VU VRIJE UNIVERSITEIT AMSTERDAM

Staatstoezicht op de Mijnen
Ministerie van Economische Zaken en Klimaat

Appendix: Risk analysis of worldwide salt cavern storage

and its implications for the Dutch cavern storage industry

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Appendix 1: Inventarisation of published storage caverns

Appendix 2: Inventarisation of worldwide published incidents in cavern storage

Title page: De Marssteden Diesel storage surface installation, in Enschede, The Netherlands photograph taken by Wim Eising.

Appendix 1: Inventarisation of published storage caverns

A list of all the cavern fields found during this study. It contains all published cavern fields as of 1 September 2021.

Index

Dumrea, Albania

Storage	Natural Gas
Owner	Albpetrol JSC

Activity	Inactive, planned
Salt structure	Salt dome

The Dumrea diapir is set to be solution mined for the creation of natural gas storage caverns by Albpetrol JSC. Not much more is known at this time.

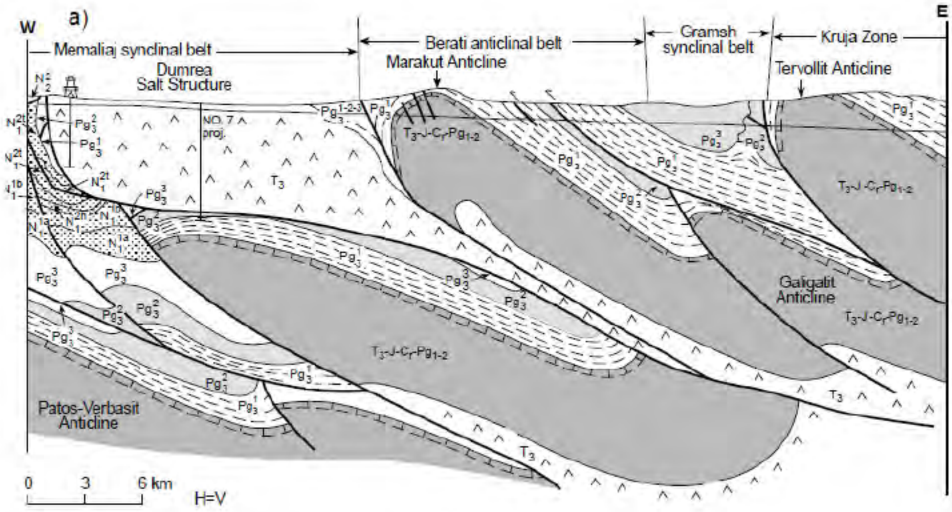

Figure 1 Dumrea salt structure. From (Velaj et al., 1999)

References: (Horváth et al., 2018; Velaj et al., 1999)

Abovyan, Armenia

Storage	Natural Gas
Number of caverns	19 wells
Size: height, diameter	
Working gas volume	160mln m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1962
Owner	ArmRosGazprom

Over 95% of Armenian households and industries are connected to the natural gas network. The storage caverns in Yerevan are situated in the Armenian Basin, consisting of Tertiary salts. The caverns lie at a depth of 750-1050m.

Figure 2 Abovyan gas storage site plan, from (Energy Charter Secretariat, 2008) and references therein.

References: (Energy Charter Secretariat, 2008; Horváth et al., 2018), Gazprom to increase gas volumes in Armenian underground storage facilities | Finport.am

Mozyrskoye, Belarus

Storage	Natural Gas
Working gas volume	5.52 TWh

Activity	Active
Commissioned in	2008
Owner	Gaszprom Transgaz Belarus

The storage caverns in Mozyrskoye are situated in the Pripyat Basin, where the salt deposits are of Upper Devonian age. Additional expansions of about 830mln m^3 working gas is currently under construction.

References: (Horváth et al., 2018)

Mirovo, Bulgaria

Storage	Natural Gas
Number of caverns	1
Volume	$300000m^3$

Activity	Inactive-1993
Salt structure	Salt dome
Commissioned in	1975
Owner	Geosol

The storage caverns holding diesel were located in the Mirovo salt dome, 50km west of Varn and were active from 1975-1993. The area contains many more caverns for brine production.

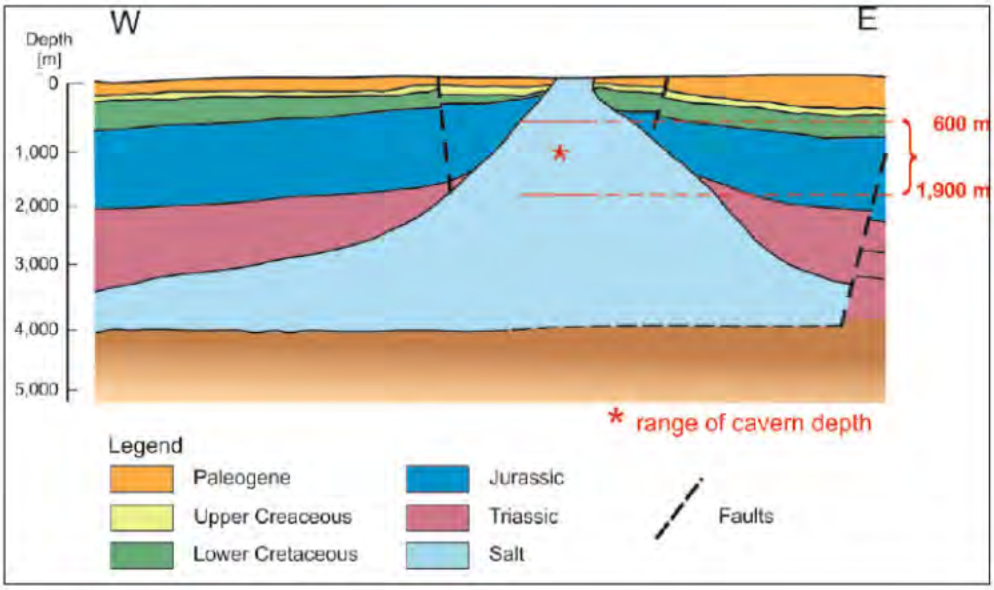

Figure 3 Mirovo salt dome, from (Knoll et al., 1995).

References: (Horváth et al., 2018; Knoll et al., 1995)

Alberta, Canada

Storage	Natural Gas
Number of caverns	>100
Commissioned in	1970s

Activity	Active
Salt structure	Bedded salts
Owners	CHEVRON, BP, ATCO PIPELINES Ltd., WILLIAMS, DOW CHEMICALS, NCE PETRFUND, NORTHWESTERN UTILITES Ltd.

In the Strathacona county, northeast of Fort Saskatchewan and Edmonton there are over 100 storage caverns for natural gas. They are located in the Lotsberg formation (Lower Devonian age) and the Cold Lake formation of the Central Alberta sub-basin. 6 of the caverns are owned by NORTHWESTERN UTILITIES Ltd.

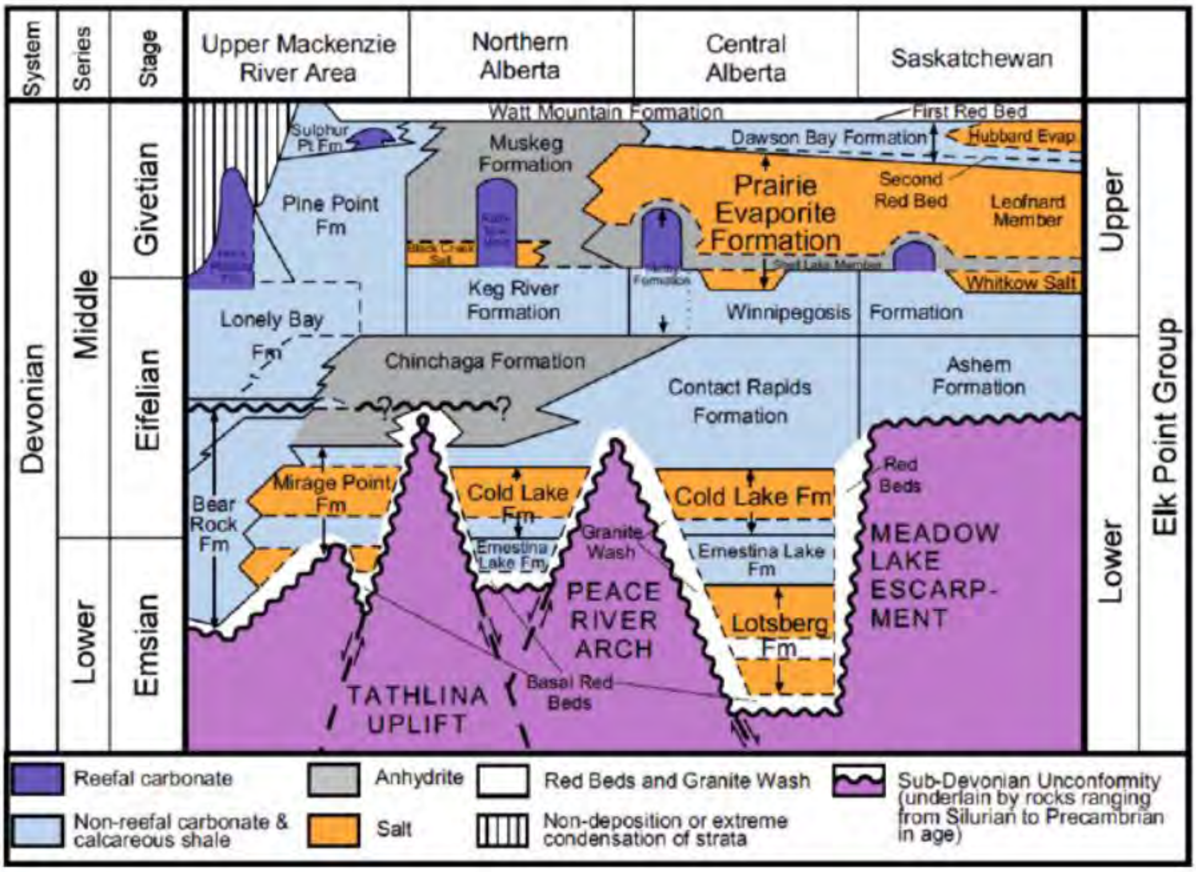

Figure 4 Elk Point group, showing the Lotsberg and Cold Lake formations, from (Grobe, 2000).

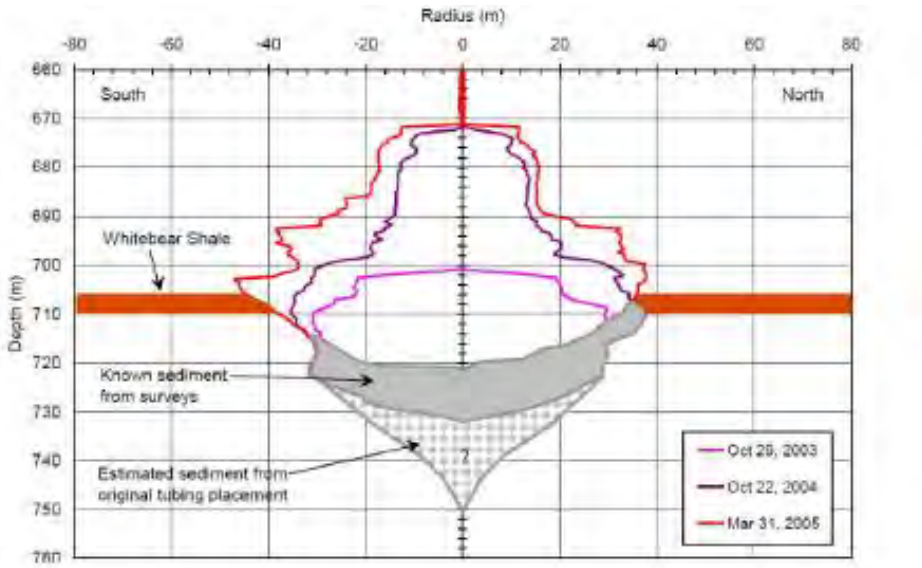

Figure 5 Salt heterogeneity (shale and anhydrite layer in the Cold Lake formation) near cavern #1 (Foster Creek facility) affecting cavern shape, from (Reed & Greene, 2012).

References: (Grobe, 2000; Horváth et al., 2018; Reed & Greene, 2012; Réveillère et al., 2017)

Ontario, Canada

Storage	Hydrocarbons
Number of caverns	79

Activity	Active
Salt structure	Bedded Salts
Owners	PLAINS (LPG, NGL) and DOW CHEMICAL CANADA Inc.

There are 79 storage caverns located in the Michigan Basin, in Ontario. The caverns are made in the lower salt zones of the Salina formation. The depth of the caverns is 700-850m.

References: (Horváth et al., 2018)

Saskatchewan, Canada

Storage	Natural Gas
Number of caverns	24
Volume	See text.

Activity	Active
Salt structure	Bedded salts
Commissioned in	1970s
Owner	Transgas Ltd.

In Saskatchewan there are 6 sites containing storage caverns: Landis (1 Bcf, 28.32 mln m^3), Prud'Homme (6 Bcf, 169.92 mln m^3), Regina (3 Bcf, 84.96 mln m^3), Melville (3 Bcf, 84,96 mln m^3), Asquith (3 Bcf, 84.96 mln m^3) and Moosomin (2 Bcf, 56.64mln m^3). The bedded salts have a thickness of about 100-170m and are part of the Prairie Evaporite formation in the Saskatchewan sub-basin. The cavern roofs lie at a depth of 960-1636m. Dewdney field has 3 natural gas storage caverns (inactive) and 4 LPG storage caverns (active), operated by Spectra.

References: (Brouard, 2019; Crossley, 1995; Horváth et al., 2018), [CER – Market Snapshot: Where does Canada store natural gas? (cer-rec.gc.ca)]

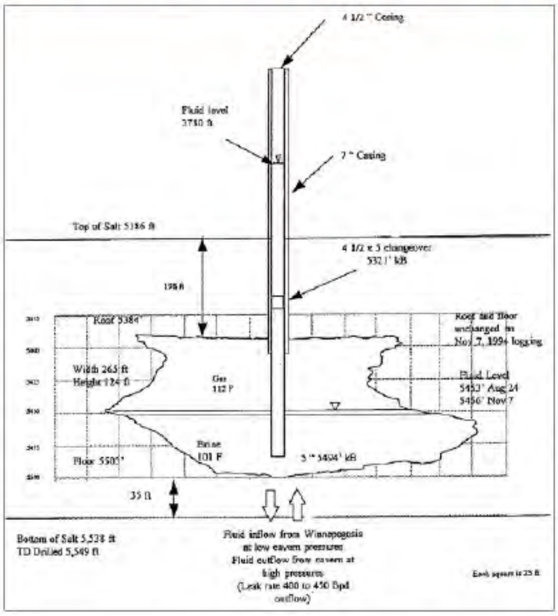

Figure 6 Cavern Regina North #1 from (Crossley, 1995).

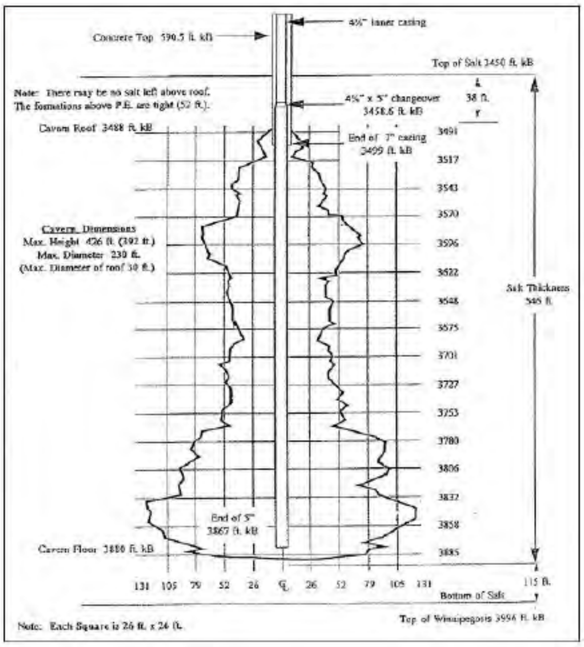

Figure 7 Cavern Melville south #3 from (Crossley, 1995).

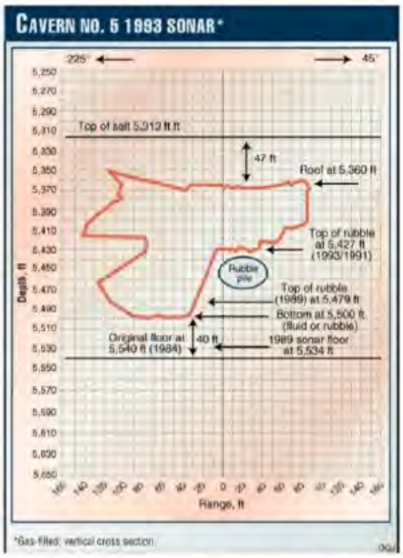

Figure 8 Cavern Regina south #5, after 2 roof falls, from (Crossley, 1998).

Jintan, China

Storage	Natural Gas
Number of caverns	23
Volume	1. 180mln m^3 2. 40mln m^3 3. 60mln m^3

Activity	Active
Salt structure	Bedded salts
Commissioned in	2007, 2016 and 2017
Owners	1. CNPC E&P 2. Sinopec 3. HK and China Gas

The storage caverns in the Jintan salt mine district, in Jiangsu are located in bedded salts which have a thickness of 160m at a depth of about 1000m. The caverns have irregularly shaped designs. Cavern JK-A operated by Sinopec experienced a roof collapse (Wang et al., 2018), this cavern has a height of 40m and a diameter of 80m.

References: (Fansheng, 2014; Horváth et al., 2018; *Underground Gas Storage in the World - 2018 Status*, 2018; Wang et al., 2018)

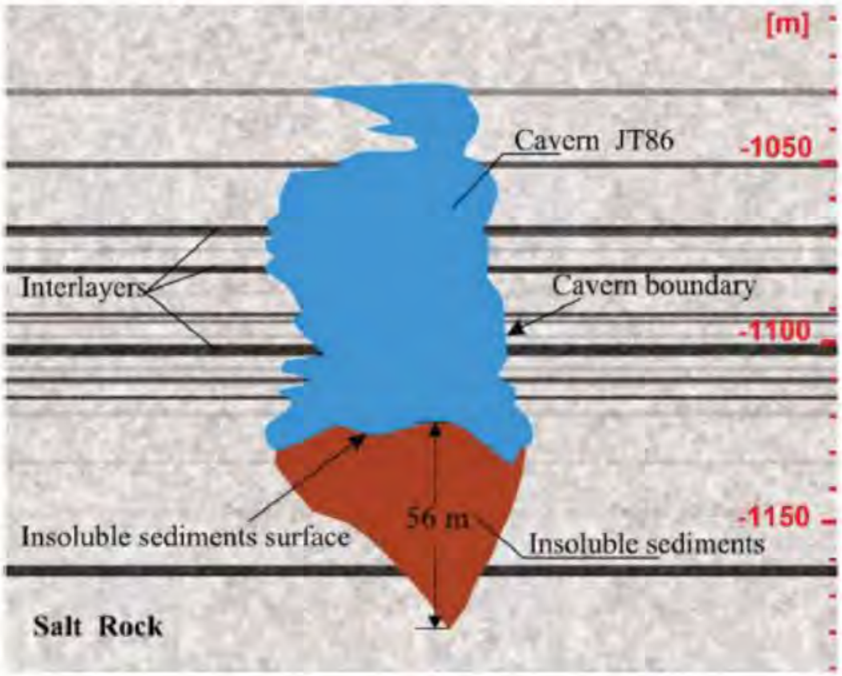

Figure 9 Cavern JT86, showing insoluble interlayers, from (Cyran, 2020).

Lille Torup, Denmark

Storage	Natural Gas
Number of caverns	7
Size: height, diameter	300-430m,55m
Volume	356000-766000 m^3

Activity	Active
Salt structure	Cylindrical salt dome
Commissioned in	1987
Owner	Gas Storage Denmark A/S

Cavern storage in the Tostrup Salt Dome in Northern Jutland has been ongoing since 1987. The caverns in the Norwegian-Danish Basin are situated in Zechstein salt and have a total volume of $435x10^6m^3$. Distance between the caverns is ~450m. A rock mechanical test on creep behaviour of the surrounding rock salt mass on TO6 resulted in spalling at a reference section of the cavern, measured with high precision sonar. TO8 has an irregular shape due to an intersection with the highly soluble "Veggerby" zone (K-/Mg-bearing salt). In TO9 a large anhydrite-dolomite block protruded the eastern wall, resulting in block fall damaging the lower part of the leaching string.

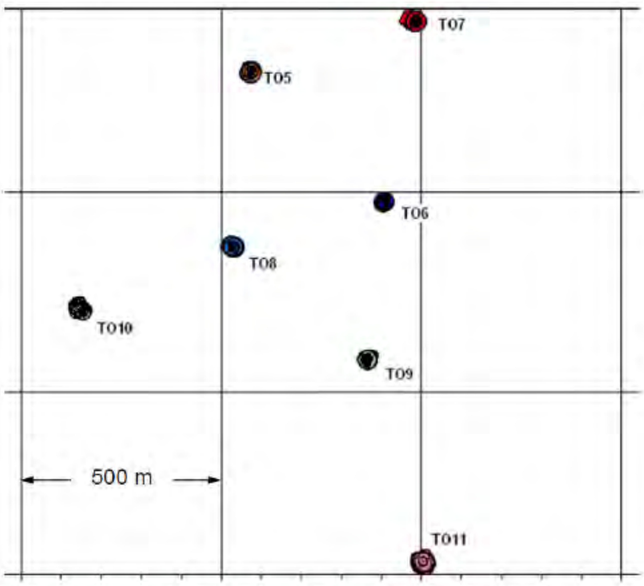

Figure 10 Map of the gas storage caverns of Lille Torup, from

Incidents include irregular cavern shapes due to heterogeneity in the salt layers, block fall and spalling.

Potential risks: preferential leakage paths due to the heterogeneity could result in a hydraulic connection between caverns.

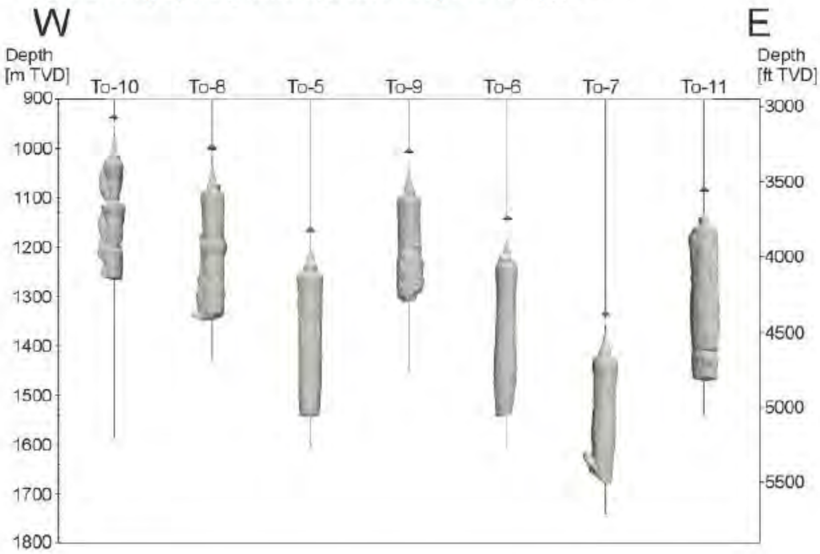

Figure 11 3D map view of the underground gas storage of Lille Torup, from (Kepplinger, 2016).

References: (Jacobsen & Nielsen, 1992; Kepplinger, 2016, 2016; Rokahr et al., 2007), www.gie.eu, www.gasstorage.dk

Alsace Sud, France

Storage	Natural Gas
Working gas volume	2.28 TWh

Activity	Inactive
Commissioned in	2022
Owner	Storengy

There are plans to make a natural gas storage cavern in the Alsace region by Storengy.

References: www.gie.eu

Carresse, France

Storage	Hydrocarbons (Liquid Propane)	**Activity**	Inactive, closed 2002
Number of caverns	4 (1 for brine production?)	**Salt structure**	Diapiric salt structure
Size: height, diameter	SPR2, height: ~20m	**Commissioned in**	Leaching started in 1960s
Volume	SPR2: 9000 m^3	**Owner**	Total E&P

The 4 storage caverns in the Aquitaine basin near Carresse have closed in 2002. The SPR2 test was conducted after closing of the caverns and lasted from 2004-2013. The SPR2 cavern is located at a depth of ~300m while the other caverns lie at a depth of ~700m.

References: (Brouard, 2019)

Etrez, France

Storage	Natural gas and LNG
Number of caverns	19
Size: height, diameter	EZ-04: height ~50m, EZ-05: height ~70m
Capacity (cushion+working gas)	0.75 Gm^3

Activity	Active
Salt structure	Bedded salts
Commissioned in	1980
Owner/operator	Géométhane/Storengy

The caverns in Etrez are part of the SALINE project and are situated in the Bresse Salt Basin, where the halite thickness is 1000-1400m. The caverns are built in two separate units: the upper unit;700-1100m deep and the lower unit; 1200-1800m deep.

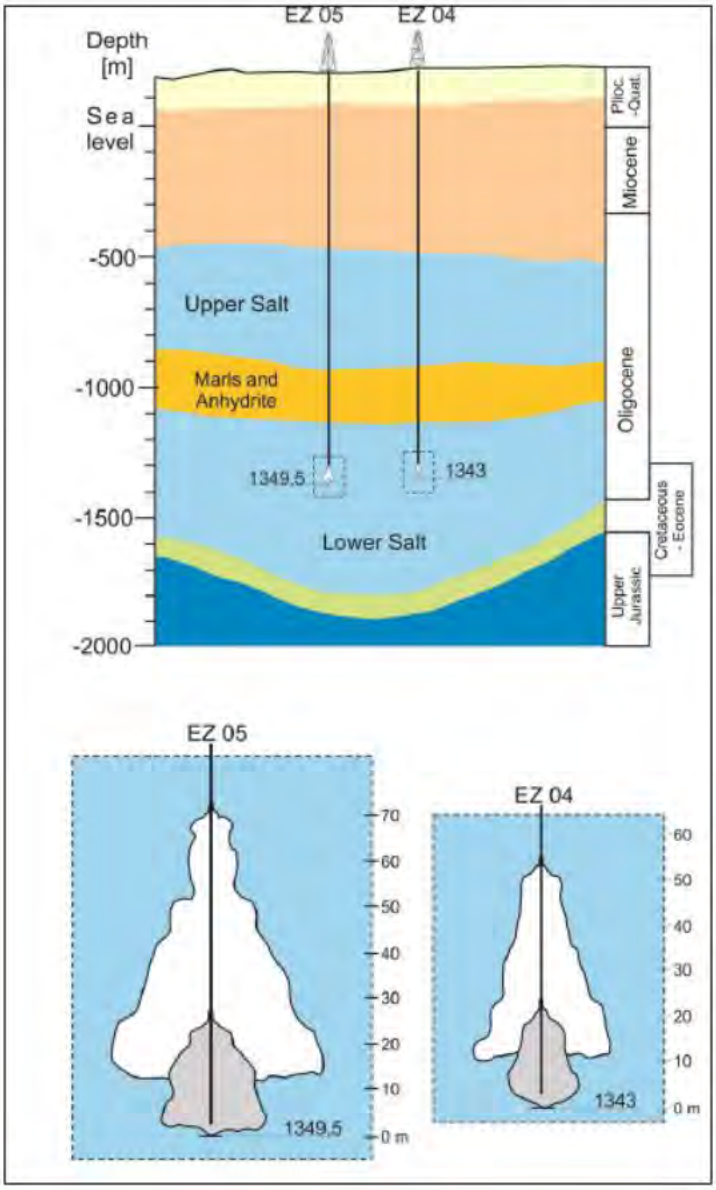

Figure 12 Etrez cavern field and close-ups of caverns EZ 05 and EZ 04, from (Lasneret & Vernet, 1978).

References: (Horváth et al., 2018; Lasneret & Vernet, 1978)

Manosque, France

Storage	1. 40% Crude oil, 60% refined products 2. Natural gas
Number of caverns	~35
Size of 1.: height, diameter	Height: 300-400m, diameter: 60-80m
Capacity (working gas + cushion gas)	1. 3.2mln m^3

Activity	Active
Salt structure	Anticlinal structure
Commissioned in	1. 1969 2. 1993
Owner	1.Géosel 2. Géométhane

The Manosque Forcalquir Basin is host to several caverns, which were all designed and leached for storage by Geostock Entrepose, all the caverns in the basin are also operated by them. The basin contains salts of Oligocene age, these layers have a thickness of 800m (900-1800m deep) and the top of the anticline lies at a depth of 100m.

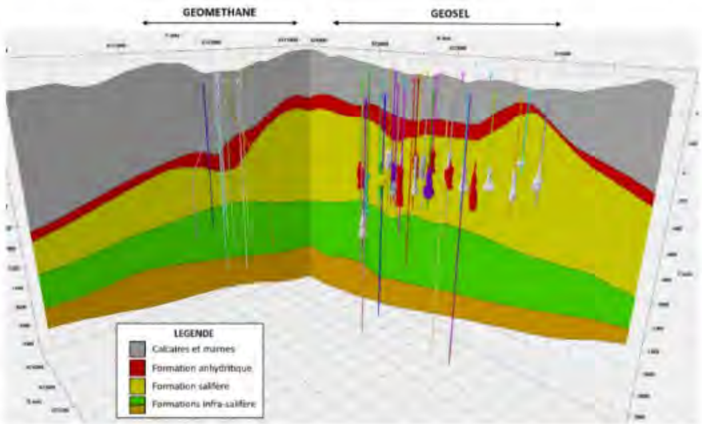

Figure 13 Manosque cavern field, from www.geosel.fr.

28 of these caverns are owned by Géosel and store crude oil and refined products. These caverns lie at a depth of 350-1000m, are 300-400m high and have a diameter of 60-80m. The other 7 caverns are rented from Géosel to Géométhane for storage of natural gas.

References: www.geosel.fr (Horváth et al., 2018)

Valence Salt basin, France

Storage	Natural gas and Hydrocarbons (Propylene)	**Activity**	Active
Number of caverns	16	**Salt structure**	Bedded salts
Owner	Storengy, Novapex	**Commissioned in**	1970

The Valence salt basin is the host of several caverns, of which 16 are currently active. The salt hosting the storage caverns in this basin has a thickness of 140m. Storengy operates 13 caverns in Tersanne, near the northern part of the basin, cavern tops have a depth of ~1400m. Storengy also operates 2 caverns storing natural gas in Hauterives, which are part of the SALINE project, the caverns are at a depth of 1500m. These caverns were commissioned in 2012. Novapex stores propylene in a cavern near Le Grand Serre.

Cavern Te02 in the Tersanne cavern field was operated from 1970-2005, after which an abandonment test took place. The volume of this cavern was 93500m^3.

References: (Brouard, 2019; Horváth et al., 2018)

Viriat, France

Storage	Hydrocarbons (Ethylene)		**Activity**	Active?
			Owner	TOTAL

North of Lyon lie the storage cavern(s) of Viriat in the department of Ain.

References: (Evans, 2008)

Bad Lauchstädt/Teutschenthal, Germany

Storage	Natural gas and Hydrocarbons (Ethylene, Propylene)
Number of caverns	20
Cavern depth	1. 780-950m 2. 700-800m 3. 820m

Activity	Active
Salt structure	Bedded salts
Commissioned in	1970s
Owner	1. VNG Gasspeicher 2. DOW Olefinverbund GmbH, LDC 3. Town gas

The caverns are located in the Stassfurt bedded salts which are 330-560m thick (from SE to NW) and about 500-1000m deep. The Stassfurt Halite has an anhydrite content of 4-5% and is located north to a Hercynian fault zone. In the area southwest of Halle, in the towns of Bad Lauchstädt and Teutschenthal 20 storage caverns are under operation. The 17 caverns at Bad Lauchstädt are operated by VNG Gasspeicher and are part of the VGS storage hub. These caverns are used for the storage of natural gas. DOW Olefinverbund GmbH operates 3 caverns at Teutschenthal, filled with hydrocarbons.

LDC town gas stored town gas (45-55% hydrogen, mixed with methane and CO2) in a cavern at Bad Lauchstädt in the 1970s. This cavern was converted to store natural gas.

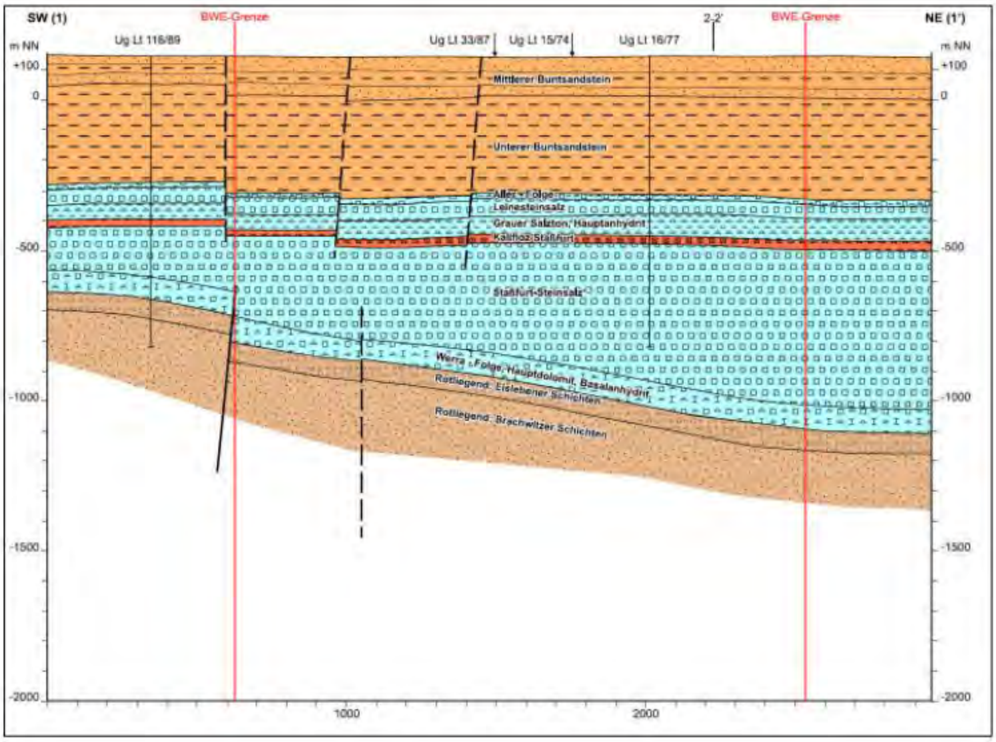

Figure 14 Cross section of the cavern field in Bad Lauchstädt/Teutschenthal, from (Arnold, 2010).

References: (Arnold, 2010; Horváth et al., 2018; Kruck, 2013)

Bernburg, Germany

Storage	Natural gas and Hydrocarbons (Propane)
Number of caverns	39
Cavern depth	1./3. 500-700m 2. 510-680m
Working gas volume	3. 1.82 TWh

Activity	Active
Salt structure	Anticlinal structure
Commissioned in	1. 1974 3. 2012
Operator	1. VNG Gasspeicher 2. Esco European salt company GmbH & Co. KG 3. Erdgasspeicher Peissen GmbH

In the Bernburg anticline, situated south of the town of Bernburg 39 storage caverns are under operation by 3 different operators. The caverns are located in the Stassfurt halite Z2. Both VNG Gasspeicher and Erdgasspeicher Peissen GmbH operate natural gas storage caverns and have 33 and 4 caverns respectively. The caverns operated by VNG Gasspeicher are part of the VNG storage hub. Erdgasspeicher Peissen GmbH have planned an expansion in 2025, 9 more caverns with a working volume of 5.08TWh are to be leached. 2 caverns storing hydrocarbons are operated by Esco European salt company GmbH & Co. KG, this cavern field is called Katharina.

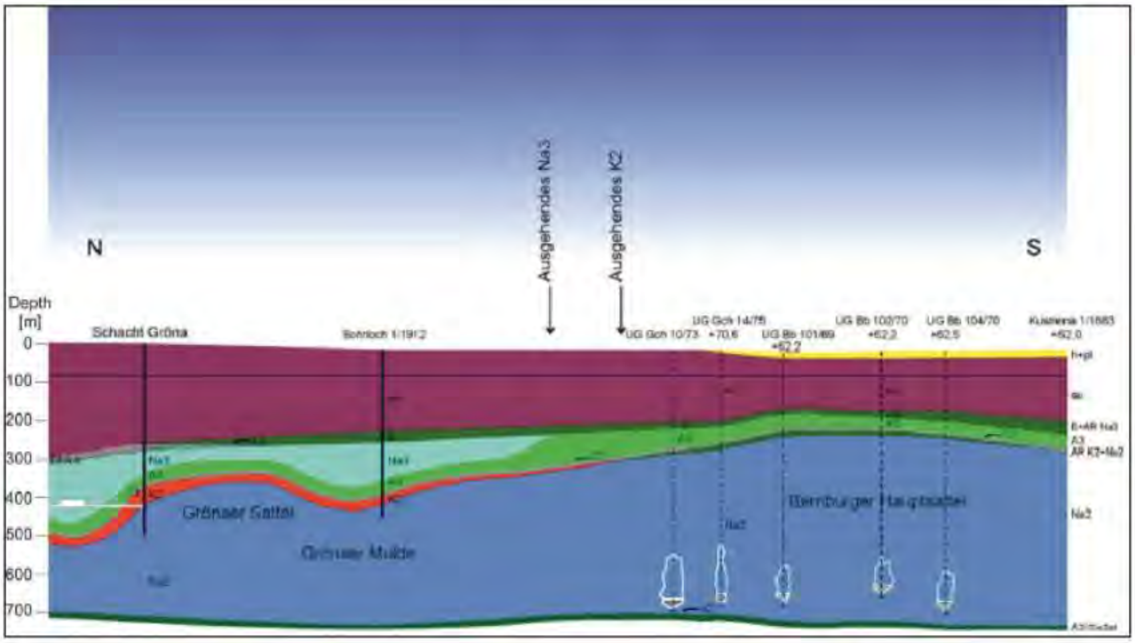

Figure 15 Bernburg salt structure cross section, showing outlines of caverns, from (Arnold & Miersch, 2001).

References: (Arnold & Miersch, 2001; Horváth et al., 2018)

Blexen, Germany

Storage	Crude Oil, gasoline and fuel oil
Number of caverns	8
Size: height, diameter	640-1430m cavern depth

Activity	Active
Salt structure	Salt dome
Commissioned in	1977
Owner/operator	Untertage-Speicher-Gesellschaft mbH

Near Bremerhaven, in the Dedesdorf salt dome, 8 storage caverns are operated by Untertage-Speicher-Gesellschaft mbH. The caverns are located in the Keuper salt and have a height of ~600m.

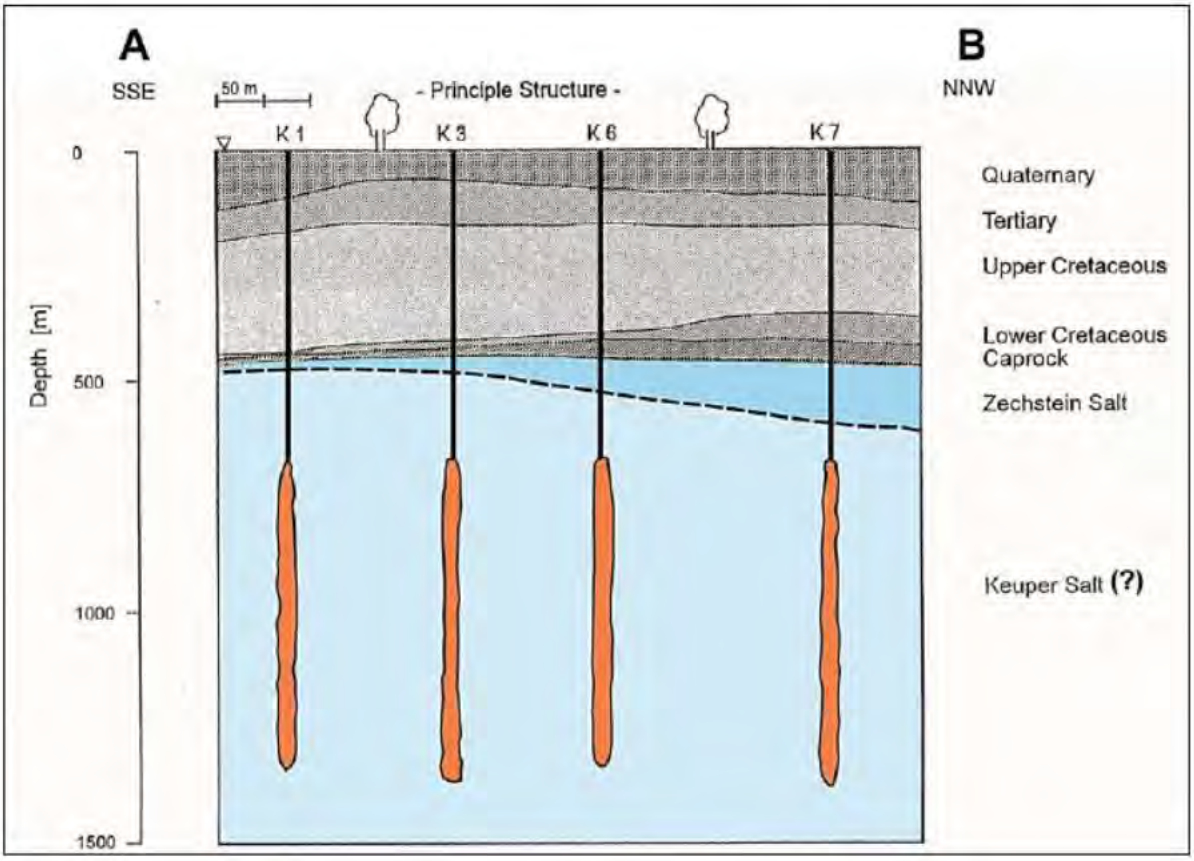

Figure 16 Blexen storage field cross section, showing the storage caverns, from (Meyer et al., 1994).

References: **(Horváth et al., 2018; Meyer et al., 1994)**

Bremen-Lesum, Germany

Storage	Natural gas and light heating oil
Number of caverns	9
Cavern depth	1. 1050-1350m 2. 1315-1780m 3. 530-1080m, height 80-280m
Volume	1. 0.86 TWh working gas volume 2. Individual caverns: 570000 m^3 and 615000 m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1./2.:2000 3. 1960s
Operator	1. Wesernetz Ein Unternehmen von SWB 2. Storengy 3. Nord-West Kavernen GmbH (NWKG)

3 operators have storage caverns near Bremen-Lesum, in the Lesum salt dome. The dome is 5.5km long and 3.5km wide. The Zechstein salt contains halite with anhydrite layers. Both Wesernetz Ein Unternehmen von SWB (2 caverns) and Storengy (2 caverns) operate natural Gas storage caverns. Nord-West Kavernen GmbH (NWKG) operates 5 caverns for storage of light heating oil, which are part of the EBV (Crude oil reserve association). Cavern L201 operated by Wesernetz Ein Unternehmen von SWB was converted from oil to gas storage.

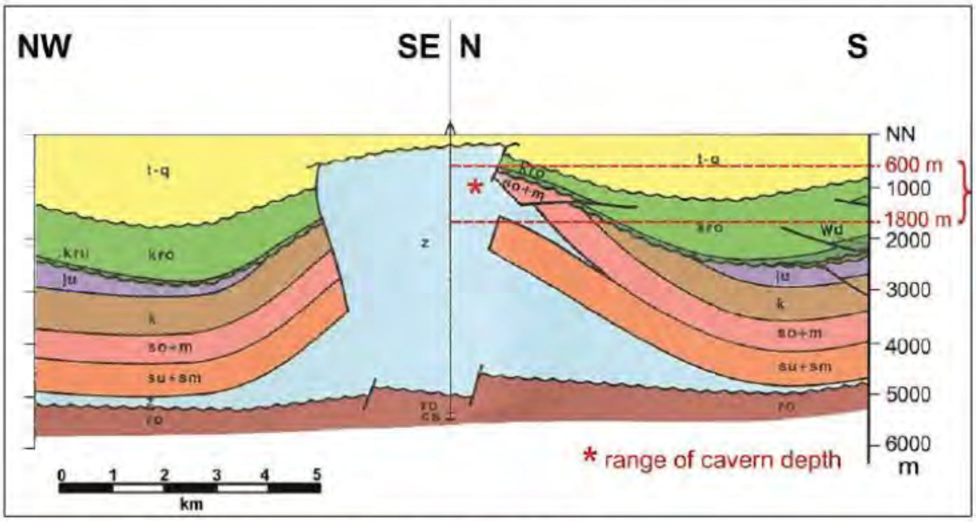

Figure 17 Lesum salt dome cross section, from (Kockel, 1996).

References: (Horváth et al., 2018; Kockel, 1996)

Empelde, Germany

Storage	Natural gas		**Activity**	Active
Number of caverns	4		**Salt structure**	Salt dome
Cavern depth	1250-1750m		**Commissioned in**	1982
Working gas volume	3.83 TWh		**Owner/operator**	GHG Gasspeicher Hannover GmbH

The storage caverns near Empelde are located in the Bethe salt dome. The dome is 8km long and 2-3km wide. The salt is highly disturbed Zechstein 2, 3 and 4, containing potash salts.

References: (Horváth et al., 2018)

Epe, Germany

Storage	Natural gas, crude oil and helium
Number of caverns	>70

Activity	Active
Cavern depth	1000-1500m

Close to the Dutch border, near Gronau and Epe, is the largest storage cavern field of the world. The caverns are located in Zechstein 1 salts, with an evaporite thickness of 200-400m, which lies at a depth of 900-1500m. All the caverns lie at this depth range. Over 70 storage caverns have been documented.

SGW owns 3 caverns used for storage of crude oil. Air liquide owns 1 cavern for the storage of helium, which operates since 2016. All other caverns are used for the storage of natural gas (Both H- and L-gas), as shown in the table below.

Operator: name	Caverns	Storage	Working Volume	Commissioned in
Eneco-Gasspeicher: Epe Eneco Gasspeicher	2 (S81,S82)	Natural gas	1.44 TWh	
Innogy: Epe NL	10 (shared with Epe H-Gas)	Natural gas	2.92 TWh	2006
Innogy: Epe H-Gas	10 (shared with Epe NL)	High caloric Gas	6.66 TWh (VGS InnEXpool)	1990
Innogy: Epe L-gas	11	Low caloric Gas	1.84 TWh	2012
KGE: Epe KGE		Natural gas	2.17 TWh	2012
Nuon: Epe Nuon		Natural gas	3.01 TWh	2007
Trianel Gasspeicher Epe GmbH & Co. KG: Epe Trianel	4	Natural gas	2.23 TWh	2008
Uniper: Epe Uniper H-Gas	39 (Shared with Epe Uniper L-Gas)	H-Gas	15.30 TWh	1976
Uniper: Epe Uniper L-Gas	39 (Shared with Epe Uniper H-Gas)	L-Gas	4.26 TWh	1977
Air Liquide: Epe Helium	1	Helium		2016
SGW: Epe SGW crude oil	3	Crude Oil		

References: (Horváth et al., 2018)

Etzel, Germany

Storage	Natural gas and crude oil	Activity	Active
Number of caverns	75 (49 for natural gas)	**Salt structure**	Salt dome
Volume	250000-700000 m^3	**Cavern depth**	900-1200m

One of the largest storage cavern fields is located southwest of Etzel. The caverns were made in the Etzel salt dome, which is 12km long and 5km wide. The roof of the diapir is 650-900m deep.

Operator: name	Caverns	Storage	Working Volume	Commissioned in
Crystal, Friedeburger Speicherbetriebsgesellschaft/ Storag Etzel GmbH: Etzel crystal	4	Natural gas	2.42 TWh	2012
EKB Storage (Etzel-Kavernenbetriebsgesellschaft)/ Storag Etzel GmbH: Etzel EKB	6	Natural gas	11.20 TWh	2012
EnBW Energie Baden-Württemberg: Etzel EnBW		Natural gas	2.42 TWh	2012
Equinor: Etzel EGL		Natural gas	2.21TWh	1993
Gas Union: Etzel ESE		Natural gas	1.58TWh	2012
OMV: Etzel ESE		Natural gas	5.30TWh	2012
Storag Etzel GmbH: Etzel crude oil	24	Crude Oil		1970s
Total: Etzel EGL		Natural gas	0.06TWh	1993
Uniper: Etzel EGL	19 (Shared with Uniper Etzel ESE)	Natural gas	11.32TWh	1993
Uniper: Etzel ESE	19 (Shared with Uniper Etzel EGL)	Natural gas	12.10TWh	2012
VNG Gasspeicher: Etzel ESE		Natural gas	1.40 TWh	2012

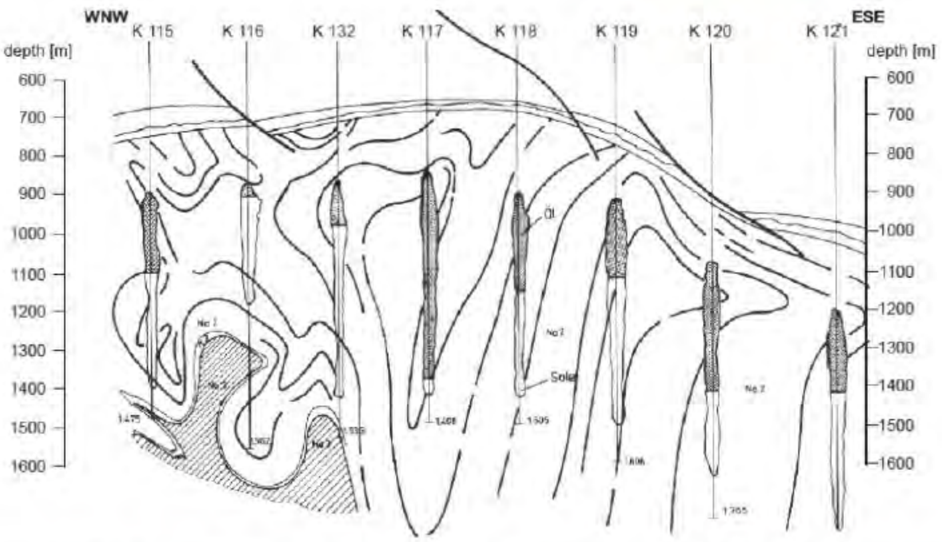

Figure 18 Etzel salt dome cross section, also showing the storage caverns, from (Cyran, 2020; Horváth et al., 2018).

References: (Cyran, 2020; Horváth et al., 2018)

Harsefeld, Germany

Storage	1. Natural gas 2. Hydrocarbons (Ethylene,Propylene, Ethylenedichloride)	Activity	Active
Number of caverns	5	**Salt structure**	Salt dome
Cavern depth	1. 1155-1670m 2. 800-1100m	**Commissioned in**	1. 1992
Working gas volume	1. 1.24 TWh	**Operator**	1. Storengy 2. Dow Deutschland Anlagengesellschaft GmbH

In the Harsefeld salt dome (9km diameter, circular shape), Storengy operates 2 cylindrical natural gas caverns near Harsefeld and Dow Deutschland Anlagengesellschaft GmbH operates 3 caverns for storage of hydrocarbons near Ohrensen. The caverns are located in Zechstein salts.

References: (Horváth et al., 2018)

Heide, Germany

Storage	1. Crude oil, diesel 2. Hydrocarbons (Butane)
Number of caverns	10
Cavern depth	1. 600-1090m (top of cavern depth) 2. 660-760m
Volume	1. 296000 m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1. ? 2. 1964
Operator	1. Nord-West Kavernengesellschaft mbH 2. Raffinerie Heide GmbH

The Heide salt dome in the Haselgebirge hosts 10 storage caverns in its Rotliegend salts. 9 of those caverns are part of the strategic reserve EBV and are operated by Nord-West Kavernengesellschaft mbH and are used for storage of crude oil and diesel. The individual caverns have a height of 225-400m. The butane storage cavern (H101) operated by Raffinerie Heide GmbH was the first cavern leached for storage in Germany.

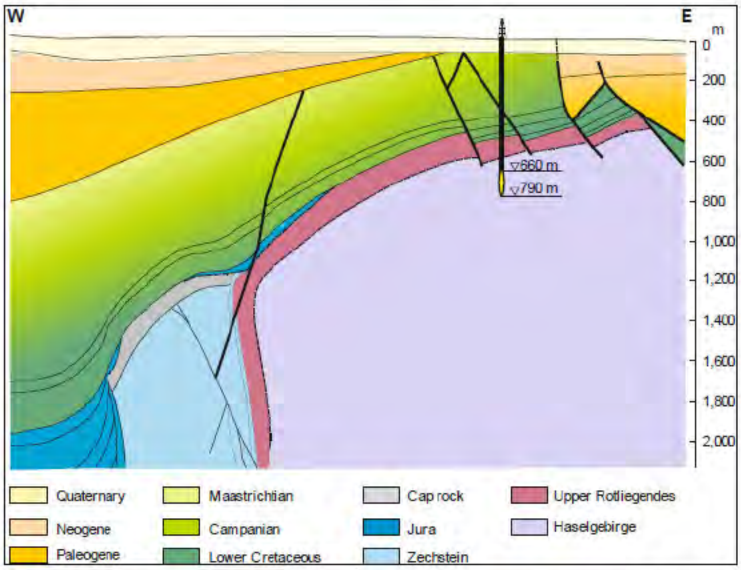

Figure 19 Heide salt dome cross section, showing cavern H 101, from (Rüddiger, 1965).

References: (Horváth et al., 2018; Rüddiger, 1965)

Huntorf and Jemgum, Germany

Storage	CAES and natural gas (both H- and L-gas)
Number of caverns	>38

Activity	Active
Salt structure	Salt domes
Operator	1. Astora/ (VNG Gasspeicher) 2. Nordwestdeutsche Krafiwerke (or: Uniper Kraftwerke GmbH) 3. EWE-Gasspeicher

The Neuenhuntorf salt dome is located 15km northeast of Oldenburg and has an oval shape that is 5.8km long and 3.5km wide. The Jemgum salt dome is 17km long and 2.5km wide. Both salt domes are part of a 50km long arced elongated salt wall. The Huntorf cavern storage is located in the Neuenhuntorf salt dome and the Nüttermoor storage caverns are located in the Jemgum salt dome. 3 operators have over 38 storage caverns, located near Huntorf and Nüttermoor. The Jemgum H caverns operated by EWE Gasspeicher are located at a depth of 950-1400m. Astora is planning to expand their Jemgum H storage to a total of 18 caverns. The CAES storage caverns are located at a depth of 650-800m and have a diameter of 60m. The Nüttermoor H-gas caverns have a height up to 700m, and diameters ranging from 35-110m. The natural gas storage cavern in Huntorf K6 is the largest natural gas cavern in Europe (1100000m3). EWE has plans to convert a storage cavern in Huntorf to hydrogen storage.

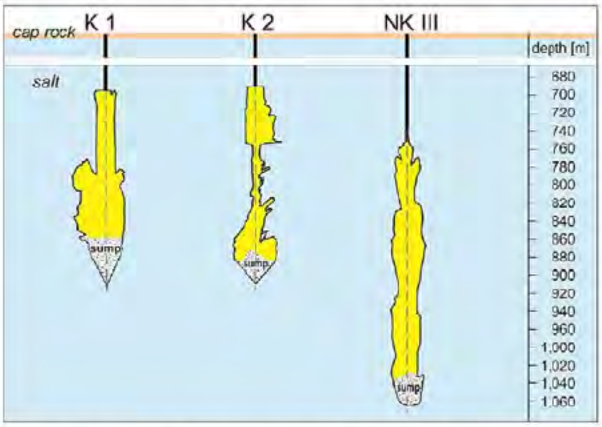

Figure 20 Huntorf storage caverns, from (Horváth et al., 2018) and references therein.

References: (Cyran, 2020; Horváth et al., 2018), Waterstofhub Noordwest-Duitsland

Operator: name	Caverns	Storage	Volume	Commissioned in
Astora/ (VNG Gasspeicher): Jemgum H		H-Gas	6.86 TWh	2013
EWE Gasspeicher: Jemgum H	8	H-Gas	3.98 TWh	2013
Nordwestdeutsche Krafiwerke (or: Uniper Kraftwerke GmbH): Druckluftspeicher Huntorf	2 (NK1, NK2)	CAES	140000-170000 m^3	1978
EWE-Gasspeicher: EWE - Zone L Nüttermoor/Huntorf (GTG)	21 (7 of which are in Huntorf: K1-K6, NKIII)	L-Gas (Nüttermoor has 1/5 for H-Gas)	9.47 TWh working volume	1972
EWE-Gasspeicher: EWE H-Gas Zone (GTG)		H-Gas		Under construction: L-gas to H-gas conversion
EWE-Gasspeicher: Nüttermoor H-1	7 (H-1, H-2, H-3)	H-Gas	1.83 TWh	1979
EWE-Gasspeicher: Nüttermoor H-2	7 (H-1, H-2, H-3)	H-Gas	1.96 TWh	1979
EWE-Gasspeicher: Nüttermoor H-3	7 (H-1, H-2, H-3)	H-Gas	2.96 TWh	1979
EWE-Gasspeicher: Nüttermoor L (GUD)		L-Gas	0.43 TWh	1979

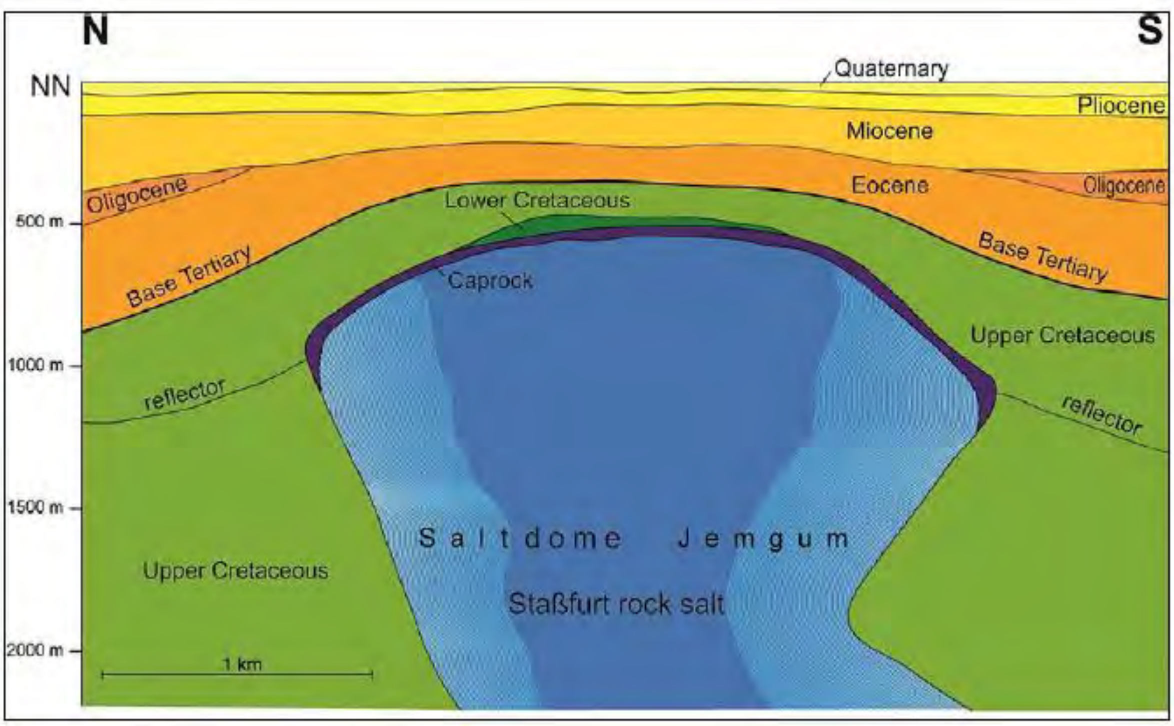

Figure 21 Jemgum salt dome cross section, from (Horváth et al., 2018) and references therein.

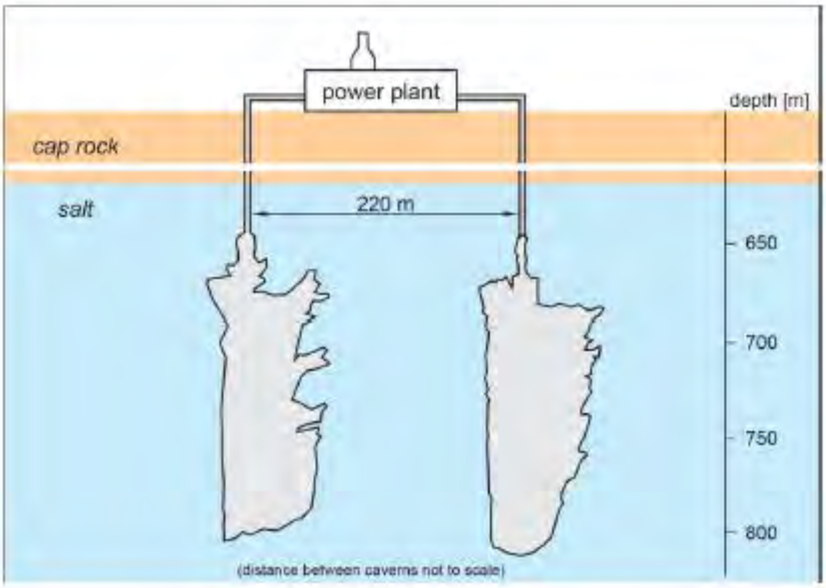

Figure 22 CAES caverns NK 1 and NK 2 in Huntorf, from (Cyran, 2020).

Kiel, Germany

Storage	Natural gas
Number of caverns	>3
Cavern depth	K101: 1,307-1,335 m
Volume	Converted cavern Kiel 101: 32000 m^3 Kiel 102: 394000 m^3 Kiel 103: 35mln m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	K101:1971 K102: 1995 K103:2014
Owner/operator	SW Kiel Speicher GmbH (Used to be owned by: Hansewerk)

In Kiel-Rönne more than 3 storage caverns are present. They reside in the Honigsee salt dome, this dome is part of the Haselgebirge and its salt content is 78%, consisting of both Rotliegend and Zechstein salts. One field is operated by SW Kiel Speicher GmbH, which contains 3 caverns: Kiel 101, 102, 103. The caverns are 300m apart from each other. The total working volume for these caverns is 0.50 TWh.

Cavern Kiel 101 was used, according to (Zivar et al., 2020), to store hydrogen (60%). This cavern operated between 80-100 bar and is currently operated between 60-192 bar.

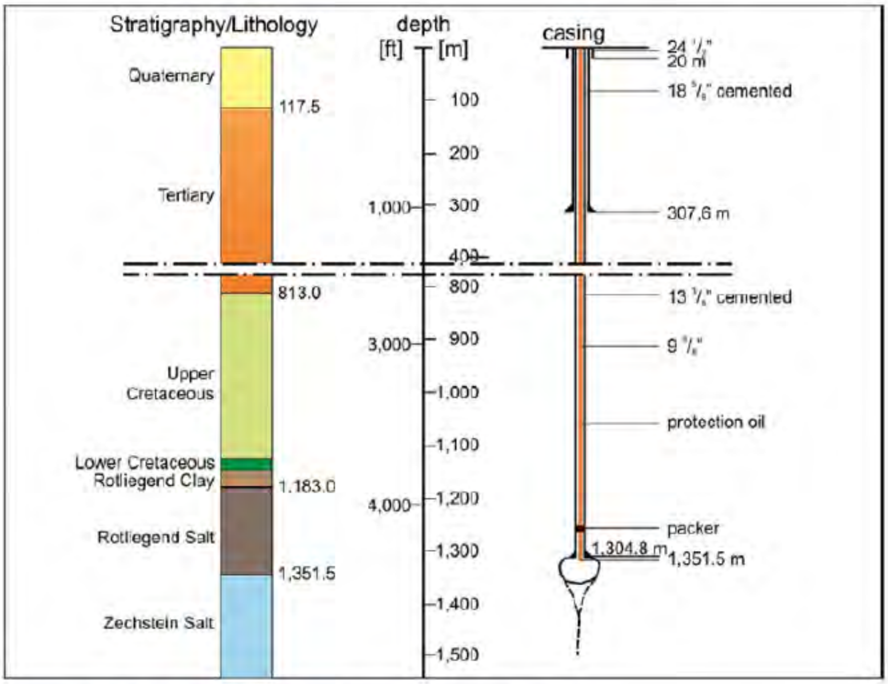

Figure 23 Kiel well profile of K101, from (Kühne et al., 1973).

References: (Horváth et al., 2018; Kühne et al., 1973; Zivar et al., 2020)

Kraak, Germany

Storage	Natural gas
Number of caverns	4
Cavern depth	900-1450m
Working gas volume	2.97 TWh

Activity	Active
Salt structure	Salt dome
Commissioned in	2000
Owner/operator	Hanse Werk/ E.ON Gasspeicher GmbH

20 km south of Schwerin lies the Kraak salt dome, which contains 4 caverns for natural gas storage. They range in height from 110-170m and diameter 40-90m. This salt dome has inhomogeneous salt, deeper areas have several transitions between Z2 and Z3 salts. At a depth of 550m a 20m thick anhydrite is present, below this layer the halite contains kieserite and carnallite. The inhomogeneous salt led to cavern K101 having a highly irregular shape.

References: (Günnewig et al., 2001; Horváth et al., 2018; Stöwer & Borgmeier, 2003)

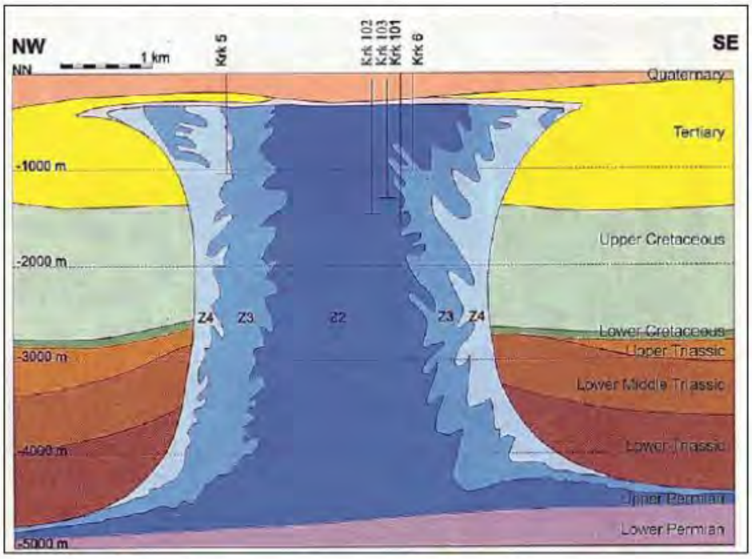

Figure 24 Kraak salt dome cross section, modified by (Horváth et al., 2018) after (Günnewig et al., 2001) .

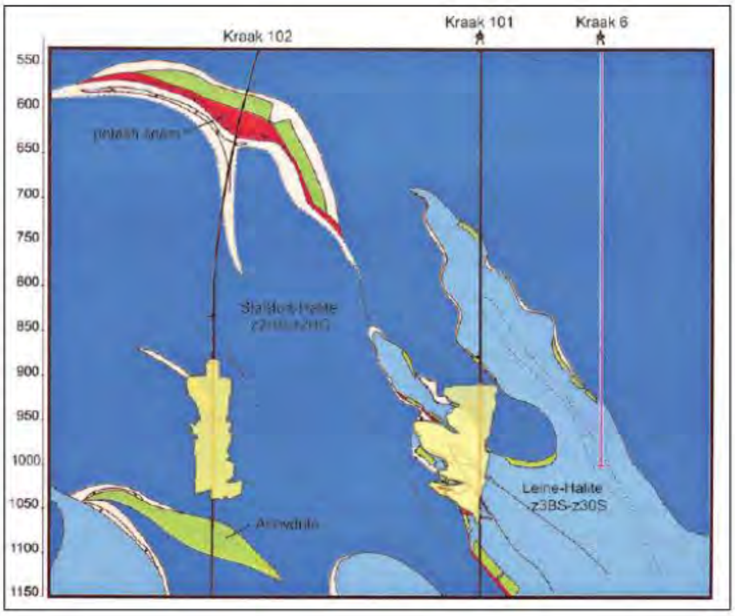

Figure 25 Cross section of caverns K101 and K102, from (Stöwer & Borgmeier, 2003).

Krummhörn, Germany

Storage	Natural gas
Number of caverns	3
Cavern depth	1500-1800m
Working gas volume	116 mill mł

Activity	Active
Salt structure	Salt dome
Commissioned in	2001
Owner/operator	Uniper Energy Storage GmbH

12km northwest of Emden lies the Groothusen salt dome, which contains 3 storage caverns. The caverns were leached in Z2, which contains thin polyhalite layers with an anhydrite content of 1-2%. The caverns are operated at 95-239 bar.

References: (Horváth et al., 2018)

Peckensen, Germany

Storage	Natural gas
Number of caverns	5
Cavern depth	1300-1450m
Working gas volume	392mln m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	2002
Owner/operator	Storengy Deutschland GmbH

The Peckensen salt dome has 5 natural gas storage caverns. The dome is 15km long and 2.4-4km wide, the cavern field is located at the northern part of the dome. Underneath the dome is a natural gas field, which is the 2nd largest gas accumulation in Europe.

References: (Horváth et al., 2018)

Reckrod, Germany

Storage	Natural gas
Number of caverns	3
Cavern depth	800-1100m
Working gas volume	1.32 TWh

Activity	Active
Salt structure	Bedded salts
Commissioned in	2001
Owner/operator	Gas union

In Reckrod, north of Eiterfeld, the Werra basin (this basin covers an area of over 1200km^2) is host to 3 natural gas storage caverns. The salt in this area has thickened due to imbrication, its thickness is 450m. The caverns were constructed in the Middle Werra Halite. The caverns have a cylindrical shape and have a diameter of 67-85m, and heights varying between 230-260m.

References: (Horváth et al., 2018)

Rüdersdorf, Germany

Storage	Natural gas (H-gas)		**Activity**	Active
Number of caverns	2		**Salt structure**	Salt pillow
Top of cavern depth	1000m		**Commissioned in**	2007
Working gas volume	1.08 TWh		**Owner/operator**	EWE-Gasspeicher

The Rüdersdorf salt pillow is located 15km southeast of berlin. It has a z2 section which is ~1900m thick.

References: (Horváth et al., 2018)

Schönebeck, Germany

Storage	Semi-finished products		**Activity**	Inactive
Number of caverns	1		**Salt structure**	Graf Moltke salt mine
Owner/operator	Chemical industry		**Commissioned in**	1971

Inside the Graf Moltke salt mine a borehole was drilled to form a cavern. The cavern is situated in Z2 halite and was used to temporarily store products for the chemical industry. The cavern is irregularly shaped. Abandonment of this cavern entailed tight sealing, a barrier-plug and cementation.

References: (Horváth et al., 2018)

Sottorf, Germany

Storage	Crude oil and petroleum products
Number of caverns	9
Cavern depth	600-1200m
Volume	95000-289000 m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1971
Owner/operator	Nord-West Kavernengesellschaft mbH (NWKG)

Southwest of Hamburg-Harburg lies the Sottorf salt dome, which is 2-2.5km in diameter. The caprock is made up 1000m of anhydrite.

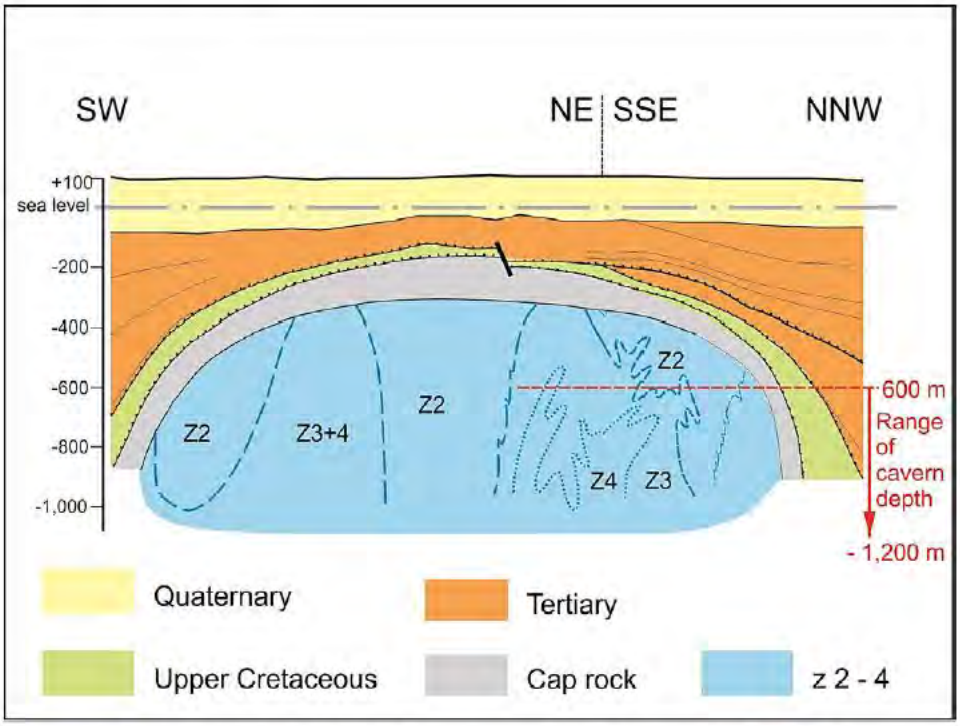

Figure 26 Cross section of the Sottorf salt dome, modified by (Horváth et al., 2018) after (Schaper & Berndt, 1973).

References: (Horváth et al., 2018; Schaper & Berndt, 1973)

Stassfurt anticline, Germany

Storage	Natural gas
Number of caverns	8
Cavern depth	One at a depth of: 430-560m, others: >930m
Working gas volume	7.29 TWh

Activity	Active
Salt structure	Anticline
Commissioned in	1996
Owner/operator	Innogy

In the Stassfurt anticline (max thickness 1100m), 8 caverns for the storage of natural gas are operated by Innogy. The caverns were leached in Z2 halites.

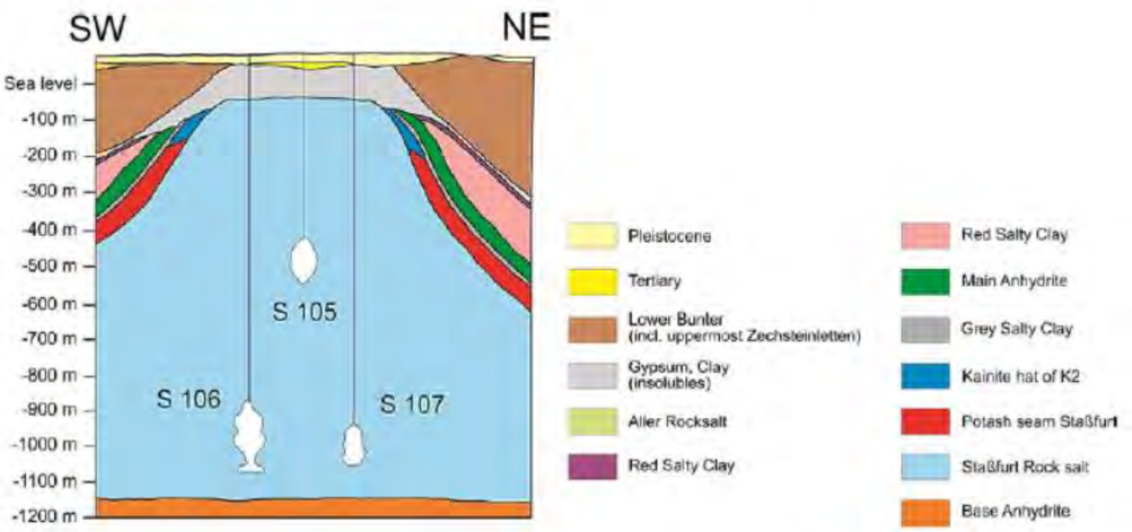

Figure 27 Stassfurt salt anticline, showing caverns S 105, 106 and 107, modified by (Horváth et al., 2018) after (Klafki & Below, 1996) .

References: (Horváth et al., 2018; Klafki & Below, 1996)

Wilhelmshaven – Rüstringen, Germany

Storage	Crude oil and petroleum products
Number of caverns	36
Casing shoe depth	1200-1600m
Working gas volume	

Activity	Active
Salt structure	Salt dome
Commissioned in	1969
Owner/operator	NWKG (subsidiary of EBV)

The caverns in the Rüstringen salt dome (located near Wilhelmshaven, diameter:5km, depth:1000-5000m) are part of the EBV: Crude Oil Reserve Association. 3 more caverns are under development.

References: (Horváth et al., 2018)

Xanten, Germany

Storage	Natural gas	**Activity**	Active
Number of caverns	8	**Salt structure**	Bedded salts
Cavern depth	>1000m	**Commissioned in**	1985
Geometric volume	68000-299000 m^3	**Owner/operator**	Innogy

The caverns are located in the Werra Basin, close to the Dutch border. The salt here is 250m thick and the caverns were solution mined in the Untere Werrasalt, Z1. They have diameters of 65-95m and have heights of 39-80m. The caverns are part of the VGS InnEXPool project, which has a total working gas volume of 6.66 TWh.

References: (Horváth et al., 2018)

Udepur, India

Storage	Crude oil
Number of caverns	8
Size: height, diameter	Diameter:110m
Volume	550000 m^3

Activity	In proposal stage
Salt structure	Bedded salts
Commissioned in	-
Owner	

There is a proposal for storage caverns in the Nagaur-Ganganagar basin, located near Udepur. The caverns would lie at a depth of 630-750m. The proposal shows 2 phases of development, at first 4 caverns will be leached followed by another leaching phase creating 4 additional caverns.

Nanda et al. shows some thought went into the sourcing of the necessary water, to be used during oil operation.

"While the leaching operation is planned to be carried out by sourcing slightly saline ground water from the shallow aquifer, the brine disposal has been contemplated through solar evaporation in shallow basins and removal of solid salt. However, for commercial oil operation, sourcing of saturated brine (to be used for compensation of withdrawing oil) is being secured through a combination of 'donor caverns' and above ground storage in a brine pond." (Nanda, 2016)

References: (Horváth et al., 2018; Nanda, 2016)

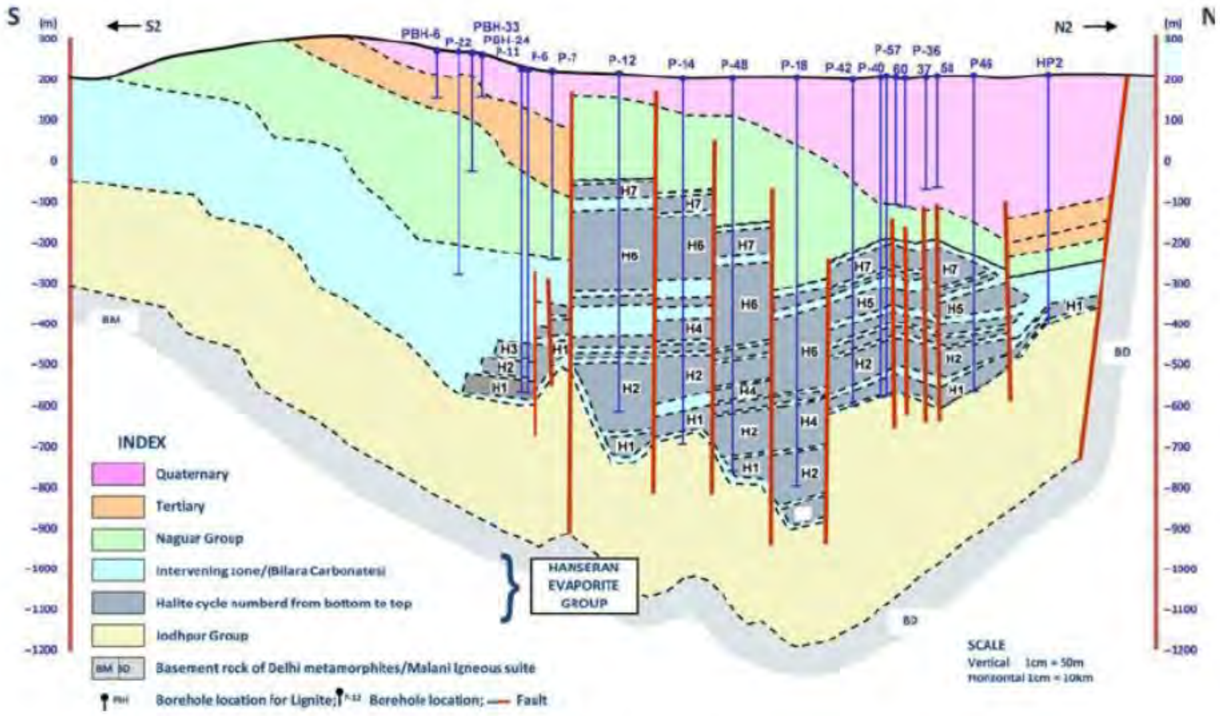

Figure 28 Nagaur-Ganganagar basin cross section, from (Cozzi et al., 2012).

Kirkuk, Iraq

Storage	Oil
Number of caverns	5
Size: height, diameter	70m, 70m
Capacity	286000 m^3

Activity	Active
Salt structure	Bedded salts
Commissioned in	1982
Owner	Gaz de France

In the Zagros basin, near Kirkuk Gaz de France has 5 storage caverns. The bedded salts of the Kirkuk salt sub-basin consist of two tertiary halites of Miocene age. These layers are at depths of 185-200m and 260-320m. The shapes of the caverns are reported to be irregular and slightly isometric.

References: (Al-Sulaiman et al., 2017; Horváth et al., 2018; Leroy, 1985)

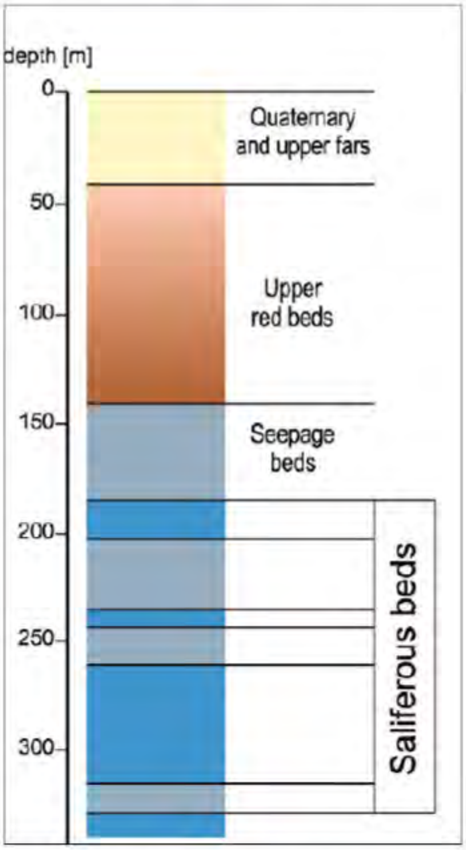

Figure 29 Borehole logs from a Kirkuk cavern, from (Leroy, 1985)

Isthmus of Tehuantepec basin, Mexico

Storage	1. Crude oil 2. Liquid hydrocarbons
Number of caverns	1. 12 2. 1 (3 more for brine production)
Cavern depth	1. 750-1050m 2. Casing shoe depth: 1161-1433m
Volume	1. 140000-200000 m^3 2. 40000-290000 m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1. 1984 2. 2013
Operator	1. Petroleos Mexicanos (Pemex) 2. Almacenamientos Subterráneos del Sureste, SA de CV

The Isthmus of Tehuantepec salt basin contains several domes, one of which is used for cavern storage. This dome, the salt dome of the Isthmian salt basin, is host to 13 storage caverns, 12 of which are operated by Petroleos Mexicanos, near Tuzandepetl. These caverns store crude oil. In a nearby town, Ixhuatlan del Sureste, the other operator, Almacenamientos Subterráneos del Sureste, SA de CV, has a cavern for the storage of Liquid Hydrocarbons.

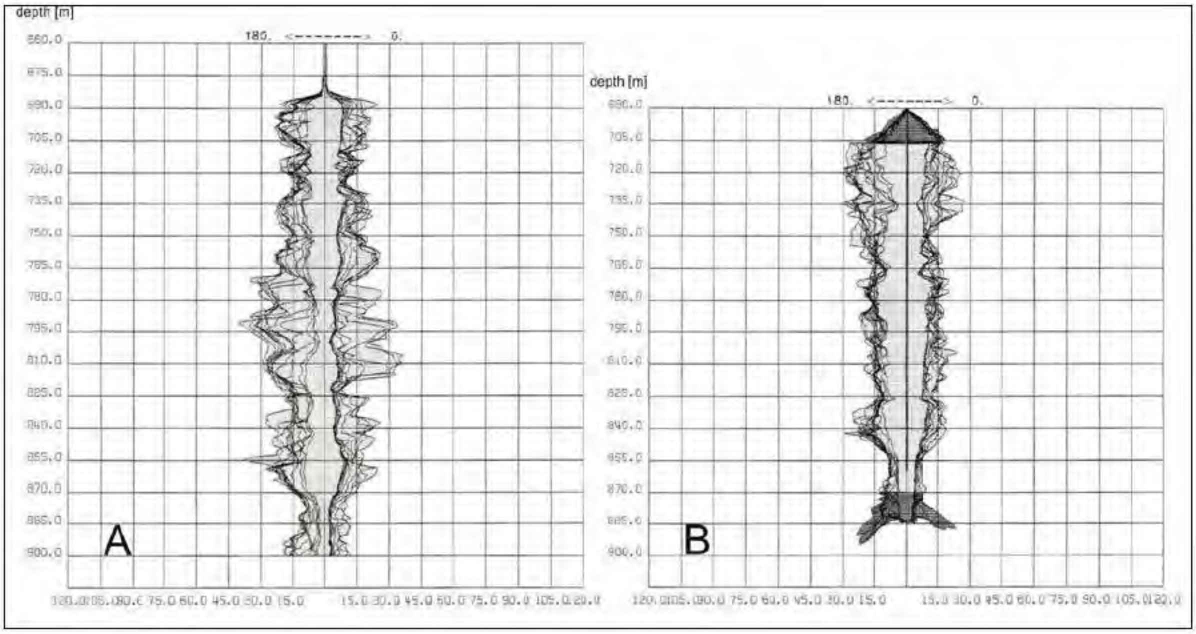

Figure 30 Tuzandepetl cavern storage, from (Garcia et al., 1995).

References: (Garcia et al., 1995; Horváth et al., 2018)

Sidi Larbi, Morocco

Storage	Hydrocarbons (Butane)
Number of caverns	2 (3?)
Owner	SOMAS

Activity	Active
Salt structure	Bedded salts
Commissioned in	1970s

In the bedded salts near Mohammedia, 30km southeast of Casablanca, cavern storage of hydrocarbons is active since the 1970s. The Upper Triassic salts are 265-542m deep and have a thickness of 180m. In the upper section these salts contain high proportion of clays, while the lower section salt has very pure 97-99% NaCl content. A third cavern was under construction.

The brine that was produced during leaching was evaporated and used industrially.

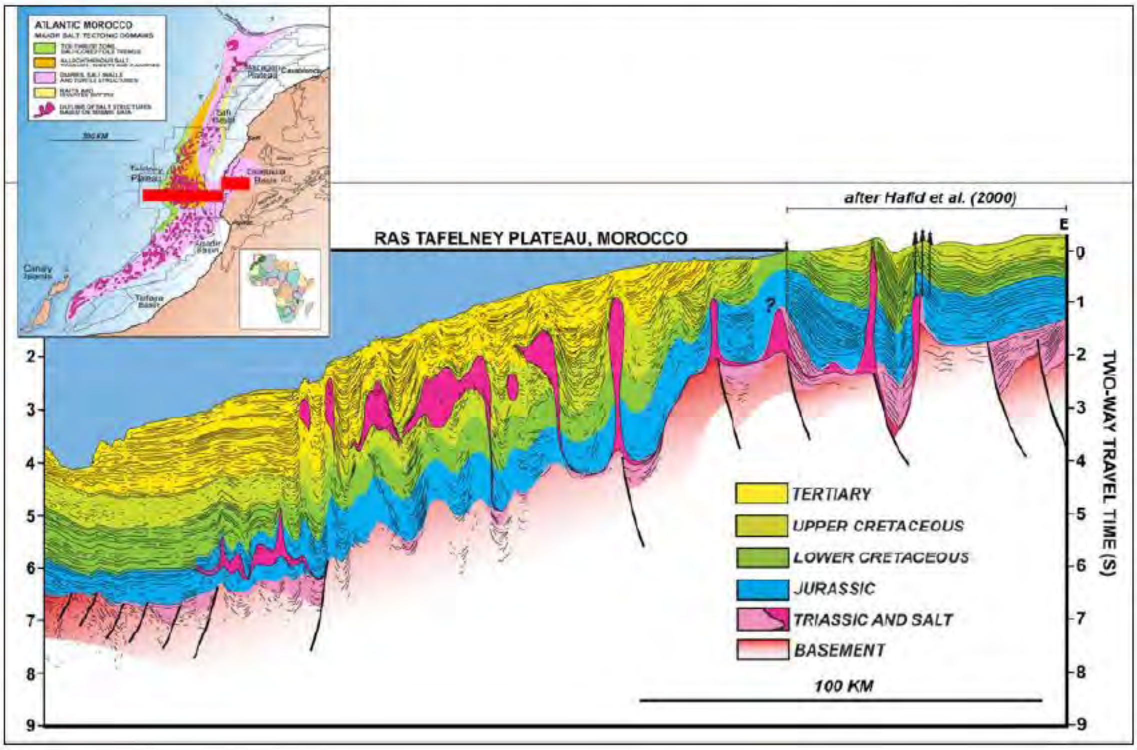

Figure 31 Cross section of offshore morocco, showing complex salt structures, from (Tari & Jabour, 2008).

References: (Horváth et al., 2018; Tari & Jabour, 2008)

Heiligerlee, The Netherlands

Storage	Nitrogen
Number of caverns	1
Depth	1016-1510m
Volume	0.86mln m3, 36mln m3 working gas

Activity	Active
Salt structure	Salt dome
Commissioned in	2012
Owner	Nederlandse Gasunie

The southern part of the Winschoten salt dome (near Heiligerlee) is host to a cavern for the storage of Nitrogen (for the use of transforming High caloric gas to Low caloric gas). The salt dome consists of Zechstein salts. Cavern HL-K was converted for this storage.

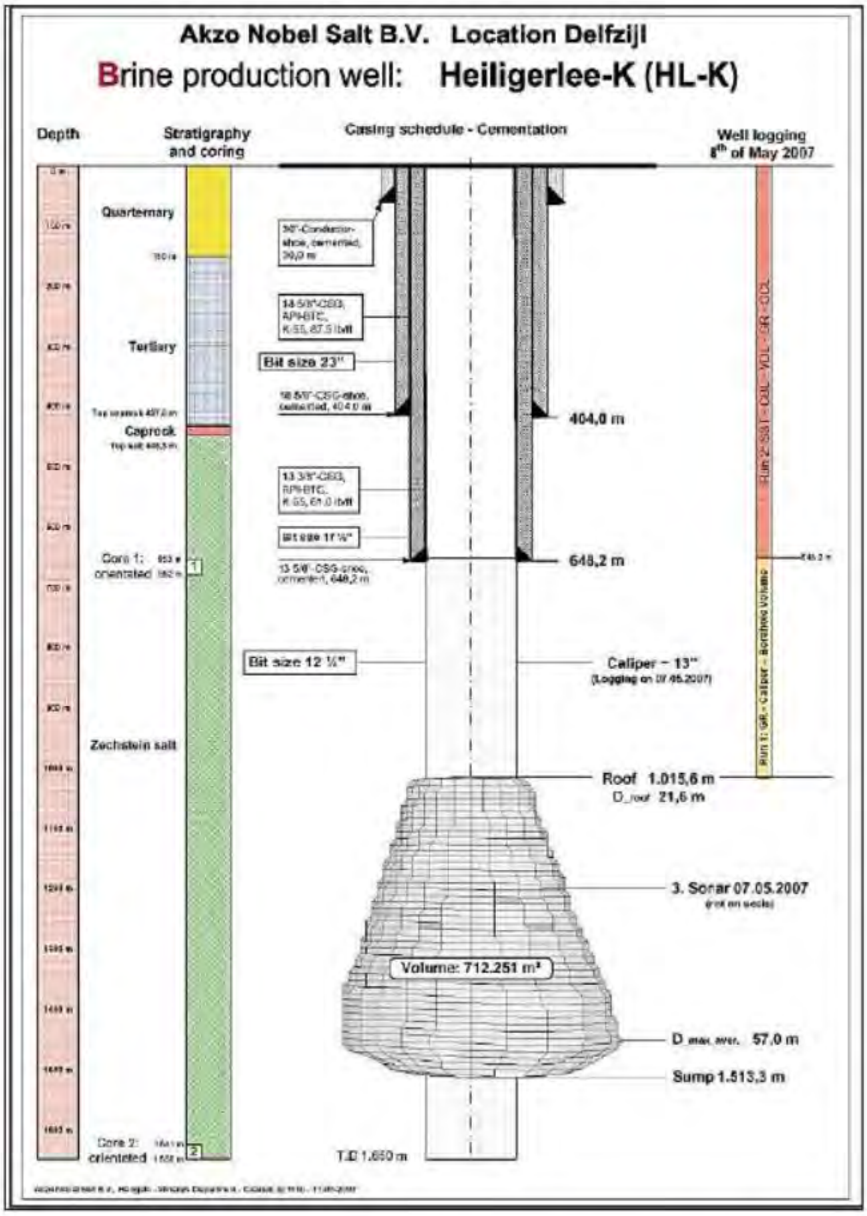

Figure 32 Heiligerlee cavern and casing schedule for nitrogen storage, from (Wagler & Draijier, 2013).

References: (Horváth et al., 2018; Wagler & Draijier, 2013)

Marssteden dieselstorage, The Netherlands

Storage	Diesel
Number of caverns	2
Depth	400-500m
Cavern volume	300000 m^3 each

Activity	Active
Salt structure	Bedded salts
Commissioned in	2010
Owner/operator	COVA (owns the petroleum)/ Nobian(/ Argos)

Near the city of Enschede, in Marssteden lie 2 caverns which store diesel for freight traffic. 250000 m3 of diesel is stored. The caverns are leached in a 50m thick salt bed.

References: www.sodm.nl

Figure 33 De Marssteden Dieselstorage, surface infrastructure, photograph taken by Wim Eising.

Zuidwending, The Netherlands

Storage	Natural gas		**Activity**	Active
Number of caverns	6		**Salt structure**	Salt dome
Depth	500-1600m		**Commissioned in**	2010
Working volume	300mln m^3		**Owner**	EnergyStock (Gasunie)

The Zuidwending salt dome near Veendam hosts 6 caverns for natural gas storage. The salts in the dome are Zechstein salts.

References: (Horváth et al., 2018), www.sodm.nl

Zuidwending CAES, The Netherlands

Storage	CAES		**Activity**	In planning phase
Owner	Corre Energy Storage bv		**Salt structure**	Salt dome
Depth	500-1600m		**Commissioned in**	2024/2025

There is another project in the Zuidwending salt dome, initiated by Corre Energy Storage bv, starting in 2024-2025, there are plans for compressed air energy storage. The cavern(s) will be leached for storage.

References: (Horváth et al., 2018), Corre Energy Storage

Zuidwending Hydrogen, The Netherlands

Storage	Hydrogen
Number of caverns	1 cavern and 1 separate well
Depth	500-1600m

Activity	In planning phase
Salt structure	Salt dome
Owner	Gasunie

Another project in the Zuidwending salt dome is currently in testing phase, initiated by Gasunie. There are plans for hydrogen storage. There are currently tests conducted on well 8A, if these tests are successful, cavern 5A will be used for further tests.

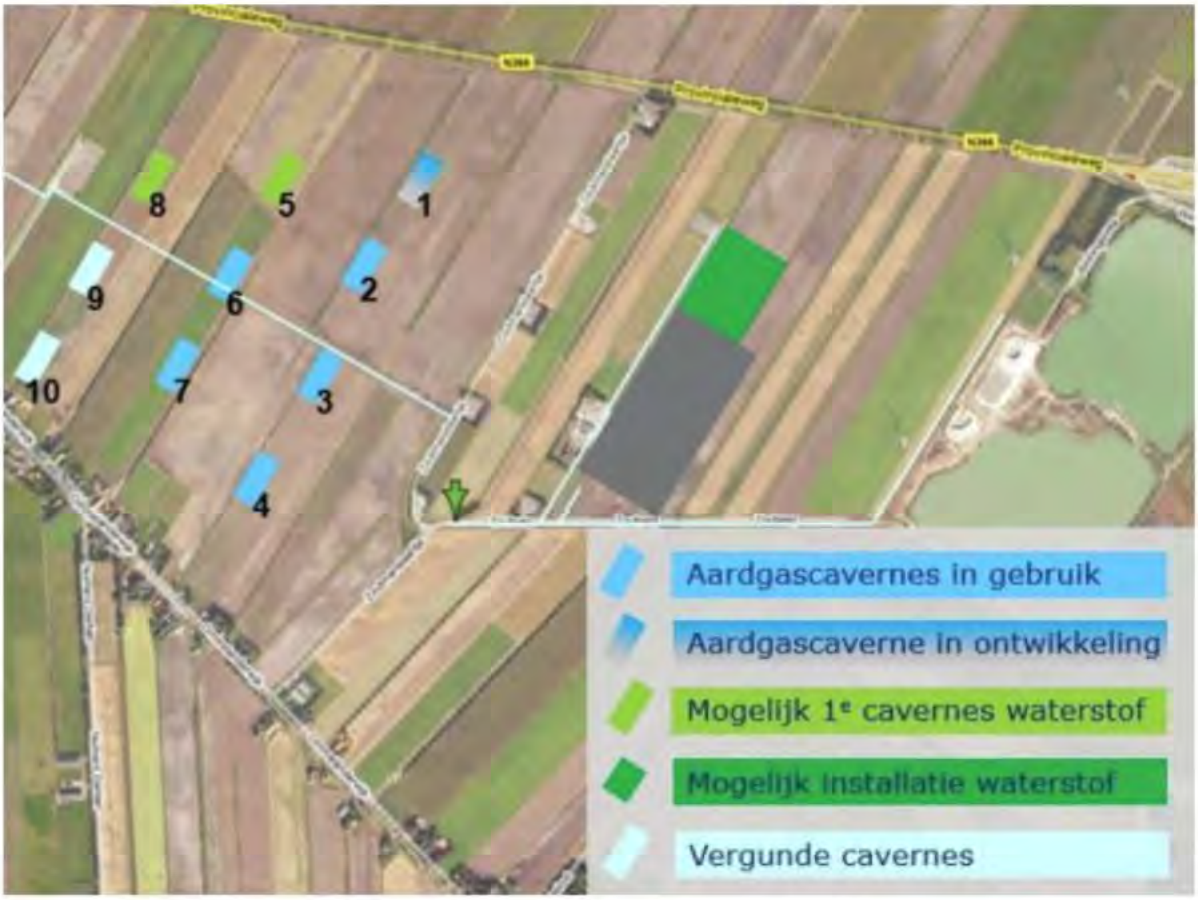

Figure 34 Zuidwending cavern field, where caverns 2,3,4,6,7 are used for natural gas storage, caverns 5 and 8 are being used for tests for hydrogen storage, from www.agbzw.nl.

References: (Horváth et al., 2018), www.agbzw.nl

Góra, Poland

Storage	Crude oil and fuel	Activity	Active
Number of caverns	7	Salt structure	Salt dome
Depth	400-700m	Commissioned in	2002, 2006
Cavern volumes	290000-580000 m^3	Owner	Inowroclaw Salt Mines "Solino" S.A.

A circular salt dome (800m diameter and 250m deep) which is part of the Central European Basin / Southern Permian Basin of Poland near Góra contains 7 caverns which were originally used for exploitation of salt. The caverns were leached in Z2 salt with a NaCl content of up to 97%. The caverns are irregularly shaped due to the heterogeneity of the salt. The salt contains insoluble sulfate rocks, coarse grained halites and K-Mg evaporites. Three new caverns should have been leached and ready for storage since 2006.

References: (Cyran, 2020; Horváth et al., 2018; Mrozinski, 2004)

Figure 35 Gorá salt dome cross section, from (Cyran, 2020).

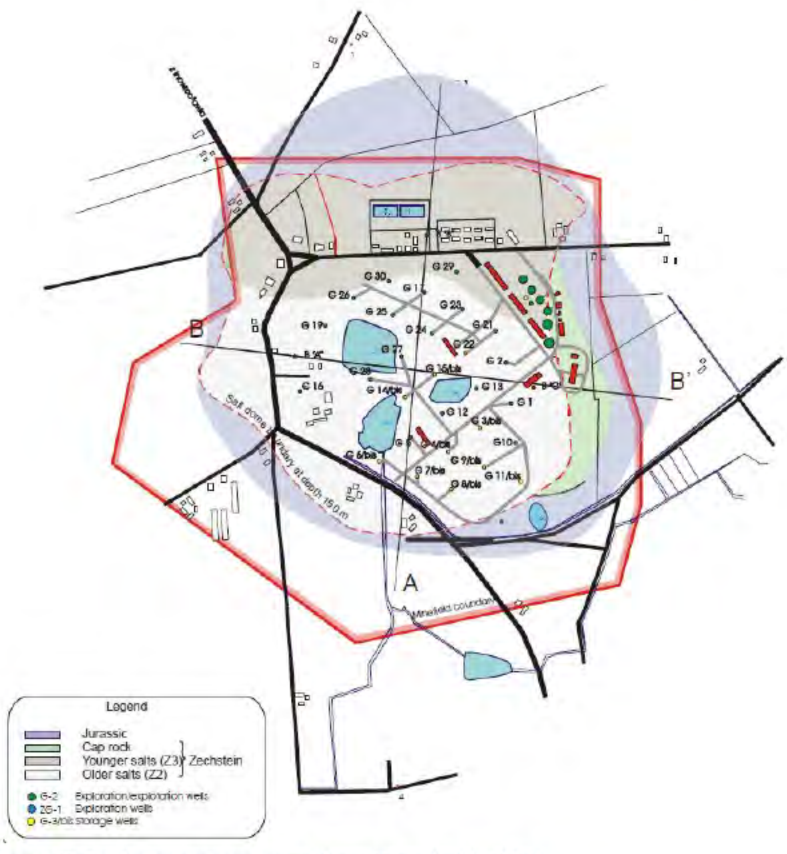

Figure 36 Gorá storage area map, from (Mrozinski, 2004).

Kosakowo, Poland

Storage	Gas (High-Methane)
Number of caverns	2
Depth	1.035-1.158m
Working volume	1.64 TWh

Activity	Active
Salt structure	Bedded salts
Commissioned in	2014
Owner	Gas Storage Poland

The caverns in Kosakowo, near Gdansk are part of the GSF Kawerna project and are situated in the Central European Basin / Southern Permian Basin of Poland. The caverns were leached in the Mechelinki salt deposit. The salt is homogeneous with NaCl contents of 96.7-97.8%. There are plans to build 10 storage caverns.

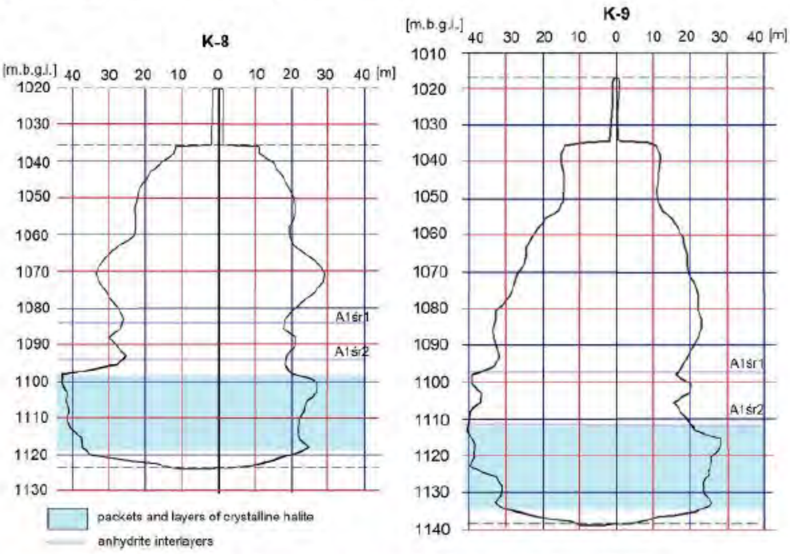

Figure 37 Cross section of caverns K-8 and K-9, from (Cyran, 2020).

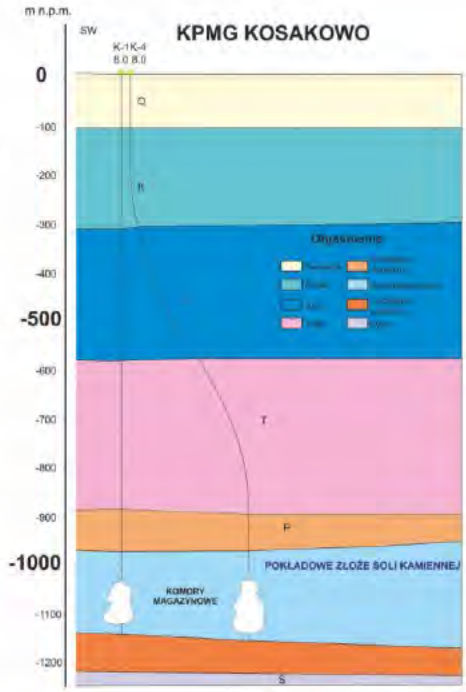

Figure 38 Cross section of the Mechelinki salt deposit, from Gas Storage Poland.

References: (Cyran, 2020; Horváth et al., 2018)

Mogilno, Poland

Storage	Gas	Activity	Active
Number of caverns	11	Salt structure	Salt dome
Depth	600-1600m	Owner	Gas Storage Poland
Capacity	586mln m³ (working volume: 6.24 TWh)		

The caverns in the Mogilno salt dome (4.5km long, 600m wide, 250m depth) are situated in Zechstein salts. The dome is part of the Central European Basin/ Southern Permian Basin of Poland. The caverns are part of the GSF Kawerna project. The heterogeneity of the salts made the caverns have irregular shapes. The wide variety of depths and storage capacities of the caverns are associated with the heterogeneity of the salt dome. The distance between the wellheads is 250m. 3 additional caverns are being formed through leaching.

In the nearby town of Damasławek, there are plans to make gas storage caverns by GAZ System, they will be under construction in 2026 and are supposed to have a working volume of 9.00TWh.

References: (Cyran, 2020; Horváth et al., 2018; Kosciuszko, 1997; Ślizowski et al., 2009)

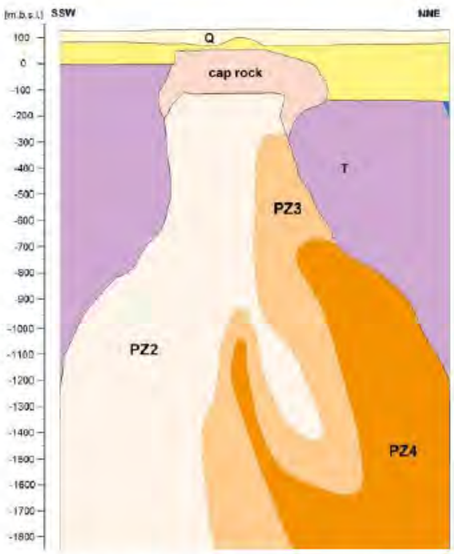

Figure 39 Mogilno salt dome cross section, showing the different geologies present, where PZ4, PZ3 and PZ2 represent, respectively, Youngest Halite, Younger Halite and Older Halite. from (Cyran, 2020).

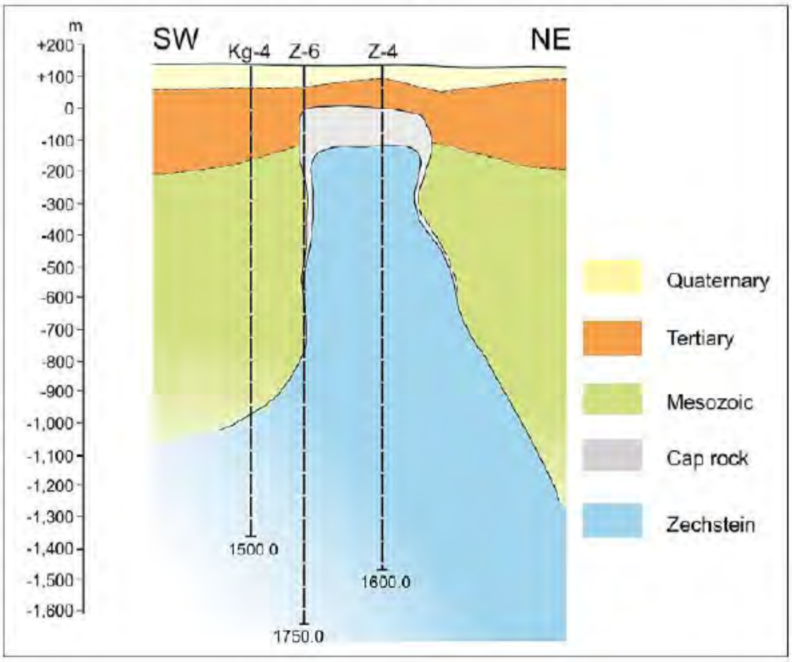

Figure 40 Mogilno salt dome cross section showing the depths of caverns Kg-4, Z-6, Z-4, from (Kosciuszko, 1997).

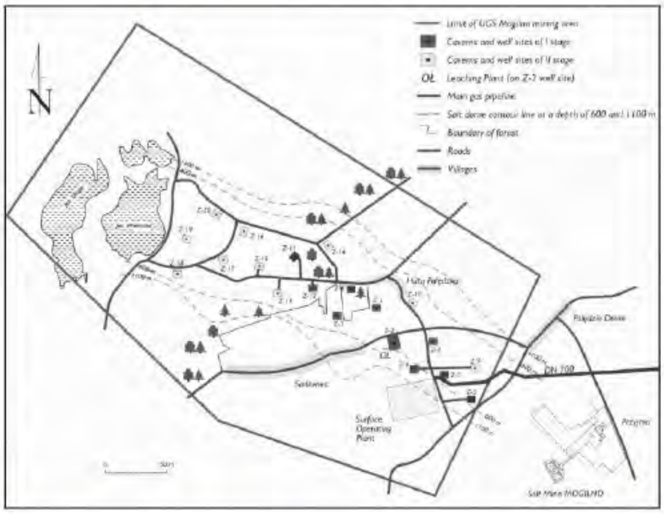

Figure 41 Map of the Mogilno caverns, from (Ślizowski et al., 2009).

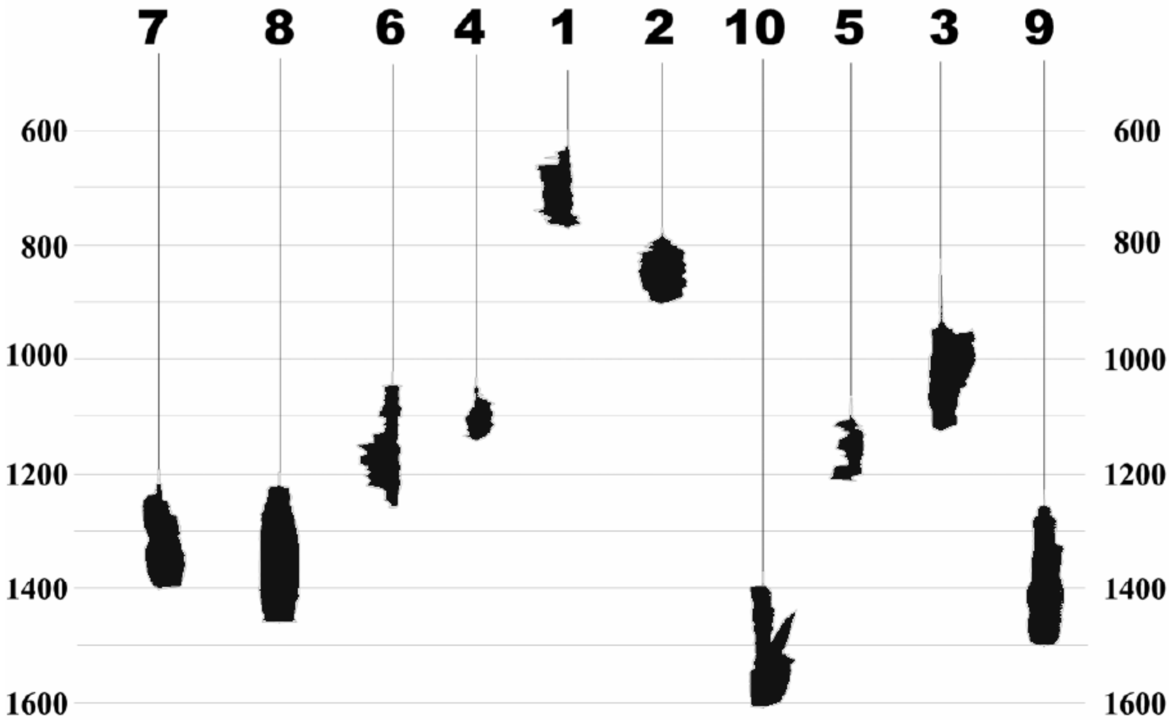

Figure 42 Showing cavern depths as well as 2D shapes, from (Ślizowski et al., 2009).

Carriço, Portugal

Storage	Natural gas and LNG
Number of caverns	6
Depth	900-1500m
Working volume	3.57 TWh

Activity	Active
Salt structure	Diapiric salt wall
Commissioned in	2003
Owner	REN Armazenagem (former owner: Transgás)

In Sines, Carriço, 18km south of Figueira da Foz, 6 gas storage caverns are inside the Monte Real salt structure, it is not a salt dome, nor is it a bedded salt. This is a 2km thick diapiric salt wall. The lithology is described as a salt breccia, because the salt formation is a highly disturbed mass of salt with insoluble intercalations; which are the result of a long sequence of tectonic events. These intercalations consist of anhydrite, dolomite and claystone and together make up about 10% of the rock salt formation. Two of the caverns were formerly salt extraction sites. There is no more brine production since the leaching of the final cavern for storage.

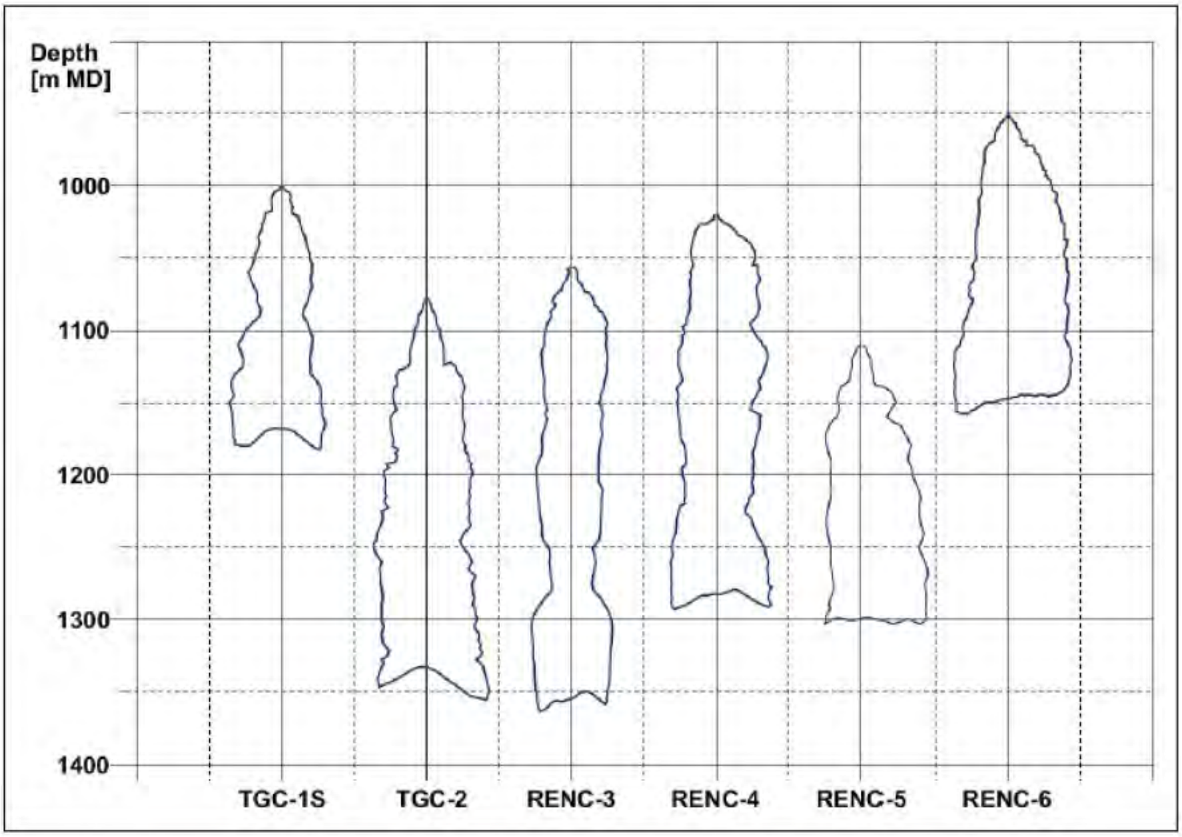

Figure 43 Cross section of the caverns located in Carriço, from (Horváth et al., 2018) and references therein.

References: (Horváth et al., 2018)

Astrakhan, Russia

Storage	Gas condensate		Activity	Inactive, abandoned

In the Caspian Sea region storage took place in salt caverns created by nuclear explosions. It was used to store gas condensate. An incident occurred, leading to the abandonment of the cavern(s).

References: (Evans, 2008)

Kaliningradskoye, Russia

Storage	Gas
Number of caverns	2
Working volume	2.87 TWh

Activity	Active
Commissioned in	2013
Owner	GAZPROM2

As of 2013, there are 2 gas storage caverns in Kaliningradskoye, Kaliningrad, there will be up to 5 caverns and all caverns will be expanded to 400000m3 (the two caverns currently have individual volumes of 230000m3). The caverns lie in the Central European Basin in a 160m thick Zechstein salt deposit. This deposit lies at a depth of 860-1030m.

References: (Horváth et al., 2018)

Karachaganak, Russia

Storage	Gas condensate		Activity	Inactive, abandoned

In the Caspian Sea region storage took place in salt caverns created by nuclear explosions. It was used to store gas condensate. An incident occurred, leading to the abandonment of the cavern(s).

References: (Evans, 2008)

Orenburg, Russia

Storage	Helium gas
Number of caverns	5 or 6
Depth	1350-1470m

Activity	Active
Commissioned in	1991
Owner	GAZPROM

In 1978 construction started on the leaching of 5 or 6 caverns for the storage of helium gas in the Cisuralian basin. The caverns are situated in Permian salt deposits near Orenburg.

References: (Horváth et al., 2018)

Angara Lena salt basin, Russia

Storage	Liquid hydrocarbons
Number of caverns	>3
Volume	Ziminskaya: 59000 m^3 total Usolskaya: 40000-50000 m^3 individual caverns

Activity	Active
Salt structure	Bedded salts

Two areas in the Angara Lena salt basin are used for storage, Ziminskaya area near the town of Zima and Usolskaya area near the town of Usolye Sibirskoye. The caverns in these areas are leached in a salt bearing section of early Cambrian age (Usolskaya Suite) which contains individual beds separated by insoluble layers of a few meters thick (Kazaryan et al., 2007). There are 3 caverns in the first area, located in an individual salt bed of a thickness of about 20m, at a depth of 1300-1325m. The second area contains several caverns in an individual salt bed of about 50m thick at a depth of 1060-1140m.

Figure 44 Salt basin of Angara-Lena, black line shows the contours of the basin, from (Kazaryan et al., 2007)

References: (Horváth et al., 2018; Kazaryan et al., 2007)

Les Pinasses, Spain

Storage	Gas
Working volume	2.7912 TWh

Activity	Planned
Commissioned in	2022
Owner	Naturgy Energy Group

There are plans by Naturgy Energy Group to store gas in caverns in the area north of Barcelona.

References: www.gie.eu

Tarsus/Mersin, Turkey

Storage	Gas		**Activity**	Under construction
Number of caverns	Up to 48		**Salt structure**	Bedded salts
Salt depth	900-1300m		**Owner**	Gazdepo A.S./Toren (subsidiaries of BENDIS)
Working volume	45.60 TWh			

In southern Turkey, near the city of Tarsus bedded salts of the Adana basin will be utilized to leach up to 48 caverns. The salt deposit is about 600m thick and contains 15% insolubles.

References: (Horváth et al., 2018), www.gie.eu

Tuz gölü, Turkey

Storage	Natural gas
Number of caverns	6 (6 more caverns are being leached)
Cavern depth	1000m
Working volume	2017: 6.27 TWh 2020: 7.41 TWh 2023: 47.88 TWh

Activity	Active
Salt structure	Salt body with diapiric shapes, caverns inside the autochthonous salt
Commissioned in	2017
Owner	BOTAŞ Petroleum Pipeline Corporation

South of the salt lake (Tuz gölü means salt lake), a salt body with a width of 2-2.5km and a length of 15km is present. The salt has a thickness of about 1500m and the top of the salt lies at a depth of 600m. There are diapiric salt shapes underneath the salt lake, which are thought to be the result of upwards leakage of brine along fractures. The caverns are leached by Geostock, 6 are currently in use for storage and 6 more caverns are being constructed. The brine that is produced is discharged to lake Tuz Gölü.

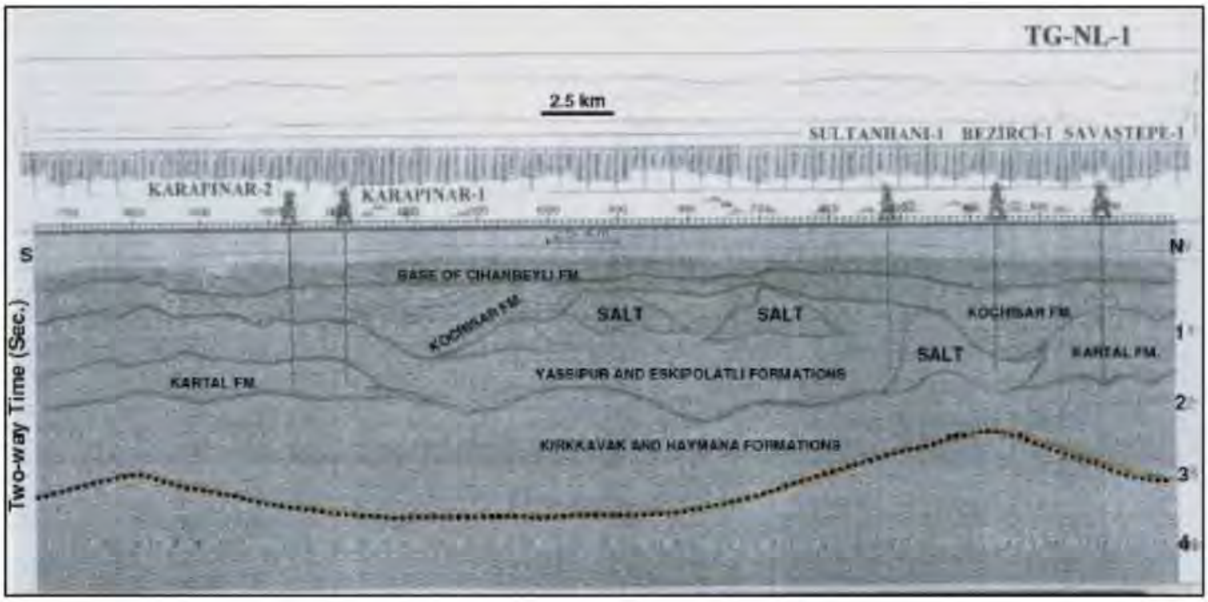

Figure 45 Seismic line cross section of the Tuz Gölü basin, from (Aydemir & Ates, 2006).

References: (Aydemir & Ates, 2006; Horváth et al., 2018), www.gie.eu

Aldbrough, United Kingdom

Storage	Natural gas
Number of caverns	9
Working volume	200mln m^3

Activity	Active
Commissioned in	2009
Owner	Scottish and Southern Energy (SSE) & Statoil

In Aldbrough, East Yorkshire, north of Hull, 9 caverns for natural gas storage are operated. They are situated in the Central European Basin in Zechstein 2 salt, the Fordon formation.

References: (Horváth et al., 2018)

Atwick/Hornsea, United Kingdom

Storage	Natural gas		**Activity**	Active
Number of caverns	9		**Salt structure**	
Cavern depth	1730-1830m		**Commissioned in**	1979
Working volume	325mln m^3		**Owner**	Scottish and Southern Energy (SSE)

Close to the Aldbrough storage lies the Atwick/Hornsea cavern field. The salt in this field is also part of the Central European Basin and the caverns were leached in Zechstein 2 salt.

References: (Horváth et al., 2018)

Warmingham, United Kingdom

Storage	Gas
Number of caverns	1. 4 2. 7
Cavern depth	1. 300-400m 2. 237-350m
Working volume	1. 25mln m^3 2. 56mln m^3

Activity	Active
Fields	1. Hole House 2. Hill Top Farm
Commissioned in	1. 2001 2. 2015
Owner	EDF Trading

South of Cheshire lie the cavern fields Hole House and Hill Top Farm. The Warmingham brinefield is part of the Cheshire basin. The caverns lie in Triassic salts, in the Northwich Halite. The caverns have diameters of 120-170m and heights between 38-89m. 5 caverns in this field are partly abandoned.

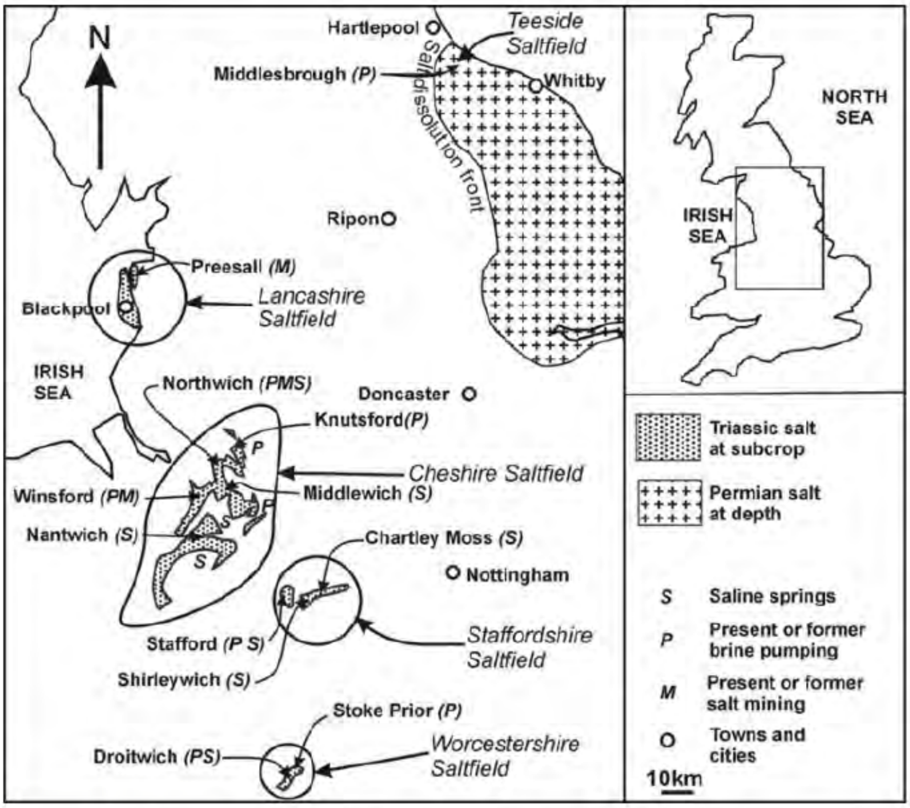

Figure 46 Map showing the salt distribution of the northern part of England, from (Cooper, 2002).

References: (Cooper, 2002; Horváth et al., 2018), www.gie.eu

Chesire, United Kingdom

Storage	Gas 6.Hydrocarbon:Ethylene
Number of caverns	1. 8 2. 8 3. Up to 28 4. 10 5. 19 6. 2
Cavern depth	1. 630-730m 2. 550-700m 3. 600-650m
Working volume	1. 2.28 TWh 2. 1.95 TWh 3. 220mln m^3 4. 6.21 TWh 5. 5.7 Twh 6.

Activity	Active
Field names	1. Holford GS 2. Holford Uniper 3. Stublach 4. Cheshire KSE 5. Holford Brinefield 6. Holford
Salt structure	Bedded salts
Owner	1. E.ON (since 2012) 2. Uniper (since 2014) 3. Storengy (since 2014) 4. King Street Energy (since 2020) 5. KGSP (since 2020) 6.

The Cheshire basin is widely used for cavern storage for mostly gas, (only field 6, Holford, has 2 caverns for the storage of Ethylene). All caverns are leached in Triassic salts of the Northwich Halite. The cavern field of E.ON (Holford GS), Storengy (Stublach) and KGSP (Holford brinefield) are known to be adjacent to each other, and have wellhead spacings of 280-300m. The caverns operated by E.ON and Storengy have heights of 100m and diameters of 90-100m. The Uniper caverns have heights of 60-80m and diameters of 80-100m. Expansions of several fields are ongoing, for example, the field operated by Storengy was planned to have a working volume of 0.4 bcm by 2020. One cavern in Holford was converted from brine production to natural gas storage (cavern Holford H-165), with a volume of 175000m^3.

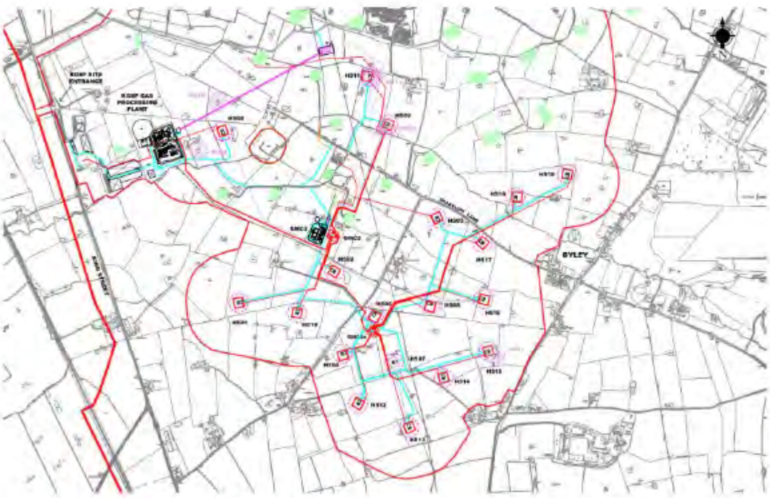

Figure 48 Map showing the KGSP field, from www.kgsp.co.uk.

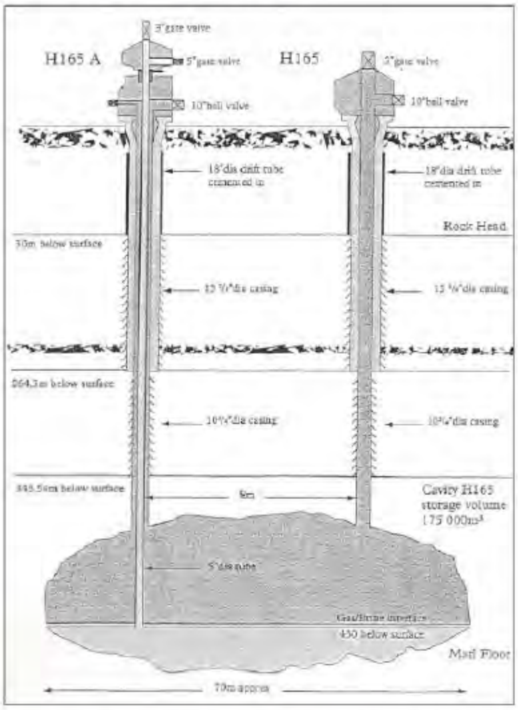

Figure 47 Cross section showing cavern Holford H165, from (Horváth et al., 2018).

References: (Horváth et al., 2018), www.gie.eu , www.kgsp.co.uk

Larne, United Kingdom

Storage	1. Natural gas 2. CAES		**Activity**	In construction phase
Cavern depth	1. 1500m		**Salt structure**	Bedded salts
Working volume	1. 1.9 TWh		**Commissioned in**	2021-
			Operator	1. Infrastrata 2. Gaelectric Energy Storage Ltd (GES)

2 Operators have plans for the storage of natural gas and CAES in Northern Ireland. The caverns of Infrastrata will be near Islandmagee and those of Gaelectric Energy Storage Ltd will be leached near Larne. Both cavern fields will be leached for storage in Permian salt beds. The salt in this region lies 1300m below the surface and has a thickness of 200m.

References: (Horváth et al., 2018)

Lancashire, United Kingdom

Storage	Natural gas		**Activity**	Active
Working volume	6.84 TWh		**Commissioned in**	2020
			Owner	Halite Energy

Halite Energy owns a cavern field in Lancashire, with a total working volume of 6.84 TWh.

References: www.gie.eu

Morecambe bay, United Kingdom

Storage	Natural gas
Working volume	17.1 TWh

Activity	Planned
Owner	Stag Energy

There are plans for an offshore cavern field for natural gas storage by Stag Energy.

References: www.gie.eu

Saltholme/Teesside, United Kingdom

Storage	1. Natural gas (44 caverns), Nitrogen (1 cavern), Hydrocarbons (14 caverns) 2. Hydrogen 95% (3 caverns at Teesside)	**Activity**	Active
Number of caverns	61	**Salt structure**	Bedded salt
Cavern depth	2. 350-450m	**Commissioned in**	2. 1972
Working volume	2. 210000 m^3	**Owner**	1. INEOSChlor/SABIC Petrochemicals 2. SABIC Petrochemicals

In the Central European Basin, north of Middlesbrough two operators have caverns for the storage of several products. The caverns were leached in the Boulby Halite formation, in the northern field of Middlesbrough, called Saltholme. 4 caverns in the field operated by INEOSCHlor/SABIC Petrochemicals were converted for gas storage by Huntsman. The hydrogen storage is called Teesside, and contains 95% Hydrogen in elliptically-shaped caverns which have individual volumes of 70000m3.

References: (Caglayan et al., 2020; Horváth et al., 2018; Zivar et al., 2020)

Wilton, United Kingdom

Storage	1. Natural gas, Hydrocarbons 2. Nitrogen	**Activity**	Active
Number of caverns	1. 5 caverns for natural gas, 5 caverns for hydrocarbons 2. 2 caverns	**Salt structure**	Bedded salt
		Operator	1. SABIC Petrochemicals 2. SembCorp/BOC

East of Middlesbrough lies the south field called Wilton. Both SABIC Petrochemicals and SembCorp/BOC operate caverns here. The cavern lie in the Central European Basin inside the Boulby Halite formation.

References: (Horváth et al., 2018)

McIntosh, Alabama, United States of America

Storage	1. Natural gas 2. CAES		**Activity**	Active
Number of caverns	1. 5 2. 1		**Salt structure**	Salt dome
Cavern depth	2. 450m		**Commissioned in**	1. 1992 2. 1991
Cavern volume	2. 56000 m^3		**Owner/ Operator**	1. Sempra LNG / Bay Gas storage company ltd. 2. Dresser-Rand group

The McIntosh salt dome in McIntosh, Washington county, Alabama contains caverns for the storage of natural gas and CAES. The dome lies in the Mississippi salt basin and can be described as a shallow, flat-topped piercement dome. The top of the salt lies at a depth of 122m, with a thin caprock on top of 0-40m. Above the caprock lie unconsolidated sediments.

References: (Horváth et al., 2018)

Goodyear, Arizona, United States of America

Storage	LPG (Propane)		Activity	Active?

Situated in Goodyear, Arizona lie cavern(s) for the storage of propane.

References: (Evans, 2008)

Luke salt body, Arizona, United States of America

Storage	Hydrocarbons (Butane, Propane)		**Activity**	Active
			Salt structure	Bedded salts

The Luke salt body near Glendale, Arizona consists of bedded salts that are 2-15mln years old. The salt body is thought to be at least 100 km2 with an average thickness of 1000m.

References: (Horváth et al., 2018)

Iowa city, Iowa, United States of America

Storage	HVL (highly volatile liquids)		**Activity**	Active?

The only storage location in Iowa hosts cavern(s) for the storage of HVL.

References: (Réveillère et al., 2017)

Conway, Kansas, United States of America

Storage	LPG (Propane), NGL
Caverns	Almost 300 (600 total in Kansas)
Cavern depth	Deeper than 120m

Activity	Active?
Salt structure	Bedded salts
Commissioned in	1951

The Conway field (situated in McPherson county) contains caverns for the storage of LPG and NGL, the salts are part of the Hutchinson Salt Member of the Permian Wellington formation.

References: **(Bérest et al., 2019; Ratigan et al., 2002; Réveillère et al., 2017)**

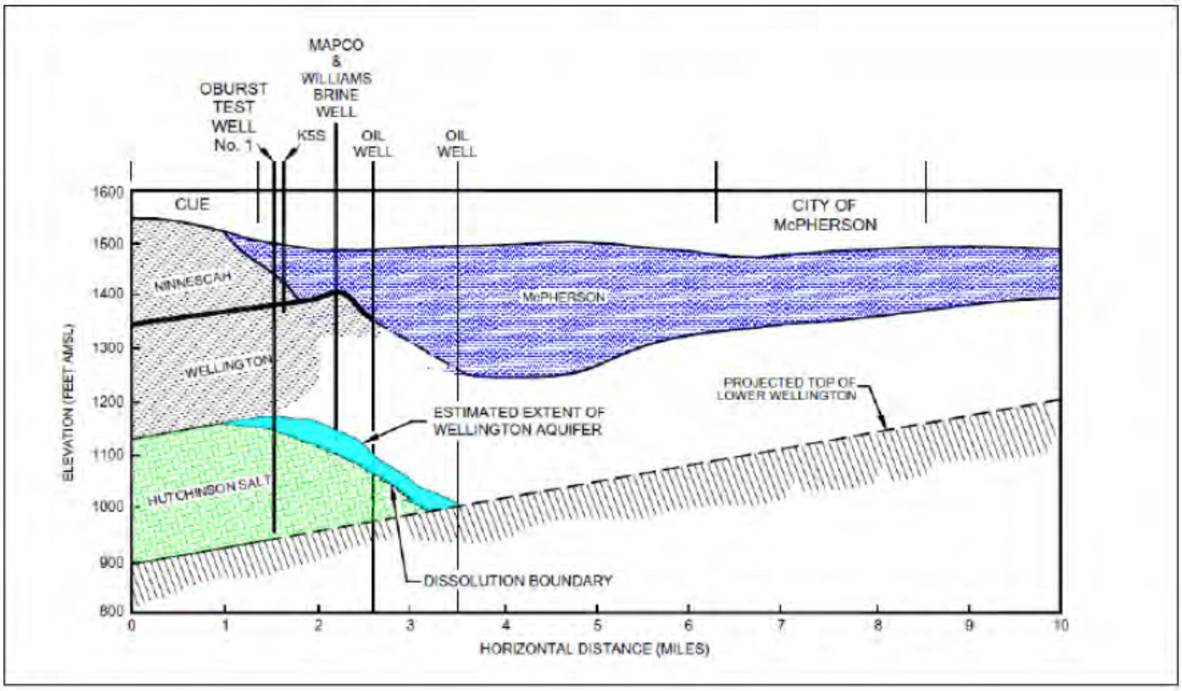

Figure 49 Cross section of the Williams-CUE facility, from (Ratigan et al., 2002).

Hutchinson, Kansas, United States of America

Storage	Natural gas
Caverns	
Cavern depth	200-280m

Activity	Active
Salt structure	Bedded salts
Commissioned in	1980s

The Hutchinson field in Kansas is home to storage caverns containing natural gas, the salts are made up of the lower parts of the Hutchinson Salt Member of the Permian Wellington formation. The caverns were abandoned, and later re-opened and filled with natural gas in the 1990s.

References: (Bérest et al., 2019; Kansas Geological Survey Website, 2001)

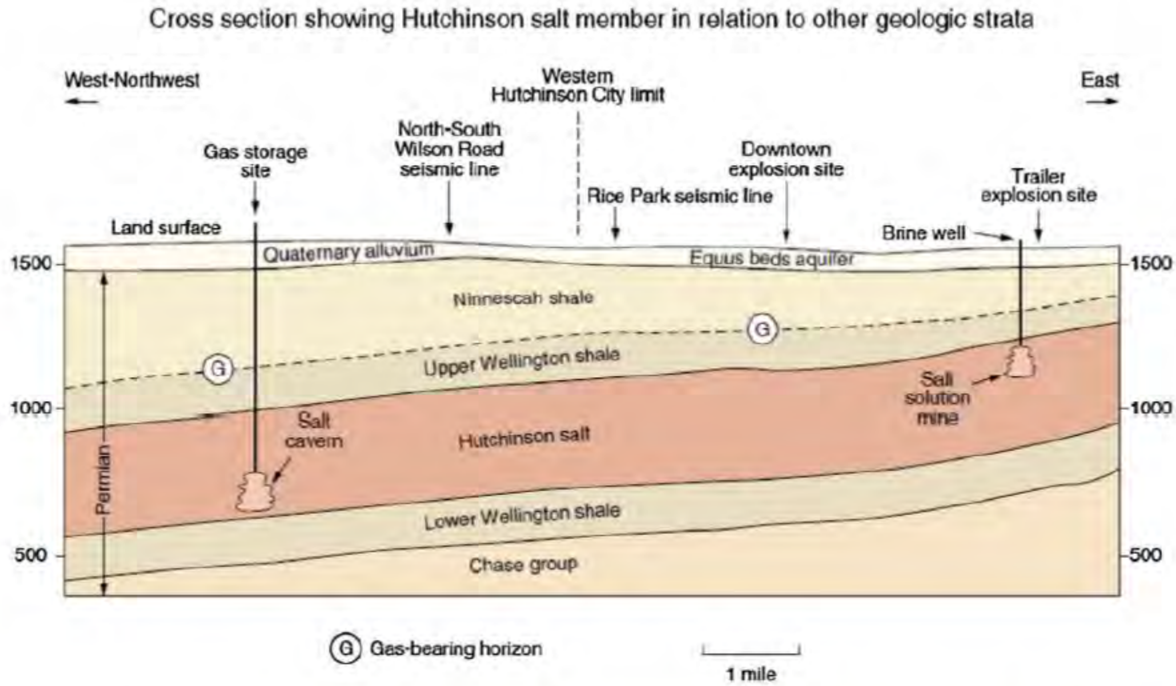

Figure 50 Hutchinson leakage pathway, elevation in feet. The leakage migrated along the dashed G-G line, which are fractured dolomite layers, from (Kansas Geological Survey Website, 2001).

Kansas, United States of America

Storage	Hydrocarbons (LPG)
Storage fields	9
Wells	382
Working volume	73mln barrels (US)

Activity	Active
Salt structure	Bedded salts
Operator	Several

Kansas contains 9 different storage locations for hydrocarbons, with 382 storage wells, which is more than any other U.S.A. state. 94 of these wells are in monitoring status. The caverns are leached in Permian salts: Hutchinson salt, Lower Cimarron salt and Blain salt. Brine production is also very active, in 2000, 2944000 tons of salt was produced.

References: (Horváth et al., 2018)

McPherson, Kansas, United States of America

Storage	LPG(Propane), HVL (Highly volatile liquids)	**Activity**	Active?
Operator	National Cooperative refinery association	**Commissioned in**	Before 1966

McPherson has cavern(s) for both the storage of LPG as well as HVL.

References: (Evans, 2008)

Yaggy, Kansas, United States of America

Storage	Natural gas

Activity	Active

Yaggy has cavern(s) for the storage of natural gas.

References: (Yang et al., 2013)

Yoder, Kansas, United States of America

Storage	LPG (propane)		**Activity**	Active?
Cavern depth	Deeper than 120m		**Salt structure**	Bedded salts
			Commissioned in	1951

Located in Yoder, Reno county, cavern(s) for the storage of propane exist. The caverns are situated in the Hutchinson salt member of the Permian Wellington formation.

References: (Bérest et al., 2019)

Anse la Butte, Louisiana, United States of America

Storage	Hydrocarbons (LPG)
Number of caverns	5

Activity	Active
Salt structure	Salt domal
Owner	Enterprise Products

In the St. Martin-Lafayette Parishs in Louisiana lies the Anse la Butte salt dome. This dome is part of the Texas-Louisiana coastal basin. The top of the salt lies at a depth of 42m.

References: (Horváth et al., 2018)

Bayou Choctaw, Louisiana, United States of America

Storage	Crude oil, Natural gas and Liquid hydrocarbons
Number of caverns	>6
Working volume	1. 76.0 million barrels (US)

Activity	Active
Salt structure	Salt dome
Commissioned in	1987
Owner/operator	1. US Department of Energy (DOE) / Fluor Federal Petroleum Operations 2. Boardwalk Partners

The Iberville Parish in Louisiana is home to storage caverns. The caverns are situated in an oval shaped dome that has a length of 1.4km and a width of 1.1km. The top of the salt lies at a depth of 192m. The 6 caverns of the US Department of Energy are operated by Fluor Federal Petroleum Operations, and are used for the storage of crude oil. These caverns are part of the Strategic Petroleum Reserve. The collapse of cavern BC-7 (Brine production, 1942-1954) created a sinkhole lake, this collapse was due to pressure loss when the cavern roof leached to the caprock bottom. BC-4 has been abandoned and faces similar dangers as BC-7 (its roof intrudes into the caprock).

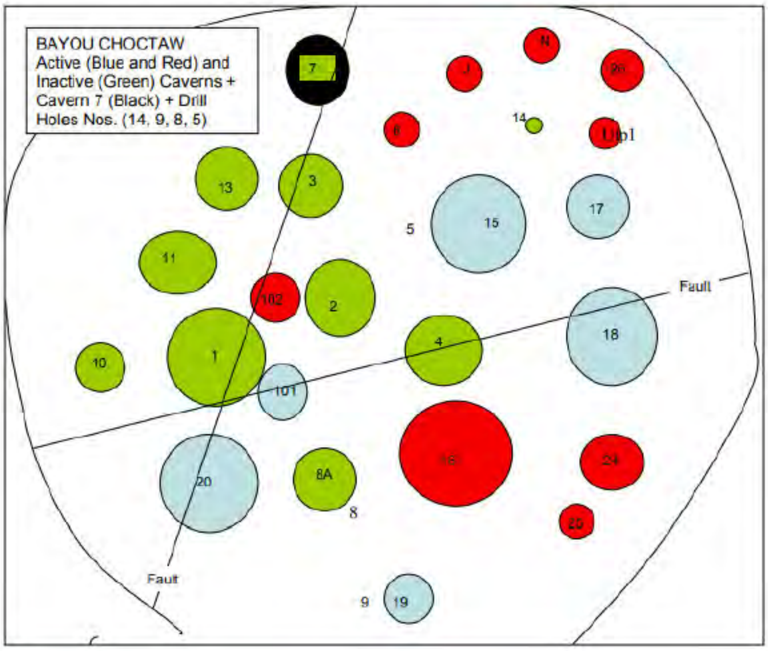

Figure 51 Schematic map of the Bayou Choctaw dome, from (Munson, 2007).

References: (Horváth et al., 2018; Looff, 2017; Munson, 2007)

Clovelly dome, Louisiana, United States of America

Storage	Crude oil and brine storage	Activity	Active
Number of caverns	8	**Salt structure**	Salt dome
Capacity	7mln m^3 (4mln m^3 in the brine storage reservoir)	**Owner**	Louisiana Offshore Oil Port (LOOP)

The Clovelly dome storage terminal in Lafourche Parish, Louisiana contains caverns for storage. The top of the salt lies at a depth of 370m. Most caverns have 5 wells for high inflow rates from super tankers.

Cavern 14 failed to pass its MIT in 1992, it was found that the cavern had an irregular shape.

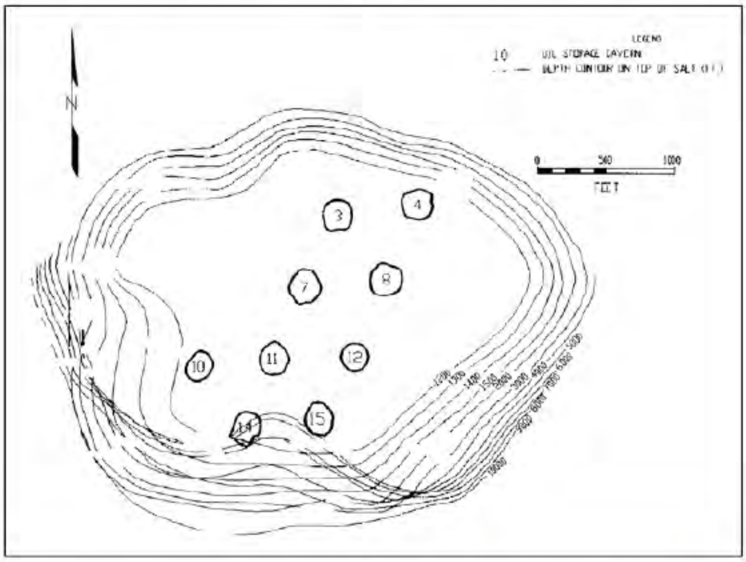

Figure 52 Map of the Clovelly salt dome, showing the storage caverns, from (McCauley et al., 1998).

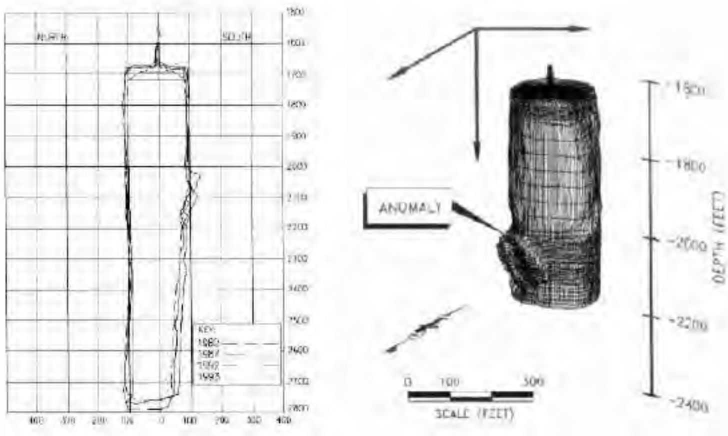

Figure 53 Cavern 14, irregular shape, from (McCauley et al., 1998).

References: (Brouard, 2019; Horváth et al., 2018; McCauley et al., 1998)

Crowville, Louisiana, United States of America

Storage	Natural gas
Number of caverns	2

Activity	Active
Salt structure	Salt dome
Owner	Perryville Gas Storage (affiliate of Cardinal Gas)

In Franklin Parish, Louisiana, lies the Crowville salt dome. It is situated in the Mississippi salt basin. The top of the salt lies at a depth of 245m. In 2017 a second cavern was added.

References: (Horváth et al., 2018)

Grand Bayou, Louisiana, United States of America

Storage	Natural gas	Activity	Active
Commissioned in	1970s	Salt structure	Elongated salt dome (Napoleonville salt dome)

Located in Napoleonville, just a few 100 meters from the bayou corne sinkhole, are caverns for the storage of natural gas. The Louann salt hosts the caverns and is of mid-late Jurassic origin. The caverns are part of the Magnolia hub.

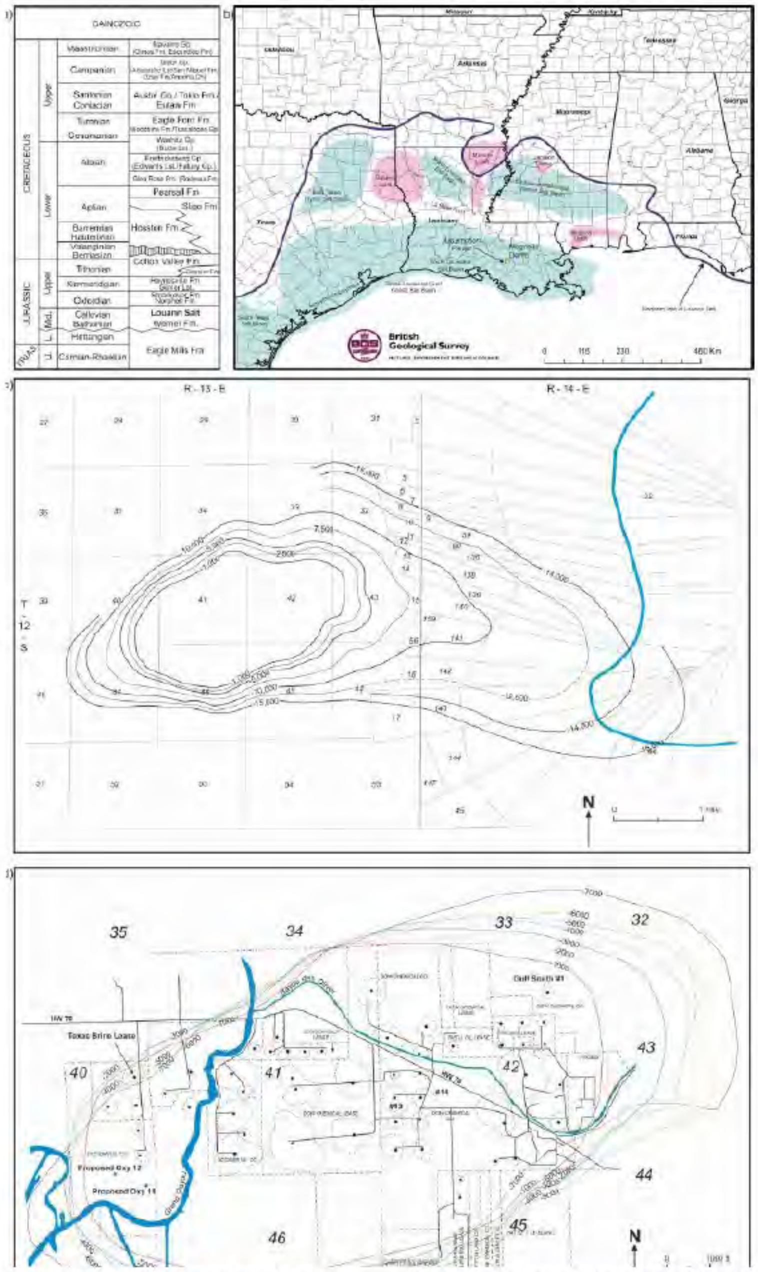

Figure 54 A: Stratigraphy of the Louann salt, B: Location of the Magnolia salt dome, C: Napoleonville salt dome structure map, D: Contour map of the Napoleonville salt dome, from (Réveillère et al., 2017) and references therein.

References: (Réveillère et al., 2017)

Jefferson island, Louisiana, United States of America

Storage	Natural gas	**Activity**	Active
Number of caverns	2	**Salt structure**	Salt dome
Working gas volume	161.4mln m^3	**Owner**	AGL Resources

In Iberia Parish, Louisiana, the Jefferson island salt dome is host to 2 caverns for the storage of natural gas. The top of the salt lies about 10 meters below the surface. A lake exists over most parts of the salt dome.

References: (Horváth et al., 2018)

Jennings, Louisiana, United States of America

Storage	Natural gas	**Activity**	Active
Number of caverns	4	**Salt structure**	Salt dome
Working gas volume	708mln m^3	**Commissioned in**	1995
		Owner	Egan Hub Partners L.P. (EHP) (subsidiary of Spectra Energy)

The Jennings salt dome is located near Evangeline in the Acadia Parish, Louisiana. The top of the salt lies at a depth of 900m.

References: (Horváth et al., 2018)

Napoleonville, Louisiana, United States of America

Storage	1. Natural gas 2. Liquid hydrocarbons	Activity	Active
Number of caverns	Several, not specified	Salt structure	Salt dome
Cavern depth	600-1800m	Commissioned in	
Working gas volume		Operator	1. Pontchartrain and Bridgeline 2. DOW, Enlink and Promix

The Napoleonville salt dome is located near the town of Bayou Corne in the Assumption Parish, Louisiana. Storage caverns for both natural gas and liquid hydrocarbons are present, as well as brine production caverns.

The Napoleonville salt dome is home to a major cavern failure. One of the brine production caverns was located too close to the edge of the salt dome, resulting in the sediments on the edge of the dome to fall into the cavern. This created a massive sinkhole of ~160000m2.

References: (Bérest, 2017; Horváth et al., 2018)

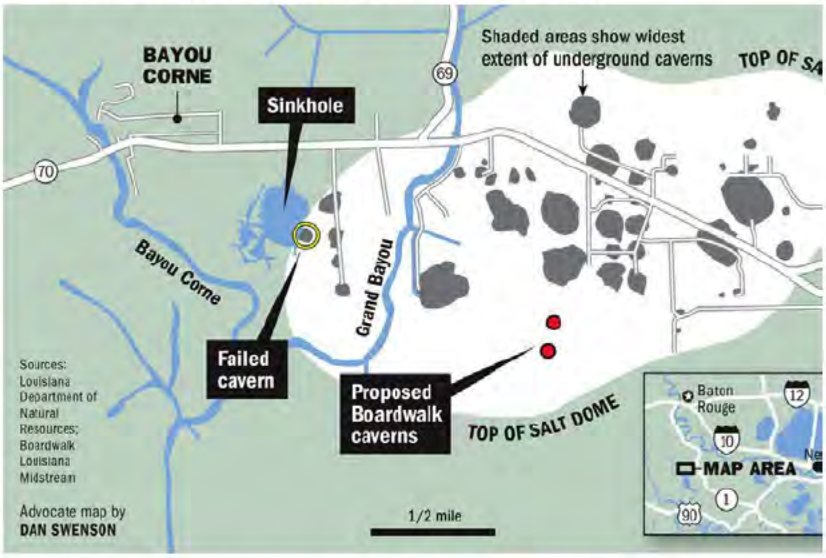

Figure 56 Map of the Bayou Corne sinkhole, from www.theadvocate.com.

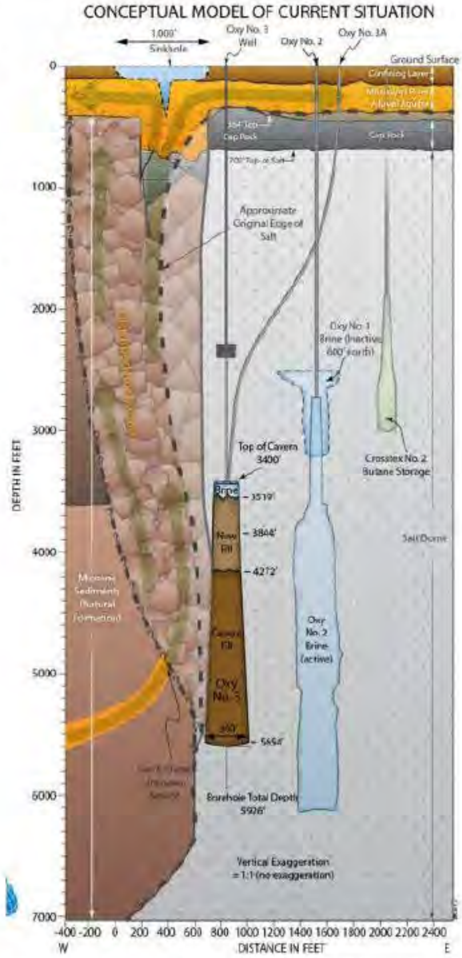

Figure 55 Model of the incident at Bayou Corne, showing the proximity of cavern Oxy3 to the edge of the salt dome, from (Bérest, 2017) and references therein.

North Louisiana salt dome, Louisiana, United States of America

Storage	Natural gas	**Activity**	Active
Number of caverns	Several, not specified	**Salt structure**	Salt dome

The North Louisiana salt dome has limited storage of natural gas. It is located in the North Louisiana basin and storage occurs both in old solution mined caverns as well as newly developed caverns.

References: (Horváth et al., 2018)

Pine Prairie, Louisiana, United States of America

Storage	1. Natural gas 2. Hydrocarbons (LPG)		**Activity**	1. Active 2. Inactive
Number of caverns	1. 5 2. 2		**Salt structure**	Salt dome
Commissioned in	1. 2008		**Owner**	2. Targa resources (before: Warren Petroleum Company)
Working gas volume	1. 1.19 billion m^3 (US Billion)→ 1190mln m^3			

The Pine Prairie salt dome in Evangeline county, Louisiana contains 5 caverns for the storage of natural gas. The cavern field is called the PPEC, Pine Prairie Energy Center. There used to be caverns for the storage of hydrocarbons.

References: (Horváth et al., 2018)

Port Barre, Louisiana, United States of America

Storage	Natural gas		**Activity**	Active
Number of caverns	4		**Salt structure**	Salt dome
Top of cavern	1385-1515m		**Commissioned in**	2007
Working gas volume	821mln m^3		**Owner**	Spectra Energy

In the St. Landry parish, Louisiana there is a cavern field called Bobcat Gas Storage. Its caverns lie inside the Port Barre salt dome and have heights of 365-460m. There is an application pending for multi-cavern crude oil storage.

References: (Horváth et al., 2018)

Section 28, Louisiana, United States of America

Storage	Hydrocarbons (LPG)
Number of caverns	Several, not specified

Activity	Active
Salt structure	Salt dome
Operator	Enterprise Products

The Section 28 salt dome lies in St. Martin Parish, Louisiana. It contains several caverns for hydrocarbon storage. The top of the salt lies at a depth of 360m.

References: (Horváth et al., 2018)

Sorrento, Louisiana, United States of America

Storage	1. Natural gas 2. Hydrocarbons (LPG)
Number of caverns	20

Activity	Active
Salt structure	Salt dome
Owner	5 companies

In Ascension Parish, Louisiana, lies the Sorrento salt dome. The top of this salt lies at a depth of 524m.

References: (Horváth et al., 2018)

Starks, Louisiana, United States of America

Storage	Natural gas

Activity	Planned

There are plans for natural gas cavern storage in the Starks salt dome, located in Calcasieu Parish, Louisiana. The top of the salt lies at a depth of 470m.

References: (Horváth et al., 2018)

Sulphur mines, Louisiana, United States of America

Storage	Crude oil	**Activity**	Inactive
Number of caverns	Several, not specified	**Salt structure**	Salt dome
Unspecified volume	3.8mln m^3	**Commissioned in**	1977
		Owner	US Department of Energy (DOE)

The Sulphur mines salt dome (610m diameter) in Calcasieu Parish, Louisiana contained storage caverns for crude oil. The depth of the top of the salt is 445m. The caverns were part of the Strategic Petroleum Reserve. The dome is also used for Frasch mining of the Sulphur in the caprock.

Storage	Hydrocarbons (LPG)	**Activity**	Active
Owner	Boardalk Partners and Sasol	**Salt structure**	Salt dome

Boardalk partners and Sasol have hydrocarbon storage inside the dome.

References: (Horváth et al., 2018)

Venice, Louisiana, United States of America

Storage	Hydrocarbons (LPG)
Storage fields	9

Activity	Inactive
Salt structure	Salt dome
Operator	Targa resources (before: Warren Petroleum Company)

The Venice salt dome is located in the Plaquemines Parish in Louisiana. The top of the salt lies at a depth of 123m. The storage inside the dome is out-of-service.

References: (Horváth et al., 2018)

West Hackberry, Louisiana, United States of America

Storage	1. Crude oil and brine storage 2. Hydrocarbons (LPG)		**Activity**	Active
Number of caverns	1. 21-23 2. Multi-cavern		**Salt structure**	Salt dome
			Commissioned in	1. 1970s
Capacity	1. 220.4mln barrels (US), 35mln m^3 crude oil storage capacity		**Owner/ Operator**	1. US Department of Energy (DOE) / Fluor Federal Petroleum Operations 2. Targa resources (before: Warren Petroleum Company)

The West Hackberry salt dome lies in the Cameron Parish in Louisiana. The dome has an elongated shape, its length is 2.4km and its width is 0.8km. The top of the salt lies at a depth of 549m. The crude oil (and brine) storage is part of the Strategic Petroleum Reserve.

References: (Horváth et al., 2018)

Michigan basin, Michigan, United States of America

Storage	Hydrocarbons (Ethylene gas)	**Activity**	Active
Number of caverns	>70	**Salt structure**	Bedded salt
Cavern depth	<1200m		

In 4 counties of Michigan over 70 caverns are used for storage. The caverns are leached in the Salina salt in the southern and central part of the Michigan basin. One of these storage cavern fields is situated in Midland in the Detroit River series salt, it is used for the storage of Ethylene gas, it started operating in 1959.

References: (Horváth et al., 2018)

Bond, Mississippi, United States of America

Storage	Gas		**Activity**	Active
Number of caverns	3		**Salt structure**	Salt dome
			Project	Mississippi Hub Natural Gas Storage project

In Simpson county, Mississippi near the town of Magee lies the Bond salt dome. It is part of the Mississippi salt basin, this dome is one of the most northeasterly salt domes of the basin. The cavern field is part of the Mississippi Hub Natural Gas Storage project and there is permission to leach one more cavern.

References: (Horváth et al., 2018)

Eminence, Mississippi, United States of America

Storage	Natural gas
Number of caverns	3

Activity	Active
Salt structure	Salt dome

The Eminence salt dome is located in the Mississippi salt basin in Covington county, Mississippi. It was the first solution mined gas storage cavern in the United States Gulf Coast. The salt lies at a depth of 750m.

References: (Horváth et al., 2018)

New Home, Mississippi, United States of America

Storage	Natural gas		**Activity**	Active
Number of caverns	3		**Salt structure**	Salt dome
			Owner	Leaf River Energy Center

The New Home salt dome (2.4km diameter) is located in Smith county, in Mississippi, and is part of the Mississippi salt basin. The top of the salt lies at a depth of 790m.

References: (Horváth et al., 2018; Looff, 2017)

Petal, Mississippi, United States of America

Storage	1. Natural gas 2. Liquid hydrocarbons
Number of caverns	1. Several 2. 5

Activity	Active
Salt structure	Salt dome
Owner/Operator	1. Boardwalk Partners / Gulf south pipeline 2. Enterprise products, Lone Star NGLs and Targa Resources

Caverns for the storage of natural gas and liquid hydrocarbons are present in the Petal salt dome of the Mississippi salt basin. The dome lies in the Forrest county, Mississippi. The depth of the top of the salt lies at a depth of 530m.

References: (Horváth et al., 2018)

Carthage, Missouri, United States of America

Storage	Propane		Activity	Active?

The only cavern storage location located in Missouri. This location has cavern(s) for the storage of propane.

References: (Réveillère et al., 2017)

New York State, United States of America

Storage	Natural gas
Number of caverns	>15

Activity	Active
Salt structure	Bedded salts

In New York State 2 cavern fields are host to natural gas storage caverns. Both fields are inside the Northeastern Appalachian basin, and are of Silurian age. The bedded salts are tectonically thickened and are the uppermost salt zone called Salina F. There is a field in Central New York and in South Central New York, the South Central field contains bedded salts that underwent the most tectonic deformation. It is brecciated and tectonically homogenized.

References: (Horváth et al., 2018)

Elk City, Oklahoma, United States of America

Storage	LPG (Propane)
Commissioned in	After 1954

Activity	Active
Salt structure	Bedded salts

The only storage location in Oklahoma. The cavern(s) are located in the Blaine Formation, which has alternating layers of salt, anhydrite and shales. The last cemented casings are located at a depth of 410m.

References: (Bérest et al., 2019)

Barbers Hill, Texas, United States of America

Storage	Hydrocarbons (Propane, Butane, Ethane) and Natural gas
Number of caverns	140 (including brine production)
Capacity	60mln m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1950s
Operator	Targa resources (formerly known as Warren Petroleum Company), Enterprise and 5 other operators.

Mont Belvieu, Texas, is the home to over 140 caverns. The caverns were leached in the Barbers Hill salt dome, which is part of the Tertiary Gulf coast basin. The dome has a length of 3.5km and a width of 2.7km at a depth of 610m. Targa resources owns 30 of the caverns for the storage of hydrocarbons and natural gas, with a capacity of 15mln m3. Abandonment tests were performed on Enterprise West Wells No. 10W, No. 11W, No. 14W, and No. 15W2. A hydraulic connection between brine production caverns 16E and 2E occurred in 2004.

Cavern field at Mt. Belvieu (Barbers Hill salt dome) showing outline of salt dome and caverns (Cartwright and Ratigan, 2005)

Figure 57 Map of the Barbers Hill salt dome, showing the outlines of the caverns, from (Looff, 2017).

References: (Horváth et al., 2018; Looff, 2017)

Bethel, Texas, United States of America

Storage	1./2. Natural gas 3. CAES		**Activity**	1./2. Active 3. Planned
Number of caverns	1. 2 2. 3 (#1, #2a, #3)		**Salt structure**	Salt dome
Capacity	1. 280mln m^3 (in 2005) 2. 295mln m^3 (in 2005)		**Operator**	1. Atmos Pipeline-Texas 2. Energy Transfer Fuel LP

The caverns in Bethel, in Anderson County, Texas, lie in the Bethel salt dome, where the top of the salt lies at a depth of 505m. The caverns are leached in Louann salt. There are plans for CAES in the dome.

References: (Horváth et al., 2018)

Big Hill, Texas, United States of America

Storage	Crude oil
Number of caverns	14
Cavern depth	700-1525m
Capacity	170 million barrels (US)

Activity	Active
Salt structure	Salt dome
Commissioned in	1991
Owner	US Department of Energy (DOE)

In Jefferson County, Texas, the Big Hill salt dome (1.6km diameter) is host to 14 caverns for the storage of crude oil. They are part of the Strategic Petroleum Reserve.

There was an incident with cavern #103, a salt fall occurred. This has been analysed by (Munson et al., 2004).

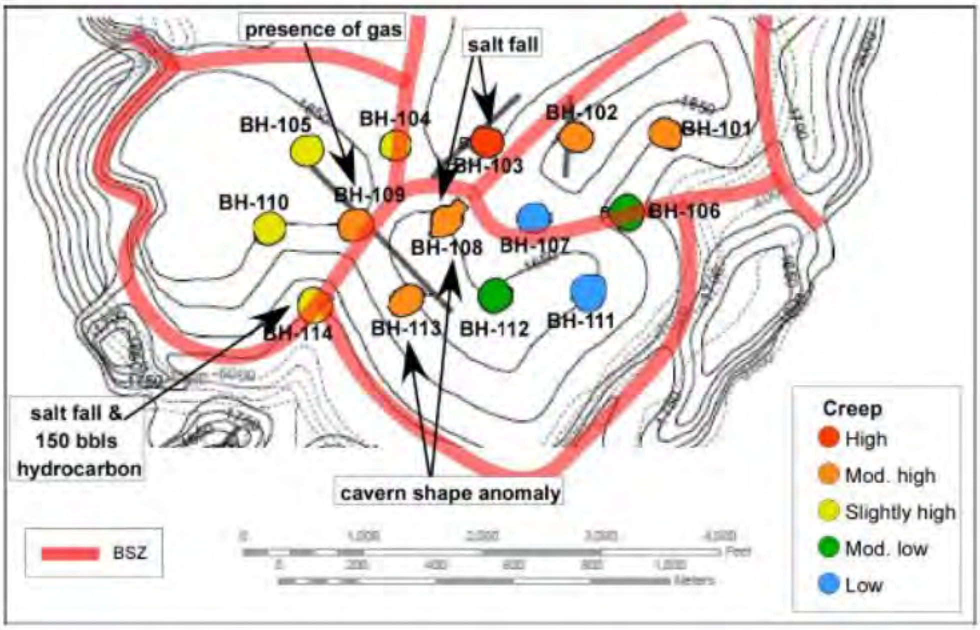

Figure 58 Map of the Big Hill salt dome, showing caverns and their creep rates, from (Looff, 2017).

References: (Horváth et al., 2018; Looff, 2017; Munson et al., 2004)

Boling, Texas, United States of America

Storage	1.Natural gas 2. Liquid Hydrocarbons
Number of caverns	1. 5 2. 1
Working volume	1. 4.76mln m^3 2. 1.59mln m^3

Activity	Active
Salt structure	Salt dome
Owner	Enterprise Products

In Boling, Texas, the Boling salt dome is host to 6 storage caverns. The dome has an oval shape and is 8km in length, 4.5km in width. The top of the salt lies at a depth of 154m.

References: (Horváth et al., 2018)

Brenham, Texas, United States of America

Storage	Hydrocarbons (LPG)	**Activity**	Inactive- 1992
Number of caverns	1	**Salt structure**	Salt dome

The Brenham salt dome, in the Washingtion-Austin counties, Texas, was host to one cavern for the storage of hydrocarbons. The top of the salt lies at a depth of 350m. An incident took place, the cavern experienced 'overfill' in 1992. This created an LPG ignition event, after this the cavern was plugged and abandoned. The incident led to new storage well regulations in Texas.

References: (Horváth et al., 2018)

Bryan Mound, Texas, United States of America

Storage	Crude oil
Number of caverns	19
Cavern depth	450m
Capacity	247.1 million barrels (US)

Activity	Active
Salt structure	Salt dome
Commissioned in	1986
Owner	US Department of Energy (DOE)

The Bryan Mound salt dome in Brazoria county, Texas, is host to 19 caverns for the use of storage. The dome has a circular shape and has a diameter of 1830m. The caverns are part of the Strategic Petroleum Reserve.

This site has experienced the most hanging string events of the 4 SPR sites which are thought to be related to salt falls, which are shown of the figure below.

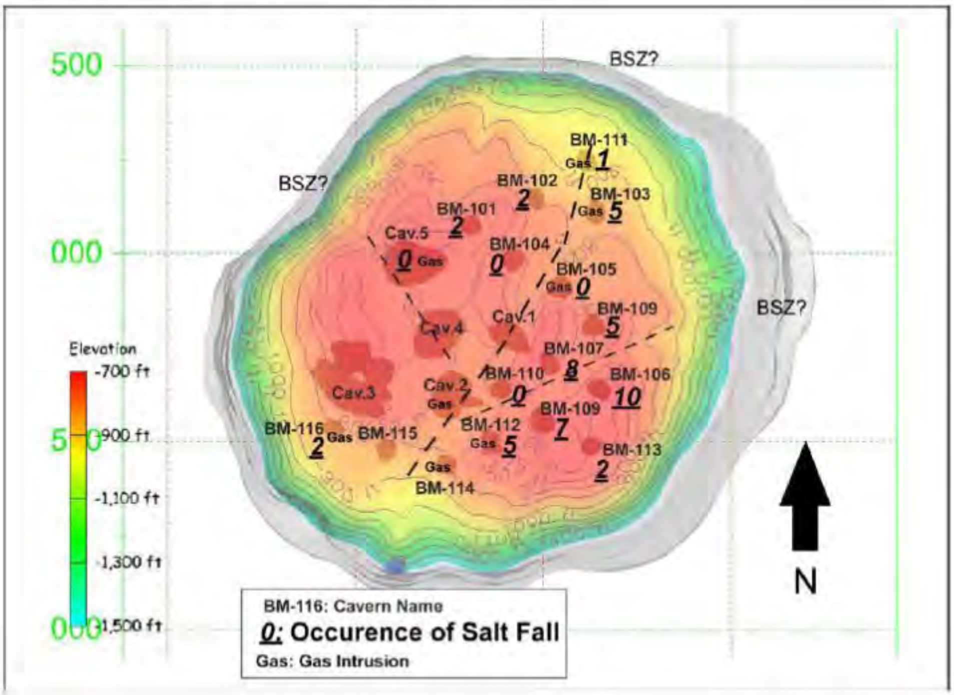

Figure 59 Map of the Bryan Mound salt dome, the numbers indicate the amount of salt falls which have occurred in the caverns, from (Looff, 2017).

Occurrence of salt fall	Cavern Name
10	BM106
8	BM107
7	BM109
5	BM103(*), BM108, BM112(*)
4	Cavern 5(*)
2	BM101, BM102, BM113, BM116(*)
1	BM111(*)
0	BM104, BM105(*), BM115, Cavern 1, Cavern 4
No information	BM114(*), Cavern 2(*)

Note: (*) gas intrusion in cavern

Figure 60 Table showing the number of salt falls per cavern, from (Looff, 2017).

References: (Horváth et al., 2018; Looff, 2017)

Byrd, Texas, United States of America

Storage	Natural gas		**Activity**	Active
Number of caverns	4		**Salt structure**	Salt dome
			Owner	Plains All American Pipeline

In Smith County, Texas, lies the Byrd salt dome. It is part of the Mississippi salt basin. The top of the salt lies at a depth of 625m.

References: (Horváth et al., 2018)

Clemens salt dome, Texas, United States of America

Storage	1. Hydrocarbons (LPG) 2. Hydrogen (95%), Natural gas and LPG	**Activity**	Active
Number of caverns	Several, not specified	**Salt structure**	Salt dome
Cavern depth	2. Top of cavern: 800m, mean depth 1000m	**Commissioned in**	1. ? 2. 1983
Working volume	2. Individual cavern: 58000 m^3	**Owner/operator**	1. Phillips 66 2. Chevron Philips Chemical company

In Brazoria county, Texas, lies the Clemens salt dome, in which caverns for storage are situated. The dome is part of the Gulf Coast basin.

References: (Caglayan et al., 2020; Horváth et al., 2018; Zivar et al., 2020)

Clute, Texas, United States of America

Storage	LPG (Ethylene)	**Activity**	?
Commissioned in	1961	**Salt structure**	Domal salt
		Operator	South Texas Pipeline Company

The storage cavern(s) in Clute are located in an active salt dome, the Stratton Ridge dome. Its caprock is about 100m thick.

References: (Bérest et al., 2019; Réveillère et al., 2017)

Delaware basin, Texas, United States of America

Storage	Natural gas		**Activity**	Active
Fields	Several		**Salt structure**	Bedded salts
			Owner	Chevron and PPM Energy

The Delaware basin in the southwest of Texas contains several cavern fields for the storage of natural gas. The caverns are leached in Upper Permian salts. 2 of these fields are Keystone gas storage facility (owned by Chevron) and Waha (owned by PPM Energy).

References: (Horváth et al., 2018), PPM Energy, Chevron

East Tyler, Texas, United States of America

Storage	Hydrocarbons (LPG)		**Activity**	Active
Number of caverns	11		**Salt structure**	Salt dome
			Operator	Texas Eastman

The East Tyler salt dome lies in Smith county, Texas. The top of the salt lies at a depth of 270m.

References: (Horváth et al., 2018)

Fannet, Texas, United States of America

Storage	Hydrocarbons (LPG)
Operator	Valero

Activity	Active
Salt structure	Salt dome

The Fannet salt dome is situated in Jefferson county, Texas. And contains cavern(s) for the storage of hydrocarbons in the northern part of the dome. The top of the salt lies at a depth of about 634m. There is also a cavern for production waste disposal in the south-central part of the dome.

References: (Horváth et al., 2018)

Hainesville, Texas, United States of America

Storage	Hydrocarbons (LPG)		**Activity**	Inactive
Number of caverns	2		**Salt structure**	Salt dome
			Operator	Suburban Propane

In Smith county, Texas, the Hainesville salt dome used to host 2 caverns for the storage of Hydrocarbons. The top of the salt lies at a depth of 350m. The caverns were abandoned after a propane leakage, which caused an ignition event.

References: (Horváth et al., 2018)

Hull, Texas, United States of America

Storage	Hydrocarbons (LPG)	**Activity**	Active
Operator	ExxonMobil	**Salt structure**	Salt dome

The Hull salt dome in Liberty county, Texas, contains caverns for the storage of hydrocarbons. The top of the salt lies at a depth of 181m. In 2008 a large sinkhole (45m deep, 180m diameter) was the result of a brine disposal well in or near the salt dome.

References: (Horváth et al., 2018)

Loop, Texas, United States of America

Storage	Natural gas		**Activity**	Active

Salt cavern storage location at Loop, stores natural gas.

References: (Evans, 2008)

Markham, Texas, United States of America

Storage	1. Natural gas 2. Hydrocarbons
Number of caverns	Several

Activity	Active

Markham storage in Matagorda county in Texas contains caverns for the storage of natural gas and hydrocarbons. The top of the salt lies at a depth of 430m.

References: (Horváth et al., 2018)

Midland basin, Texas, United States of America

Number of wells	>75

Activity	Active
Operators	9 operators

In Texas, east of the Delaware basin, lies the Midland basin. It is the home of over 75 wells for storage operated by 9 companies. The caverns are all situated in the Solado formation.

References: (Horváth et al., 2018)

Mineola, Texas, United States of America

Storage	LPG (Propane)		**Activity**	Active
Commissioned in	1950s		**Salt structure**	Domal Salt

Storage of LPG in domal salt, active since the end of the 1950s.

References: (Bérest et al., 2019; Brouard, 2019; Yang et al., 2013)

Moss Bluff, Texas, United States of America

Storage	1. Natural gas 2. Hydrogen
Number of caverns	1. 4 or 5 2. 1
Cavern depth	2. Top of cavern: 800m, Mean depth:1200m
1. Working gas volume 2. Cavern volume	1. 651mln m^3 2. 566000 m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	2. 2007
Operator	1. Spectra Energy 2. Praxair

The Moss Bluff salt dome in the Gulf Coast salt basin in Liberty county, Texas, contains caverns for the storage of natural gas (Spectra Energy) and hydrogen (Praxair). Praxair has permits for a second hydrogen cavern in the dome.

Cavern 1 of Spectra Energy experienced a blow out in 2004.

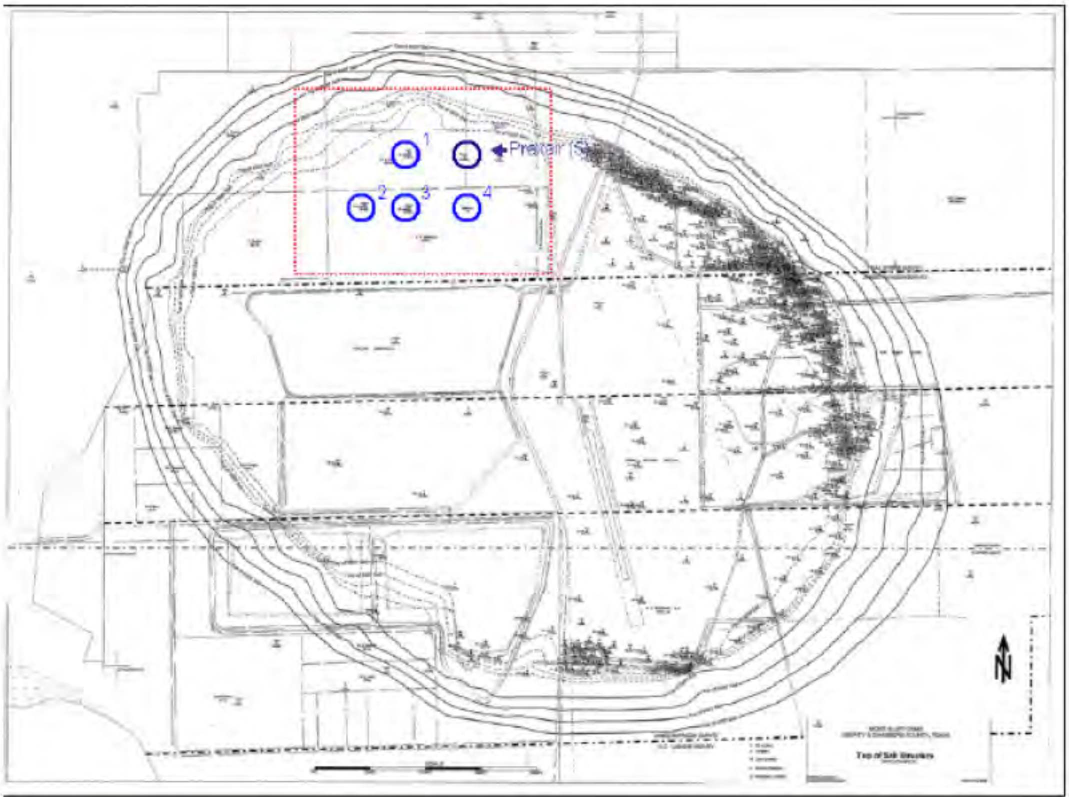

Figure 61 Moss Bluff salt dome map, modified by (Réveillère et al., 2017) after (Rittenhour & Heath, 2012).

References: (Horváth et al., 2018; Rittenhour & Heath, 2012)

North Dayton, Texas, United States of America

Storage	Natural gas		**Activity**	Active
Owner	Kinder Morgan		**Salt structure**	Salt dome

Kinder Morgan owns a cavern field in Liberty county, Texas, inside the North Dayton salt dome. The depth to the top of the salt is 244m.

References: (Horváth et al., 2018)

Odessa, Texas, United States of America

Storage	LPG (Propane)		Activity	?

Storage of LPG in Odessa, Texas.

References: (Evans, 2008)

Pierce Junction, Texas, United States of America

Storage	1. Crude oil 2. Hydrocarbons (LPG) 3. Natural gas
Number of caverns	1. 2 2. 7 3. 1

Activity	Active
Operator	1. Fairway Energy 2. Enterprise Products and Texas Brin 3. Reliant Energy
Salt structure	Salt dome

The Pierce Junction salt dome in Harris county, Texas contains 10 storage caverns.

References: (Horváth et al., 2018)

Sour lake, Texas, United States of America

Storage	Hydrocarbons (LPG)
Number of caverns	Not specified

Activity	Active
Salt structure	Salt dome
Operator	Flint Hills and Motiva

The Salt lake dome is situated in the Hardin county, in Texas. The dome is circular and shallow, and its center lies at a depth of 260m.

References: (Horváth et al., 2018)

Spindletop, Texas, United States of America

Storage	1. Brine supply 2. Hydrocarbons (LPG) 3. Hydrogen (95%) 4. Natural gas	Activity	Active
Number of caverns	1. 1 2. 1 3. 1 4. 8	Salt structure	Salt dome
Depth of cavern	3. 1340m		
Individual volume	3. 906000 m^3	Operator	1. Texas Brine Company, LLC 2. Coastal Caverns Inc. 3. Air Liquide 4. 3 operators

The Spindletop salt dome is located in Jefferson county, Texas. The dome is part of the Gulf Coast basin and the depth to the top of the salt is 336m. 6 operators have 11 caverns in this salt dome.

In 2001 a gas storage cavern and a brine production cavern became interconnected, which is a "significant unanticipated geomechanical development" (Johnson, 2003).

References : (Caglayan et al., 2020; Horváth et al., 2018; Johnson, 2003; Zivar et al., 2020)

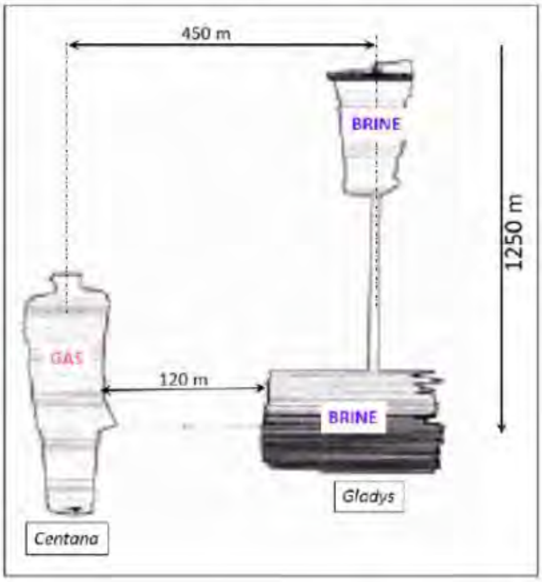

Figure 62 Showing the caverns Centana 1 and Gladys 2, which became interconnected, from (Johnson, 2003).

Stratton Ridge, Texas, United States of America

Storage	Natural gas		Activity	Inactive

Formerly a brine cavern, was converted to a storage cavern but failed to pass an MIT and was never operated.

References: (Evans, 2008; Réveillère et al., 2017)

Saltville, Virginia, United States of America

Storage	Natural gas
Number of caverns	1
Cavern depth	800-1200m

Activity	Active
Salt structure	Bedded salts
Owner	Spectra Energy

The bedded salts in Saltville, Virginia, host one cavern for natural gas storage. The storage is located in the southern rim of the Appalachian basin and the salt is of Silurian age. The bedding contains local disruptions due to thrust faulting and recrystallised zones.

References: (Horváth et al., 2018)

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Appendix 2: Inventarisation of worldwide published incidents in cavern storage

The tables with descriptions of the incidents contain citations from the work consulted during the research. These citations are marked with quotation marks, showing the sources at the bottom of the tables.

Index

Abovyan, Armenia

Storage	Natural Gas
Number of caverns	19 wells
Size: height, diameter	
Working gas volume	160mln m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1962
Owner	ArmRosGazprom

Over 95% of Armenian households and industries are connected to the natural gas network. The storage caverns in Yerevan are situated in the Armenian Basin, consisting of Tertiary salts. The caverns lie at a depth of 750-1050m.

Figure 63 Abovyan gas storage site plan, from (Energy Charter Secretariat, 2008) and references therein.

References: (Energy Charter Secretariat, 2008; Horváth et al., 2018) [Gazprom to increase gas volumes in Armenian underground storage facilities | Finport.am]

Caverns N6 and N9 experienced leakages.

Incident	N6 and N9 well leakages, Unknown date
Cause	Failure of the wells
Escalation factors	Poor maintenance due to shortage of funds since 1985, earthquake in 1988
Top event	Well integrity loss (leakage of natural gas)
Effects	Loss of gas, lower operating pressures and thus a lower capacity (190mil m^3 to 80-100mil m^3)
References	(Horváth et al., 2018)

Alberta, Canada (Fort Saskatchewan)

Storage	Natural Gas
Number of caverns	>100
Commissioned in	1970s

Activity	Active
Salt structure	Bedded salts
Owners	CHEVRON, **BP**, ATCO PIPELINES Ltd., WILLIAMS, DOW CHEMICALS, NCE PETRFUND, NORTHWESTERN UTILITES Ltd.

In the Strathacona county, northeast of Fort Saskatchewan and Edmonton there are over 100 storage caverns for natural gas. They are located in the Lotsberg formation (Lower Devonian age) and the Cold Lake formation of the Central Alberta sub-basin. 6 of the caverns are owned by NORTHWESTERN UTILITIES Ltd.

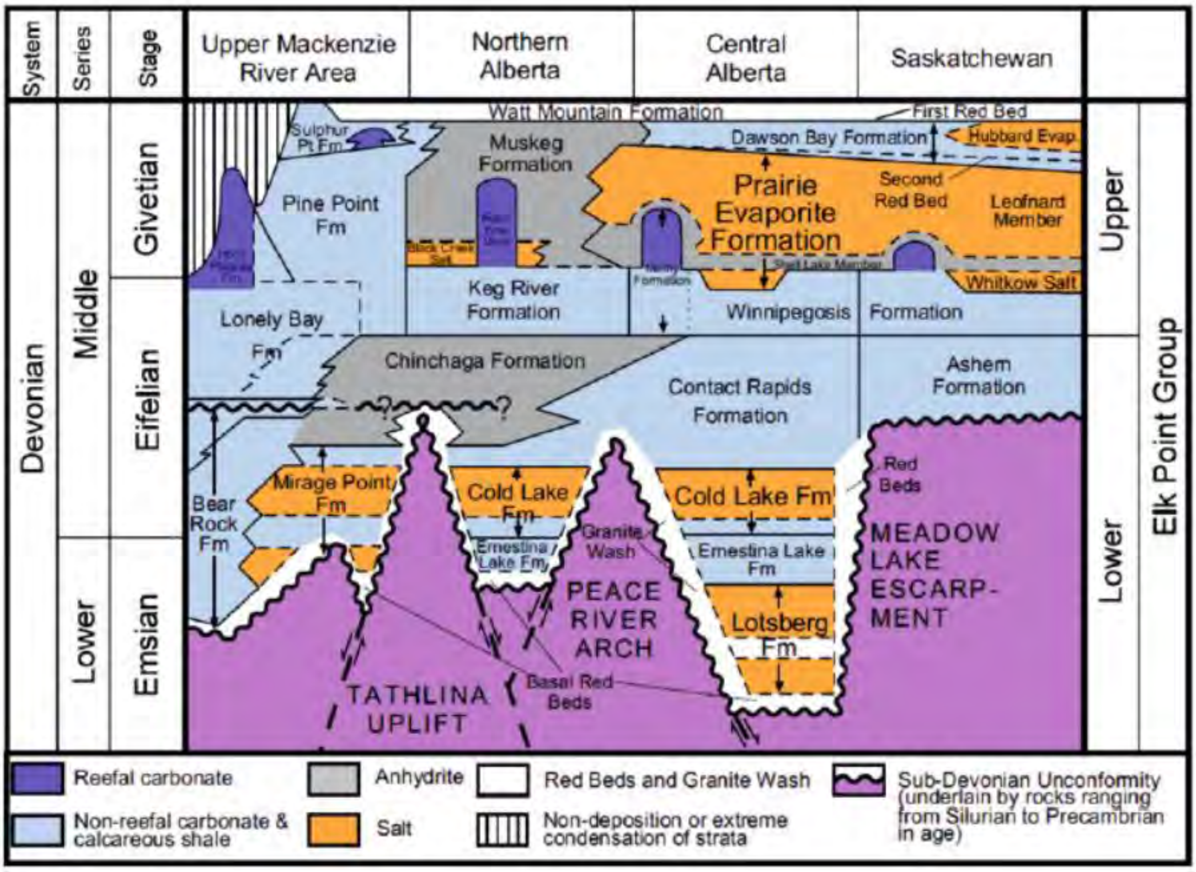

Figure 64 Elk Point group, showing the Lotsberg and Cold Lake formations, from (Grobe, 2000).

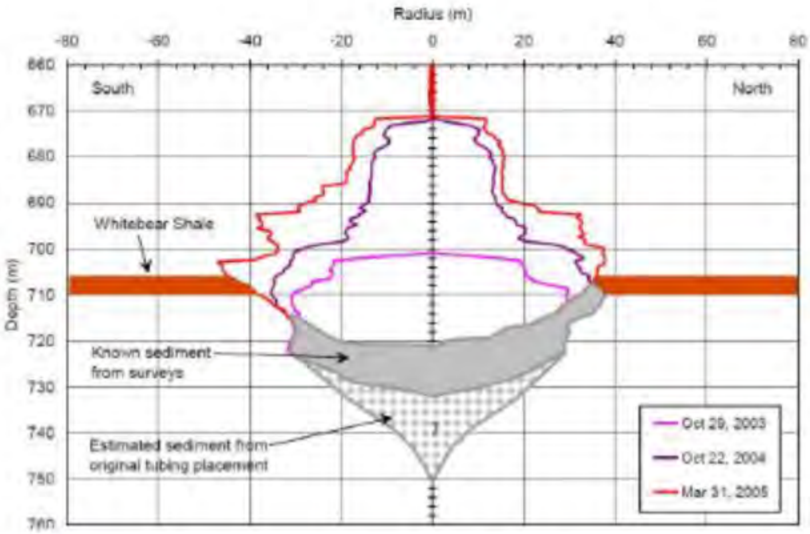

Figure 65 Salt heterogeneity (shale and anhydrite layer in the Cold Lake formation) near cavern #1 (Foster Creek facility) affecting cavern shape, from (Reed & Greene, 2012).

References: (Grobe, 2000; Horváth et al., 2018; Reed & Greene, 2012; Réveillère et al., 2017)

In 2001, in a storage cavern operated by BP, an ethane leakage occurred.

Incident	**BP cavern well leakage, 26th of August 2001**
Cause	The elbow failed due to a non-metallic inclusion from internal diameter to external diameter of the elbow, formed during the forging process
Top event	Well integrity loss (leakage of ethane)
Escalation factors	Electric arcs sparked the gas plume
Effects	Explosion and fire, 2 hours after the initial failure, Ethane leakage in a surface pipe, linking two wellheads of a double well cavern, ignition of ethane, loss of about 14500m^3 ethane
Lessons learned	BP eliminated the 2-inch line between the two wells and all Alberta NGL (natural gas liquids) wellhead lines are to be equipped with ESDs (emergency shutdowns)
References	(Réveillère et al., 2017; Yang et al., 2013)

Saskatchewan, Canada

Storage	Natural Gas
Number of caverns	24
Size: height, diameter	
Volume	See text.

Activity	Active
Salt structure	Bedded salts
Commissioned in	1970s
Owner	Transgas Ltd.

In Saskatchewan there are 6 sites containing storage caverns: Landis (1 Bcf, 28.32 mln m^3), Prud'Homme (6 Bcf, 169.92 mln m^3), Regina (3 Bcf, 84.96 mln m^3), Melville (3 Bcf, 84,96 mln m^3), Asquith (3 Bcf, 84.96 mln m^3) and Moosomin (2 Bcf, 56.64mln m^3). The bedded salts have a thickness of about 100-170m and are part of the Prairie Evaporite formation in the Saskatchewan sub-basin. The cavern roofs lie at a depth of 960-1636m.

Dewdney field has 3 natural gas storage caverns (inactive) and 4 LPG storage caverns (active), operated by Spectra.

References: (Horváth et al., 2018), [CER – Market Snapshot: Where does Canada store natural gas? (cer-rec.gc.ca)]

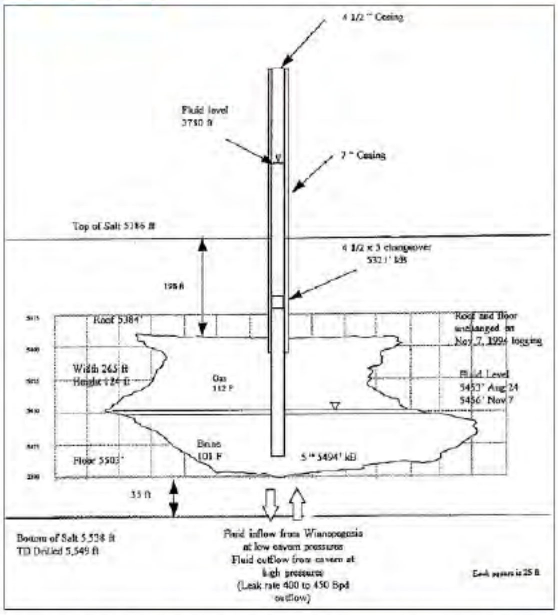

Figure 66 Cavern Regina North #1 from (Crossley, 1995).

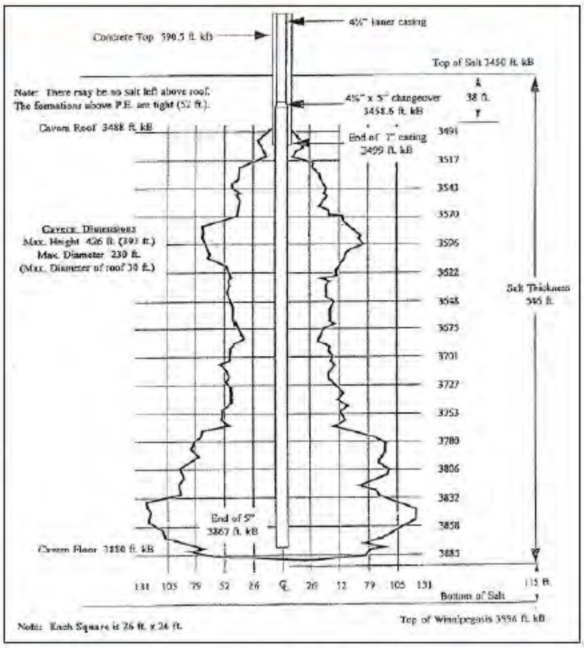

Figure 67 Cavern Melville south #3 from (Crossley, 1995).

[Multiple incidents occurred in several sites in Saskatchewan.]

Incident	Cavern 5 of Regina South field roof fall, 1989
Cause	roof (block) fall-> pressure drop
Top event	Cavern integrity loss (roof collapse/fall--> large pressure drop)
Escalation factors	Presence of a reservoir layer/receptor
Effects	Inventory loss (natural gas), fast leakage suggests leakage away from wellbore into the reservoir
Lessons learned	Cavern was operated at lower pressure after the incident
References	(Brouard, 2019)

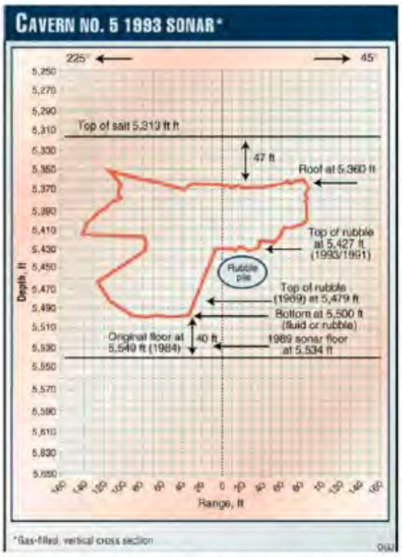

Figure 68 Cavern Regina south #5, after 2 roof falls, from (Crossley, 1998).

Incident	Dewdney Field casing separations, 2013
Cause	Salt heterogeneity: multiple horizontal mudstone seams, potash layers: "Vertical strain on the cemented casings resulting from potash fast creep and the poor tensile strength of the mudstone exceeding the casing strain limit" (Brouard, 2019)
Top event	Well integrity loss (separated casings at multiple wells)
Effects	Void/path volume of 14.7m^3, horizontal fractures in the mudstone seams
References	(Brouard, 2019; Coleman Hale, 2015)

Incident	Prud'Homme blow out, October 2014
Cause	Steel casing failure 2m below the ground
Top event	Well/pipeline integrity loss (Ethane leakage)
Escalation factors	High pressure gas release damaged the wellhead building resulting in a spark which caused the fire
Effects	Gas blow-out and fire
References	(Réveillère et al., 2017)

Incident	Moosomin top kill, 2011
Cause	Changing a casing hanger while keeping cavern under gas (challenging workover)
Top event	Well control issue (during workover)
Mitigation measures	Top kill: Kill fluid, pressure monitoring (leading to contingency)
Effects	No effects, workover continued as planned
References	(Réveillère et al., 2017)

Jintan, China

Storage	Natural Gas
Number of caverns	23
Size: height, diameter	
Volume	1. 180mln m^3 2. 40mln m^3 3. 60mln m^3

Activity	Active
Salt structure	Bedded salts
Commissioned in	2007, 2016 and 2017
Owners	1. CNPC E&P 2. Sinopec 3. HK and China Gas

The storage caverns in the Jintan salt mine district, in Jiangsu are located in bedded salts which have a thickness of 160m at a depth of about 1000m. The caverns have irregularly shaped designs. Cavern JK-A operated by Sinopec experienced a roof collapse (Wang et al., 2018), this cavern has a height of 40m and a diameter of 80m.

References: (Fansheng, 2014; Horváth et al., 2018; *Underground Gas Storage in the World - 2018 Status*, 2018; Wang et al., 2018)

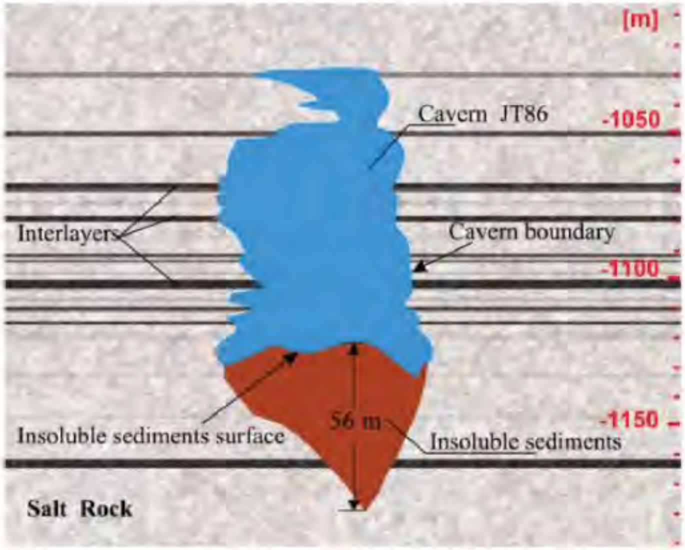

Figure 69 Cavern JT86, showing insoluble interlayers, from (Cyran, 2020).

Incident	Jintan Sinopec cavern JK-A roof collapse, November 2015
Cause	"1. A large-span flat roof, detrimental for bearing loads. 2. The decrease speed of internal gas pressure is too fast, the loads applied to the cavern roof cannot be transferred in a timely fashion, causing a stress concentration zone to form." "3. The self-weight aggravates local damage leading to massive collapse."
Top event	Cavern instability (roof collapse)
Effects	Irregular shape, remarkably, cavern volume increased: possible explanations: unsaturated brine continues to dissolve rock salt during sealing tests and debrining, or a survey sonar error.
Lessons learned	Strict control of gas pressure and its decrease speed to avoid future roof collapsing
References	(Wang et al., 2018)

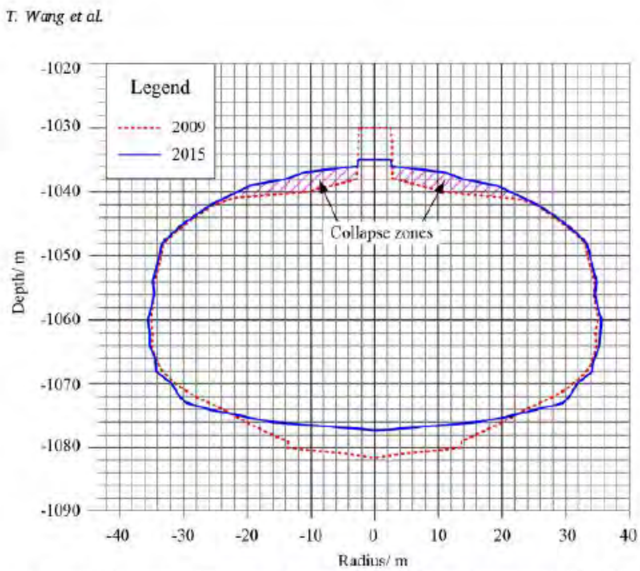

Figure 70 Sonar surveys of cavern JK-A, from (Wang et al., 2018)

Incident	**Jintan Sinopec cavern L block fall, 2015**
Cause	Tensile failure, thermal effect due to gas cyclic loading increases the stress field around the cavern wall, triggering block fall at flat sections of the cavern roof coupled with mechanical loading
Top event	Cavern instability (block fall)
Effects	Irregular shape
References	(Li et al., 2021)

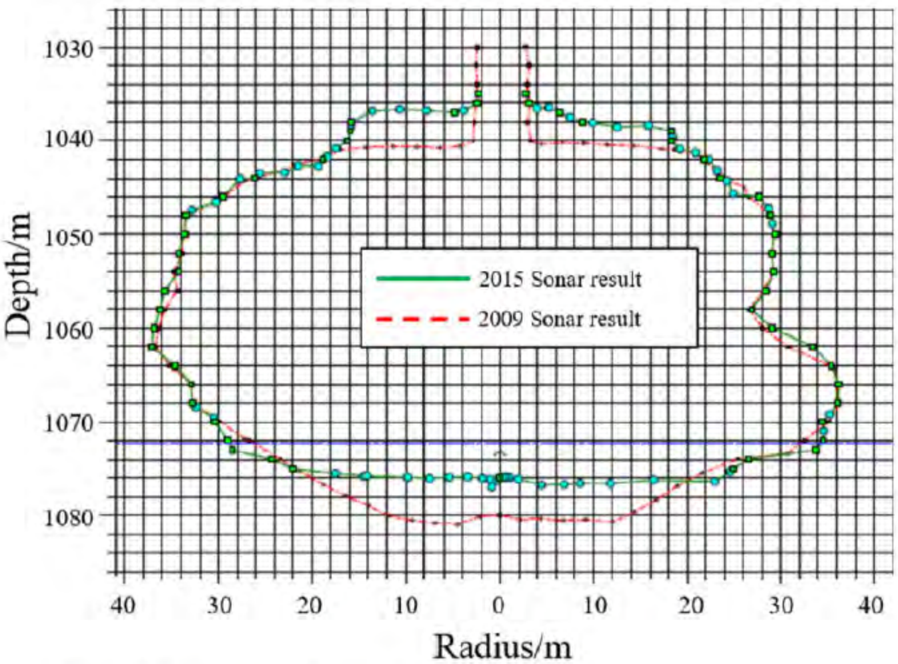

Figure 71 Sonar surveys of cavern L, from (Li et al., 2021)

Lille Torup, Denmark

Storage	Natural Gas
Number of caverns	7
Size: height, diameter	300-430m,55m
Volume	356000-766000 m^3

Activity	Active
Salt structure	Cylindrical salt dome
Commissioned in	1987
Owner	Gas Storage Denmark A/S

Cavern storage in the Tostrup Salt Dome in Northern Jutland has been ongoing since 1987. The caverns in the Norwegian-Danish Basin are situated in Zechstein salt and have a total volume of $435 \times 10^6 m^3$. Distance between the caverns is ~450m. A rock mechanical test on creep behaviour of the surrounding rock salt mass on TO6 (leached in Z1, Na1 salt) resulted in spalling at a reference section of the cavern, measured with high precision sonar. TO8 (leached in Z1, Na2 salt) has an irregular shape due to an intersection with the highly soluble "Veggerby" zone (K-/Mg-bearing salt). In TO9 (leached in Z1, Na2 salt) a large anhydrite-dolomite block protruded the eastern wall, resulting in block fall damaging the lower part of the leaching string.

Incidents include irregular cavern shapes due to heterogeneity in the salt layers, block fall and spalling.

Potential risks: preferential leakage paths due to the heterogeneity could result in a hydraulic connection between caverns.

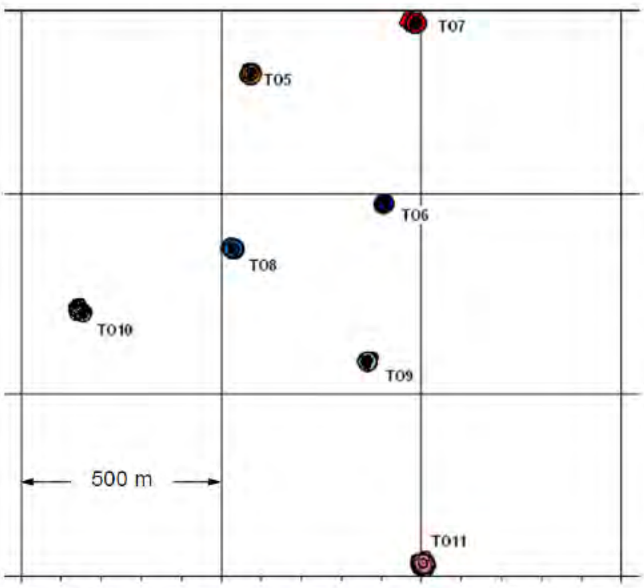

Figure 72 Map of the gas storage caverns of Lille Torup, from (Rokahr et al., 2007).

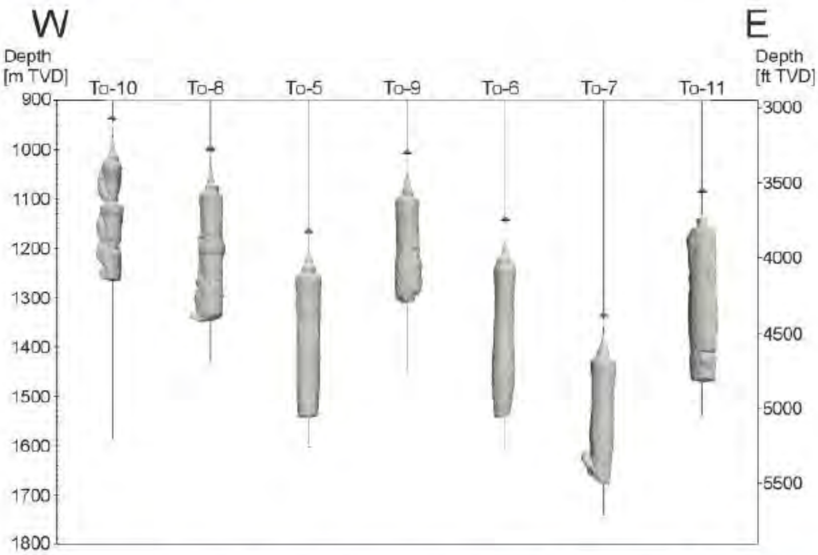

Figure 73 3D map view of the underground gas storage of Lille Torup, from (Kepplinger, 2016).

References: (Jacobsen & Nielsen, 1992; Kepplinger, 2016; Rokahr et al., 2007), www.gie.eu, www.gasstorage.dk

Incident	TO-6 Test, January-March 2005
Cause	Rock mechanical test on cavern creep
Top event	Cavern instability (Spalling)
Effects	Local cavern divergence, irregular shape
References	(Jacobsen & Nielsen, 1992; Rokahr et al., 2007)

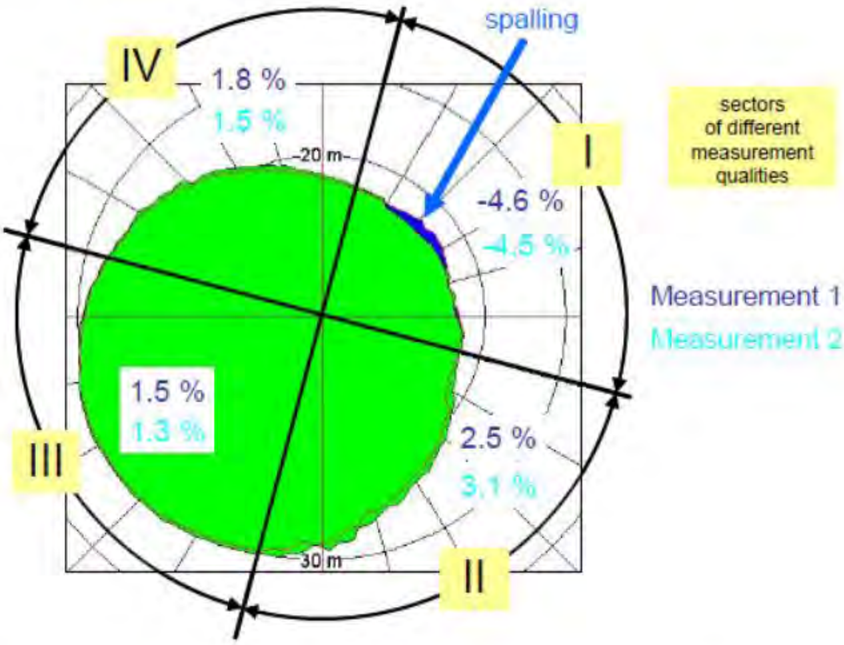

Figure 74 TO-6 test results, from (Jacobsen & Nielsen, 1992; Rokahr et al., 2007).

Incident	TO-8 irregular shape during leaching, unknown date
Cause	Salt heterogeneity (highly soluble potassium zone)
Top event	Cavern instability (soluble layers intersecting the cavern)
Effects	Irregular shape
References	(Jacobsen & Nielsen, 1992)

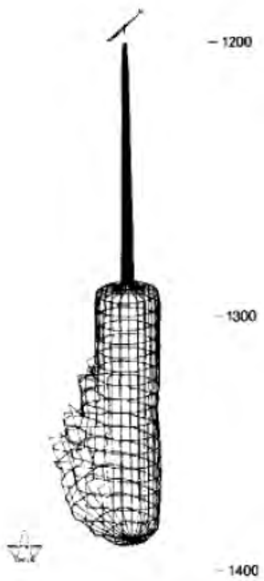

Figure 75 The shape of cavern TO-8 showing the effects of salt heterogeneity, from (Jacobsen & Nielsen, 1992).

Incident	**TO-9 well damage due to block fall, during leaching**
Cause	Salt heterogeneity--> protruding block--> Cavern instability (block fall)
Top event	Well integrity loss (damage to well) due to cavern instability (block fall)
Mitigating measures	Step-leaching during the remained of cavern formation
Effects	Damage to lower part of the leaching string, cavern was completed using step leaching (total volume: 356000m^3
References	(Jacobsen & Nielsen, 1992)

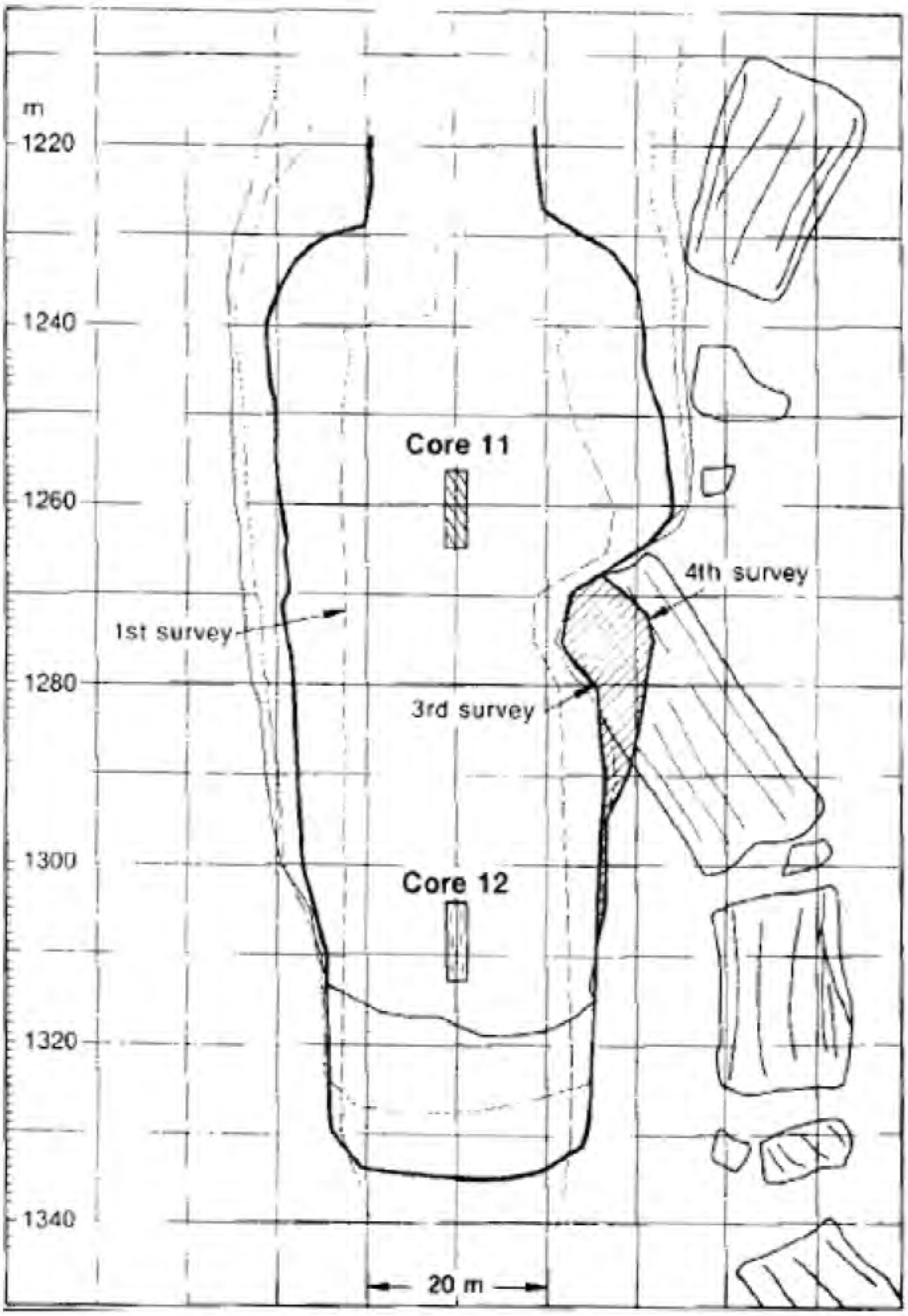

Figure 76 Showing cavern TO-9, salt heterogeneity resulting in block fall, from (Jacobsen & Nielsen, 1992).

Manosque, France

Storage	3. 40% Crude oil, 60% refined products 4. Natural gas	**Activity**	Active
Number of caverns	~35	**Salt structure**	Anticlinal structure
Size of 1.: height, diameter	Height: 300-400m, diameter: 60-80m	**Commissioned in**	1. 1969 2. 1993
Capacity (working gas + cushion gas)	1. 3.2mln m^3	**Owner**	1.Géosel 2. Géométhane

The Manosque Forcalquir Basin is host to several caverns, which were all designed and leached for storage by Geostock Entrepose, all the caverns in the basin are also operated by them. The basin contains salts of Oligocene age, these layers have a thickness of 800m (900-1800m deep) and the top of the anticline lies at a depth of 100m.

28 of these caverns are owned by Géosel and store crude oil and refined products. These caverns lie at a depth of 350-1000m, are 300-400m high and have a diameter of 60-80m. The other 7 caverns are rented from Géosel to Géométhane for storage of natural gas.

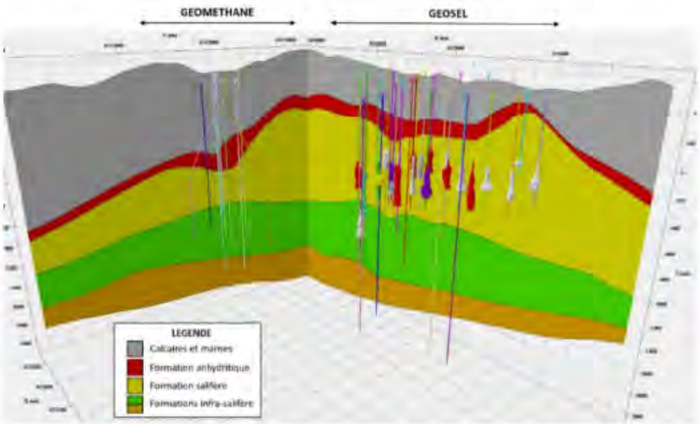

Figure 77 Manosque cavern field, from www.geosel.fr.

References: (Horváth et al., 2018) www.geosel.fr

Incident	**Naphtha leakage, 2013**
Cause	Unknown cause
Top event	Pipeline integrity loss (leakage)
Effects	Leakage of Naphtha
References	(Réveillère et al., 2017)

Valence Salt basin, France

Storage	Natural gas and Hydrocarbons (Propylene)	**Activity**	Active
Number of caverns	16	**Salt structure**	Bedded salts
Owner	Storengy, Novapex	**Commissioned in**	1970

The Valence salt basin is the host of several caverns, of which 16 are currently active. The salt hosting the storage caverns in this basin has a thickness of 140m. Storengy operates 13 caverns in Tersanne, near the northern part of the basin, cavern tops have a depth of ~1400m. Storengy also operates 2 caverns storing natural gas in Hauterives, which are part of the SALINE project, the caverns are at a depth of 1500m. These caverns were commissioned in 2012. Novapex stores propylene in a cavern near Le Grand Serre.

Cavern Te02 in the Tersanne cavern field was operated from 1970-2005, after which an abandonment test took place. The volume of this cavern was 93500m^3.

References: (Brouard, 2019; Horváth et al., 2018)

Incident	**Capacity loss in 2 caverns, 1970-1979**
Cause	High creep rate due to low operating pressures (which might be related to process errors like design errors or human failure)
Top event	Cavern instability (creep closure)
Effects	2 caverns lost capacity, but are still operational, 2 later caverns have higher minimum operating pressures and are more stable, effective volume loss of 35%, subsidence: settlement rate of 40mm/a, influence rate 2000m
References	(Evans, 2008; Yang et al., 2013)

Viriat, France

Storage	Hydrocarbons (Ethylene)

Activity	Active?
Owner	TOTAL

North of Lyon lie the storage cavern(s) of Viriat in the department of Ain.

References: (Evans, 2008)

Incident	**Gas cloud, 1986**
Cause	Rupture of compressor unit (broken ground facilities)
Top event	Pipeline integrity loss (Ethylene leakage)
Effects	Gas cloud, all gas leaked
References	(Evans, 2008; Yang et al., 2013)

Bad Lauchstädt/Teutschenthal, Germany

Storage	Natural gas and Hydrocarbons (Ethylene, Propylene)	**Activity**	Active
Number of caverns	20	**Salt structure**	Bedded salts
Cavern depth	4. 780-950m 5. 700-800m 6. 820m	**Commissioned in**	1970s
		Owner	4. VNG Gasspeicher 5. DOW Olefinverbund GmbH, LDC 6. Town gas

The caverns are located in the Stassfurt bedded salts which are 330-560m thick (from SE to NW) and about 500-1000m deep. The Stassfurt Halite has an anhydrite content of 4-5% and is located north to a Hercynian fault zone. In the area southwest of Halle, in the towns of Bad Lauchstädt and Teutschenthal 20 storage caverns are under operation. The 17 caverns at Bad Lauchstädt are operated by VNG Gasspeicher and are part of the VGS storage hub. These caverns are used for the storage of natural gas. DOW Olefinverbund GmbH operates 3 caverns at Teutschenthal, filled with hydrocarbons.

LDC town gas stored town gas (45-55% hydrogen, mixed with methane and CO2) in a cavern at Bad Lauchstädt in the 1970s. This cavern was converted to store natural gas.

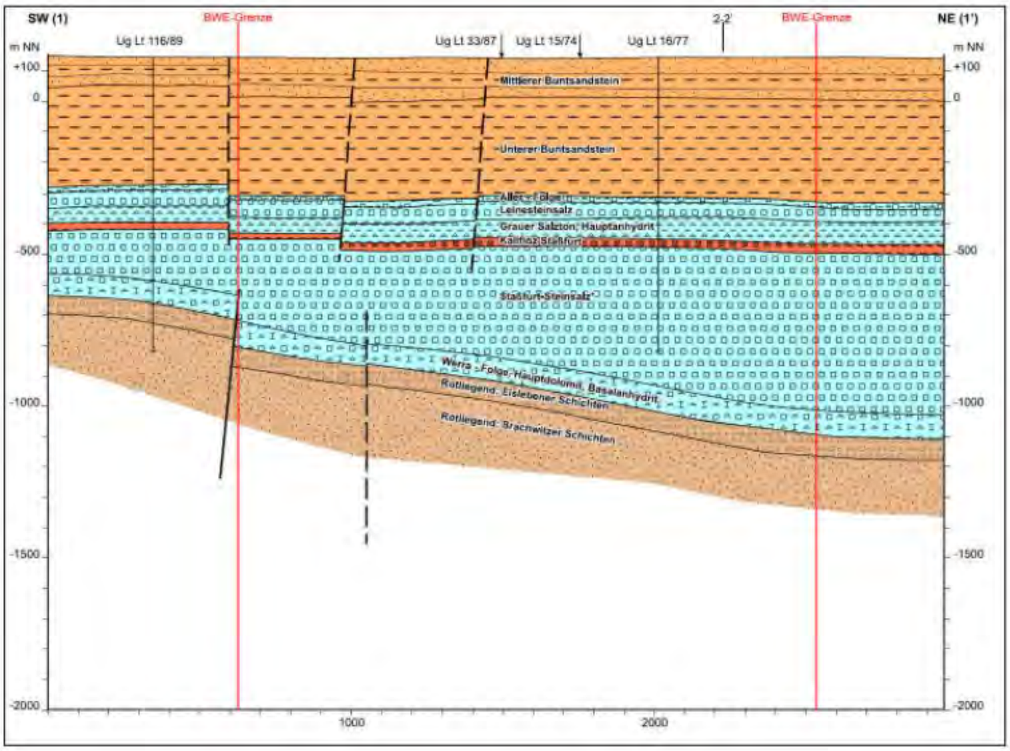

Figure 78 Cross section of the cavern field in Bad Lauchstädt/Teutschenthal, from (Arnold, 2010).

References: (Arnold, 2010; Horváth et al., 2018; Kruck, 2013)

Incident	Town gas cavern (Cavern Ug Lt 15/74) blow out, 1984
Cause	Tool got stuck during wireline survey, upper part of the wellhead had to be lifted up, during which the immediate pressure lifted part of the wellhead
Top event	Well control issue
Effects	Blow out of town gas resulting in gas release to the atmosphere
References	(Réveillère et al., 2017)

Incident	Ethylene cavern leakage, March 29th 1988
Cause	"Pressure drop (7.5MPa to 4 MPa) due to failed last cemented casing which ruptured allowing for leakage. The leakage was two-step: first, gas slowly filled an aquifer at 100-140m depth, generating uplift and opening a new breach in the severely stretched casing. This resulted in a significantly increased leak rate, a pressure drop in the cavern and 1h later the blow-out."
Escalation factors	Connection to an aquifer
Top event	Well integrity loss (Ethylene leakage)
Mitigation measures	Evacuation of the area surrounding the cavern (8km2)
Effects	"Surface dome and crack. Lateral migration in permeable layers and vertical migration along a fault zone up to the surface. 1 hour after pressure drop first eruption (blow-out) of water-ethylene mixture 50m from the well, several other eruptions followed later. 60 % to 80 % of the cavern inventory was released over the course of several days. Fractures and crevasses displaced concrete road pads and fractures were found in a building at the crest of the uplift ellipsoid. Ground uplift of 1.5m before the eruption. Distance from the wellhead: 50-250m. Ethylene dilution was swift, alignment of blow-out spots was checked through aerial photos."
Lessons learned	Annular space is monitored and an 8 5/8 string is set in the casing.
References	(Bérest et al., 2019; Katzung et al., 1996; Yang et al., 2013)

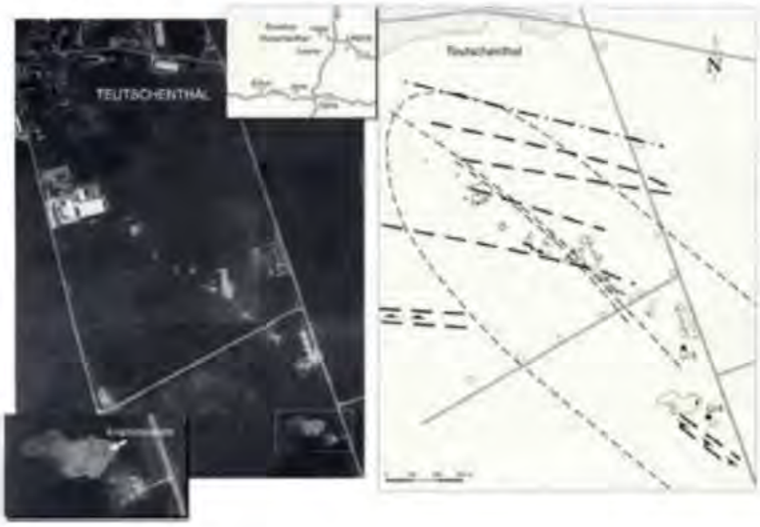

Figure 79 Aerial photo of the March 29th 1988 incident, showing the main eruption fracture on the left and right side showing fault zones, modified by (Bérest et al., 2019) from Katzung et al., 1996).

Epe, Germany

Storage	Natural gas, crude oil and helium
Number of caverns	>70

Activity	Active
Cavern depth	1000-1500m

Close to the Dutch border, near Gronau and Epe, is the largest storage cavern field of the world. The caverns are located in Zechstein 1 salts, with an evaporite thickness of 200-400m, which lies at a depth of 900-1500m. All the caverns lie at this depth range. Over 70 storage caverns have been documented.

SGW owns 3 caverns used for storage of crude oil. Air liquide owns 1 cavern for the storage of helium, which operates since 2016. All other caverns are used for the storage of natural gas (Both H- and L-gas), as shown in the table below.

Operator: name	Caverns	Storage	Working Volume	Commissioned in
Eneco-Gasspeicher: Epe Eneco Gasspeicher	2 (S81,S82)	Natural gas	1.44 TWh	
Innogy: Epe NL	10 (shared with Epe H-Gas)	Natural gas	2.92 TWh	2006
Innogy: Epe H-Gas	10 (shared with Epe NL)	High caloric Gas	6.66 TWh (VGS InnEXpool)	1990
Innogy: Epe L-gas	11	Low caloric Gas	1.84 TWh	2012
KGE: Epe KGE		Natural gas	2.17 TWh	2012
Nuon: Epe Nuon		Natural gas	3.01 TWh	2007
Trianel Gasspeicher Epe GmbH & Co. KG: Epe Trianel	4	Natural gas	2.23 TWh	2008
Uniper: Epe Uniper H-Gas	39 (Shared with Epe Uniper L-Gas)	H-Gas	15.30 TWh	1976
Uniper: Epe Uniper L-Gas	39 (Shared with Epe Uniper H-Gas)	L-Gas	4.26 TWh	1977
Air Liquide: Epe Helium	1	Helium		2016
SGW: Epe SGW crude oil	3	Crude Oil		

References: (Horváth et al., 2018)

The Epe storage field had a crude oil leakage in 2014, cavern 5S from SGW had a loss of wellbore integrity (pressure drop of 0.36MPa) which led to migration of the oil, ultimately reaching the surface (Bérest et al., 2019).

Incident	**Epe crude oil spill in Cavern 5S, 2014**
Cause	Partly failed screwed connection of the well casing at 217m (which is significantly above the salt, at the weakest point), which was caused by cavern convergence inducing the movement of the rock mass up to the depth of the well casing failure 23rd and 24th of February: a pressure drop of 0.36MPa was recorded
Top event	Well integrity loss (Loss of wellbore integrity, crude oil leakage of the well casing)
Mitigation measures	Pumping out the oil, soil remediation
Effects	Oil spill at the surface, a family was evacuated for a few days
Lessons learned	Future storage caverns in Germany will require a double barrier (as a prevention measure) installation for all wells
References	(Bérest et al., 2019; Réveillère et al., 2017)

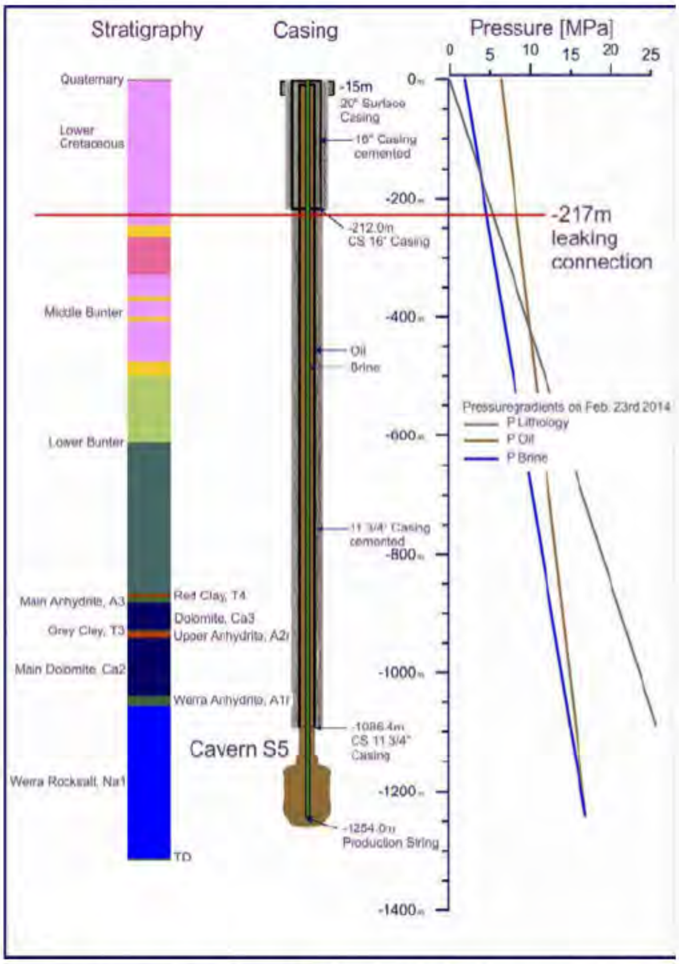

Figure 80 Crude oill spill in 2014, showing the leaking connection, from (Réveillère et al., 2017) and references therein.

Huntorf and Jemgum, Germany

Storage	CAES and natural gas (both H- and L-gas)
Number of caverns	>38

Activity	Active
Salt structure	Salt domes
Operator	4. Astora/ (VNG Gasspeicher) 5. Nordwestdeutsche Krafiwerke (or: Uniper Kraftwerke GmbH) 6. EWE-Gasspeicher

The Neuenhuntorf salt dome is located 15km northeast of Oldenburg and has an oval shape that is 5.8km long and 3.5km wide. The Jemgum salt dome is 17km long and 2.5km wide. Both salt domes are part of a 50km long arced elongated salt wall. The Huntorf cavern storage is located in the Neuenhuntorf salt dome and the Nüttermoor storage caverns are located in the Jemgum salt dome. 3 operators have over 38 storage caverns, located near Huntorf and Nüttermoor. The Jemgum H caverns operated by EWE Gasspeicher are located at a depth of 950-1400m. Astora is planning to expand their Jemgum H storage to a total of 18 caverns. The CAES storage caverns are located at a depth of 650-800m and have a diameter of 60m. The Nüttermoor H-gas caverns have a height up to 700m, and diameters ranging from 35-110m. The natural gas storage cavern in Huntorf K6 is the largest natural gas cavern in Europe (1100000m3). EWE has plans to convert a storage cavern in Huntorf to hydrogen storage.

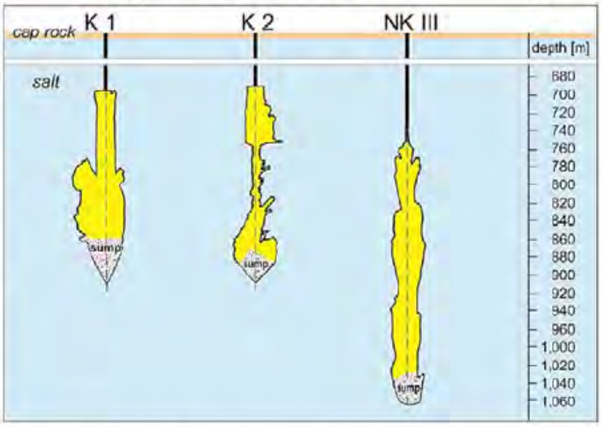

Figure 81 Huntorf storage caverns, from (Horváth et al., 2018) and references therein.

References: (Cyran, 2020; Horváth et al., 2018), Waterstofhub Noordwest-Duitsland

Operator: name	Caverns	Storage	Volume	Commissioned in
Astora/ (VNG Gasspeicher): Jemgum H		H-Gas	6.86 TWh	2013
EWE Gasspeicher: Jemgum H	8	H-Gas	3.98 TWh	2013
Nordwestdeutsche Krafiwerke (or: Uniper Kraftwerke GmbH): Druckluftspeicher Huntorf	2 (NK1, NK2)	CAES	140000-170000 m^3	1978
EWE-Gasspeicher: EWE - Zone L Nüttermoor/Huntorf (GTG)	21 (7 of which are in Huntorf: K1-K6, NKIII)	L-Gas (Nüttermoor has 1/5 for H-Gas)	9.47 TWh working volume	1972
EWE-Gasspeicher: EWE H-Gas Zone (GTG)		H-Gas		Under construction: L-gas to H-gas conversion
EWE-Gasspeicher: Nüttermoor H-1	7 (H-1, H-2, H-3)	H-Gas	1.83 TWh	1979
EWE-Gasspeicher: Nüttermoor H-2	7 (H-1, H-2, H-3)	H-Gas	1.96 TWh	1979
EWE-Gasspeicher: Nüttermoor H-3	7 (H-1, H-2, H-3)	H-Gas	2.96 TWh	1979
EWE-Gasspeicher: Nüttermoor L (GUD)		L-Gas	0.43 TWh	1979

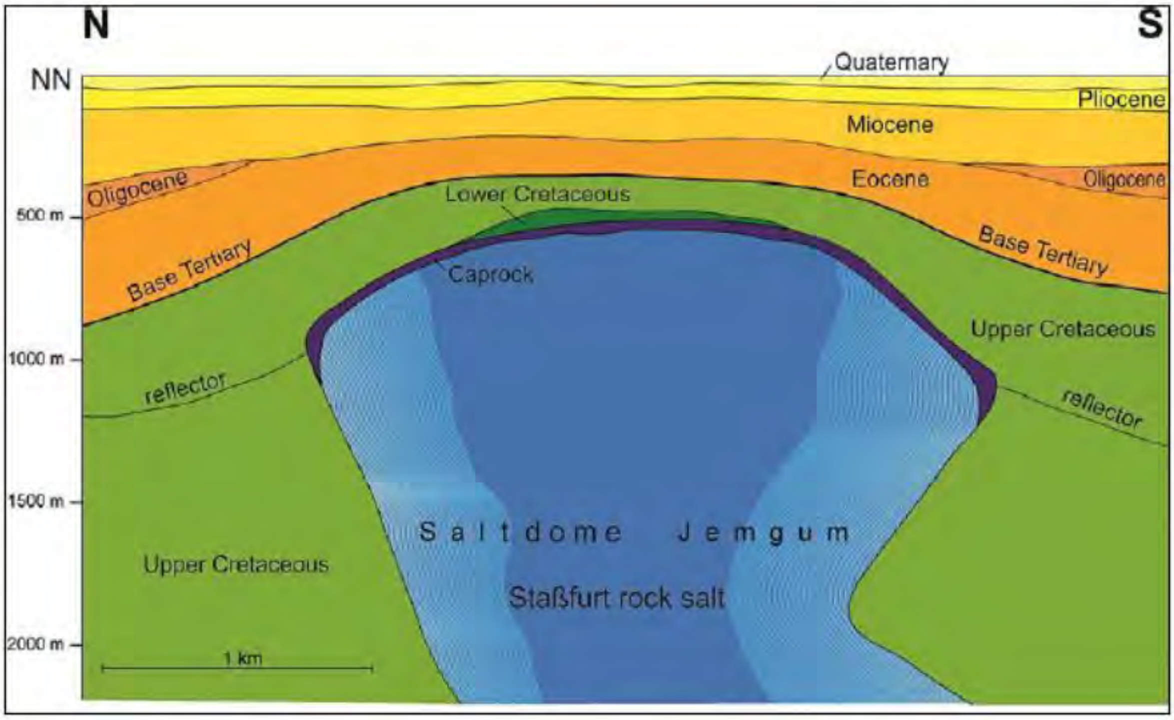

Figure 82 Jemgum salt dome cross section, from (Horváth et al., 2018) and references therein.

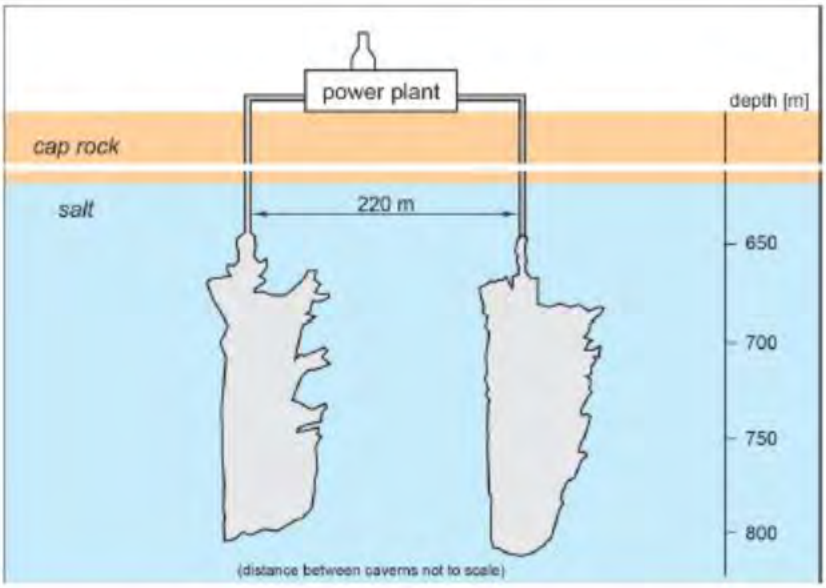

Figure 83 CAES caverns NK 1 and NK 2 in Huntorf, from (Cyran, 2020).

Incident	**Nüttermoor, 2002**
Cause	Pressure rise in a monitoring annulus
Top event	Well integrity/control loss Heavy operations(?)
Effects	No leakage
References	(Réveillère et al., 2017)

Kiel, Germany

Storage	Natural gas
Number of caverns	>3
Cavern depth	K101: 1,307-1,335 m
Volume	Converted cavern Kiel 101: 32000 m^3 Kiel 102: 394000 m^3 Kiel 103: 35mln m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	K101:1971 K102: 1995 K103:2014
Owner/operator	SW Kiel Speicher GmbH (Used to be owned by: Hansewerk)

In Kiel-Rönne more than 3 storage caverns are present. They reside in the Honigsee salt dome, this dome is part of the Haselgebirge and its salt content is 78%, consisting of both Rotliegend and Zechstein salts. One field is operated by SW Kiel Speicher GmbH, which contains 3 caverns: Kiel 101, 102, 103. The caverns are 300m apart from each other. The total working volume for these caverns is 0.50 TWh.

Cavern Kiel 101 was used, according to (Zivar et al., 2020), to store hydrogen (60%). This cavern operated between 80-100 bar and is currently operated between 60-192 bar.

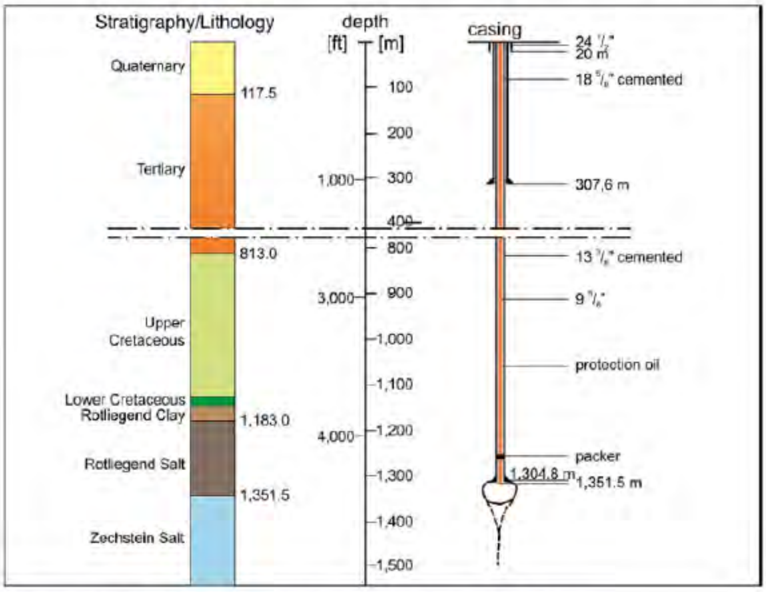

Figure 84 Kiel well profile of K101, from (Kühne et al., 1973).

References: (Horváth et al., 2018; Kühne et al., 1973; Zivar et al., 2020)

Incident	Capacity loss, 1960-present
Cause	Low cavern pressures resulting in creep and salt heterogeneity (high amounts of insolubles resulting in cavern volume reduction (cavern is smaller than desirable)
Top event	Cavern instability (creep closure, compaction of insoluble sediments) Anomaly (insoluble) zones
Effects	Cavern capacity loss (12.3% volume loss in 45 days)
References	(Evans, 2008; Yang et al., 2013)

Kraak, Germany

Storage	Natural gas
Number of caverns	4
Cavern depth	900-1450m
Working gas volume	2.97 TWh

Activity	Active
Salt structure	Salt dome
Commissioned in	2000
Owner/operator	Hanse Werk/ E.ON Gasspeicher GmbH

20 km south of Schwerin lies the Kraak salt dome, which contains 4 caverns for natural gas storage. They range in height from 110-170m and diameter 40-90m. This salt dome has inhomogeneous salt, deeper areas have several transitions between Z2 and Z3 salts. At a depth of 550m a 20m thick anhydrite is present, below this layer the halite contains kieserite and carnallite. The inhomogeneous salt led to cavern K101 having a highly irregular shape.

References: (Günnewig et al., 2001; Horváth et al., 2018; Stöwer & Borgmeier, 2003)

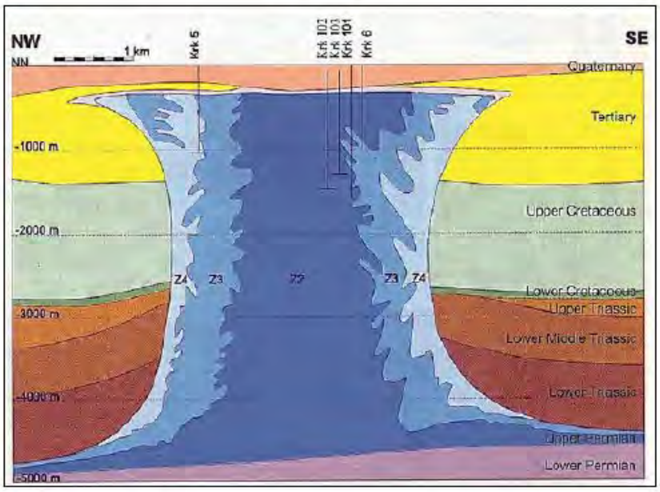

Figure 85 Kraak salt dome cross section, modified by (Horváth et al., 2018) after Günnewig et al., 2001).

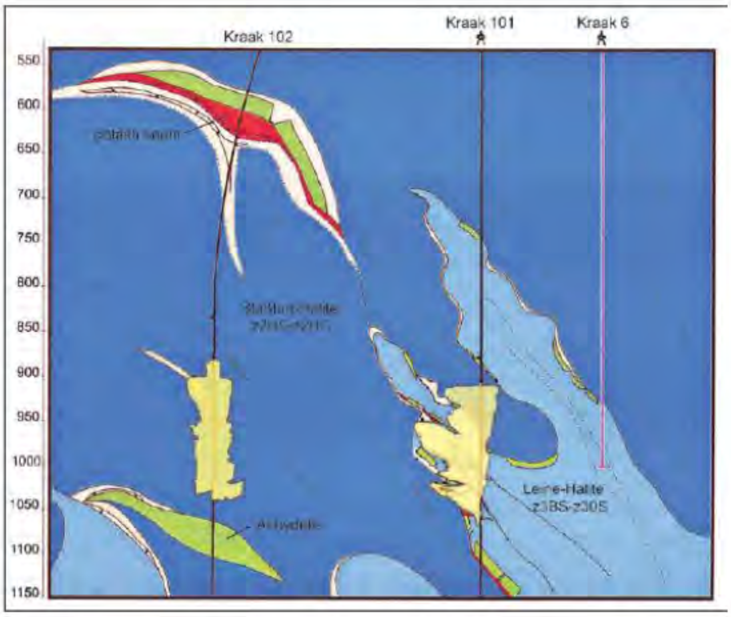

Figure 86 Cross section of caverns K101 and K102, from (Stöwer & Borgmeier, 2003).

Incident	Cavern K101 irregular shape, 1997-1999
Cause	Effects of salt heterogeneity during solution mining
Top event	Cavern instability (irregular shape)
Effects	Irregular shape
References	(Horváth et al., 2018)

Wilhelmshaven – Rüstringen, Germany

Storage	Crude oil and petroleum products	**Activity**	Active
Number of caverns	36	**Salt structure**	Salt dome
Casing shoe depth	1200-1600m	**Commissioned in**	1969
Working gas volume		**Owner/operator**	NWKG (subsidiary of EBV)

The caverns in the Rüstringen salt dome (located near Wilhelmshaven, diameter: 5km, depth: 1000-5000m) are part of the EBV: Crude Oil Reserve Association. 3 more caverns are under development.

References: (Horváth et al., 2018)

Incident	**Irregular casing shapes, 1999**
Top event	Irregular casing shapes (might be related to creep)
References	(Réveillère et al., 2017)

Kirkuk, Iraq

Storage	Oil
Number of caverns	5
Size: height, diameter	70m, 70m
Capacity	286000 m^3

Activity	Active
Salt structure	Bedded salts
Commissioned in	1982
Owner	Gaz de France

In the Zagros basin, near Kirkuk Gaz de France has 5 storage caverns. The bedded salts of the Kirkuk salt sub-basin consist of two tertiary halites of Miocene age. These layers are at depths of 185-200m and 260-320m. The shapes of the caverns are reported to be irregular and slightly isometric.

References: (Al-Sulaiman et al., 2017; Horváth et al., 2018; Leroy, 1985)

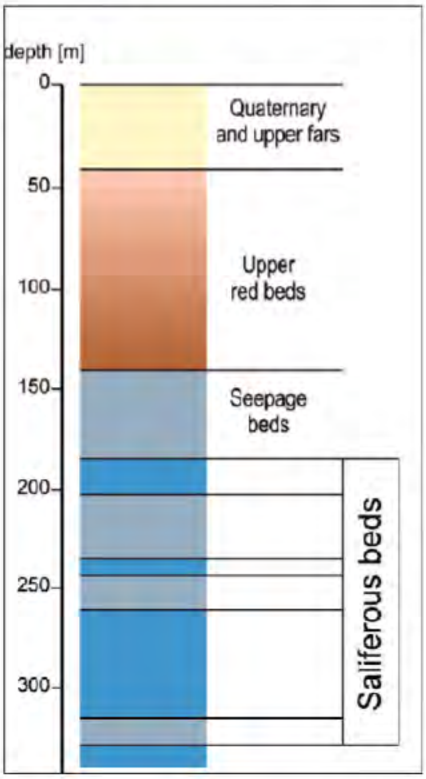

Figure 87 Borehole logs from a Kirkuk cavern, from (Leroy, 1985)

Incident	**Multiple caverns, irregular shapes/thin wall/bad operating conditions, 1989-2015**
Cause	Salt heterogeneity (marls and silt as inclusions in the salt bed)
Top event	Cavern instability (bad operation conditions)
Effects	1 of the 5 caverns (number 5) abandoned due to proximity to the edge of the salt (2m to the top of the salt), Irregular shapes (longitudinal extension to SW direction of cavern number 2, also close proximity to salt edge, but usable for storage after MIT (mechanical integrity test)), volume increase of cavern 6 and 7 due to bad operation conditions (increased filling and unloading operations).
References	(Al-Sulaiman et al., 2017)

Several figures on the next page showcase the cavern instability.

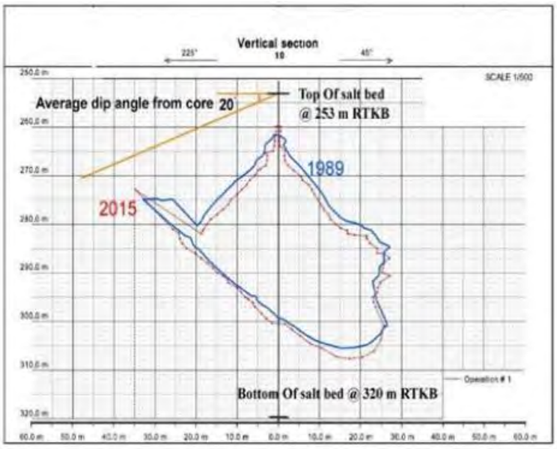

Figure 88 Sonar survey of cavern 2, from (Al-Sulaiman et al., 2017)

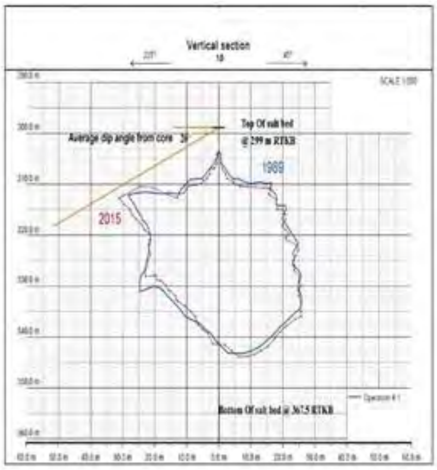

Figure 89 Sonar survey of cavern 5, from (Al-Sulaiman et al., 2017).

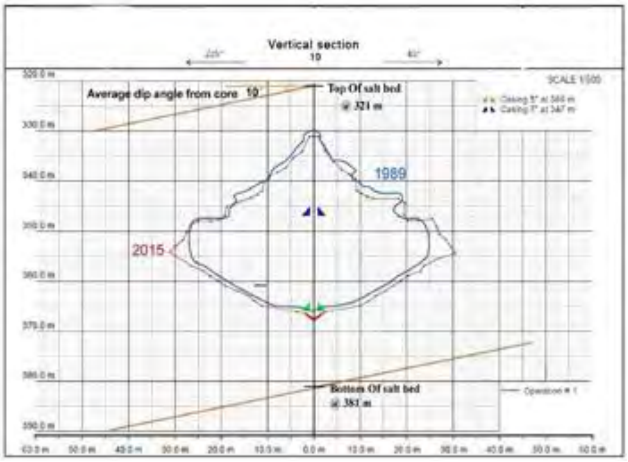

Figure 90 Sonar survey of cavern 6, from (Al-Sulaiman et al., 2017).

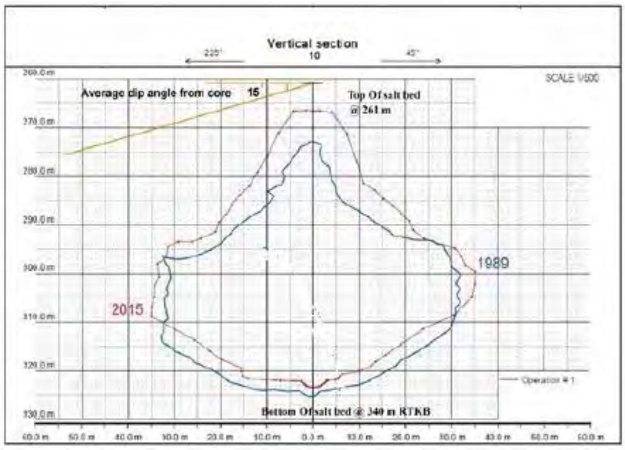

Figure 91 Sonar survey of cavern 7, from (Al-Sulaiman et al., 2017).

Góra, Poland

Storage	Crude oil and fuel
Number of caverns	7
Depth	400-700m
Cavern volumes	290000-580000 m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	2002, 2006
Owner	Inowroclaw Salt Mines

A circular salt dome (800m diameter and 250m deep) which is part of the Central European Basin / Southern Permian Basin of Poland near Góra contains 7 caverns which were originally used for exploitation of salt. The caverns were leached in Z2 salt with a NaCl content of up to 97%. The caverns are irregularly shaped due to the heterogeneity of the salt. The salt contains insoluble sulfate rocks, coarse grained halites and K-Mg evaporites. Three new caverns should have been leached and ready for storage since 2006.

References: (Cyran, 2020; Horváth et al., 2018; Mrozinski, 2004)

Figure 92 Gorá salt dome cross section, from (Cyran, 2020).

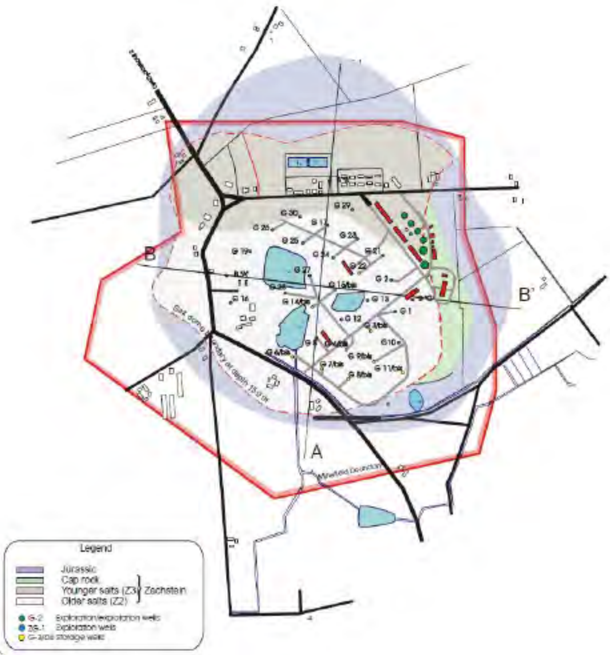

Figure 93 Gorá storage area map, from (Mrozinski, 2004).

Incident	Irregular shape, 2004-2005
Cause	Salt heterogeneity (steep dipping K-Mg salts, highly soluble)
Top event	Cavern instability (salt heterogeneity)
Effects	Irregular shape, formation of side pocket traps leading to the abandonment of fuel storing in caverns G-21 and G-23
References	(Mrozinski, 2004)

Mogilno, Poland

Storage	Gas		Activity	Active
Number of caverns	11		Salt structure	Salt dome
Depth	600-1600m		Owner	Gas Storage Poland
Capacity	586mln m³ (working volume: 6.24 TWh)			

The caverns in the Mogilno salt dome (4.5km long, 600m wide, 250m depth) are situated in Zechstein salts. The dome is part of the Central European Basin/ Southern Permian Basin of Poland. The caverns are part of the GSF Kawerna project. The heterogeneity of the salts made the caverns have irregular shapes. The wide variety of depths and storage capacities of the caverns are associated with the heterogeneity of the salt dome. The distance between the wellheads is 250m. 3 additional caverns are being formed through leaching.

In the nearby town of Damasławek, there are plans to make gas storage caverns by GAZ System, they will be under construction in 2026 and are supposed to have a working volume of 9.00TWh.

References: **(Cyran, 2020; Horváth et al., 2018; Kosciuszko, 1997; Ślizowski et al., 2009)**

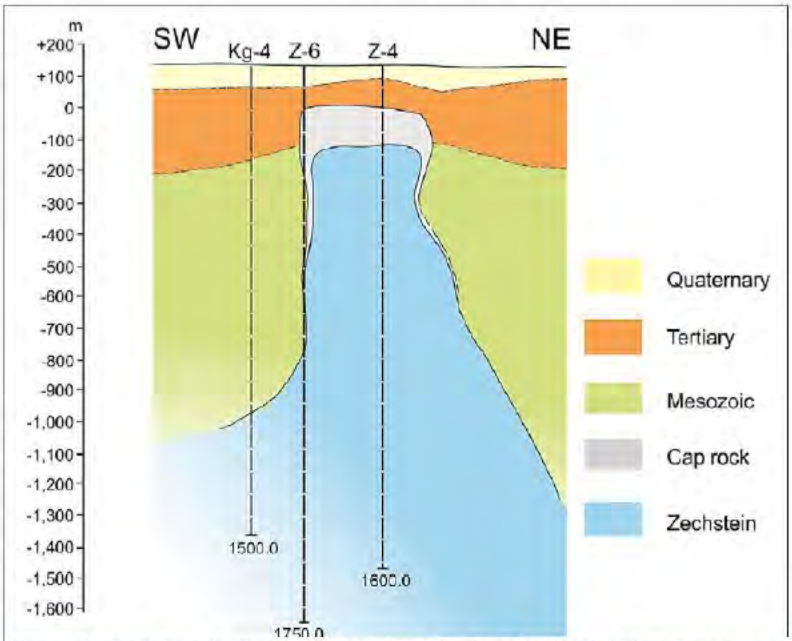

Figure 94 Mogilno salt dome cross section showing the depths of caverns Kg-4, Z-6, Z-4, from (Kosciuszko, 1997).

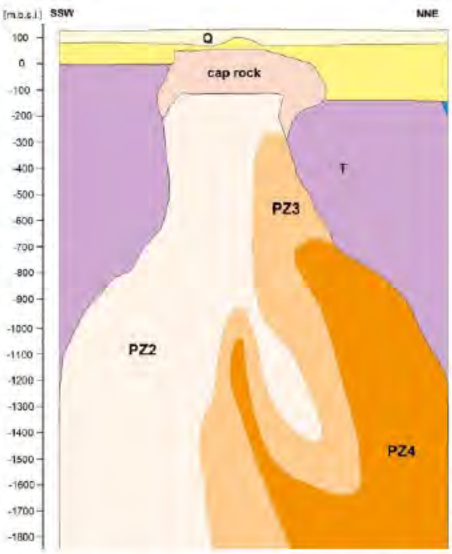

Figure 95 Mogilno salt dome cross section, showing the different geologies present, where PZ4, PZ3 and PZ2 represent, respectively, Youngest Halite, Younger Halite and Older Halite. from (Cyran, 2020).

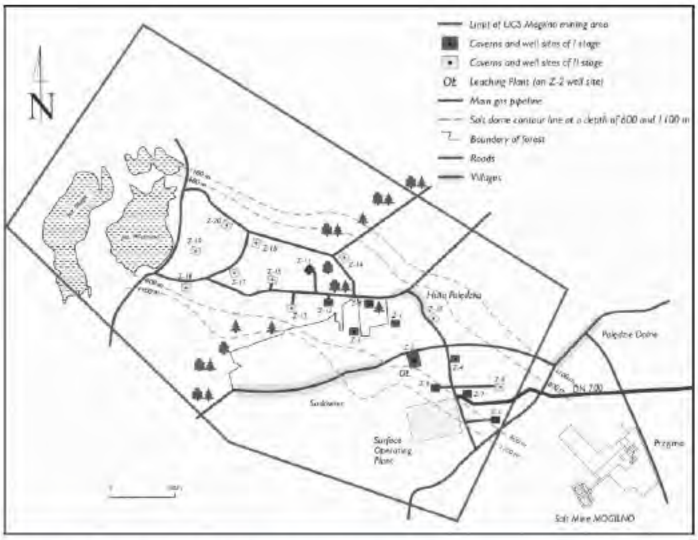

Figure 96 Map of the Mogilno caverns, from (Ślizowski et al., 2009).

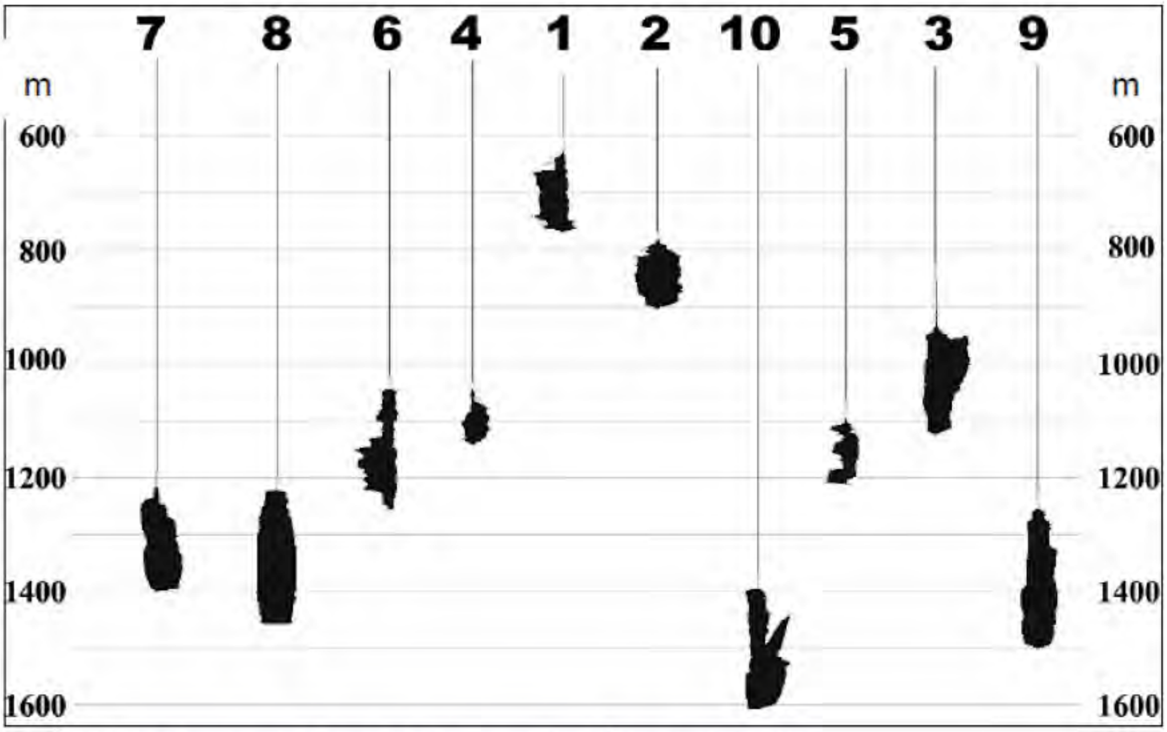

Figure 97 Showing cavern depths as well as 2D shapes, from (Ślizowski et al., 2009).

Incident	**Several caverns in the Mogilno salt dome, irregular shape, unknown date**
Cause	Salt heterogeneity
Top event	Cavern instability (salt heterogeneity)
Effects	Irregular shape only in some cases the final shape was as designed
References	(Cyran, 2020; Horváth et al., 2018)

Astrakhan, Russia

Storage	Gas condensate		Activity	Inactive, abandoned

In the Caspian Sea region storage took place in salt caverns created by nuclear explosions. It was used to store gas condensate. An incident occurred, leading to the abandonment of the cavern(s).

References: (Evans, 2008)

Incident	**5 of the 6 caverns of the Soviet PNE program and gas production ministry, integrity loss, 1983-1988**
Cause	5 of 6 caverns created by nuclear explosions suffer wall creep/closure due to no internal pressure (low pressure)
Top event	Cavern integrity loss (creep, collapse, fractures)
Effects	Abandoned (filling with water), leakage to overburden?
References	(Evans, 2008)

Karachaganak, Kazachstan, former USSR

Storage	Gas condensate		Activity	Inactive, abandoned

In the Caspian Sea region storage took place in salt caverns created by nuclear explosions. It was used to store gas condensate. An incident occurred, leading to the abandonment of the cavern(s).

References: (Evans, 2008)

Incident	**The last cavern (of 6) from the PNE program and gas production ministry, fractures, 1984-1994**
Cause	Nuclear explosion created cavities
Top event	Cavern integrity loss (fractures)
Effects	Both cavern and wellbore fill with water, cavern abandoned before commissioning
References	(Evans, 2008)

Goodyear, Arizona, United States of America

Storage	LPG (Propane)		Activity	Active?

In Goodyear, Arizona, lie cavern(s) for the storage of propane.

References: (Evans, 2008)

Incident	Propane loss, Unknown date
Cause	Corrosion hole in well casing at a depth about 91m below ground
Top event	Well integrity loss (Propane leakage)
Effects	Propane loss (several million cubic feet)
References	(Evans, 2008)

Iowa city, Iowa, United States of America

Storage	HVL (highly volatile liquids)		Activity	Active?

The only storage location in Iowa hosts cavern(s) for the storage of HVL.

References: (Réveillère et al., 2017)

Incident	**Highly volatile liquid release, January 23rd 1975**
Cause	Chiller failed (Which is used for cooling of the HVL before storage)
Top event	Pipeline integrity loss (HVL leakage)
Effects	HVL release, ignition, fire and explosion, 2 fatalities
References	(Réveillère et al., 2017)

Incident	**Compressor failure, April 1987**
Cause	Flexible pipe of compressor failed
Top event	Pipeline integrity loss (HVL leakage)
Escalation factors	Due to ignition a relief valve failed in open position-> release of all of the HVLs out of the underground cavern over a period of 60 days
Effects	Release of HVLs, ignition, fire and explosion
References	(Réveillère et al., 2017)

Conway, Kansas, United States of America

Storage	LPG (Propane), NGL
Caverns	Almost 300 (600 total in Kansas)
Cavern depth	Deeper than 120m

Activity	Active?
Salt structure	Bedded salts
Commissioned in	1951

The Conway field (situated in McPherson county) contains caverns for the storage of LPG and NGL, the salts are part of the Hutchinson Salt Member of the Permian Wellington formation.

References: (Bérest et al., 2019; Ratigan et al., 2002; Réveillère et al., 2017)

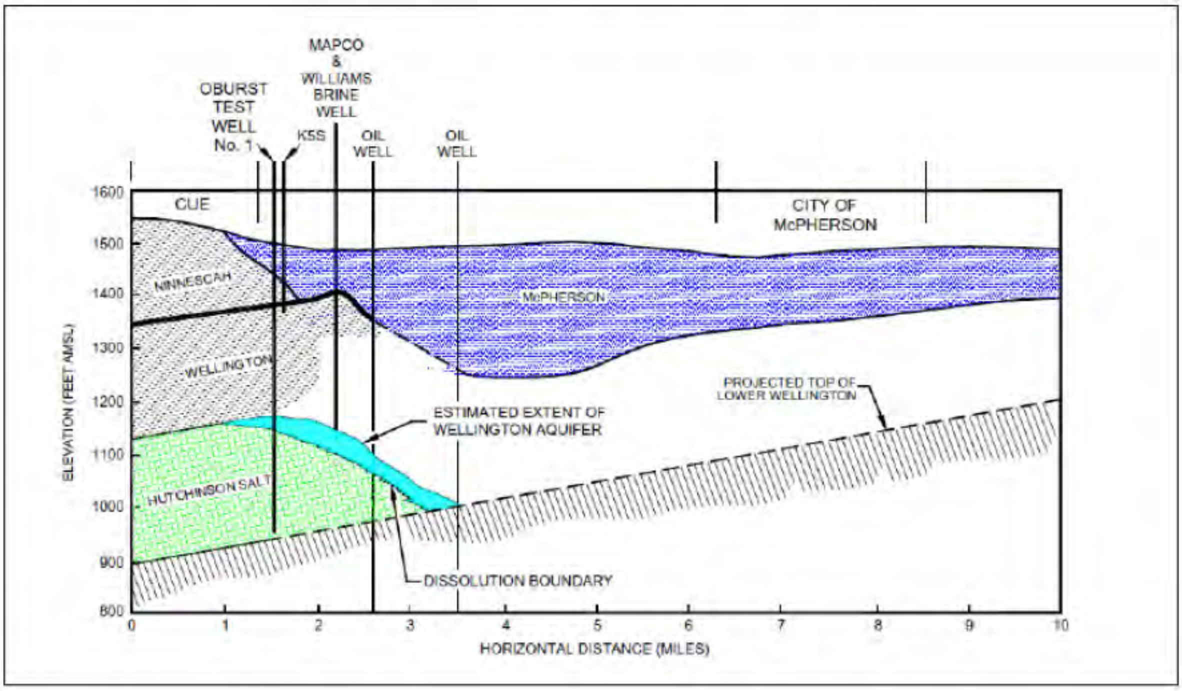

Figure 98 Cross section of the Williams-CUE facility, from (Ratigan et al., 2002).

Incident	Gas leakage from private wells, 1980 (1966-2000 in total)
Cause	Poor cement bonding
Escalation factors	Hydrated caprock (saline aquifer)
Top event	Well integrity loss (Gas Leakage)
Mitigation measures	Analysis of geological data, temperature logs, CBL, 8 monitoring wells drilled, 71 operating wells evaluated
Effects	Contamination of groundwater (wells). 120 people had to be evacuated. Some caverns have been abandoned and/or recompleted, lessening the groundwater pollution
References	(Bérest et al., 2019; Johnson & Hoffine, 2004; Réveillère et al., 2017; Yang et al., 2013)

Hutchinson, Kansas, United States of America

Storage	Natural gas
Caverns	
Cavern depth	200-280m

Activity	Active
Salt structure	Bedded salts
Commissioned in	1980s

The Hutchinson field in Kansas is home to storage caverns containing natural gas, the salts are made up of the lower parts of the Hutchinson Salt Member of the Permian Wellington formation. The caverns were abandoned, and later re-opened and filled with natural gas in the 1990s.

References: (Bérest et al., 2019; Kansas Geological Survey Website, 2001)

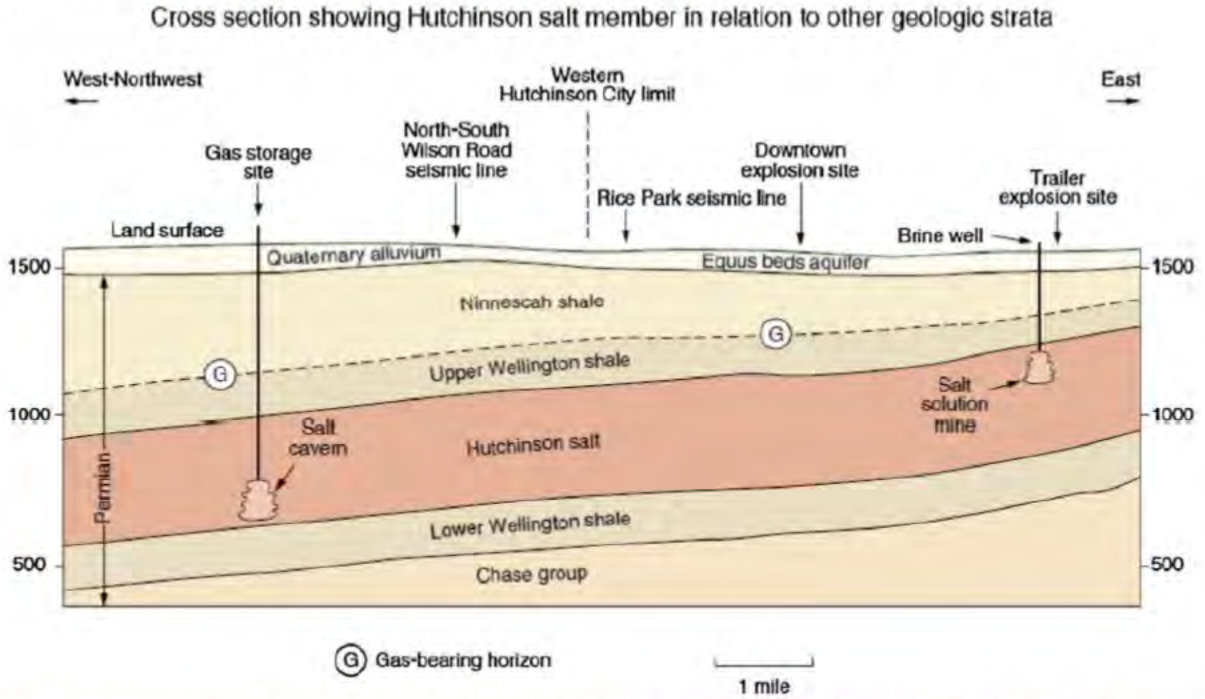

Figure 99 Hutchinson leakage pathway, elevation in feet. The leakage migrated along the dashed G-G line, which are fractured dolomite layers, from (Kansas Geological Survey Website, 2001).

Incident	Gas leakage, January 17th 2001
Cause	Breach in the cemented casing (damaging of the cemented casing during the re-drilling operation of this formerly plugged and abandoned cavern converted to gas storage)
Escalation factors	Fractured level: gas slowly filling a 13-km long sub horizontal fractured level
Top event	Well integrity loss (Natural gas leakage)
Mitigation measures	250 evacuees
Effects	"Lateral migration of gas over a distance of 8km, leading to geyser gas releases (12 in total) 2 of which exploded and an explosion under a store. 15 minutes after the first downtown blast and 13km NW from Hutchinson technicians recorded a pressure drop in a Yaggy gas storage cavern of 0.7MPa in cavern S-1 (immediately thought to be related) and it was plugged and a downhole video was run revealing a large curved slice in the casing at a depth of about 180m, thought to be remains of the former abandonment of the storage cavern. The next day an explosion of natural gas (from a long forgotten brine well) occurred under a mobile home resulting in 2 deaths, 1 injured."

Lessons learned	"New regulations were imposed: mandatory double casing in wells, corrosion control. Restrictions on well-conversion (caverns designed for LPG storage could not be converted for gas storage and plugged caverns cannot be reopened and reused), maximum pressure gradient of 1.73×10^{-2} MPa/m at the production casing shoe, new testing requirements (an MIT every 5 years)" (Bérest et al., 2019)
References	(Bérest et al., 2019; Réveillère et al., 2017)

McPherson, Kansas, United States of America

Storage	LPG(Propane), HVL (Highly volatile liquids)	**Activity**	Active?
Operator	National Cooperative refinery association	**Commissioned in**	Before 1966

McPherson has cavern(s) for both the storage of LPG as well as HVL.

References: (Evans, 2008)

Incident	**Propane leakage, 1966**
Cause	Unknown cause
Top event	Well Integrity loss (Propane leakage)
Effects	Gas observed escaping from casing annulus area of 8 propane storage wells
References	(Evans, 2008)

Incident	**Cavern overfilling (HVL), June 23rd 1989**
Cause	Possibly an operating error
Top event	Well control loss (overfilling)
Effects	HVL's released to the brine pond and ignited.
References	(Réveillère et al., 2017)

Yaggy, Kansas, United States of America

Storage	Natural gas

Activity	Active

Yaggy has cavern(s) for the storage of natural gas.

References: (Yang et al., 2013)

The incident described below is likely the same incident as described in the Hutchinson section.

Incident	**Natural gas leakage, 2001**
Cause	Casing bend
Top event	Well integrity loss (Natural gas leakage)
Mitigation measures	Hundreds of people evacuated
Effects	Fire, explosion, 2 fatalities, loss of 5600000m3 natural gas
References	(Yang et al., 2013)

Yoder, Kansas, United States of America

Storage	LPG (propane)		**Activity**	Active?
Cavern depth	Deeper than 120m		**Salt structure**	Bedded salts
			Commissioned in	1951

Located in Yoder, Reno county, cavern(s) for the storage of propane exist. The caverns are situated in the Hutchinson salt member of the Permian Wellington formation.

References: (Bérest et al., 2019)

Incident	**Propane leakage, June 1980**
Cause	Poor cement bonding
Top event	Well integrity loss (Propane leakage)
Effects	Leakage to the atmosphere, Propane blow-out
References	(Bryson, 1980; Réveillère et al., 2017)

Bayou Choctaw, Louisiana, United States of America

Storage	Crude oil, Natural gas and Liquid hydrocarbons	**Activity**	Active
Number of caverns	>6	**Salt structure**	Salt dome
Working volume	1. 76.0 million barrels (US)	**Commissioned in**	1987
		Owner/operator	1. US Department of Energy (DOE) / Fluor Federal Petroleum Operations 2. Boardwalk Partners

The Iberville Parish in Louisiana is home to storage caverns. The caverns are situated in an oval shaped dome that has a length of 1.4km and a width of 1.1km. The top of the salt lies at a depth of 192m. The 6 caverns of the US Department of Energy are operated by Fluor Federal Petroleum Operations, and are used for the storage of crude oil. These caverns are part of the Strategic Petroleum Reserve. The collapse of cavern BC-7 (Brine production, 1942-1954) created a sinkhole lake, this collapse was due to pressure loss when the cavern roof leached to the caprock bottom. BC-4 has been abandoned and faces similar dangers as BC-7 (its roof intrudes into the caprock).

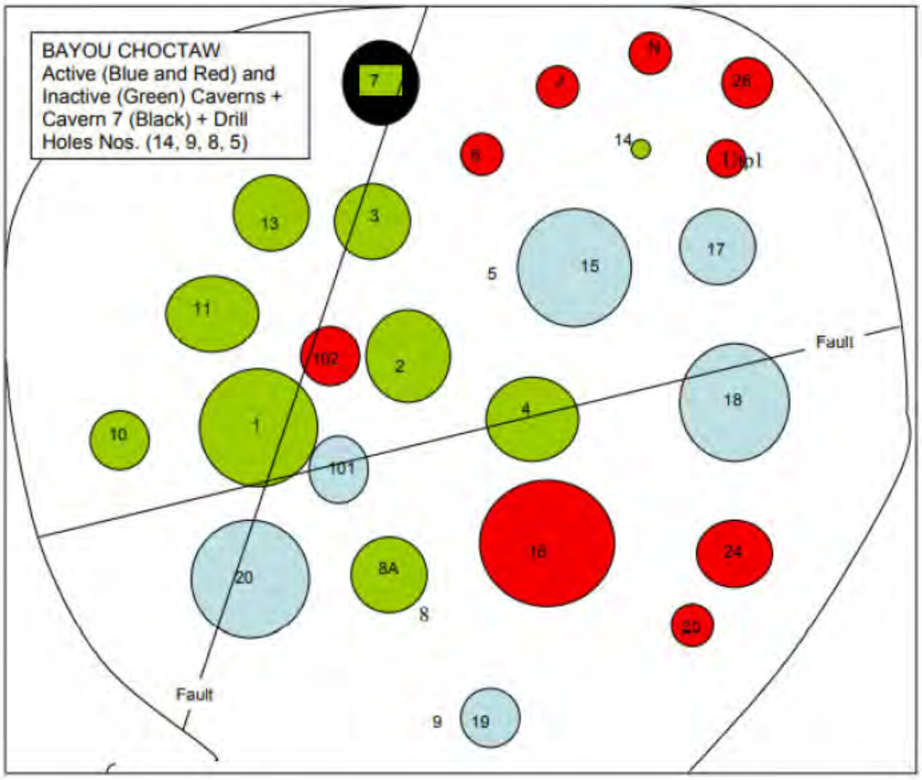

Figure 100 Schematic map of the Bayou Choctaw dome, from (Munson, 2007).

References: (Horváth et al., 2018; Looff, 2017; Munson, 2007)

Incident	**Brine production Cavern BC-7 collapse, 1954**
Cause	Cavern roof reached the caprock (due to uncontrolled leaching operations), which caused a large pressure drop (so it was not a caprock?)
Escalation factors	Porous caprock
Top event	Cavern integrity loss (dissolution)
Effects	Sinkhole lake (254m), abandonment of cavern BC-4 (which had high predictions of salt falls), collapse of overburden into the developing cavern number 7 due to uncontrolled leaching operations (solution of pillar located between caverns)
References	(Horváth et al., 2018; Looff, 2017; Munson, 2007; Yang et al., 2013)

Clovelly dome, Louisiana, United States of America

Storage	Crude oil and brine storage
Number of caverns	8
Capacity	7mln m^3 (4mln m^3 in the brine storage reservoir)

Activity	Active
Salt structure	Salt dome
Owner	Louisiana Offshore Oil Port (LOOP)

The Clovelly dome storage terminal in Lafourche Parish, Louisiana contains caverns for storage. The top of the salt lies at a depth of 370m. Most caverns have 5 wells for high inflow rates from super tankers.

Cavern 14 failed to pass its MIT in 1992, it was found that the cavern had an irregular shape.

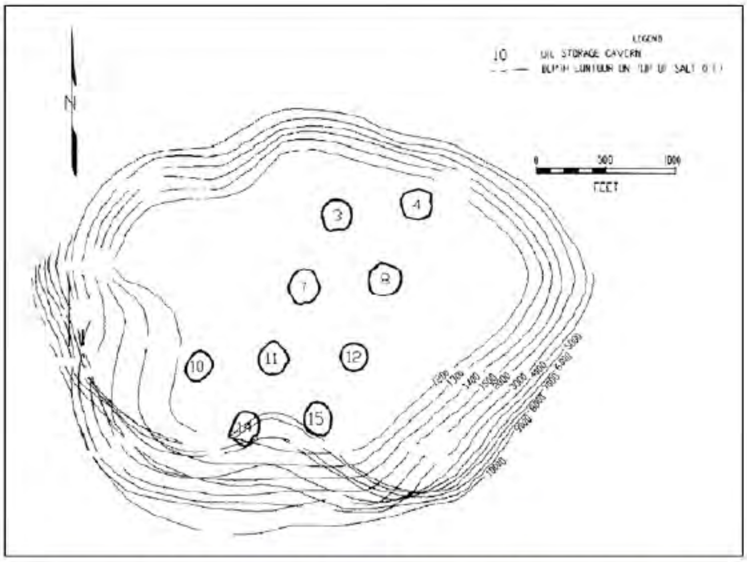

Figure 101 Map of the Clovelly salt dome, showing the storage caverns, from (McCauley et al., 1998).

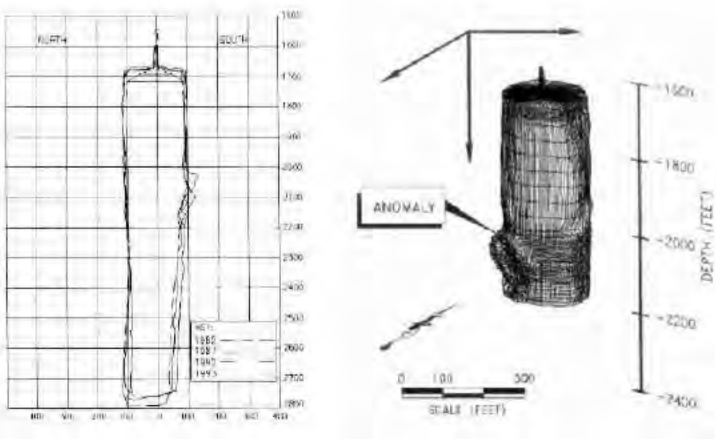

Figure 102 Cavern 14, irregular shape, from (McCauley et al., 1998).

References: (Brouard, 2019; Horváth et al., 2018; McCauley et al., 1998)

Incident	**Irregularly shaped cavern, 1992**
Cause	Salt heterogeneity--> pressure drop
Escalation factors	Cavern was found to be close to the edge of the salt (insufficient thickness of salt wall to act as a barrier)
Top event	Cavern integrity loss (preferential leakage path to outside the salt dome (sandstone layer), crude oil leakage)
Mitigating measures	Oil was removed after cavern failed MIT test
Effects	Irregular shape, cavern leaching the salt overhang. (cavern dissolved to caprock), cavern abandonment, crude oil leakage
References	(Brouard, 2019; Horváth et al., 2018; Yang et al., 2013)

Grand Bayou, Louisiana, United States of America

Storage	Natural gas	Activity	Active
Commissioned in	1970s	Salt structure	Elongated salt dome (Napoleonville salt dome)

Located in Napoleonville, just a few 100 meters from the bayou corne sinkhole, are caverns for the storage of natural gas. The Louann salt hosts the caverns and is of mid-late Jurassic origin. The caverns are part of the Magnolia hub.

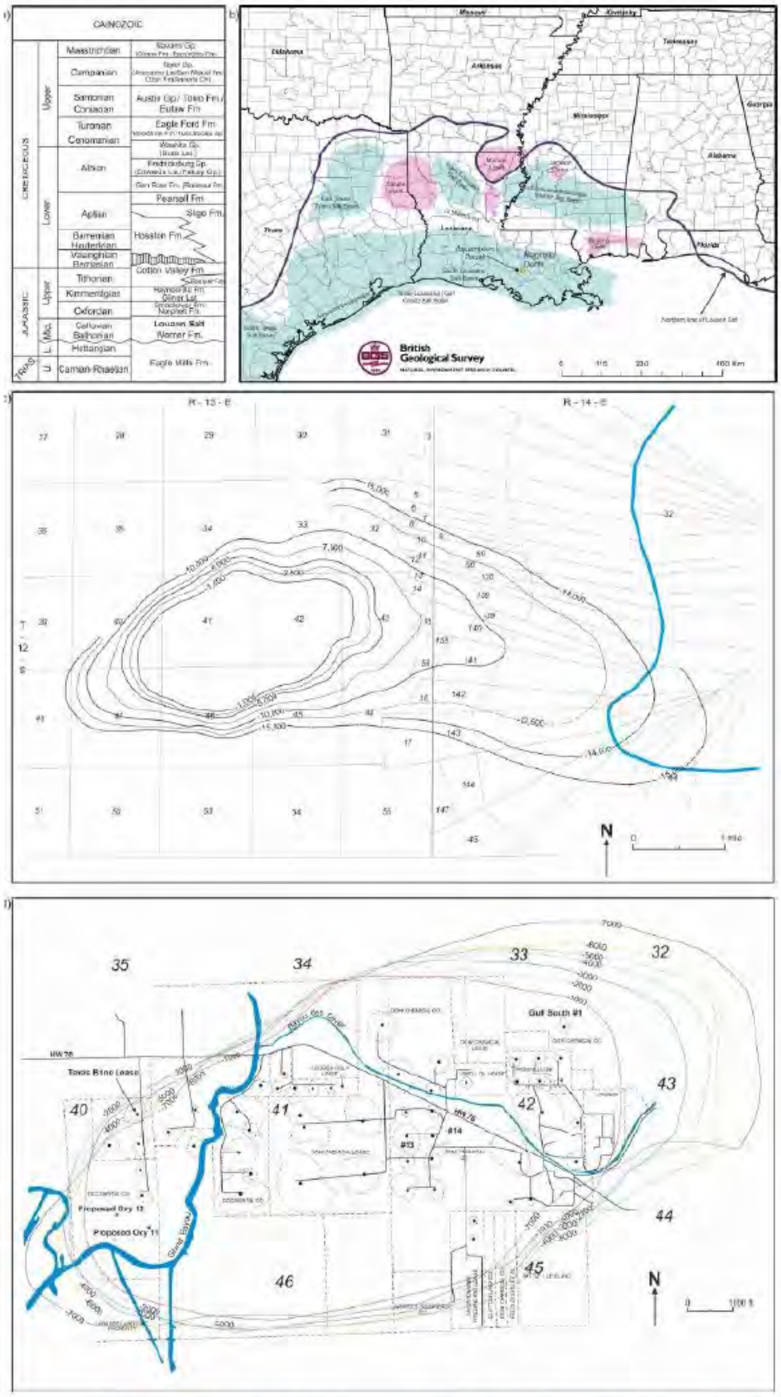

Figure 103 A: Stratigraphy of the Louann salt, B: Location of the Magnolia salt dome, C: Napoleonville salt dome structure map, D: Contour map of the Napoleonville salt dome, from (Réveillère et al., 2017) and references therein.

References: **(Réveillère et al., 2017)**

Incident	1999
Top event	Corrosion issues
References	(Réveillère et al., 2017)

Incident	Gas leakage, December 24th 2003
Cause	Crushed casing, or, cracks near the couplings (video evidence points to this as the possible cause), potentially related to improper back welding, or separation of three or four 13 3/8" casings connections (breach at 440m)
Top event	Well integrity loss (Natural gas leakage via a nearby aquifer, to the surface)
Escalation factors	Reservoir
Mitigation measures	30 people were evacuated for 30 days, "Plugged the wells and installed 36 vent wells into the aquifer over the salt dome. Of these, 17 collected or burned off gas, removing 10.62 mcm (375 mcf) before the wells were closed down in July 2004" From (Réveillère et al., 2017) and references therein.
Effects	Gas boiling at the surface above 2 storage caverns, release of about 9.9 Mcm of gas in a matter of hours, bottom plug is set, 36 boreholes drilled to the aquifer layer, 17 find gas, caverns filled with brine.
References	(Réveillère et al., 2017; Yang et al., 2013)

Napoleonville, Louisiana, United States of America

Storage	1. Natural gas 2. Liquid hydrocarbons	Activity	Active
Number of caverns	Several, not specified	**Salt structure**	Salt dome
Cavern depth	600-1800m	**Operator**	1. Pontchartrain and Bridgeline 2. DOW, Enlink and Promix

The Napoleonville salt dome is located near the town of Bayou Corne in the Assumption Parish, Louisiana. Storage caverns for both natural gas and liquid hydrocarbons are present, as well as brine production caverns.

The Napoleonville salt dome is home to a major cavern failure. One of the brine production caverns was located too close to the edge of the salt dome, resulting in the sediments on the edge of the dome to fall into the cavern. This created a massive sinkhole of ~160000m2. Close to cavern Oxy3 lies a butane storage cavern. See Grand Bayou for more incidents which have occered at the Napoleonville salt dome.

References: (Horváth et al., 2018)

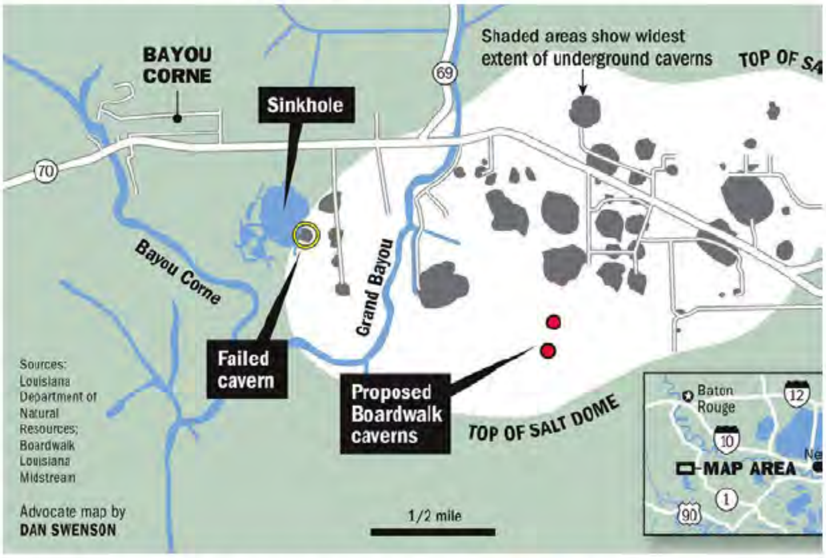

Figure 105 Map of the Bayou Corne sinkhole, from www.theadvocate.com.

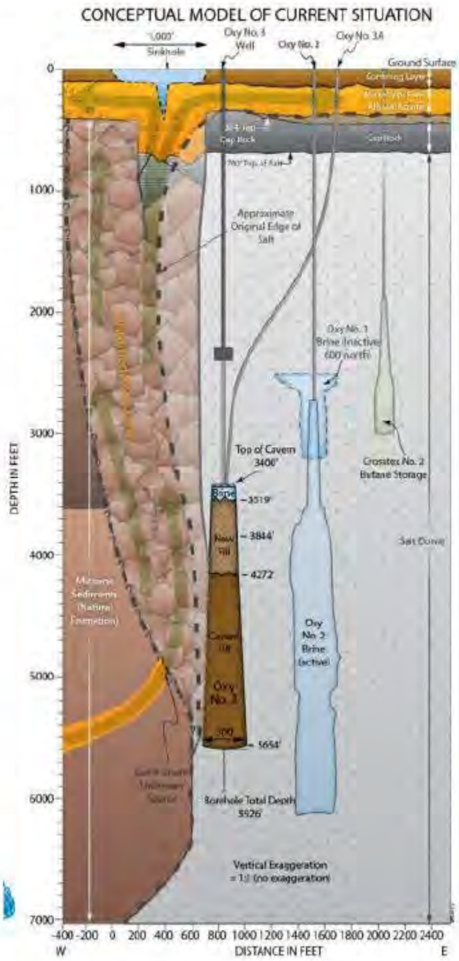

Figure 104 Model of the incident at Bayou Corne, showing the proximity of cavern Oxy3 to the edge of the salt dome, from (Bérest, 2017) and references therein.

Incident	Brine production cavern Oxy3, sinkhole lake at Bayou Corne, 2012
Cause	Cap rock failure: crack (thin cap rock)
Escalation factors	Proximity to edge of salt
Top event	Cavern integrity (collapse, cap rock failure)
Effects	Sinkhole lake
References	(Horváth et al., 2018)

Sulphur mines, Louisiana, United States of America

Storage	Crude oil	Activity	Inactive
Number of caverns	Several, not specified	Salt structure	Salt dome
Unspecified volume	3.8mln m^3	Commissioned in	1977
		Owner	US Department of Energy (DOE)

The Sulphur mines salt dome (610m diameter) in Calcasieu Parish, Louisiana contained storage caverns for crude oil. The depth of the top of the salt is 445m. The caverns were part of the Strategic Petroleum Reserve. The dome is also used for Frasch mining of the Sulphur in the caprock.

Storage	Hydrocarbons (LPG)	Activity	Active
Owner	Boardalk Partners and Sasol	Salt structure	Salt dome

Boardalk partners and Sasol have hydrocarbon storage inside the dome.

References: (Horváth et al., 2018)

Incident	1-A cavern affecting an exploration well, October 20th 2004
Cause	Leaking gas from Sasol's 1-A cavern under high pressure (cause unknown), causing pressure in the formation outside the salt dome
Top event	Cavern integrity loss (Gas leakage)
Effects	Blowout of oil and gas from an exploration well. Following a nine-day trial, the jury found Sasol's cavern was defective and Sasol's unsafe operation of this cavern posed an unreasonable risk of harm to locals and caused financial damage to Yellow Rock.
References	(Evans, 2008)

West Hackberry, Louisiana, United States of America

Storage	1. Crude oil and brine storage 2. Hydrocarbons (LPG)
Number of caverns	1. 21-23 2. Multi-cavern
Capacity	1. 220.4mln barrels (US), 35mln m³ crude oil storage capacity

Activity	Active
Salt structure	Salt dome
Commissioned in	1. 1970s
Owner/ Operator	1. US Department of Energy (DOE) / Fluor Federal Petroleum Operations 2. Targa resources (before: Warren Petroleum Company)

The West Hackberry salt dome lies in the Cameron Parish in Louisiana. The dome has an elongated shape, its length is 2.4km and its width is 0.8km. The top of the salt lies at a depth of 549m. The crude oil (and brine) storage is part of the Strategic Petroleum Reserve.

References: (Horváth et al., 2018)

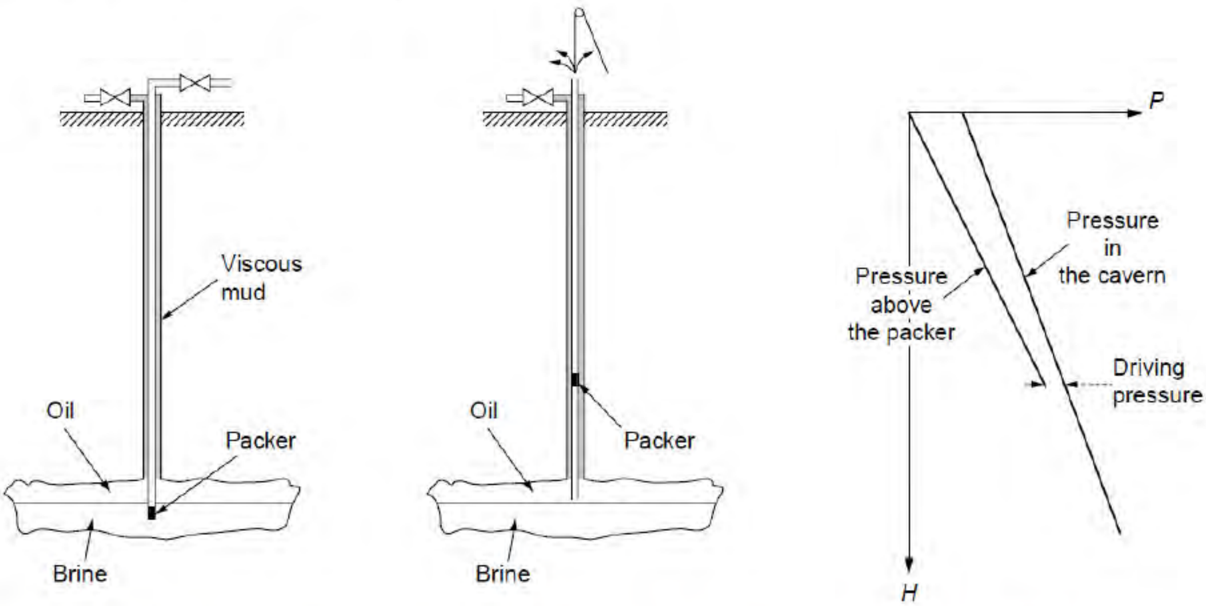

Figure 106 Blow-out of West Hackberry, due to slipping of an inflatable packer, from (Bérest & Brouard, 2003).

Incident	**Excessive subsidence, 1970s**
Cause	Excessive creep of salt
Top event	Cavern instability
Effects	Subsidence: surface settlement rate 75mm/a, influence range: 750m
References	(Yang et al., 2013)

Incident	Cavern 6 blow-out, September 21st 1978
Cause	An inflatable packer slipped (during repairs) and the oil pushed it to the surface
Top event	Well control loss
Effects	Blow out (geyser of oil), fire, 1 reported death, 1 injured, crude oil release, 14-20m$ loss, environmental pollution, influenced area was 90000m2
References	(Bérest & Brouard, 2003; Réveillère et al., 2017; Yang et al., 2013)

Eminence, Mississippi, United States of America

Storage	Natural gas		Activity	Active
Number of caverns	3		Salt structure	Salt dome

The Eminence salt dome is located in the Mississippi salt basin in Covington county, Mississippi. It was the first solution mined gas storage cavern in the United States Gulf Coast. The salt lies at a depth of 750m.

References: (Horváth et al., 2018)

Incident	Cavern 1 volume loss, 1970-1972
Cause	Gas filled at low pressure (28MPa, geostatic pressure at cavern depth: 38-45MPa)--> excessive salt creep
Top event	Cavern instability (creep closure) Cavern was not kept at sufficient pressure→ cavern creep led to unwanted cavern volume loss
Mitigation measures	Maintaining a higher minimum pressure over extended time periods and less dewatering
Effects	Cavern volume loss: more than 40%, (Accelerated subsidence)
References	(Bérest et al., 2019; Yang et al., 2013)

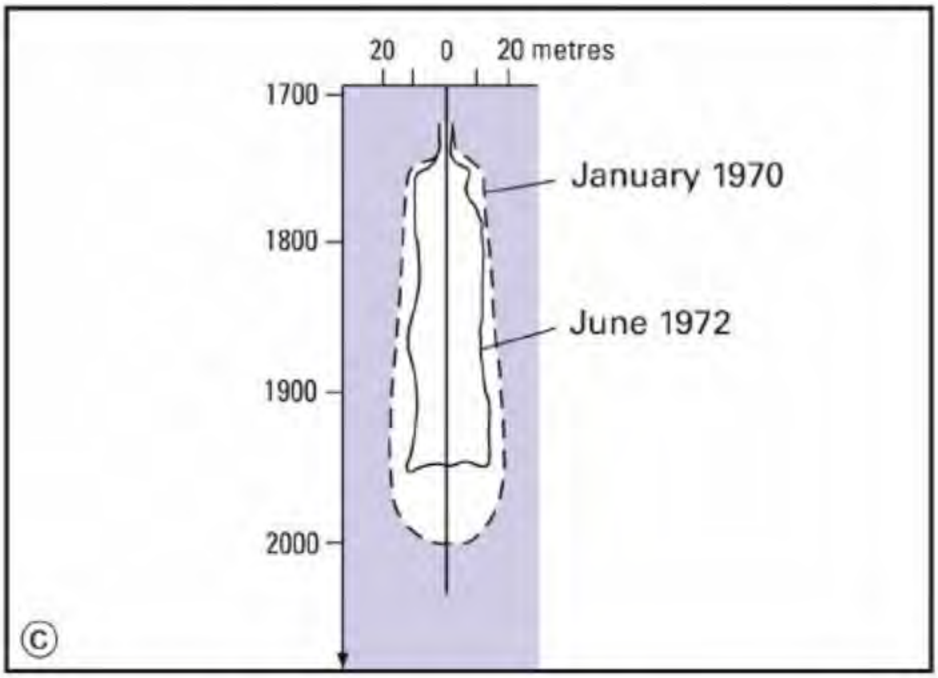

Figure 107 Effects of salt creep on Eminence cavern #1, modified by and redrawn by (Bérest et al., 2019), after several references therein.

Incident	Cavern 4 abandonment, 2004
Cause	Unknown cause
Top event	Well integrity loss (casing failure)
Mitigation measures	Early abandonment of the cavern, filled with water and shut in
References	(Bérest et al., 2019)

Incident	**Gas leakage, December 26th 2010**
Cause	Shallow failure of the well completion (due to salt creep--> overstretching of the casings above the cavern.)--> pressure drop of 2.46MPa in 1min, probably due to fast cavern closure rate (40% in one year), frequent re-brining (cyclicity)
Top event	Well integrity loss (Natural gas leakage)-->gas migration, large unexpected pressure drop
Mitigation measures	Short term: "Two dozen families evacuated for 12 days…" Long term: "…Monitoring and gas extraction wells were drilled (245 shallow boreholes drilled, 13 boreholes drilled to the caprock). 4 caverns were taken out of service, and the 3 remaining ones of the field had their operation range restricted" (Réveillère et al., 2017) (maximum operating pressure lowered)
Effects	Water / gas geysers releases (from shallow boreholes) to the atmosphere. The leak escaped from the ground around wellhead 1, Partial venting
References	(Bérest et al., 2019; Réveillère et al., 2017)

Petal, Mississippi, United States of America

Storage	1. Natural gas 2. Liquid hydrocarbons
Number of caverns	1. Several 2. 5

Activity	Active
Salt structure	Salt dome
Owner/Operator	1. Boardwalk Partners / Gulf south pipeline 2. Enterprise products, Lone Star NGLs and Targa Resources

Caverns for the storage of natural gas and liquid hydrocarbons are present in the Petal salt dome of the Mississippi salt basin. The dome lies in the Forrest county, Mississippi. The depth of the top of the salt lies at a depth of 530m.

References: (Horváth et al., 2018)

Incident	**Overfilling, August 1974**
Cause	Human error
Top event	Well control loss (overfilling)
Mitigation measures	3000 evacuees
Effects	Cavern damage(?), Fire, explosion, 24 injured, homes destroyed within 7km
References	(Evans, 2008; Réveillère et al., 2017; Yang et al., 2013)

Incident	**2 caverns (filled with alkyfeed) experienced overfilling, July 1986**
Cause	High pressure due to overfilling (Process error)
Top event	Cavern integrity loss (Structural integrity loss and overfilling)
Mitigation measures	200 evacuees
Effects	14 injured (burns), large crated formed, a tanker fell in the crater
References	(Réveillère et al., 2017)

Carthage, Missouri, United States of America

Storage	Propane		Activity	Active?

The only cavern storage location located in Missouri. This location has cavern(s) for the storage of propane.

References: (Réveillère et al., 2017)

Incident	Cavern overfilling, November 16th 1989
Top event	Cavern overfilling (Unclear if well control loss or cavern integrity incident)
Effects	Release of propane, ignition
References	(Réveillère et al., 2017)

Elk City, Oklahoma, United States of America

Storage	LPG (Propane)
Commissioned in	After 1954

Activity	Active
Salt structure	Bedded salts

The only storage location in Oklahoma. The cavern(s) are located in the Blaine Formation, which has alternating layers of salt, anhydrite and shales. The last cemented casings are located at a depth of 410m.

References: (Bérest et al., 2019; Fay, 1973)

Incident	Well leakage, February 1973
Cause	Unknown cause, partly explained by a poorly cemented annulus, poor bonding between 35.5m and 341m
Escalation factors	Migration through a porous formation, Doxey shales. Poorly cemented annulus.
Top event	Well integrity loss (LPG leakage)
Escalation factors	Reservoir
Mitigation measures	Soil gas sampling and analysis, storage emptied
Effects	Crater appeared in level grassland, with siltstone blocks thrown about and several 30-ton boulders lifted to an upright position, trees were tilted 45 degrees. Blow-out.
Lessons learned	Leakage zone now has two casings and a monitoring annulus, no more leakages have been reported. Water-filled annular space.
References	(Bérest et al., 2019; Réveillère et al., 2017)

Figure 108 Left photograph shows the central crater, the right photograph shows one of the pressure cracks, from (Fay, 1973).

Barbers Hill, Texas, United States of America

Storage	Hydrocarbons (Propane, Butane, Ethane) and Natural gas
Number of caverns	140 (including brine production)
Capacity	60mln m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	1950s
Operator	Targa resources (formerly known as Warren Petroleum Company), Enterprise and 5 other operators.

Mont Belvieu, Texas, is the home to over 140 caverns. The caverns were leached in the Barbers Hill salt dome, which is part of the Tertiary Gulf coast basin. The dome has a length of 3.5km and a width of 2.7km at a depth of 610m. Targa resources owns 30 of the caverns for the storage of hydrocarbons and natural gas, with a capacity of 15mln m3. Abandonment tests were performed on Enterprise West Wells No. 10W, No. 11W, No. 14W, and No. 15W2. A hydraulic connection between brine production caverns 16E and 2E occurred in 2004.

References: (Bérest & Brouard, 2003; Cartwright & Ratigan, 2005; Horváth et al., 2018; Looff, 2017)

Figure 109 Map of the Barbers Hill salt dome, showing the outlines of the caverns, from (Looff, 2017).

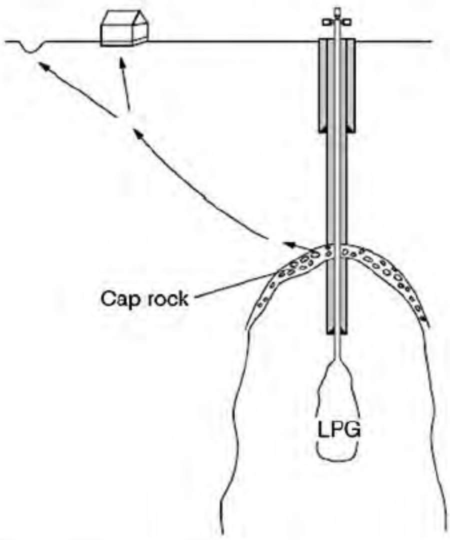

Figure 110 Sketch of the 1980 LPG leak, from (Bérest & Brouard, 2003).

Incident	Well leakage, September 17th 1980
Cause	Breach in the well casing (casing damage due to corrosion), pressure drop, weak cementation at cavern's neck--> pipe corrosion, crack generation
Top event	Well integrity loss (Propane Leakage)

Mitigation measures	Short term: 50 people evacuated (75 families according to (Yang et al., 2013)) for 180 days. Long term: Drilling holes into the water table to find and vent the gas.
Effects	1 fatality (no casualties according to (Bérest et al., 2019), Gas leakage to the atmosphere , fire and an explosion in a house due to a spark (20 days after pressure drop). Groundwater contamination. Caverns emptied, 23 million m^3 of propane loss, cavern which experienced the pressure drop filled with brine
References	(Bérest et al., 2019; Yang et al., 2013)

Incident	**Propane leakage, October 1984**
Cause	Casing failure unknown cause
Top event	Well integrity loss (Propane leakage)
Effects	Loss of propane
References	(Réveillère et al., 2017; Yang et al., 2013)

Incident	**Propane leakage, November 5th 1985**
Cause	Surface pipe at NGL terminal cut
Top event	Pipeline integrity loss (Propane Leakage)
Escalation factors	Ignition
Mitigation measures	2000 evacuees (more than 17000 evacuated according to (Yang et al., 2013))
Effects	2 dead (workers), Product loss (110m^3 of propane consumed and a large amount of propane leakage), fire (fire was fed from 5 caverns), explosion
References	(Evans, 2008; Yang et al., 2013)

Incident	**Excessive subsidence, 1988-1993**
Cause	Excessive creep of salt
Top event	Cavern instability
Effects	Subsidence: surface settlement rate 20-40mm/a, influence range: 1500m
References	(Yang et al., 2013)

Incident	**Hydraulic connection between brine production cavern 16E and 2E, 2004**
Cause	"Diesel was added to the pad but "a corresponding downward movement in the interface was not observed"" (Brouard, 2019), and the blanket diesel was lost. Salt heterogeneity (boundary shear zone plane with higher salt porosity) causing a hydraulic connection. An MIT (mechanical integrity test) was performed which showed a hydraulic connection between wells 2E and 16E (their walls are at a distance of 90m from each other).
Top event	Cavern integrity loss (roof leakage, diesel)
Effects	Hydraulic connection between wells 2E and 16E
References	(Brouard, 2019)

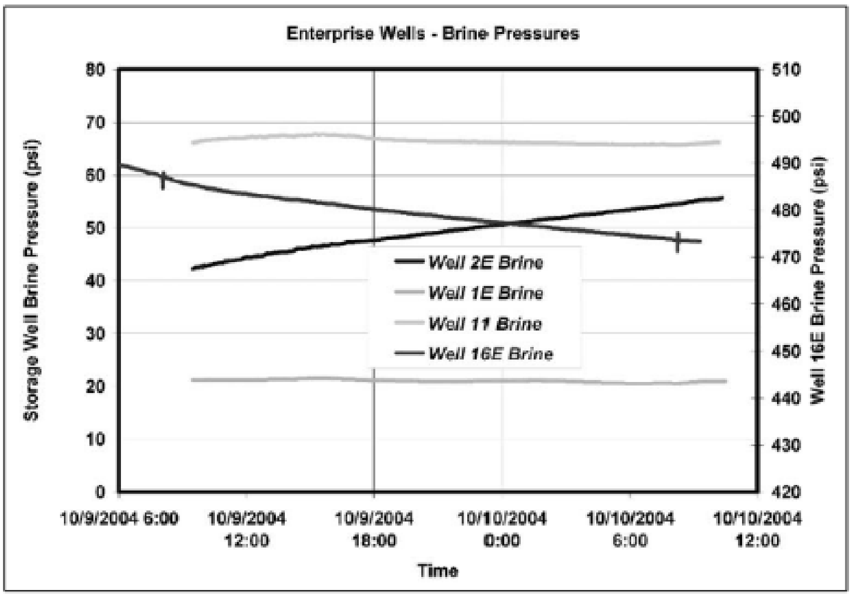

Figure 111 Pressure vs time of well 16E during MIT, from (Cartwright & Ratigan, 2005).

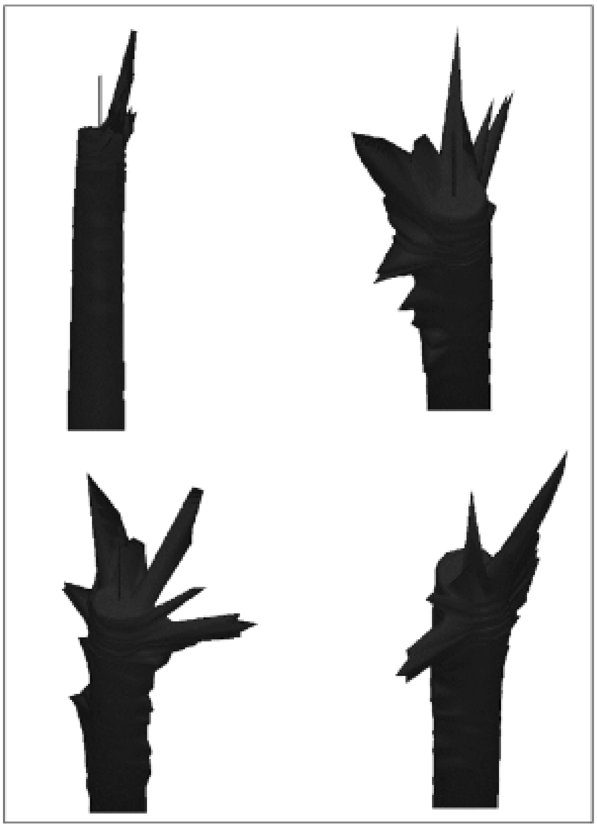

Figure 112 Isometric illustrations of cavern roof of 16E, derived from sonar surveys, from (Cartwright & Ratigan, 2005).

Big Hill, Texas, United States of America

Storage	Crude oil
Number of caverns	14
Cavern depth	700-1525m
Capacity	170 million barrels (US)

Activity	Active
Salt structure	Salt dome
Commissioned in	1991
Owner	US Department of Energy (DOE)

In Jefferson County, Texas, the Big Hill salt dome (1.6km diameter) is host to 14 caverns for the storage of crude oil. They are part of the Strategic Petroleum Reserve.

There was an incident with cavern #103, a salt fall occurred. This has been analysed by (Munson et al., 2004).

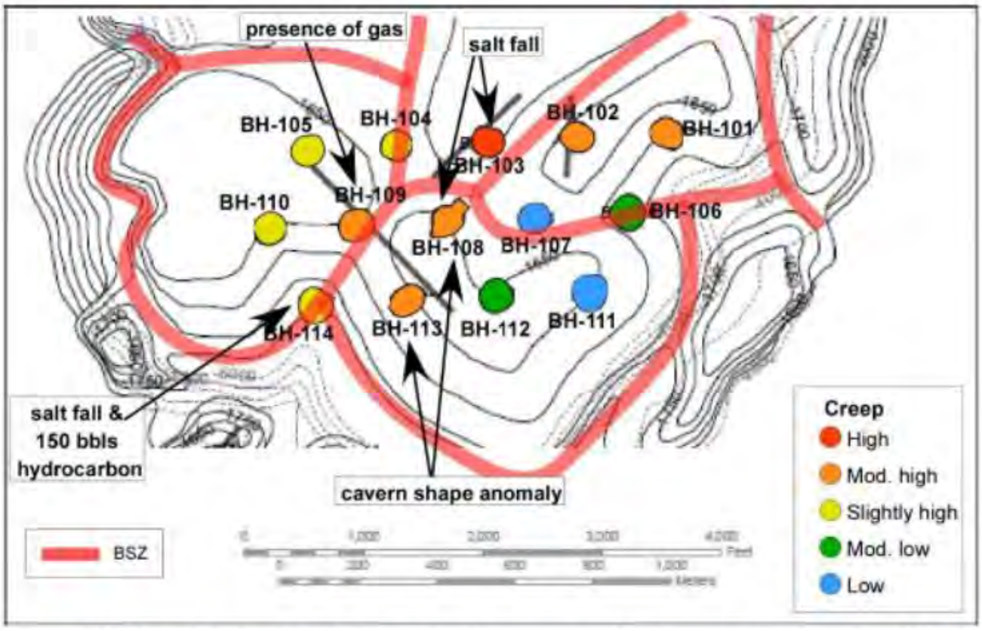

Figure 113 Map of the Big Hill salt dome, showing caverns and their creep rates, from (Looff, 2017).

References: (Horváth et al., 2018; Looff, 2017; Munson et al., 2004)

Incident	Excessive subsidence, 1988-1993
Cause	Excessive creep of salt
Top event	Cavern instability
Effects	Subsidence: surface settlement rate 90mm/a, influence range: 1000m
References	(Yang et al., 2013)

Incident	Cavern 103 salt fall, 2002
Cause	Stress-driven mechanical instabilities due to inhomogeneous salt dissolution (also during initial leaching)
Top event	Cavern instability (salt fall, between 2 sonar measurements: July 26th, 2001 and March 2002)
Effects	Bottom elevation of 7 feet (15000tons of salt), the brine string is buried in debris from the event
References	(Horváth et al., 2018; Munson et al., 2004)

Boling, Texas, United States of America

Storage	1.Natural gas 2. Liquid Hydrocarbons
Number of caverns	1. 5 2. 1
Working volume	1. 4.76mln m^3 2. 1.59mln m^3

Activity	Active
Salt structure	Salt dome
Owner	Enterprise Products

In Boling, Texas, the Boling salt dome is host to 6 storage caverns. The dome has an oval shape and is 8km in length, 4.5km in width. The top of the salt lies at a depth of 154m.

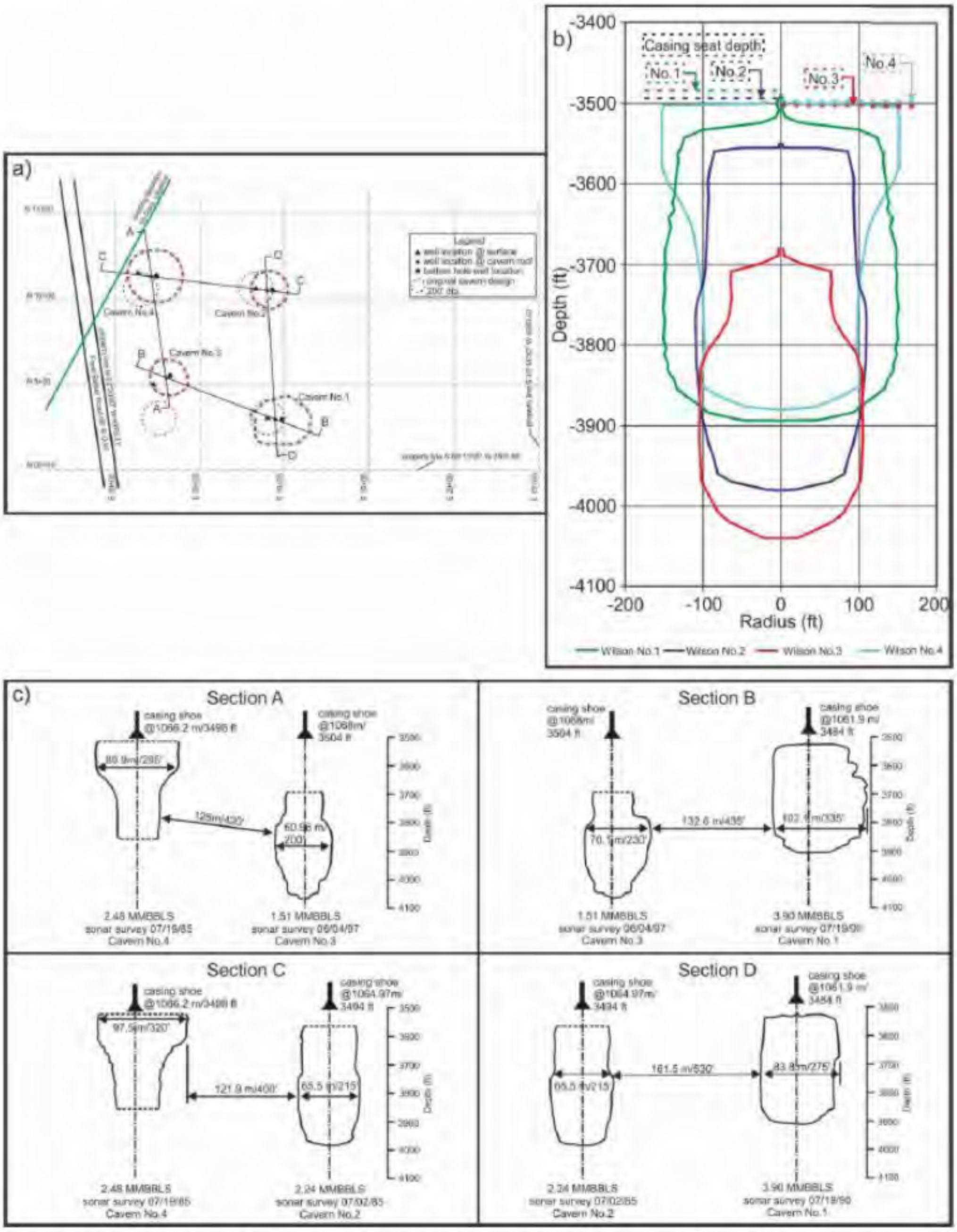

Figure 114 A: Locations of caverns 1-4 in the Boling salt dome, B: cross sections of the caverns based on sonar surveys, C: Cross section vies of the caverns, redrawn by (Réveillère et al., 2017) from (Osnes et al., 2007).

References: (Horváth et al., 2018; Osnes et al., 2007)

Incident	Well integrity wells 1,2,4, 2005
Cause	Overstretching of the casing due to tensile failures (due to salt creep) (confirmed by numerical analysis): significant casing coupling partings close to the roof of the cavern always near a casing connection (salt dragging the casing toward the cavern), casing shoe too close to the cavern, pressure loss/drop. Salt dragging was facilitated by the flat roofs and the absence of cavern necks.
Top event	Well integrity loss (Natural gas leakage well 1,2,4 (not 3 because casing shoe distance to cavern is higher)
Effects	Loss of product, well repair procedure (new casing shoe 30m higher than the original one)
Lessons learned	(Thompson et al., 2007) suggests that the most important lesson learned from this case history is that the depth of the cemented casing shoe should be located as much as several hundred feet above a gas cavern roof to ensure the long-term integrity of the cemented casing. The magnitude of the offset from the cavern roof to the casing shoe depends on the cavern shape and depth, the gas service cycle, and the characteristics of the production casing.
References	(Bérest et al., 2019; Réveillère et al., 2017; Thompson et al., 2007)

Brenham, Texas, United States of America

Storage	Hydrocarbons (LPG)
Number of caverns	1

Activity	Inactive- 1992
Salt structure	Salt dome

The Brenham salt dome, in the Washington-Austin counties, Texas, was host to one cavern for the storage of hydrocarbons. The top of the salt lies at a depth of 350m. An incident took place, the cavern experienced 'overfill' in 1992. This created an LPG ignition event, after this the cavern was plugged and abandoned. The incident led to new storage well regulations in Texas.

References: (Horváth et al., 2018)

Incident	Overfilling, October 7th 1991
Cause	Overfilling and valve failure (process error)
Top event	Well control loss (overfill)
Escalation factors	Ignition of gas cloud due to a spark created by a car
Mitigation measures	50 people evacuated
Effects	LPG release in the brine pond, LPG (gas cloud) ignition/explosion, 3 deaths, 23 injured, 26 homes destroyed, 33 homes damaged area of effect 3km2, loss of 52500m3 lpg, cavern is inactive, plugged and abandoned
Lessons learned	New storage regulations in Texas
References	(Horváth et al., 2018; Yang et al., 2013)

Bryan Mound, Texas, United States of America

Storage	Crude oil
Number of caverns	19
Cavern depth	450m
Capacity	247.1 million barrels (US)

Activity	Active
Salt structure	Salt dome
Commissioned in	1986
Owner	US Department of Energy (DOE)

The Bryan Mound salt dome in Brazoria county, Texas, is host to 19 caverns for the use of storage. The dome has a circular shape and has a diameter of 1830m. The caverns are part of the Strategic Petroleum Reserve.

This site has experienced the most hanging string events of the 4 SPR sites which are thought to be related to salt falls, which are shown of the figure below.

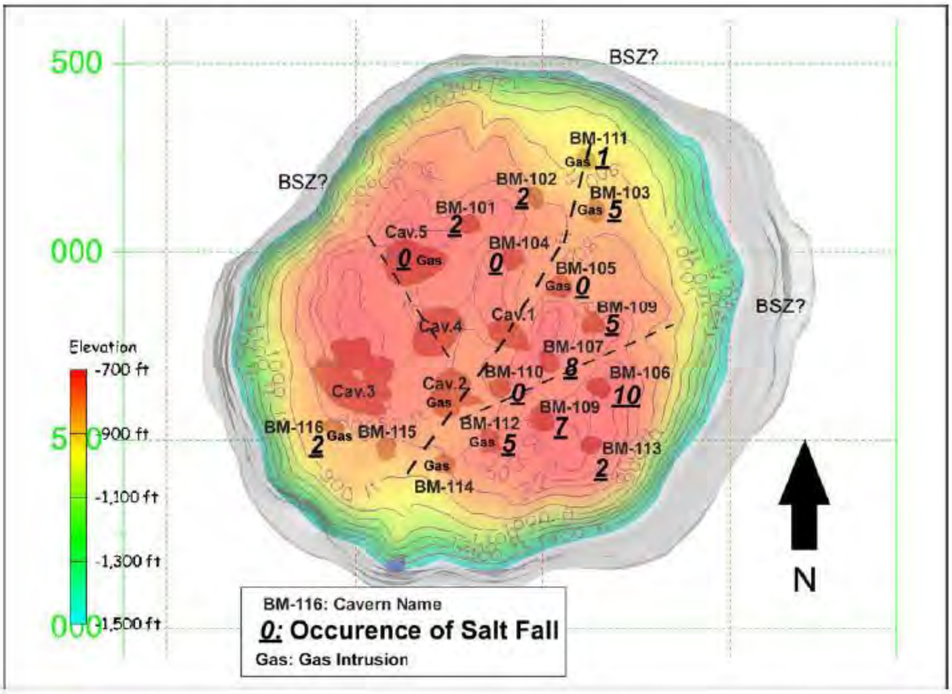

Figure 8: Top of salt map from Bryan Mound salt dome with inferred boundary shear zones and salt spines with cavern locations and occurrence of salt falls (modified from Sobolik and Ehgartner, 2009).

Figure 115 Map of the Bryan Mound salt dome, the numbers indicate the amount of salt falls which have occurred in the caverns, from (Looff, 2017).

Occurrence of salt fall	Cavern Name
10	BM106
8	BM107
7	BM109
5	BM103(*), BM108, BM112(*)
4	Cavern 5(*)
2	BM101, BM102, BM113, BM116(*)
1	BM111(*)
0	BM104, BM105(*), BM115, Cavern 1, Cavern 4
No information	BM114(*), Cavern 2(*)

Note: (*) gas intrusion in cavern

Figure 116 Table showing the number of salt falls per cavern, from (Looff, 2017).

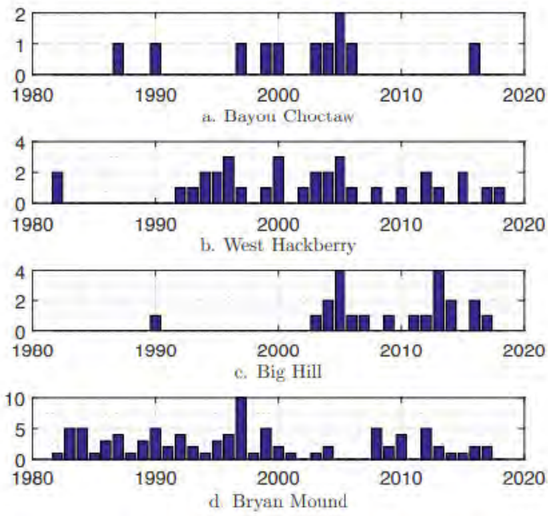

Figure 117 Salt falls through the years, at several sites, from (Looff, 2017).

References: (Hart, 2018; Horváth et al., 2018; Looff, 2017)

Incident	**Unspecified gas, 1950s**
Cause	Unknown cause
Top event	Loss of wellhead pressure
Effects	Caverns abandoned empty, 30 years later still stable
References	(Evans, 2008)

Incident	**Excessive subsidence, 1982-1998**
Cause	Excessive creep of salt
Top event	Cavern instability
Effects	Subsidence: surface settlement rate 36mm/a, influence range: 600m
References	(Yang et al., 2013)

Incident	**Salt falls, 1980-2017**
Cause	Cavern instability (~49 Salt falls spread over 12 caverns (6 caverns have not experienced salt falls))
Escalation factors	Salt heterogeneity (proximity to anomalous salt, BSZ (boundary shear zone) and shale content, anhydrite levels)
Top event	Well integrity loss (string break, sometimes resulting in crude oil leakage)
Effects	Cavern volume loss, expensive (loss of operational readiness: depressurization and workover rig placement), sometimes resulting in crude oil leakage
References	(Brouard, 2019; Hart, 2018; Looff, 2017)

Incident	**Cavern 5 area, Grass mower, September 13th 2011**
Cause	Grass mower hitting pipeline, mechanical damage
Escalation factors	Recently-hired, untrained subcontractor
Top event	Pipeline integrity loss
Effects	1 death
References	(Réveillère et al., 2017), www.energy.gov

Clute, Texas, United States of America

Storage	LPG (Ethylene)
Commissioned in	1961

Activity	?
Salt structure	Domal salt
Operator	South Texas Pipeline Company

The storage cavern(s) in Clute are located in an active salt dome, the Stratton Ridge dome. Its caprock is about 100m thick.

References: (Bérest et al., 2019; Réveillère et al., 2017)

Incident	Ethylene leakage, December 1988 - March 1989
Cause	Salt formation movement (casing failure at ~396m depth)
Top event	Well integrity loss (Ethylene leakage)
Mitigation measures	10 families evacuated
Effects	Loss of ethylene (new borehole drilled, encountering gas, flared off until April 1989), ~27000m3
References	(Bérest et al., 2019; Réveillère et al., 2017; Yang et al., 2013)

Incident	Ethylene leakage, 2004
Cause	Drilling operation resulting in tightness failure
Top event	Well control loss (Ethylene leakage)
Mitigation measures	10 families evacuated
Effects	Fire and explosion
References	(Yang et al., 2013)

Hainesville, Texas, United States of America

Storage	Hydrocarbons (LPG)
Number of caverns	2

Activity	Inactive
Salt structure	Salt dome
Operator	Suburban Propane

In Smith county, Texas, the Hainesville salt dome used to host 2 caverns for the storage of Hydrocarbons. The top of the salt lies at a depth of 350m. The caverns were abandoned after a propane leakage, which caused an ignition event.

References: (Horváth et al., 2018)

Incident	**Hainesville leakage, unknown date**
Cause	Unknown cause
Top event	Propane leakage
Escalation factors	Ignition
Effects	2 Caverns abandoned, site inactive
References	(Horváth et al., 2018)

Hull, Texas, United States of America

Storage	Hydrocarbons (LPG)		**Activity**	Active
Operator	ExxonMobil		**Salt structure**	Salt dome

The Hull salt dome in Liberty county, Texas, contains caverns for the storage of hydrocarbons. The top of the salt lies at a depth of 181m. In 2008 a large sinkhole (45m deep, 180m diameter) was the result of a brine disposal well in or near the salt dome.

References: (Horváth et al., 2018)

Incident	**Sinkhole, 2008**
Cause	Upwardly migrating cavern (collapsing cavern)
Top event	Cavern instability (shear stress higher than shear strength of the salt)
Effects	Extremely fast subsidence: Sinkhole (45m deep 180m diameter)
References	(Horváth et al., 2018)

Loop, Texas, United States of America

Storage	Natural gas		Activity	Active

Salt cavern storage location at Loop, stores natural gas.

References: (Evans, 2008)

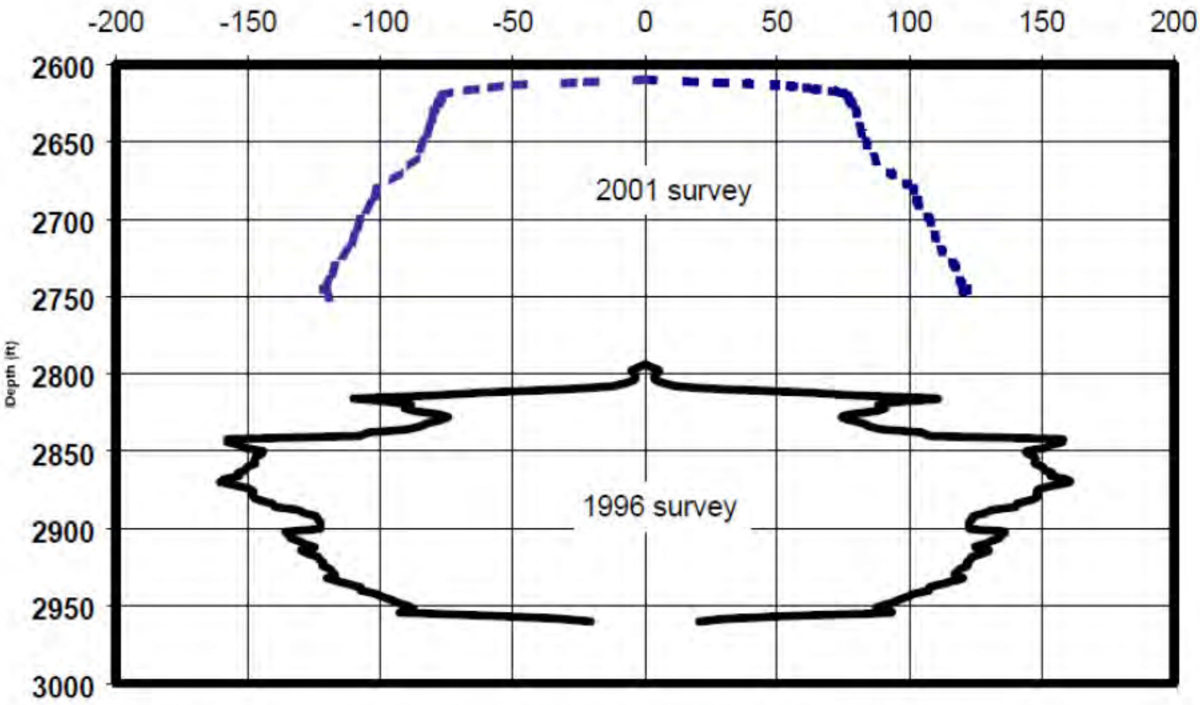

Figure 118 Showing 2 sonar surveys of Oneok Loop well number 1128 GC, from (Johnson, 2003).

Incident	Roof collapse, 1996-2001
Cause	Unknown cause, natural failure is mentioned in (Evans, 2008)
Top event	Cavern instability (roof collapse)
Mitigation measures	Enough salt roof to not collapse into the cap rock
Effects	Cavern roof moving upwards about 60m, sonar and MIT surveys conducted and storage resumed
References	(Evans, 2008; Johnson, 2003)

Mineola, Texas, United States of America

Storage	LPG (Propane)		**Activity**	Active
Commissioned in	1950s		**Salt structure**	Domal Salt

Storage of LPG in domal salt, active since the end of the 1950s.

References: (Bérest et al., 2019; Brouard, 2019; Yang et al., 2013)

The following incident is divided in two tables, to show how one incident can be part of two different bow-tie diagrams.

Incident	**Cavern integrity (fracture), 1995**
Cause	Pressure during workover
Escalation factors	Thin pillar (due to uncontrolled dissolution, related to undersaturated water injection)
Top event	Cavern integrity loss (fracture)
Escalation factors	Thin pillar
Effects	Well integrity loss 2^{nd} cavern
References	(Bérest et al., 2019; Brouard, 2019; Yang et al., 2013)

Incident	**Well integrity (Leakage), 1995**
Cause	Pressure wave from nearby cavern (Workover caused a fracture (cavern fracture due to uncontrolled dissolution and weakening of pillar, pillar cracks)) in the salt formation causing a pressure surge to a 2nd cavern, which resulted in a casing breach
Escalation factors	Thin wall between caverns due to undersaturated water injection, Thin pillar
Top event	Well integrity loss (Propane leakage)
Escalation factors	Accumulation and ignition
Effects	Product release to the groundwater and atmosphere, the gas collected (accumulation) in low-lying areas and found an ignition source (water well 15m from the product withdrawal well, followed by the cavern wellhead, damage to property). Considerable efforts were required to extinguish the fire, Underground fire
References	(Bérest et al., 2019; Brouard, 2019; Yang et al., 2013)

Moss Bluff, Texas, United States of America

Storage	1. Natural gas 2. Hydrogen
Number of caverns	1. 4 or 5 2. 1
Cavern depth	2. Top of cavern: 800m, Mean depth:1200m
1. Working gas volume **2. Cavern volume**	1. 651mln m^3 2. 566000 m^3

Activity	Active
Salt structure	Salt dome
Commissioned in	2. 2007
Operator	1. Spectra Energy 2. Praxair

The Moss Bluff salt dome in the Gulf Coast salt basin in Liberty county, Texas, contains caverns for the storage of natural gas (Spectra Energy) and hydrogen (Praxair). Praxair has permits for a second hydrogen cavern in the dome.

Cavern 1 of Spectra Energy experienced a blow out in 2004.

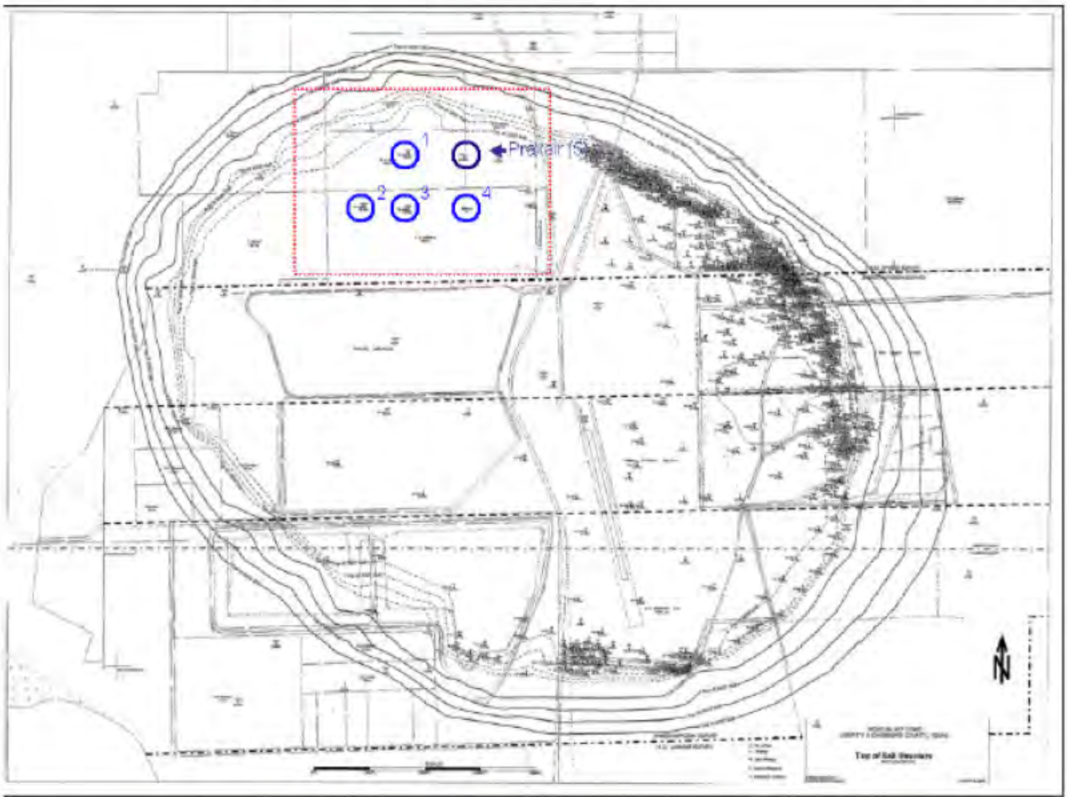

Figure 119 Moss Bluff salt dome map, modified by (Réveillère et al., 2017 after (Rittenhour & Heath, 2012).

References: (Horváth et al., 2018; Rittenhour & Heath, 2012)

Incident	**Blowout cavern 1, August 2004**
Cause	Brine pipe corrosion
Top event	Pipeline integrity loss (Natural gas leakage)
Mitigation measures	360 people evacuated (within 5km^2)
Effects	Gas blow-out that ignited and exploded, gas released and burned (Loss), wellhead damage due to heat caused by the fire, 36 million $ loss, influence range was 120m
References	(Horváth et al., 2018; Réveillère et al., 2017; Yang et al., 2013)

Odessa, Texas, United States of America

Storage	LPG (Propane)

Activity	?

Storage of LPG in Odessa, Texas.

References: (Evans, 2008)

Incident	**Pipeline integrity, March 16th 2004**
Cause	Metal gasket in a wellhead flange failed, ground facilities broken
Top event	Pipeline integrity loss (Liquid propane leakage)
Mitigation measures	Flaring off gas
Effects	More than 90000kg of liquid propane leaked
References	(Evans, 2008; Yang et al., 2013)

Sour lake, Texas, United States of America

Storage	Hydrocarbons (LPG)
Number of caverns	Not specified

Activity	Active
Salt structure	Salt dome
Operator	Flint Hills and Motiva

The Salt lake dome is situated in the Hardin county, in Texas. The dome is circular and shallow, and its center lies at a depth of 260m.

References: (Horváth et al., 2018)

Incident	Well integrity loss, 1998
Cause	Salt movement (subsidence and uplift) lead to cracks and displacement in the concrete cellar, increased stress of the well casing-> shearing of the cemented casing
Top event	Well integrity loss (LPG leakage)
Effects	Leakage, LPG loss
References	(Réveillère et al., 2017)

Spindletop, Texas, United States of America

Storage	1. Brine supply 2. Hydrocarbons (LPG) 3. Hydrogen (95%) 4. Natural gas
Number of caverns	1. 1 2. 1 3. 1 4. 8
Depth of cavern	3. 1340m
Individual volume	3. 906000 m^3

Activity	Active
Salt structure	Salt dome
Operator	1. Texas Brine Company, LLC 2. Coastal Caverns Inc. 3. Air Liquide 4. 3 operators

The Spindletop salt dome is located in Jefferson county, Texas. The dome is part of the Gulf Coast basin and the depth to the top of the salt is 336m. 6 operators have 11 caverns in this salt dome.

In 2001 a gas storage cavern and a brine production cavern became interconnected, which is a "significant unanticipated geomechanical development" (Johnson, 2003).

References: (Brouard, 2019; Caglayan et al., 2020; Horváth et al., 2018; Johnson, 2003; Zivar et al., 2020)

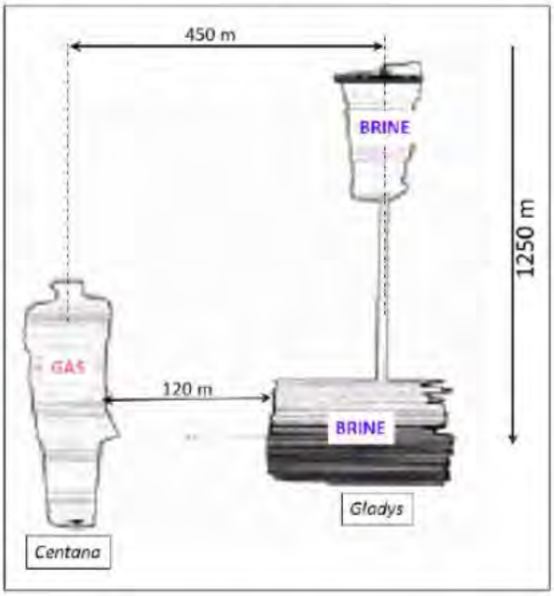

Figure 120 Showing the caverns Centana 1 and Gladys 2, which became interconnected, from (Johnson, 2003).

Incident	Hydraulic connection, 2001
Cause	Cause debated: "It is unknown whether the gas is migrating through an induced fracture, a fault plane or a seam of porous and permeable salt intersecting both caverns at an unknown altitude" (Johnson, 2003)
Top event	Cavern integrity loss (hydraulic connection between caverns, a brine production cavern and a gas storage cavern)
Mitigation measures	Flaring off gas
Effects	Remaining gas inventory was recovered and flared, loss of product, several brine production wells have been abandoned and plugged
References	(Brouard, 2019; Caglayan et al., 2020; Horváth et al., 2018; Johnson, 2003)

Stratton Ridge, Texas, United States of America

Storage	Natural gas		Activity	Inactive

Formerly a brine cavern, was converted to a storage cavern but failed to pass an MIT and was never operated.

References: (Evans, 2008; Réveillère et al., 2017)

Incident	**Failed cavern conversion, 1990s**
Cause	Excessive creep of salt in wet conditions
Escalation factors	Wet conditions
Top event	Cavern integrity loss (Natural gas leakage, failure)
Effects	Leak, failed the MIT, abandoned before operation, ground subsidence, settlement rate 40mm/a
References	(Evans, 2008)

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