operations showing the gradual improvement.

High temperature (HT) stimulation in Iceland

- Mainly through intermittent cold water injection, with periods of thermal recovery in-between the injection periods.
- Aimed at causing cracking through thermal shocking.
- Packers or high well-head pressures seldom used.
- Drills string kept in well, or drill pipes (without drill-bit or motor) placed near bottom.
- Operations last some days.
- Started around 1980.
- Used in all main HT-fields; Krafla, Svartsengi, Nesja-vellir, Hellisheidi and Reykjanes.

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HT-STIMULATION EXAMPLE 1 – KRAFLA

- The Krafla 60 MW_e geothermal power plant in NE-Iceland has been in operation since 1977. Volcanic system at 210 – 340°C.
- Example: well KJ-14 drilled to a depth of 2100 m in 1980. Circulation losses increased from 4–8 l/s to 40 l/s during stimulation.
- Stimulation successfully applied to other Krafla wells.
- Flores *et al.* (2005) show (partly based on Krafla data) that thermal fracturing is potentially the most attractive, but least understood, HT-stimulation technique.

HT-STIMULATION EXAMPLE 2 – HENGILL REGION

- Intense drilling has been ongoing in the Hengill volcanic system in SW-Iceland during the last decades. Three known geothermal fields; Nesjavellir, Hellisheidi and Hveragerdi.
- Recently stimulation procedures have been modified by continuing stimulation after drill rigs have been removed, often for a few weeks.
- Example: well HE-8, drilled to a depth 2800 m in 2003. Injectivity increased from 1-2 (kg/s)/bar to 6-7 (kg/s)/bar.
- Similar results for other wells.
- Three recent cases of seismic activity being generated by drilling/stimulation (see presentation by Grímur Björnsson).

RESULTS OF STIMULATION OPERATIONS IN ICELAND

- Stimulation success often partly due to the re-opening of feed-zones blocked by drill cuttings during drilling (reservoir pressure lower than well pressure).
- Additional improvement by a factor of 2-3 often seen. Attributed to the creation of new hydrological connections to permeable structures through:

  (1) removal of scale-deposits in fractures,

  (2) opening of existing fractures (hydraulic/thermal stresses)

  (3) or creation of new ones by hydraulic or thermal stresses.

RESULTS OF STIMULATION OPERATIONS IN ICELAND (CONT.)

- Greater LT stimulation success realized in younger Quaternary formations than in older Tertiary rocks. Crustal stress conditions certain to play a key role.
- Not clear what geological conditions are most favourable for HT stimulations.
- Clear correspondence between injectivity (end of stimulation) and productivity of HT wells does not exist (see next slide).

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Geothermal production wells in the Reykjanes HT field in SW-Iceland.

Well	Depth (m)	Temp. (°C)	II_1	II_2	PI
RN-10	2050	310	-	6.6	2.3
RN-11	2250	295	-	>10	10
RN-12	2510	290	-	8-9	20-40
RN-13	2460	290	-	4-5	1-2
RN-14	2310	290	6	6-7	-
RN-15	2510	280	3.5	4	1
RN-16	2630	220	1.2	2	-
RN-18	1820	>285	5	5.4	1.5
RN-19	2250	250-260	5	5	3
RN-21	1710	275	6	13	6
RN-22	1680	305	10	10	15
RN-23	1920	305	-	38-48	50
RN-24	2110	>275	-	10-20	38

II1 = injectivity index at the end of drilling
II2 = injectivity index at the end of stimulation operations
PI = productivity index based on production testing

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SEISMIC MONITORING IN ICELAND

Has been implemented during 3 reinjection projects:

(1) Laugaland LT-field during 1997-1999, automatic network of 6 ultra-sensitive stations, not a single event in spite of almost 30 bar injection pressure.

(2) Svartsengi HT-field in 1993, network of portable seismographs, no activity detected.

(3) Krafla HT-field in 2005, 20 station array with state-of-the-art interpretation, low activity – some related to injection.

Seismic monitoring is generally not applied during geothermal stimulation operations in Iceland. Yet, seismic activity has been detected by national seismic grid in association with long-term stimulation operations in the Hengill region, as mentioned.

STIMULATION TECHNIQUES IN ICELAND – CONCLUSIONS:

- High-pressure packer injection in low-temperature wells not as common as 2-3 decades ago, partly because of air-lift aided drilling. Method still has great potential (double packers?).
- High-temperature well stimulation through cyclic cooling and thermal shocking has proven to be effective, especially when stimulation period can be extended for several weeks after drill rig has been removed.
- Seismic monitoring should be more commonly applied during long stimulation operations, provides highly valuable resource information.
- Also reservoir monitoring (such as interference monitoring).

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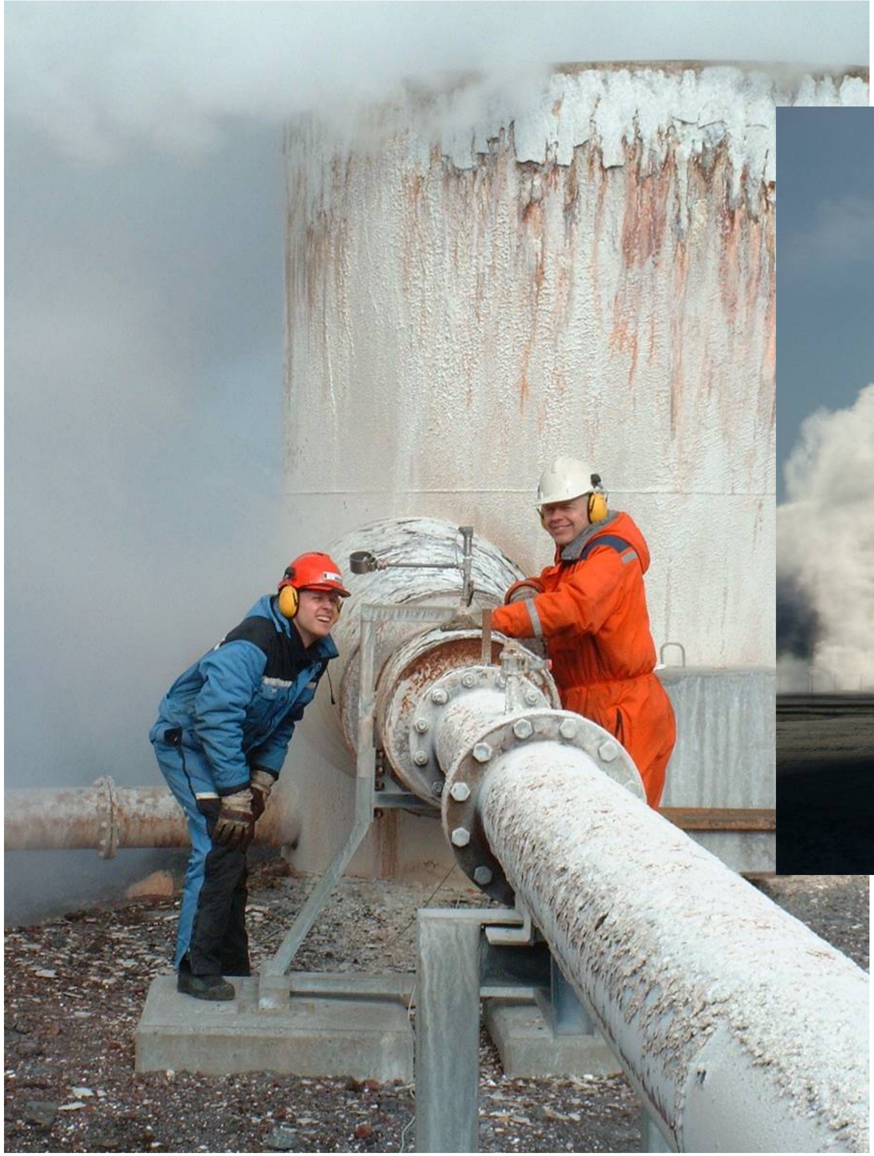

THANK YOU!