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STUDIUM GENERALE UNIVERSITY TWENTE

INTRODUCTION TO THE SALT SOLUTION MINING PROCESS AND CAVERN FORMATION

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SALT CAVERNS

Origin of salt layers in the subsurface
Geology
Salt properties and behavior
Mining technique
Cavern stability
Simple rock mechanics
    Shape & size determine stability
Stabilizing options
Conclusions
References

WHO AM I?

- Dr. Robert Hack

- PhD University Delft: Engineering Geology
- MSc Engineering Geology (University Delft) & Applied Geophysics (minor, University Utrecht)
- BSc Geology (University Leiden)

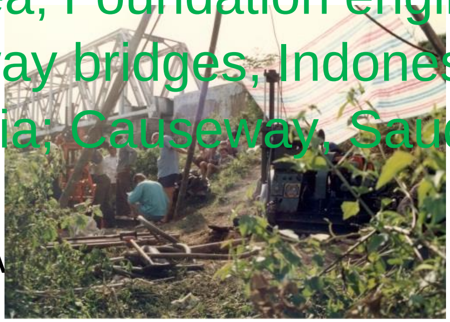
WHO AM I?

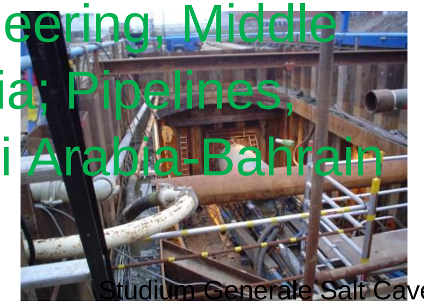
Track record:

- ITC/University Twente
- Grabowski & Poort Consultants
- Copper mines Zambia
- Ballast Nedam Contractors
- Boskalis Contractors

WHO AM I ? - WORK EXPERIENCE

- Member Commissie voor de MER Stabilisatie Salt Cavernes
- CO_2 capture and sequestration (CSS)
- Subsurface Structure Vision (STRONG), The Netherlands
- Environmental impact oil & gas industry, Netherlands
- Tunnel design & site investigation, Ukraine; Underground mining, Zambia; Slope design, South-Korea; Foundation engineering, Middle East; Railway bridges, Indonesia; Pipelines, Saudi Arabia; Causeway, Saudi Arabia-Bahrain





COMMITTEE FOR THE ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

Committee for the Environmental Impact Assessment (EIA) (Commissie voor de MER, Utrecht, The Netherlands)

- Hack is member of the Committee for the EIA for the stabilization of the salt caverns.
- The EAI report for the stabilization has not been submitted to the Committee for the EIA and the assessment of the EIA has not yet taken place.

Hence, the EIA assessment and the data thereof are not part of this presentation.

WHY ARE THERE SALT LAYERS?

Natural salt precipitated from (sea) water

Under relatively high temperatures in a dry climate:

- Salt concentration in water exceeds the maximum possible concentration when water evaporates while salt remains

Nowadays a fairly seldom feature

but, in the geological past has happened over large parts of the Earth

PRESENT DAY SALT PRECIPITATION

DIFFERENT SALTS

With increasing evaporation and increasing concentrations of minerals, a sequence of minerals precipitates from water:

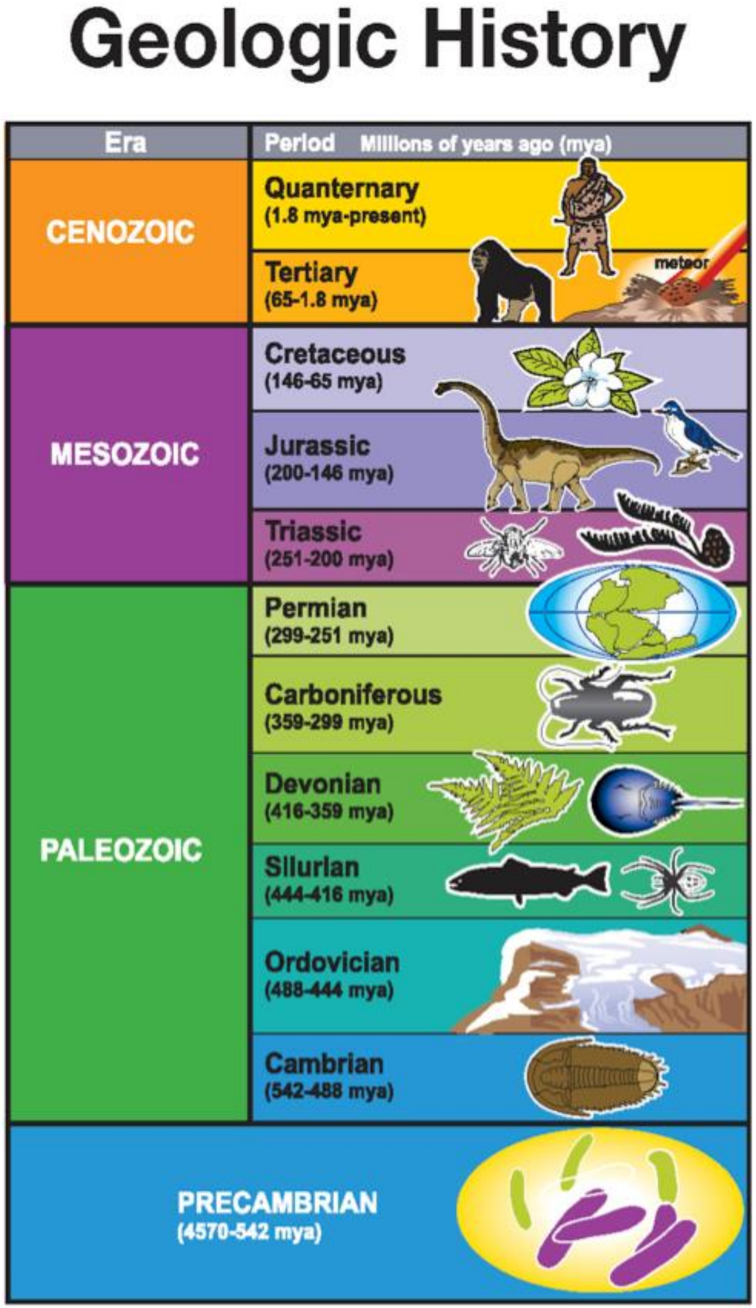
- (≈ 50% water evaporated) Carbonates (minerals with CO_3 group) among others limestone (in Dutch "kalksteen") and dolomite
- (≈ 80% evaporated) Gypsum ($CaSO_4 \cdot 2H_2O$) (in Dutch: "gips")
- Anhydrite ($CaSO_4$)
- (≈ 90% evaporated) Halite (NaCl) ("rock salt" in Dutch "keuken/tafel zout")
- Silvite (KCl)
- and a series of magesium salts: Carnallite ($KMgCl_3 \cdot 6(H_2O)$), Langbeinite ($K_2Mg_2(SO_4)_3$), Polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$), Kainite ($KMg(SO_4)Cl \cdot 3H_2O$)), Kieserite ($MgSO_4 \cdot H_2O$)

GEOLOGY

Geological times are long:

Main salt precipitation in The Netherlands happened between some 300 and 200 Million years ago (Permian, Triassic & Jurassic epochs)

The first dinosaurs walked around in the Triassic became extinct at the end of the Cretaceous, and humans where very far away in the future



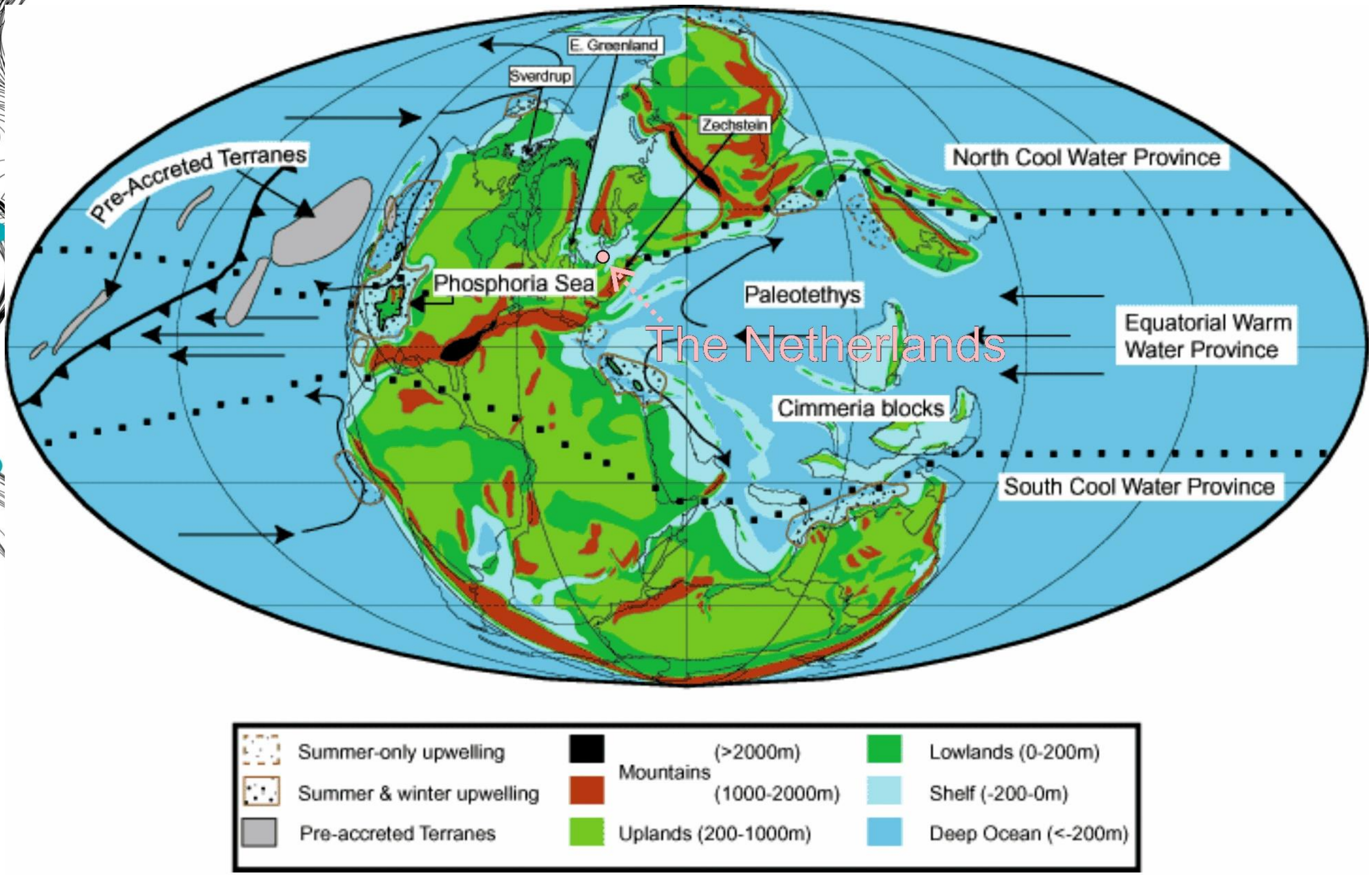
(from: http://dev.buglady.org/wp-content/uploads/2012/03/Untitled.png)

SALT DEPOSITS IN THE NETHERLANDS

In the Dutch subsurface salt deposits are known in the following geological layers:

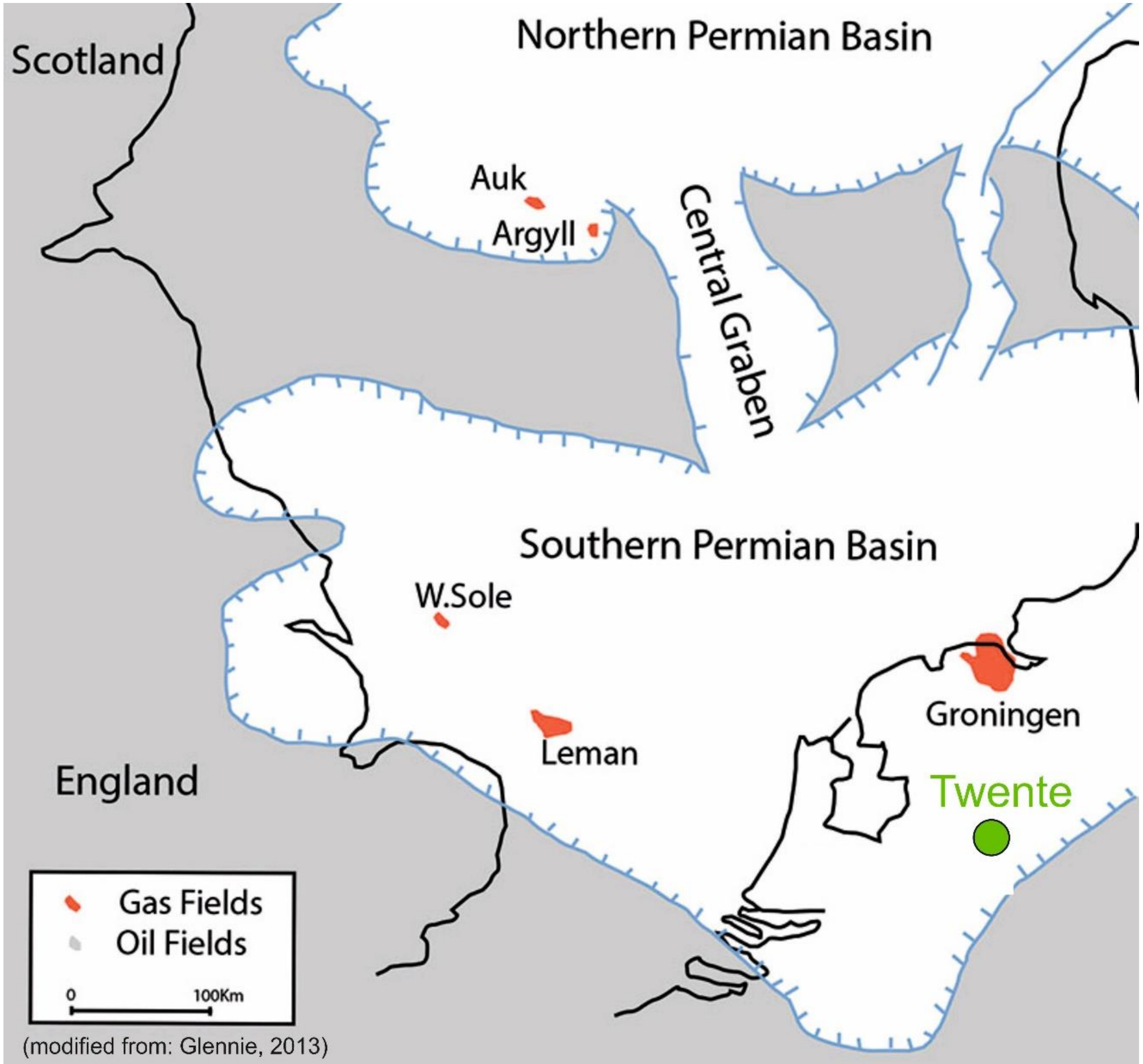
▪ Late Jurassic	
▪ Late Triassic	Keuper
▪ Middle Triassic	Musschelkalk
▪ Early Triassic	Röt (salt exploitation Twente)
▪ Late Permian	Zechstein
▪ Early Permian	Rotliegend

THE NETHERLANDS IN PERMIAN (ZECHSTEIN) EPOCH



(modified from: http://soundwaves.usgs.gov/2004/02/permian-earth.gif)

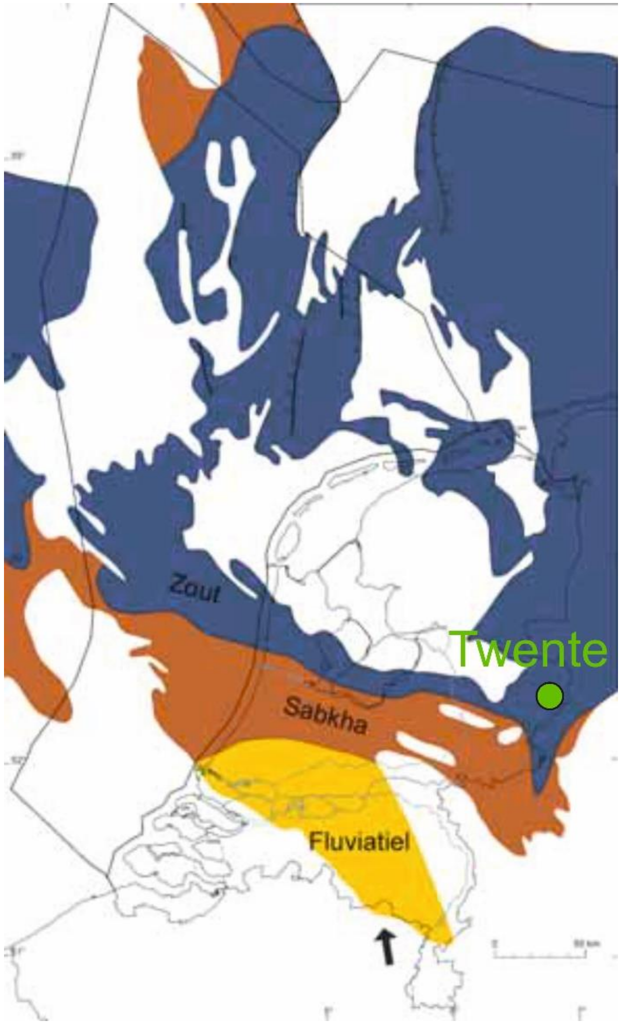
TWENTE IN ZECHSTEIN



TWENTE IN EARLY/MIDDLE TRIASSIC

Salt deposition in early middle Triassic salt deposits

Röt formation (salt exploitation Twente)



(from: Geluk, 2010)

PROPERTIES OF SALT LAYERS (1)

Two remarkable properties of salt deposits:

1. Salt layers have a very dense and tight structure when formed in crystal structure on surface, but:
   - crystals are virtually not compacted under pressure, while
   - other sediments such as sand and clay are compacted at larger depth

   Hence:

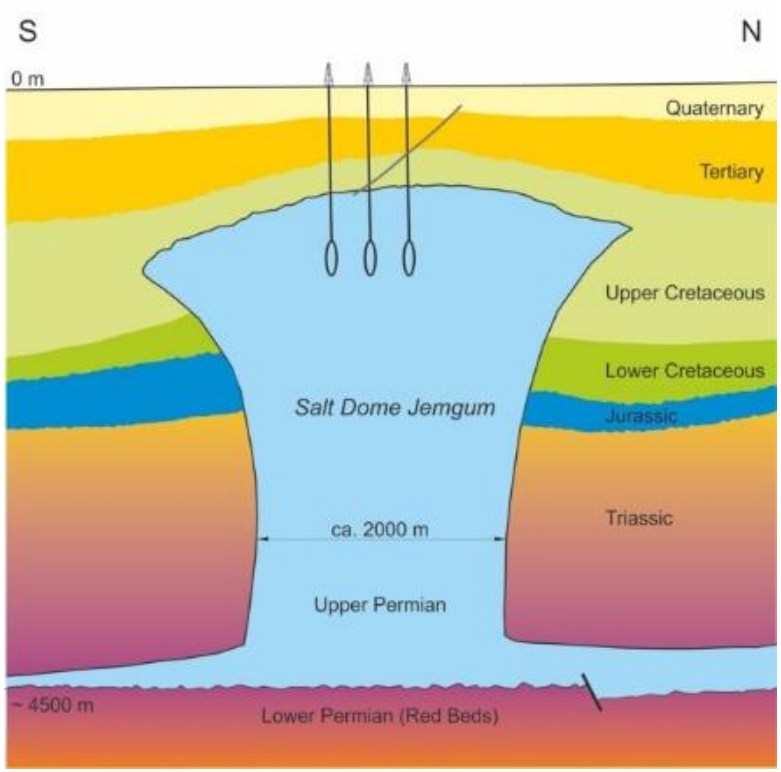
   salt is relatively heavy-weighted at earth surface, but relatively light at larger depth compared to other sediments

2. Salt is very viscous under higher temperatures and pressure

PROPERTIES OF SALT LAYERS (2)

The weight arrangement and viscous behavior cause that salt layers easily deform in geological times:

For example forming of salt domes



(from: http://www.kbbnet.de/en/technical-fields-of-activity/underground/geology/)

PROPERTIES OF SALT LAYERS (3)

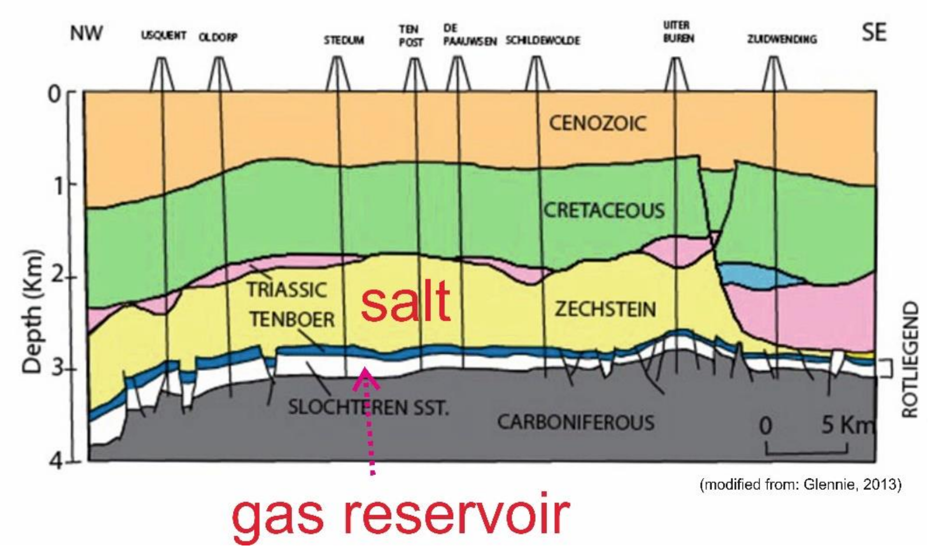
Permeability:

Salt is virtually impermeable for oil and gas

Salt layers have been the seal ("cap rock") for natural oil & gas reservoirs for many 10's to 100's millions of years

(Without the salt layer the oil & gas would in many cases have leaked to surface a long time ago)

Groningen gas field



(modified from: Glennie, 2013)

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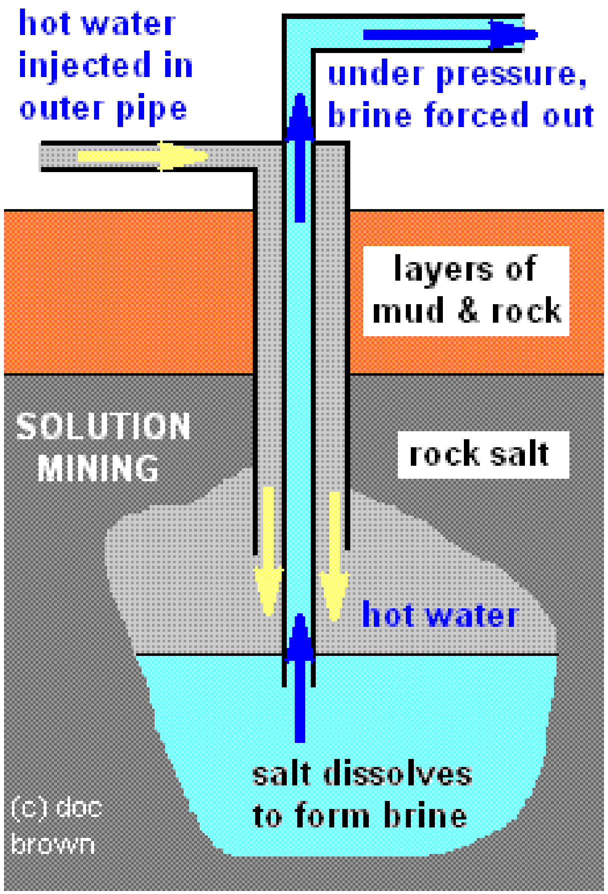
SOLUTION MINING

Salt can be mined by solution mining:

- Hot water is pumped into the salt,
- the water dissolves the salt, and
- the water with salt in solution (the "brine" in Dutch "pekel") flows back to surface

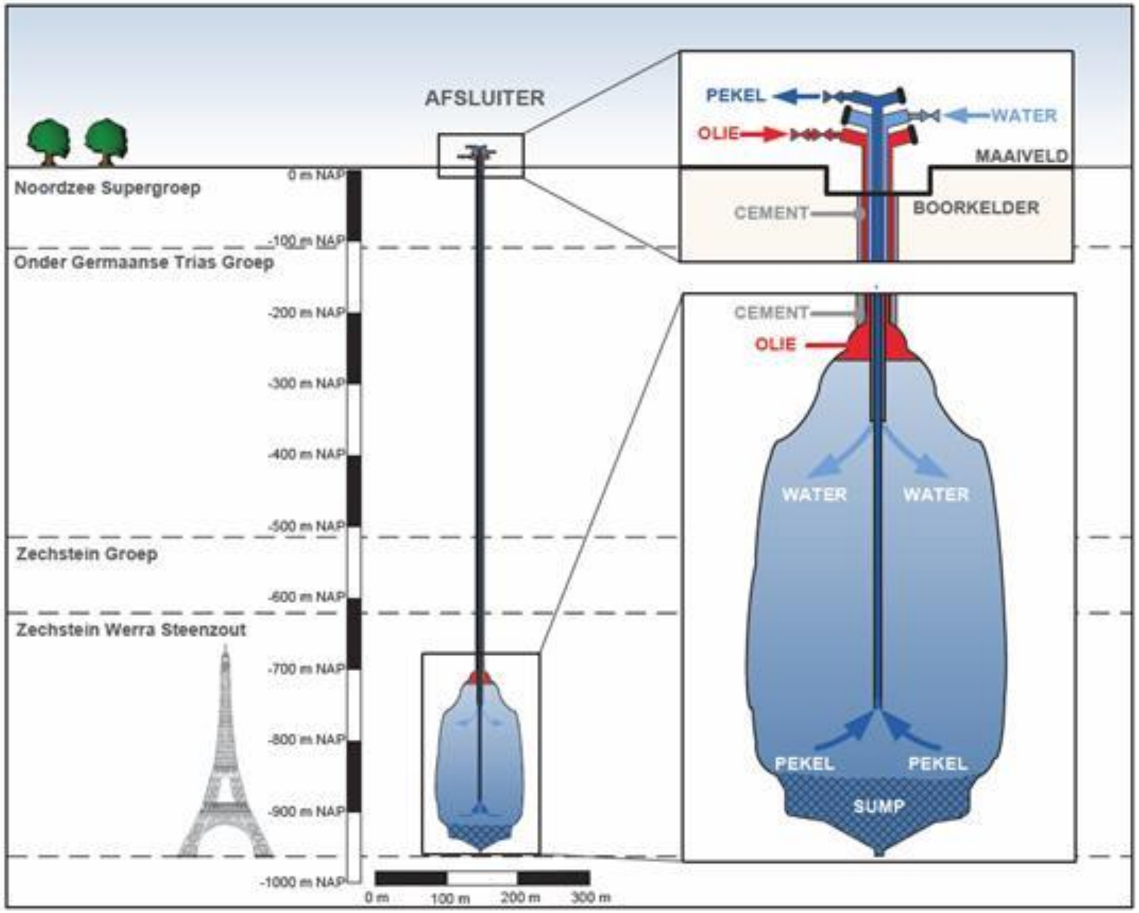
- Remaining an underground opening:
  a salt "cavern"



(from: http://www.docbrown.info/page03/The_HalogensSalt.htm)

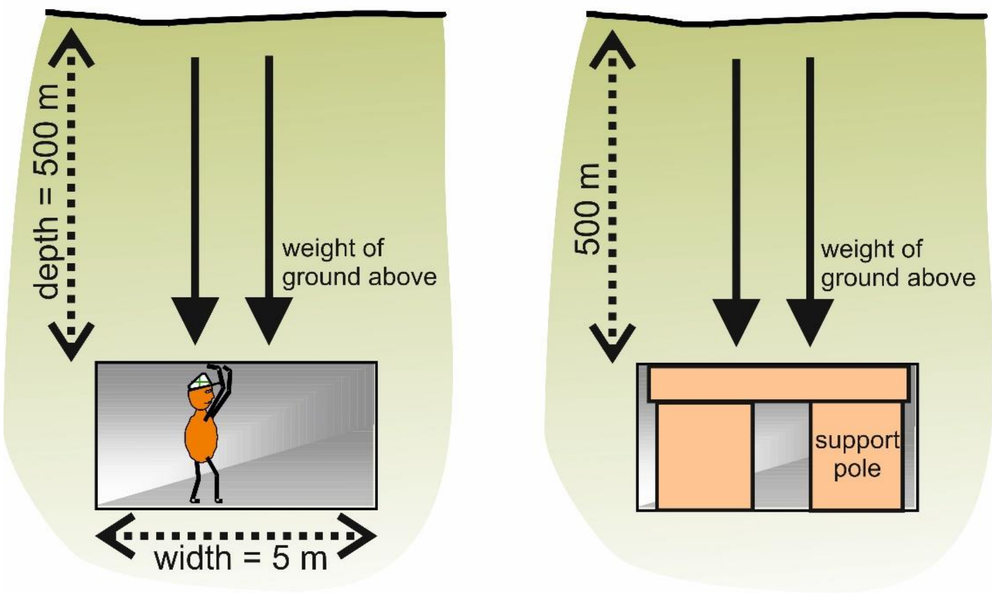
SOLUTION MINING AS DONE BY AKZO IN TWENTE

Often an oil cover (blanket) is used to protect the salt at the connection with the pipes and to be able to direct the form of the cavern



(from: https://www.akzonobel.com/hengelo/projecten/zoutwinning_haaksbergen/zoutwinningproces/)

STABILITY OF A SALT CAVERN (1)



Theoretical case:

5 m wide tunnel in salt at 500 m depth:

Weight of ground above per meter length of tunnel:
500 m (depth) x 1 m (length) x
25 kN/m^3 (weight of ground per m^3) x
5 m (wide)
≈ 60 MN per meter tunnel length

Hence: each support pole has to carry 30 MN (= 3,000,000 kg ≈ 3,000 cars !!!!!!!)

Strength of good concrete is about 20 MN/m^2
Hence: pole thickness of concrete poles has to be 1.5 m

Thus of this theoretical tunnel of 5 m wide, 3 m of the width would have to be filled with concrete !!!

......but there are plenty tunnels at 500 m depth without support;

...how is that then possible ???

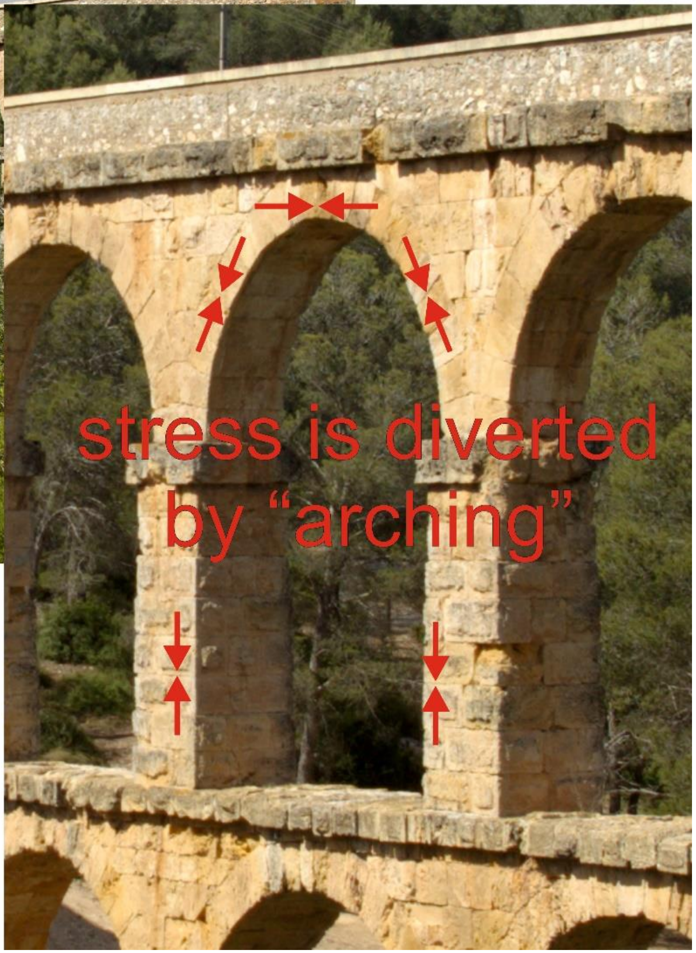
STABILITY OF A SALT CAVERN (2)

For any opening in the subsurface:

The ground carries itself by so-called “arching”

A principle already used long time ago

STABILITY OF A SALT CAVERN (3)



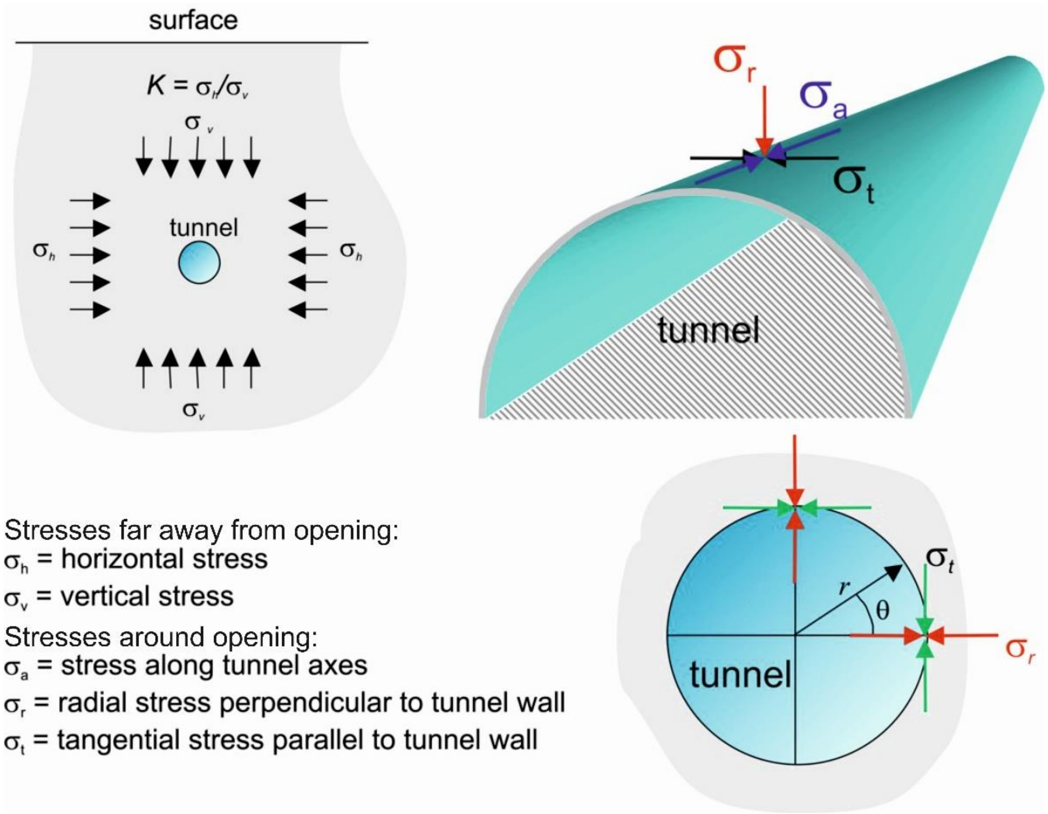
A bridge made by loose rock blocks with (virtually) no cement in between is stable because of 'arching'; all stresses between the blocks are in compression, indicated by the red arrows on the right

(2,000 year old Roman aqueduct 'Pont del Diable', near City of Tarragona, Spain; photo: Arnoldus, 2014).

STABILITY OF A SALT CAVERN (4)

Stress around an opening in the subsurface diverts in a tangential stress (parallel to the wall) and a radial stress (perpendicular to the wall) (“arching”).

If stable and no support: The radial stress = 0 at wall, otherwise the wall would move inward.



FAILURE OF SALT CAVERN (1)

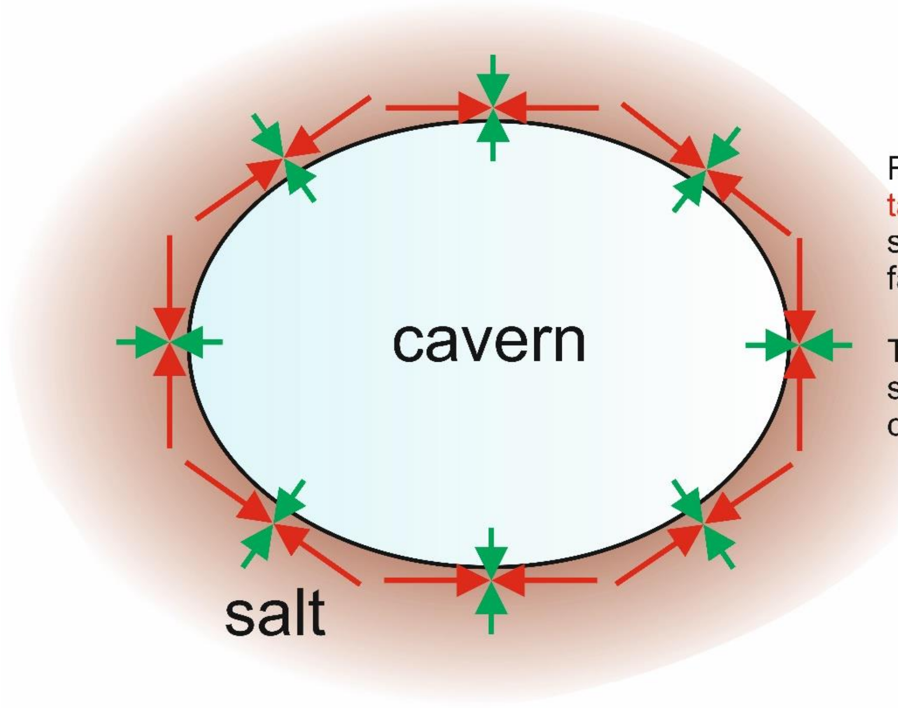
Salt caverns can fail in two modes:

- The tangential stress is too high for the material
- In the sides or roof tensile stresses occur

FAILURE OF SALT CAVERN (2)

If the tangential stress is too high for the material:

- Spalling (breaking) of side or roof material



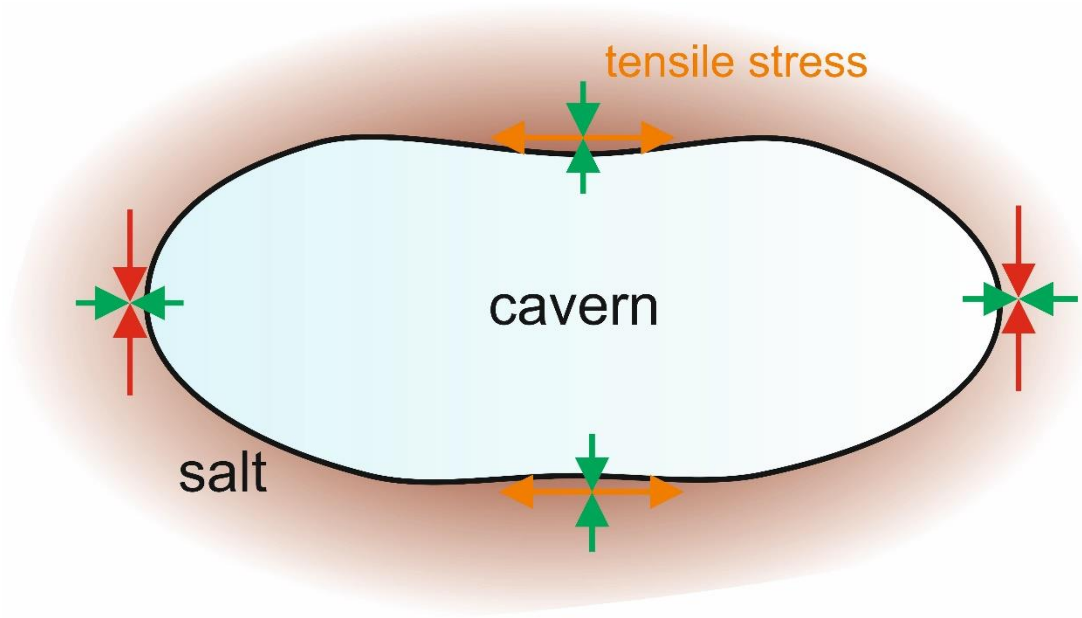
Relation between tangential and radial stress determines the failure

The lower the radial stress the more chance on failure

FAILURE OF SALT CAVERN (3)

Tensile stresses occur if:

- The form/shape of the cavern is such that side or roof can bend

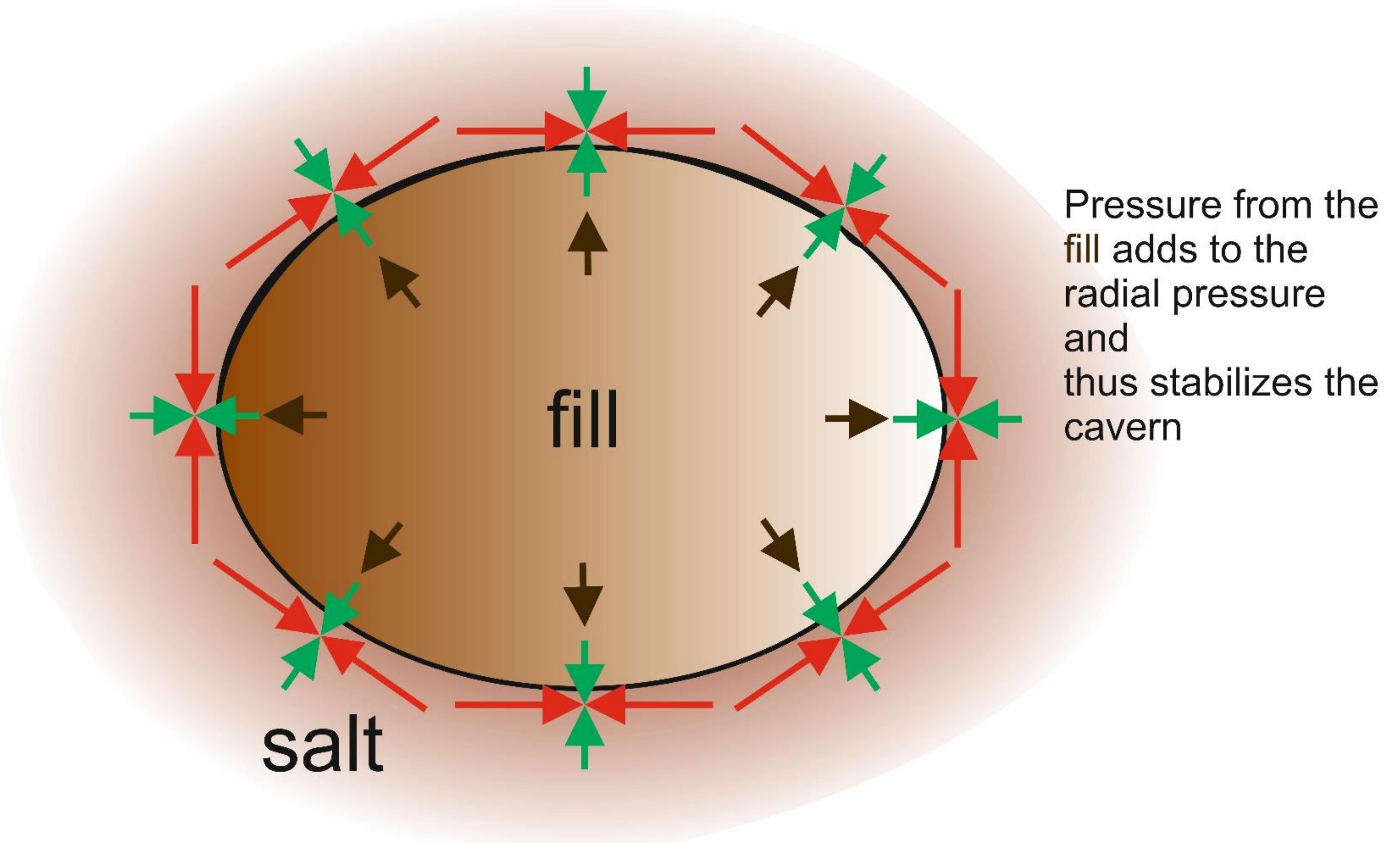


Tensile stress causes rupture of the salt and thus failure

SUPPORT TO PREVENT FAILURE

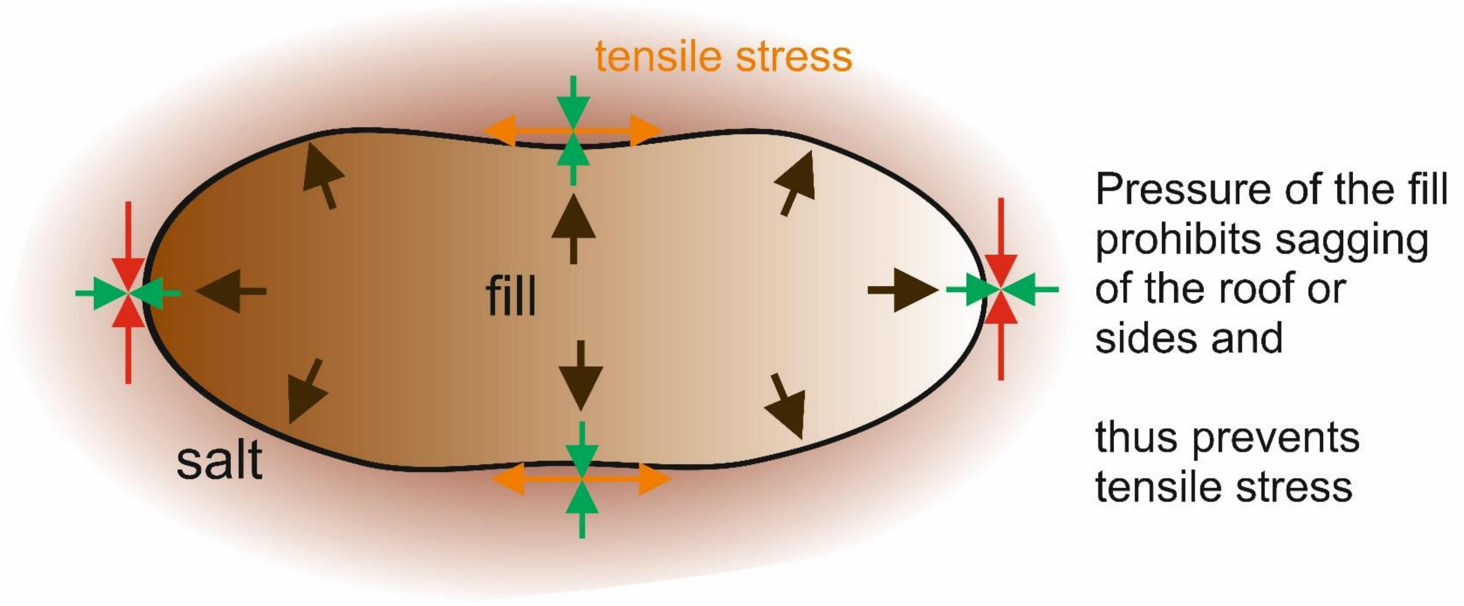
Relative little support stress is enough to stabilize an opening (remember: it should not carry the ground, but only allow the ground to “arch”)

Fill:
brine or
artificial



SUPPORT TO PREVENT FAILURE (2)

Pressure of fill prevents tensile stress



Pressure of the fill prohibits sagging of the roof or sides and

thus prevents tensile stress

BULKING (1)

- When material fails and falls in the cavern it will do so with a larger volume than originally in situ; so-called "bulking"
- The larger volume of the failed material will cause that upward migration of the cavern will stop after some length of migration

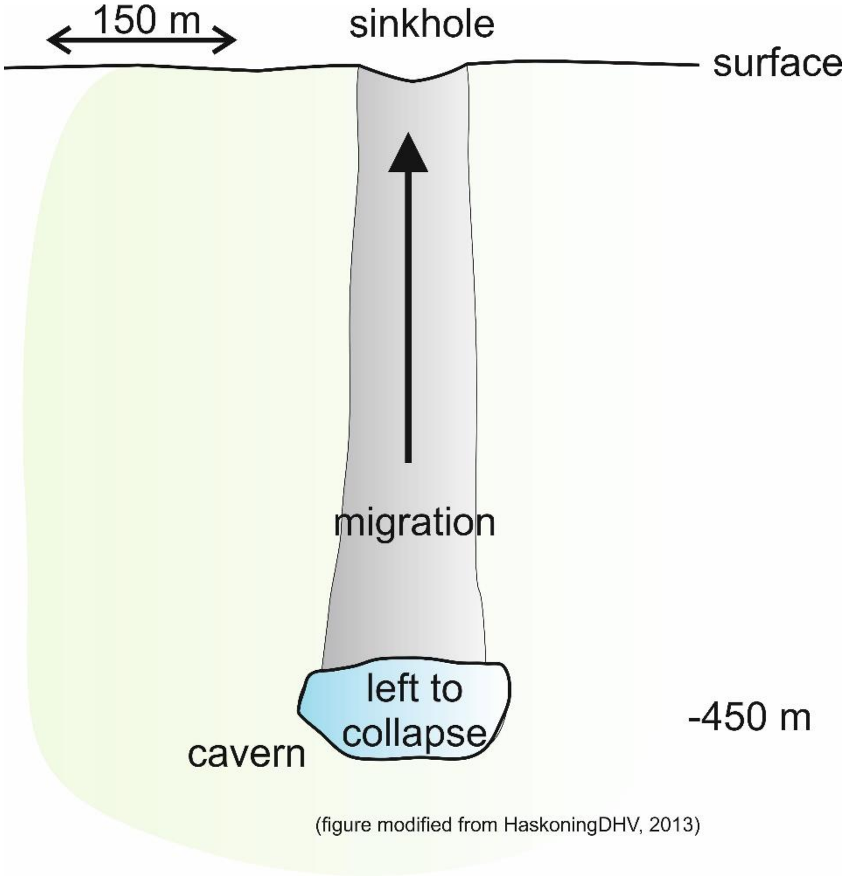
- How much it migrates depends on the material and compacting pressure
- Hence, not every failing cavern will cause notable subsidence or a sinkhole at surface, and
- Cavern does not need to be filled for 100%

BULKING (2)

- The compaction of failed material is time dependent
- It may take a considerable time to compact the failed material
- Hence, it may take time before the migrating cavern reaches surface and results in subsidence or a sinkhole

CAVERN MIGRATION

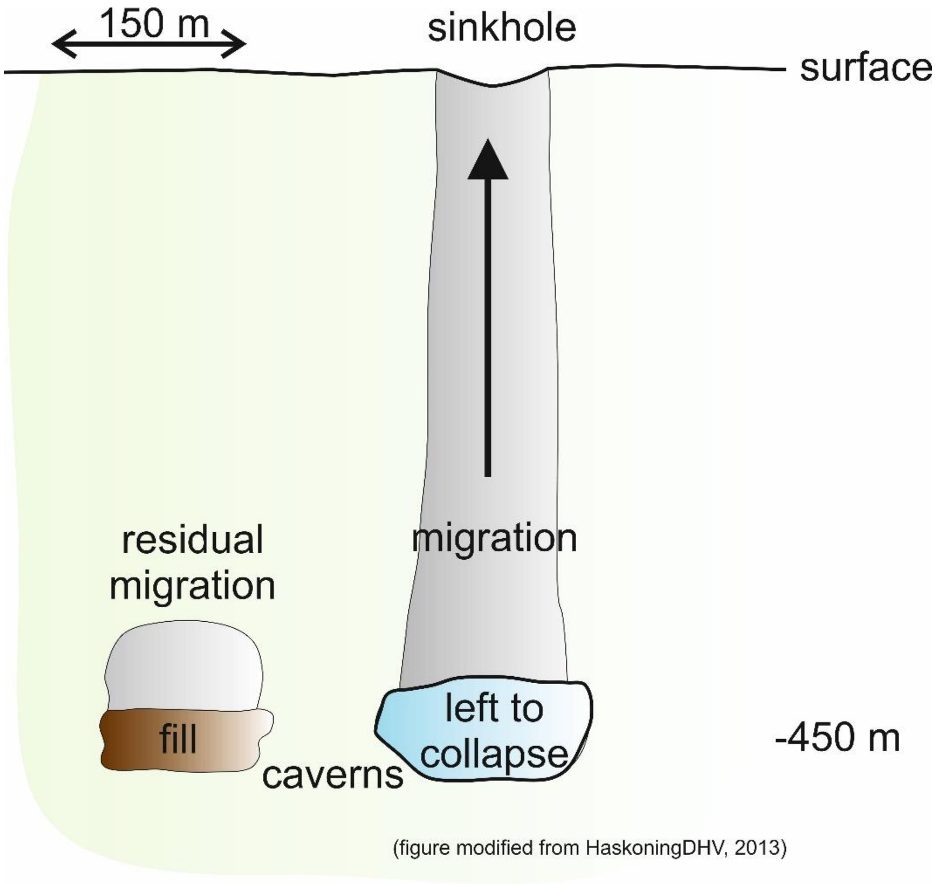
When the roof of the cavern fails the cavern will migrate upwards



(figure modified from HaskoningDHV, 2013)

CAVERN MIGRATION

However; when the cavern is (partially) filled migration will stop earlier



(figure modified from HaskoningDHV, 2013)

CAVERNS TWENTE

Older caverns in Twente have a form of a long-stretched horizontal oval and roof may sag and cave without support:

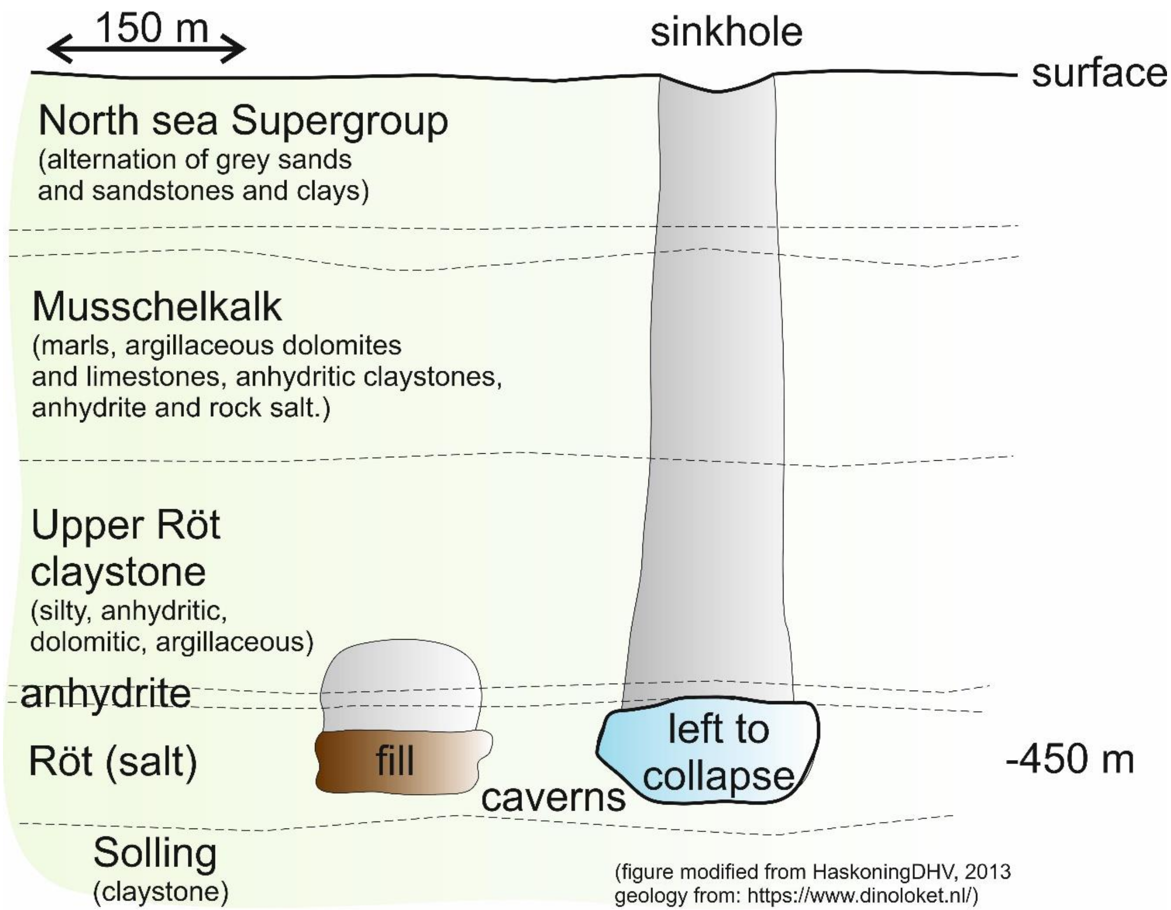
- The length of the roof allows sagging and thus tensile stress can occur in the roof with failure as result
- This may result in growing of the failure up to surface and result in a sinkhole

Sinkhole, Twente, January 1991; copyright Tubantia)

RISK ON POLLUTION OF GROUND OR DRINKING WATER

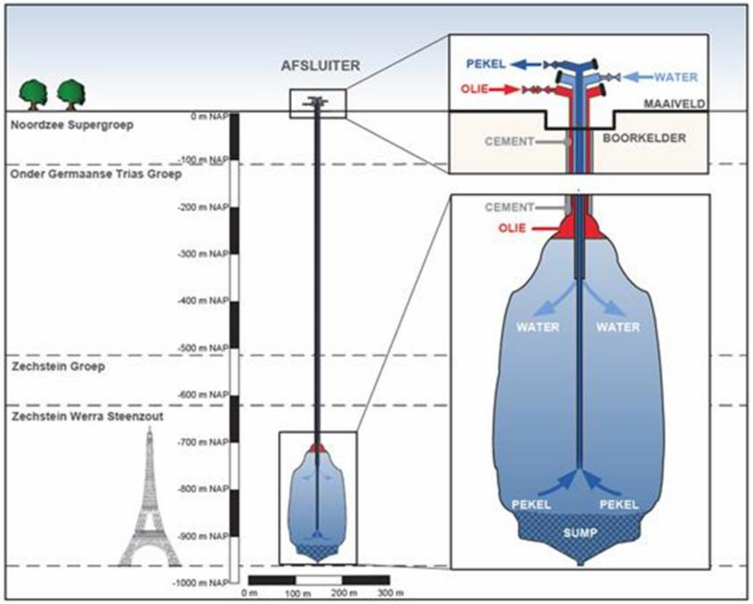
Above caverns layers of impermeable salt and sulfates, and multiple layers of low-permeability clay/ claystone/shale layers are present

(The layers above have to be impermeable otherwise there would have been no salt – salt would have been dissolved by ground water long time ago)



(figure modified from HaskoningDHV, 2013
geology from: https://www.dinoloket.nl/)

RISK ON POLLUTION OF GROUND OR DRINKING WATER



(from: https://www.akzonobel.com/hengelo/projecten/zoutwinning_haaksbergen/zoutwinningproces/)

Another feature that may indicate that the layers above are sealing:

In most newer caverns oil is present as cover; and as far as known no leakages have occurred.

Hence, chance of pollution from material in cavern to surface water in theory not very large; However, local disturbances (e.g. faults) may form a conduct for pollution.

CONCLUSIONS

- Some salt caverns may be a hazard because of surface subsidence or sinkhole forming
- Stabilizing by back fill seems a reasonable solution
- Various options for type of fill

REFERENCES

De Mulder, E.F.J., Geluk, M.C., Ritsema, I., Westerhoff, W.E. & Wong, T.E., 2003. De ondergond van Nederland. Geologie van Nederland 7. Nederlands Instituut voor Toegepaste Geowetenschappen TNO, Utrecht. ISBN: 90-5986-007-1. p. 379. (in Dutch)

Geluk, M., 2010. Zoutmeren en -zeeën in de Nederlandse ondergrond. Grondboor & Hamer. 64 (4/5). pp. 103-110. (in Dutch)

Glennie, K., 2013. Eppo Oomkens and the Discovery of Groningen Gas. AAPG Explorer. https://archives.aapg.org/explorer/2013/09sep/historical0913.cfm [Accessed: 26 October 2015]

Royal HaskoningDHV. 2013. Milieueffectrapport Pilot Stabilisatie Cavernes Twente.(in Dutch)