British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

An appraisal of Underground Gas Storage technologies and incidents, for the development of risk assessment methodology.

Sustainable and Renewable Energy Programme
Open Report OR/07/023

Volume Two – Figures and Tables

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BRITISH GEOLOGICAL SURVEY

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OPEN REPORT OR/07/023

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An appraisal of Underground Gas Storage technologies and incidents, for the development of risk assessment methodology.

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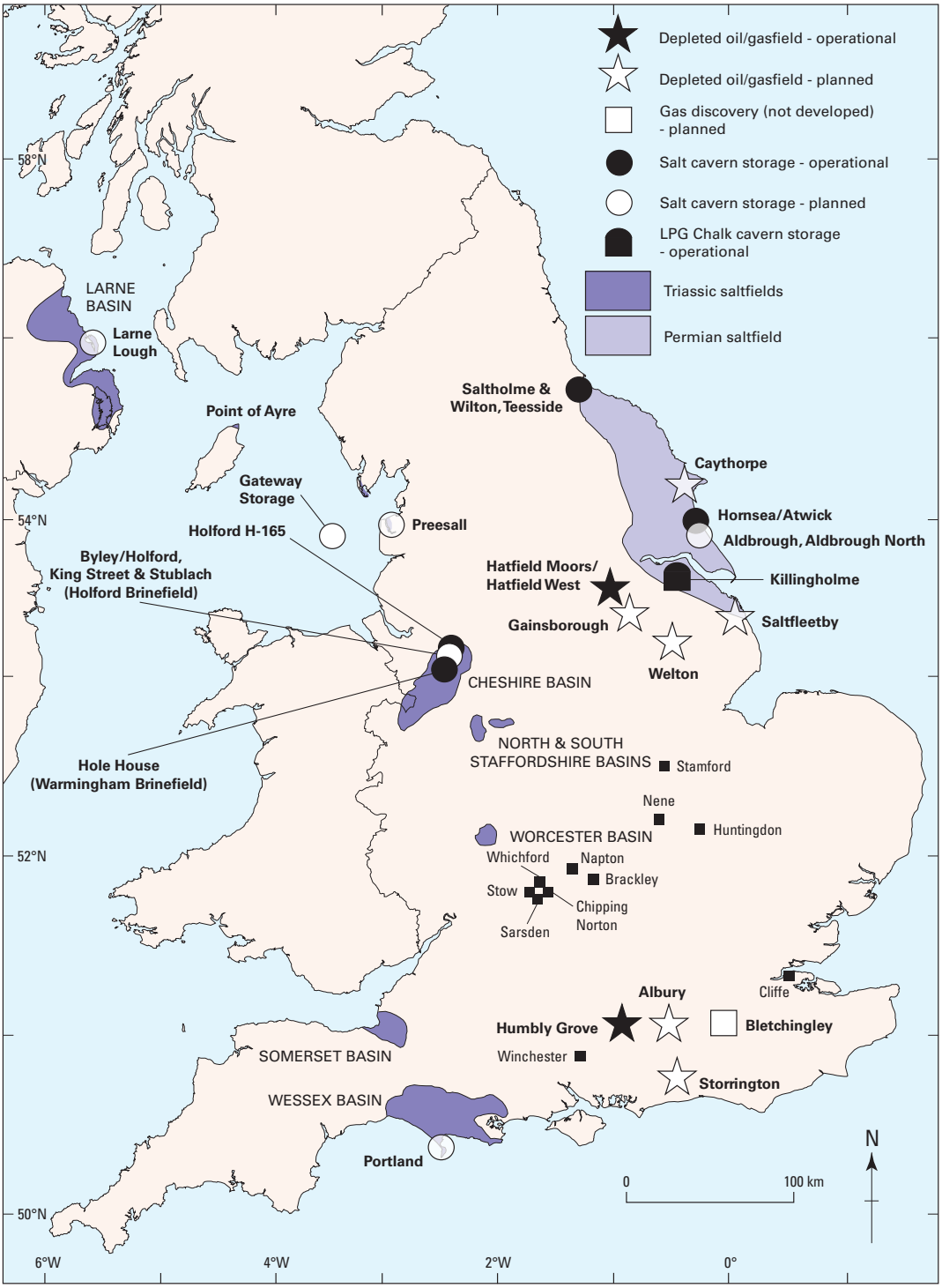

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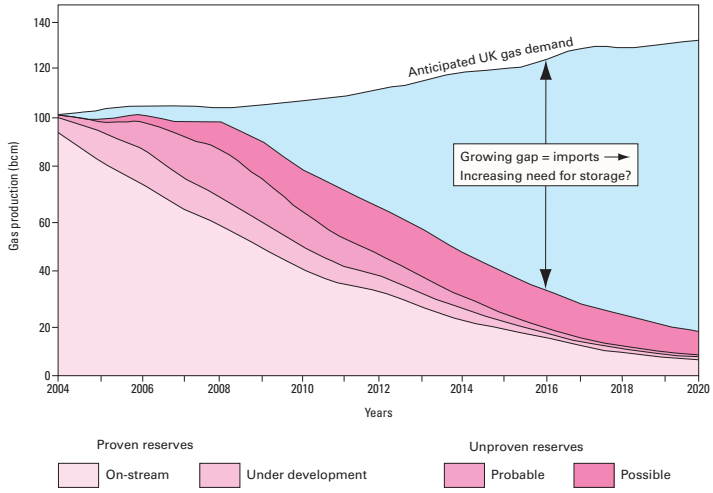

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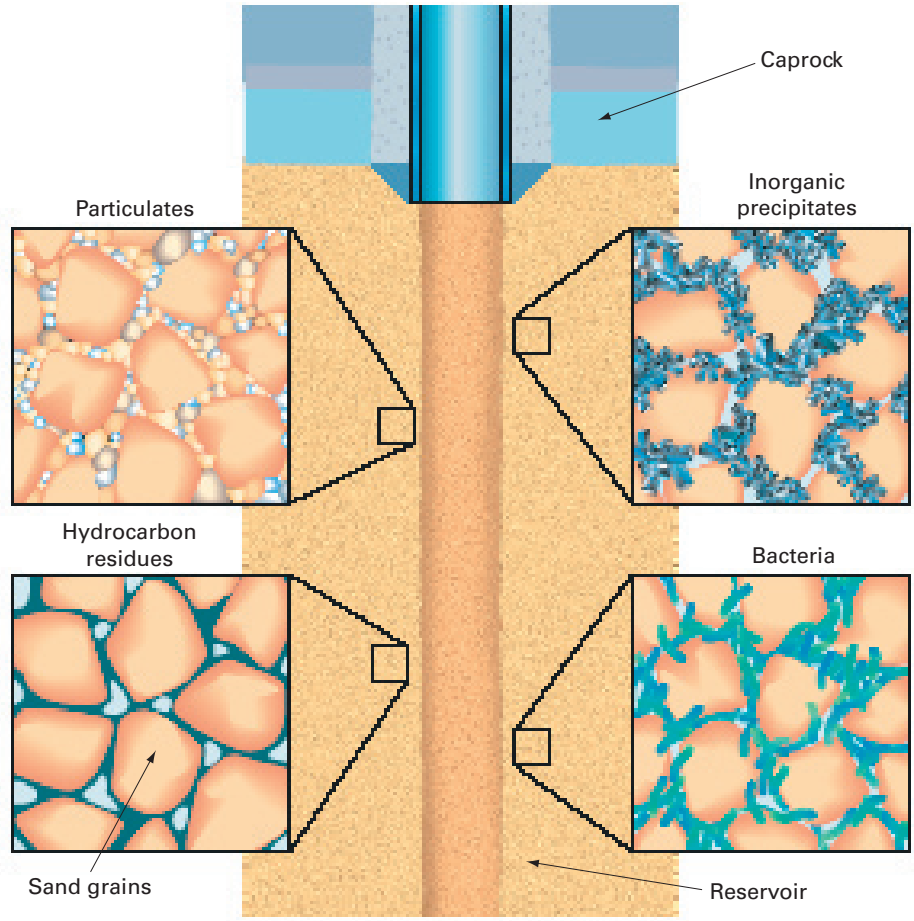

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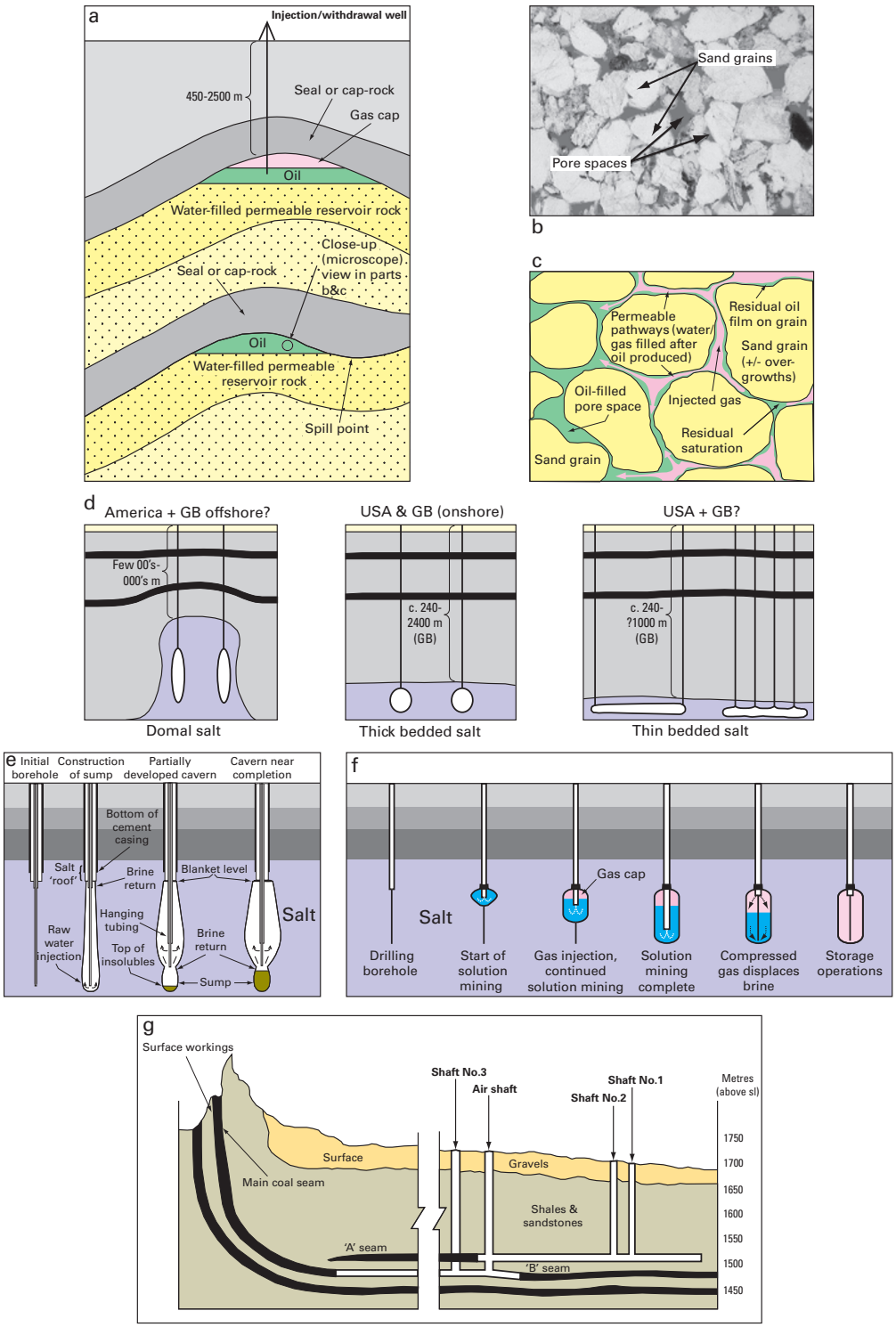

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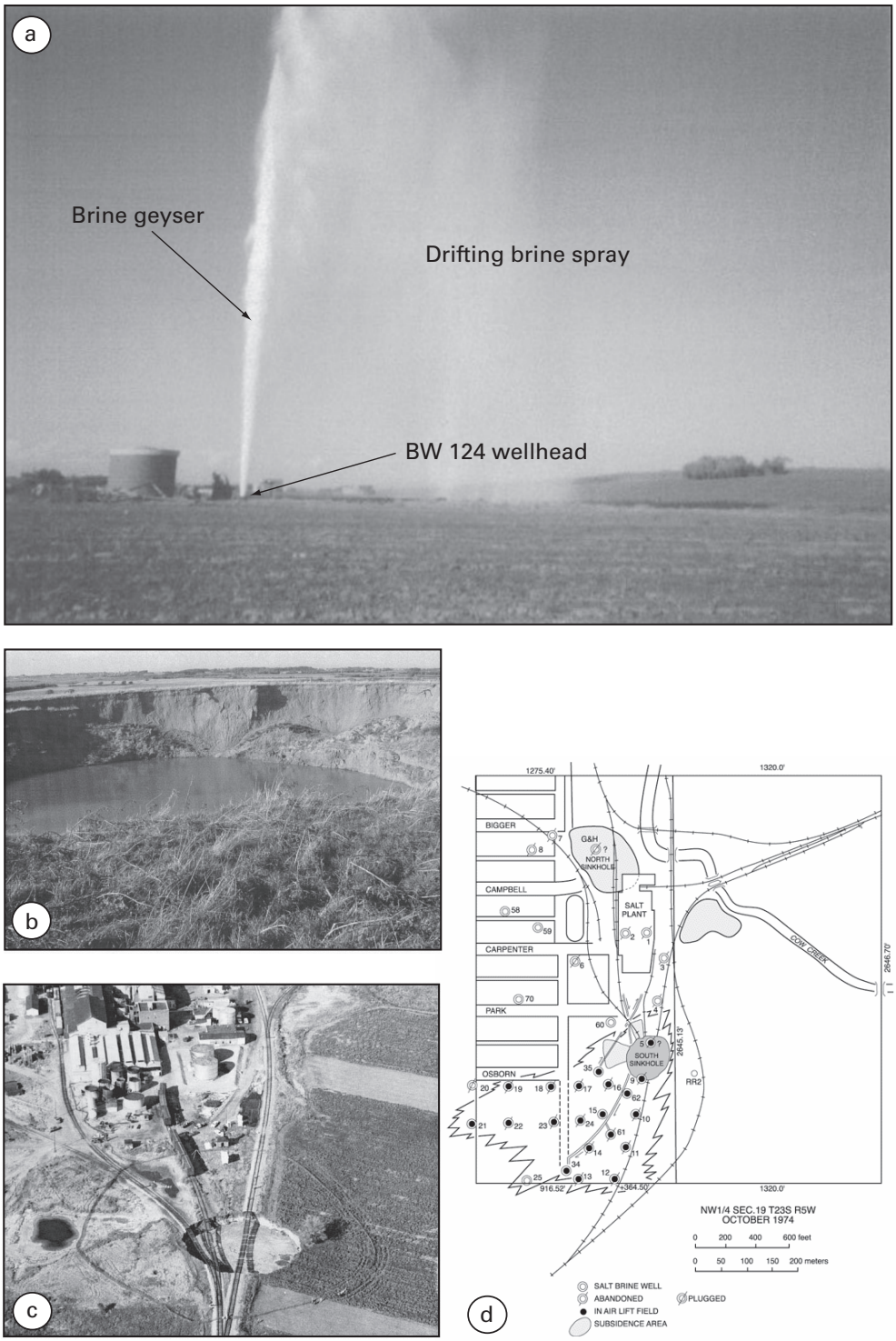

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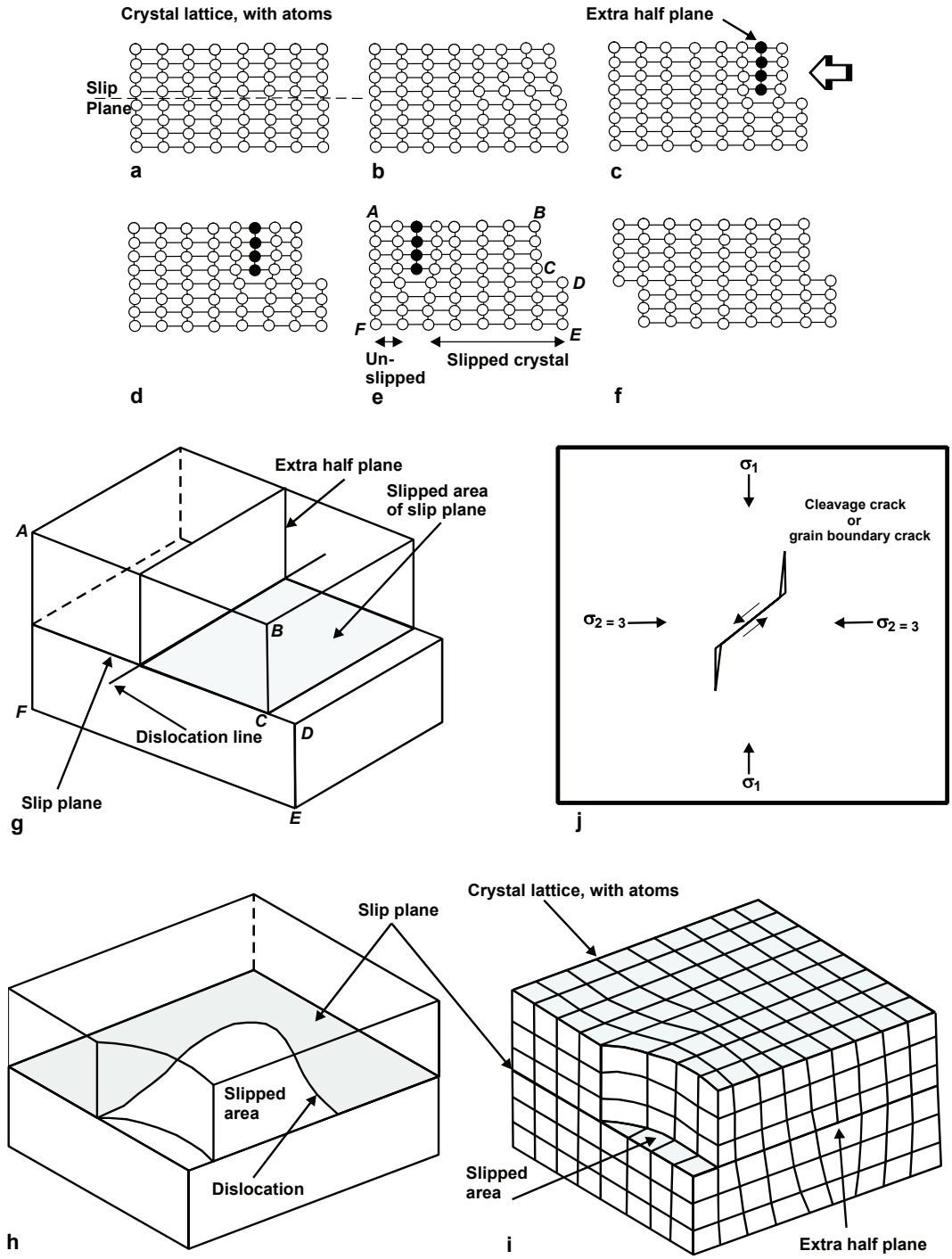

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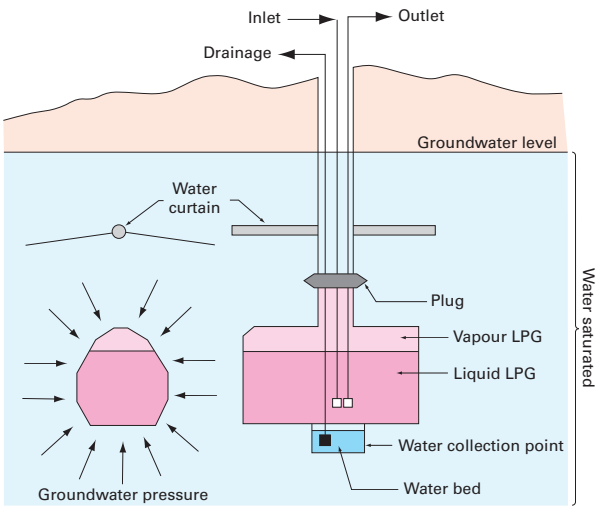

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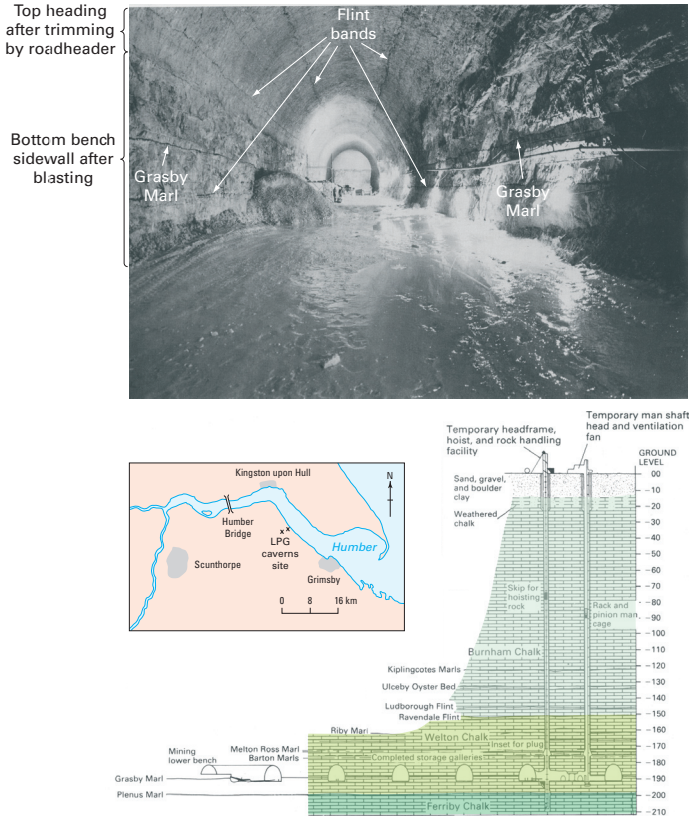

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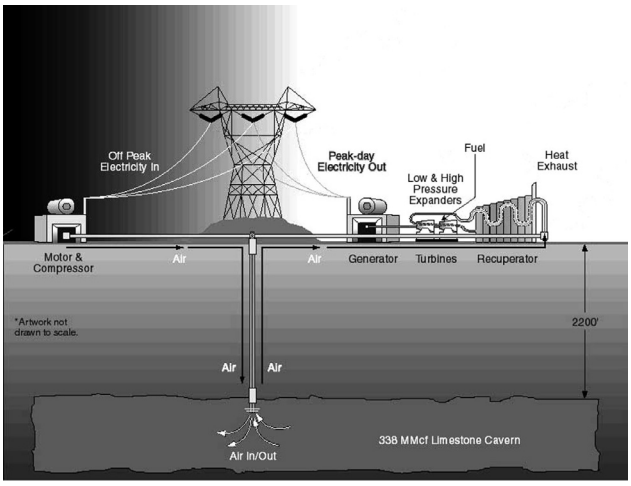

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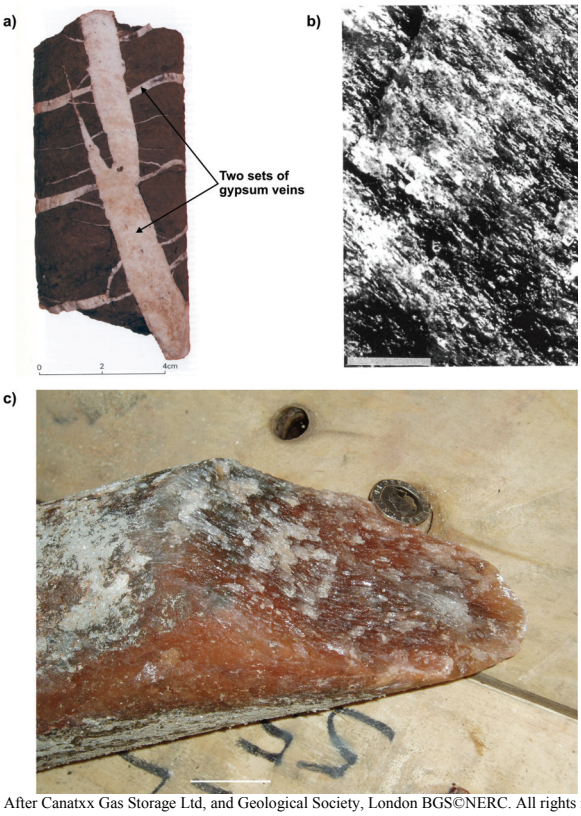

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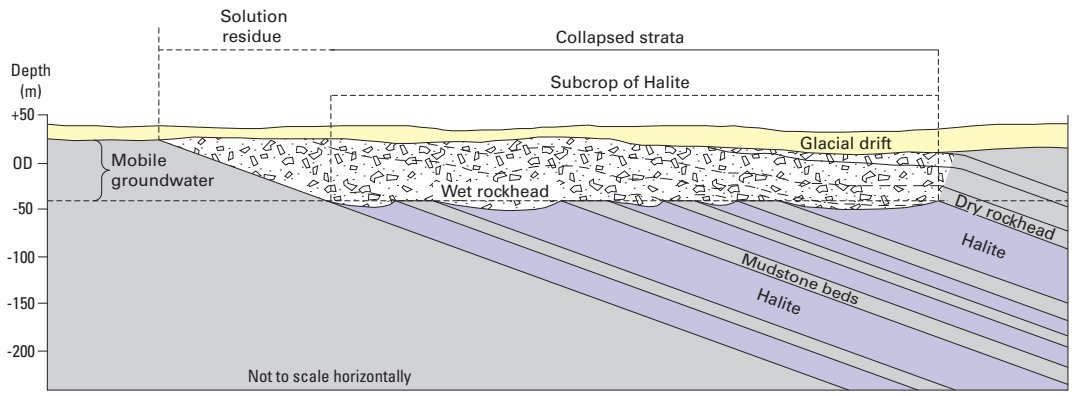

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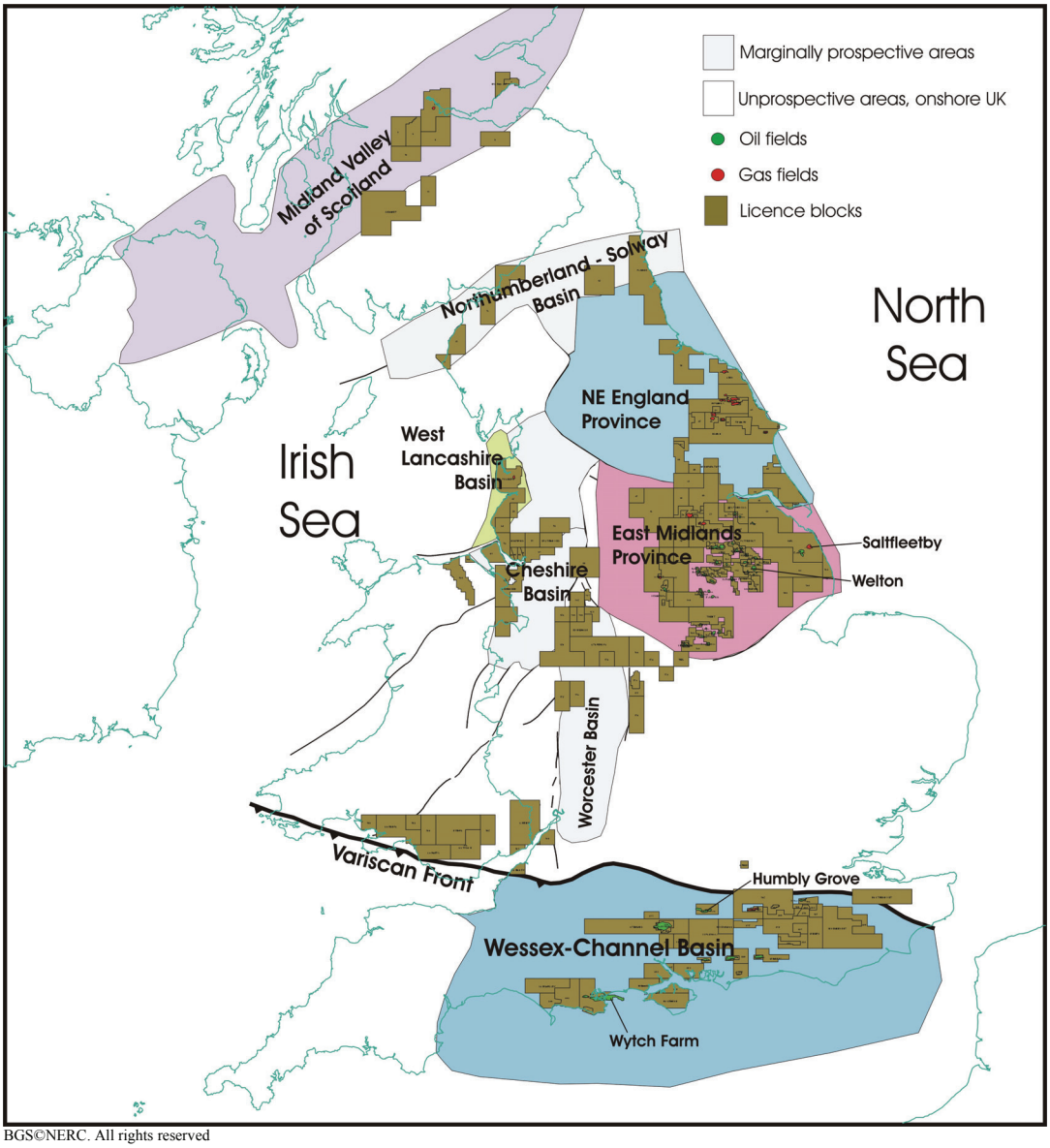

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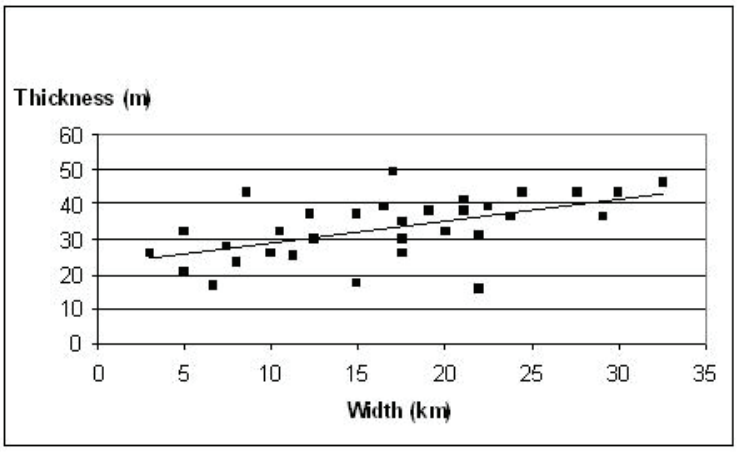

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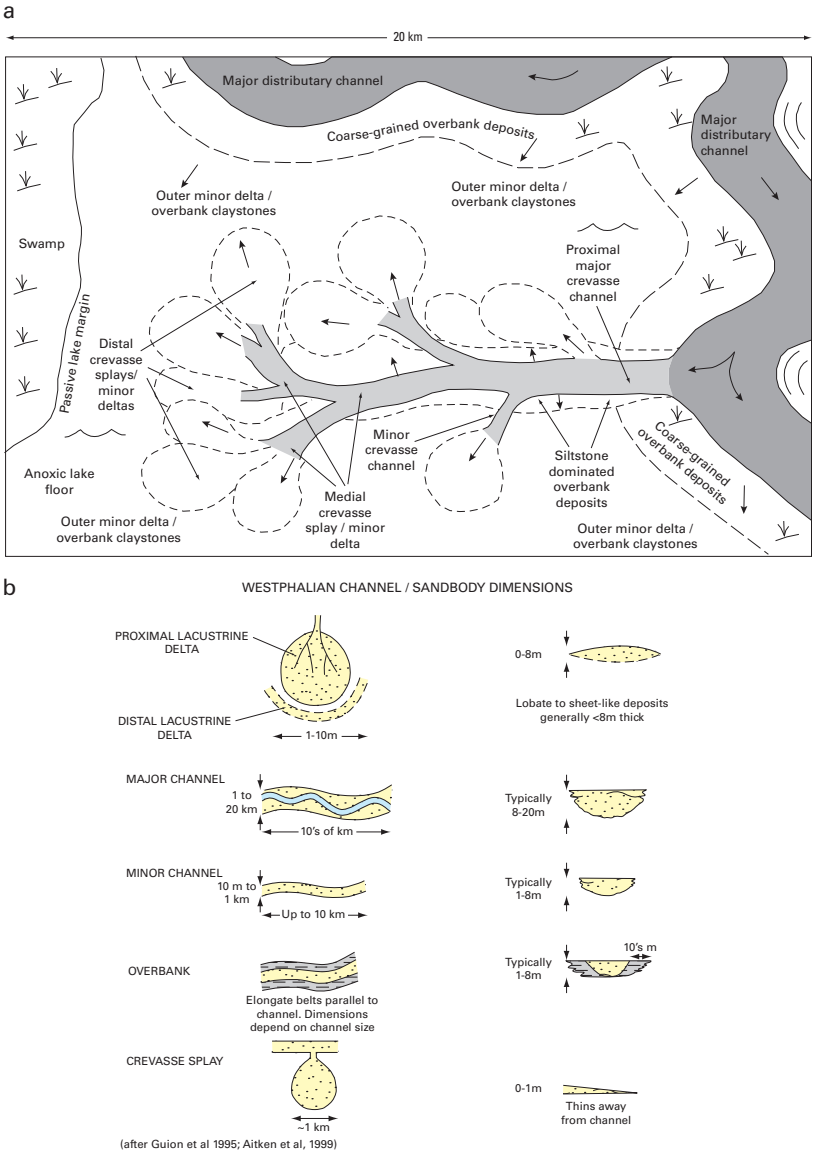


Figure 14. Westphalian depositional environments, with typical sand channel forms and dimensions (based upon Fielding, 1984; Guion et al., 1995; Aitken et al., 1999).

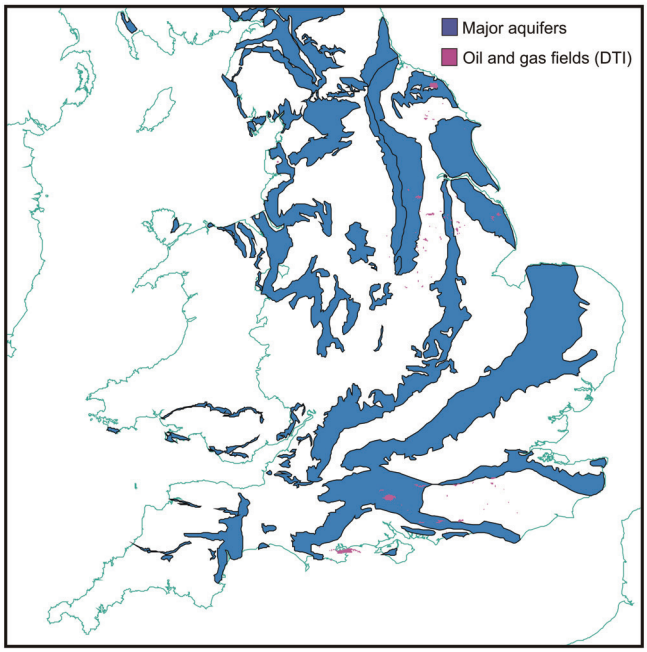


Figure 15. Major aquifers cropping out in England and Wales (courtesy of Jennifer Cunningham, BGS Wallingford). Also shown, the relationship of major aquifers to the onshore oil and gasfields.

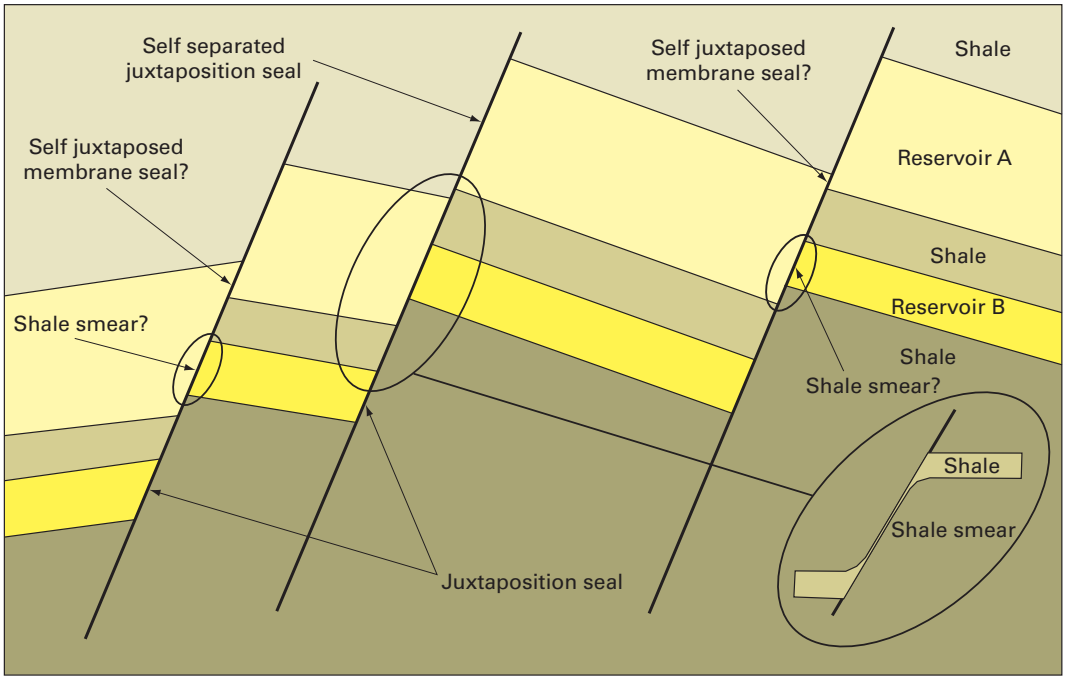


Figure 16. Schematic illustration of faulted sand-shale sequence and terminology of fault offsets and sealing configurations referred to in the text (after Færseth, 2006). Where reservoir A and reservoir B are juxtaposed across faults, the shale interval stratigraphically between the two reservoir units may be smeared along the fault to form a seal that hydraulically separates the sandstones.

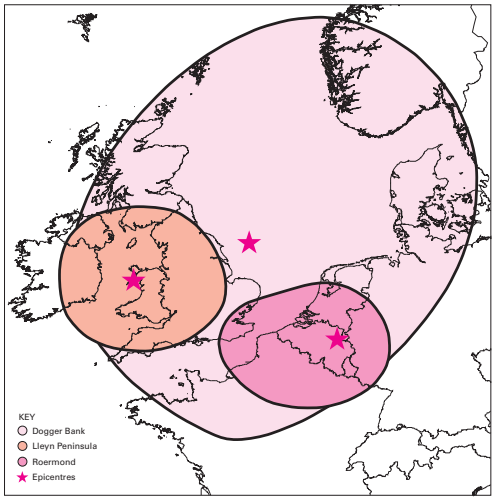


Figure 17. Sketch map of the felt area of the Dogger Bank (7/6/31), Lleyn Peninsular (19/7/84) and Roermund (Netherlands, 13/4/92) earthquakes (from Browitt & Musson, 1993).

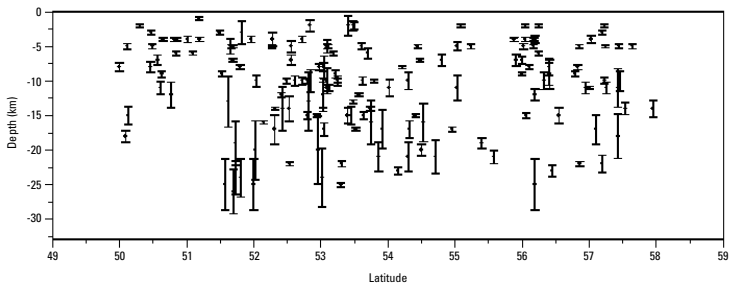


Figure 18. Cross section of UK seismicity from south to north plotted by latitude and depth, showing probable maximum vertical extent of ruptures for all earthquakes with magnitude > 3 M_L with known depths in mainland UK and the Irish Sea. Refer section 6.2 of main report for description of earthquake magnitudes (M_L).

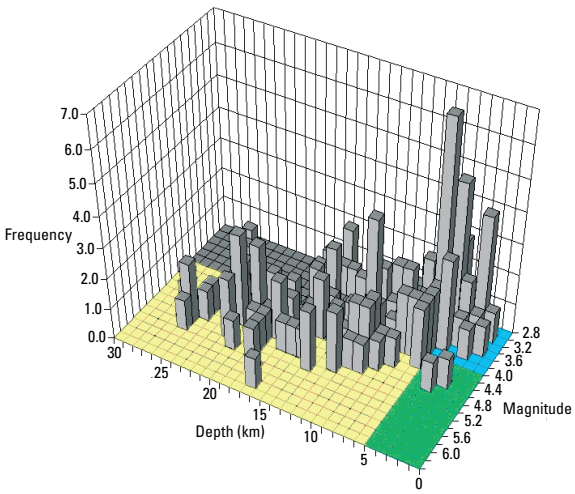
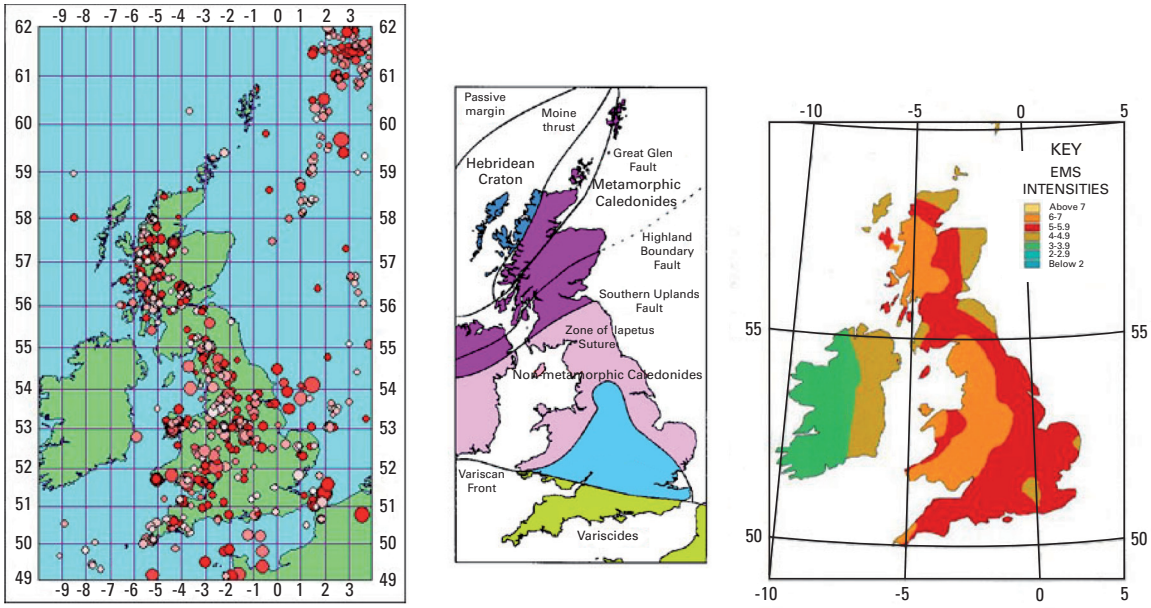
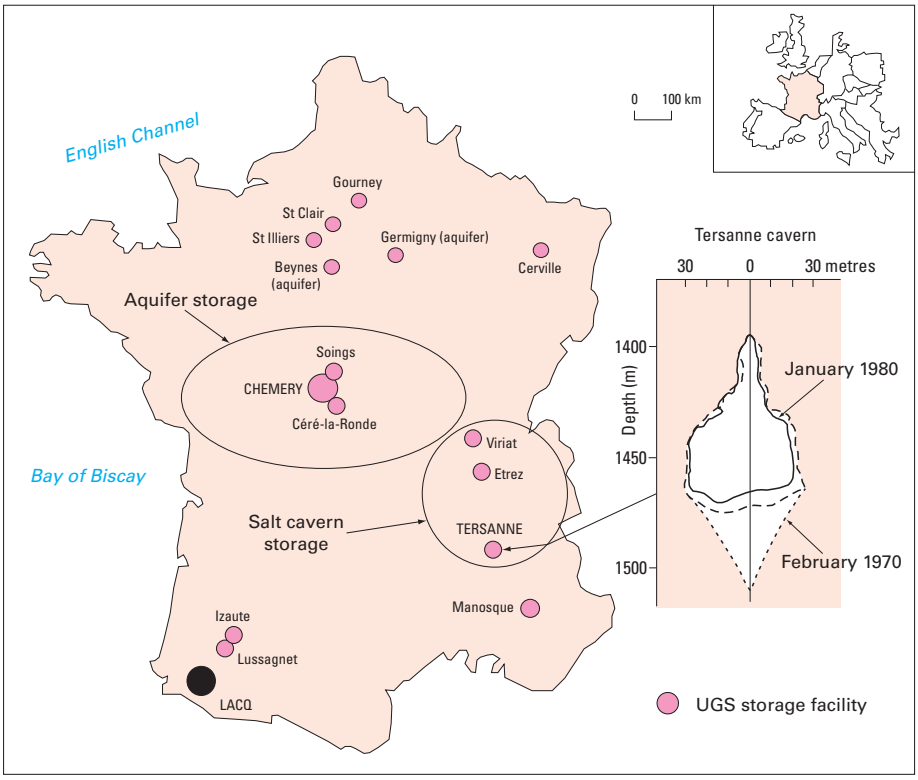


Figure 19. Numbers of UK earthquakes classed by magnitude and depth.



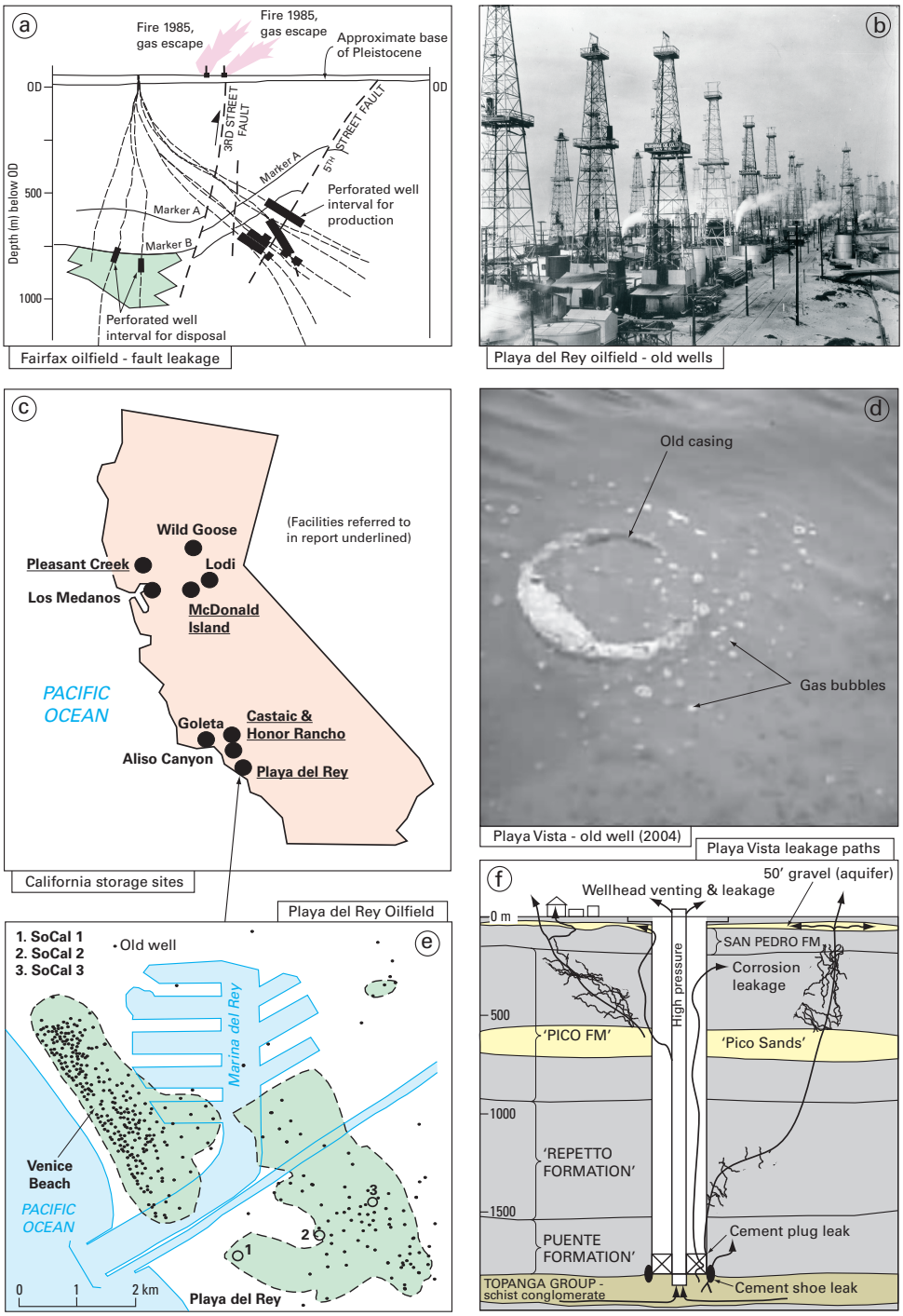
a b c

Figure 20. UK seismicity maps (from Musson, 2003b: http://www.earthquakes.bgs.ac.uk/hazard/Hazard_UK.htm). a) earthquakes in the UK, b) tectonic sketch map of the UK, c) EMS intensity hazard map for the UK.



Partly after **Bérest & Brouard** BGS©NERC. All rights reserved

Figure 21. Location of French UGS sites referred to in the text and details of the Tersanne cavern dimensions prior to and following salt creep (after Bérest & Brouard, 2003).



After Hamilton & Meehan and Seaver Center for Western History Research, Los Angeles County Museum of Natural History and saveballonawetlands BGS©NERC. All rights reserved

Figure 22. Details of Californian oilfields. a) cross section of the leakage scenario at the Fairfax Oilfield (after Hamilton & Meehan, 1992), b) skyline of oil derricks at the Playa del Rey Oilfield (after Seaver Center for Western History Research, Los Angeles County Museum of Natural History), c) general location map of depleted gasfields and gas storage sites in California and referred to in the text, d) gas bubbling up old leaking well in shallow water pond, Playa del Rey (courtesy Jeanette Vosberg, Save Ballona Wetlands.
See http://saveballona.org/techpages/well.html), e) map of the Playa del Rey and Venice Beach oilfields with known well locations, f) schematic section of Playa del Rey Oilfield showing gas leakage paths.

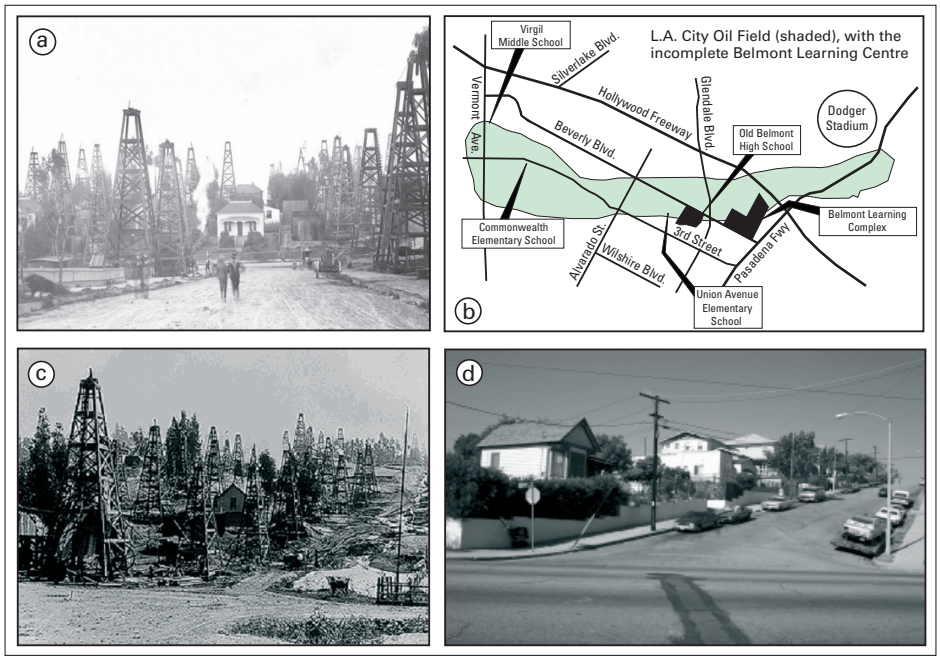


Figure 23. Illustrations of former heavily drilled areas of Los Angeles that are now densely populated urban areas. a) view of oil derricks associated with the Los Angeles City Oilfield (.c 1890; courtesy of Lena Tabilio and the California Division of Oil, Gas and Geothermal Resources. (http://www.consrv.ca.gov/index/siteMap.htm#doggr), b) map of the Belmont School area, where construction stopped due to the underlying LA City Oilfield, c) Los Angeles City Oilfield at the corner of Glendale Boulevard and Rockwood Street, circa 1900 (Photo courtesy of the Seaver Center for Western History Research, Los Angeles County Museum of Natural History, www.nhm.org), and d) Los Angeles City Oilfield at the corner of Glendale Boulevard and Rockwood Street, October 2002 (from Gamache & Frost, 2003; courtesy of the California History Room, California State Library, Sacramento, California (www.library.ca.gov/calhist/index.html).

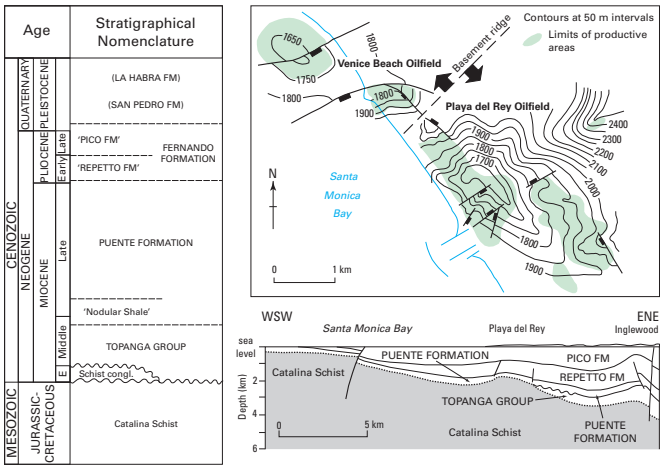


Figure 24. Stratigraphy of the Los Angeles area, structure contour map (at near top basement) of the Venice Beach and Playa del Rey oilfields and cross section of the Playa del Rey Oilfield (based upon Wright, 1991).

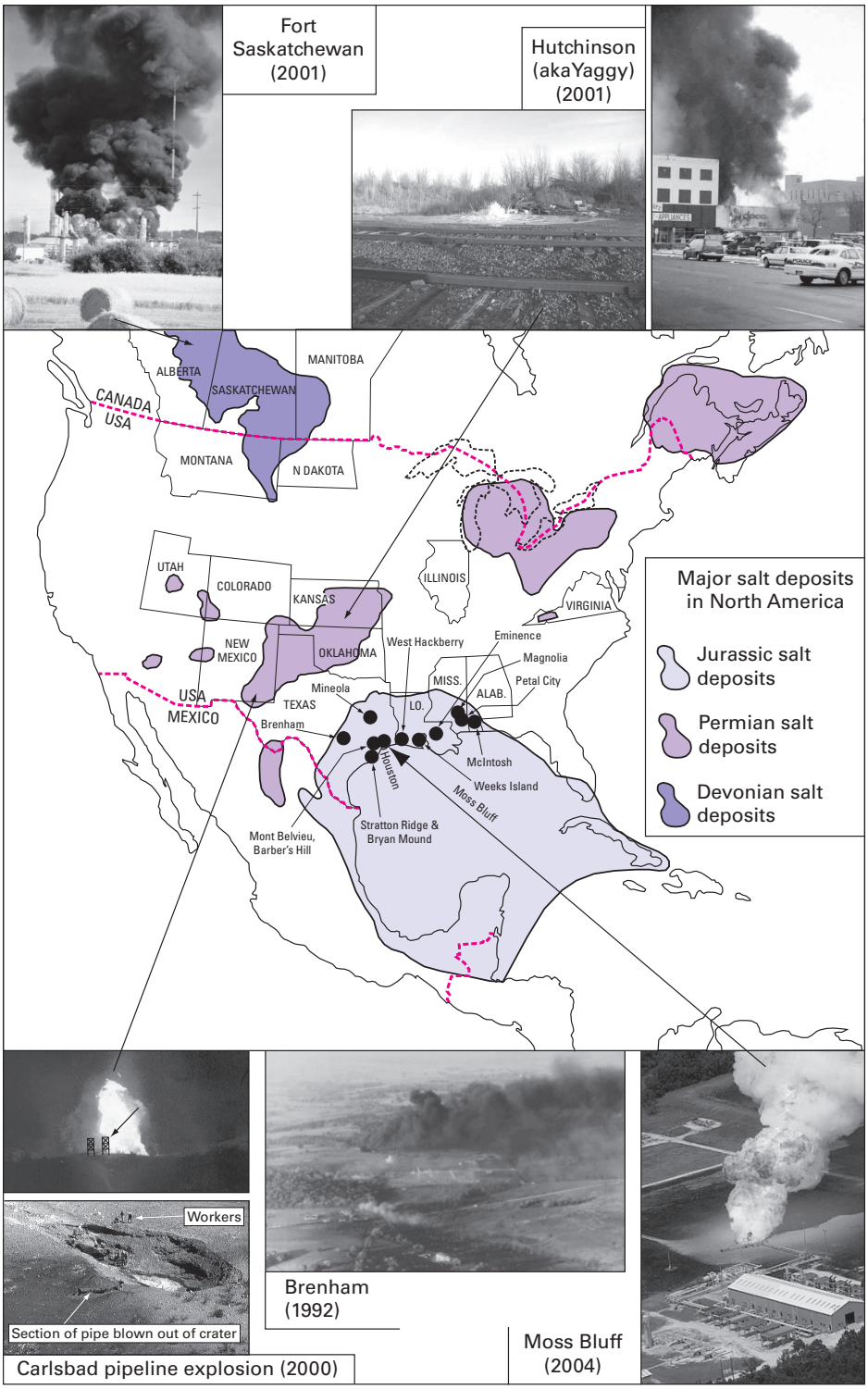
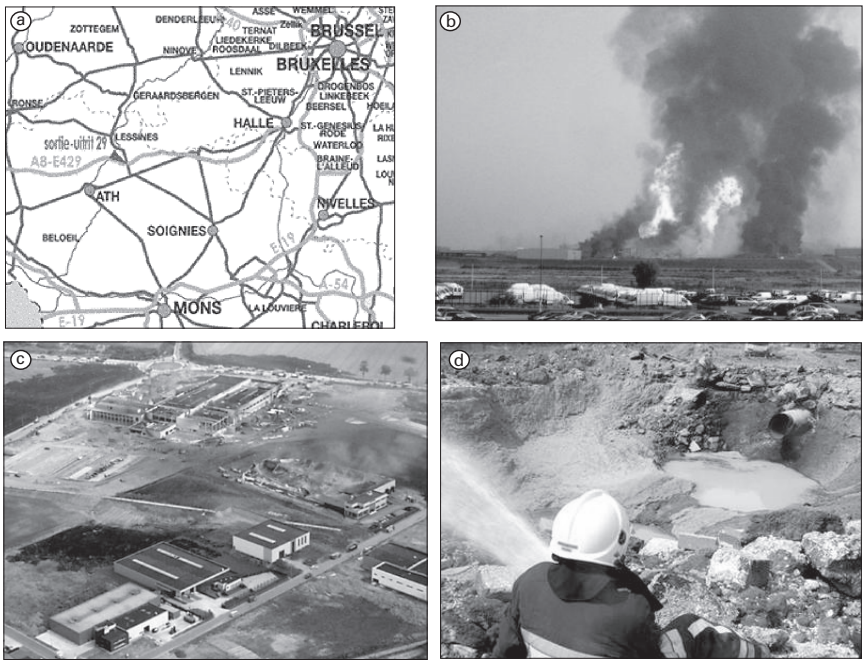
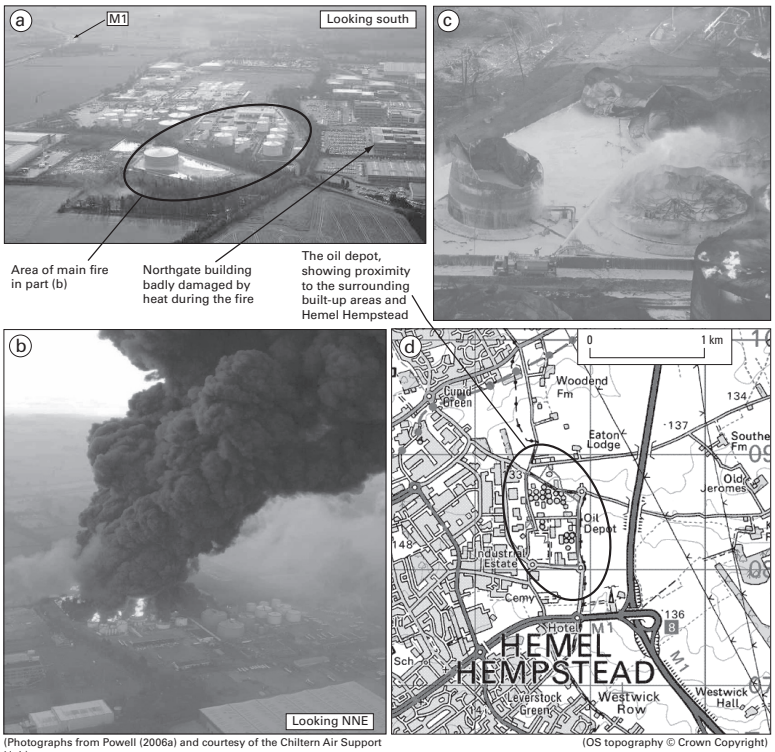


Figure 25. Major salt basins of the North America, including the main salt domes referred to in the text. Also shown, images of the major gas release incidents at Hutchinson (downtown fire, courtesy Chief Forbes, Hutchinson Fire Brigade; gas geyser, CUDD Drilling and Shannon Pope of RPC Inc), Moss Bluff (after Dave Ryan, Beaumont Enterprises http://www.thefortressweb.com), Brenham (courtesy of NTSB, 1993), Fort Saskatchewan (after Liz Nayowski, Fort Saskatchewan Record: http://www.chem.queensu.ca/chembook/articles/ethane_fire_in_fort_saskatchewan.htm), night time image of the Carlsbad pipeline incident which caused a crater 15.5 m by 34.5 m, bridge towers (estimated 10 m high) arrowed for scale (courtesy of NTSB, 2003).



After Emergency Management BGS©NERC. All rights reserved

Figure 26. The Ghislenghien gas pipeline explosion (images courtesy Emergency Management: http://www.emergency-management.net/gaspipeline2004.htm). a) location map, b) the fire following the explosion, c) view of the general site showing the burned area and d) the crater and exposed pipeline.



(Photographs from Powell (2006a) and courtesy of the Chiltern Air Support Unit)

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Figure 27. The 2005 Buncefield above ground storage incident (after Powell 2006a&b). a) aerial view of the site prior to the incident, b) the incident from the air, c) aerial view of damage to storage vessels, d) map illustrating the proximity of the storage depot to surrounding industrial and domestic buildings.

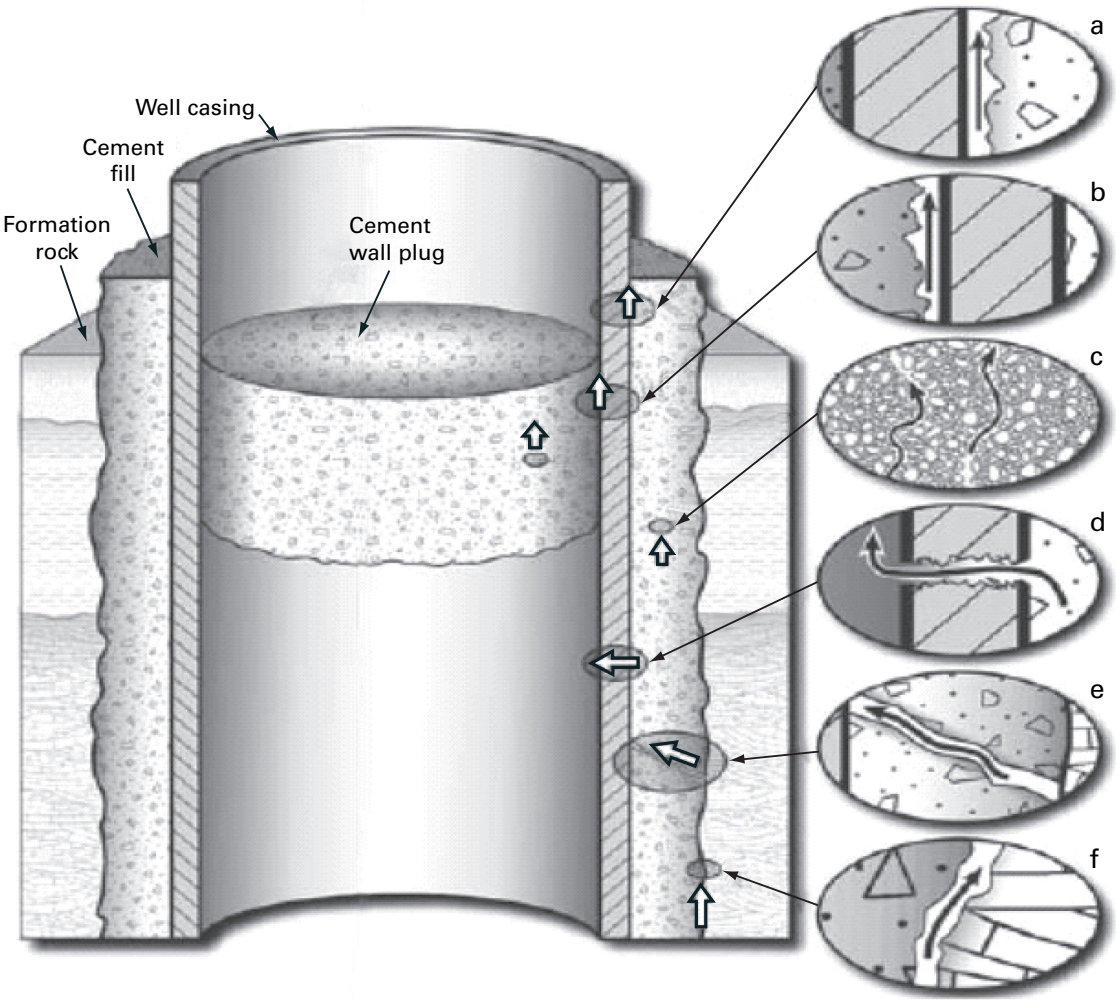

Figure 28. Schematic illustration of possible leakage pathways through an abandoned well: a) between casing and cement, b) between cement plug and casing, c) through the cement pore space due to cement degradation, d) through well casing as a result of corrosion, e) through fractures in cement, f) between cement and rock. (Figure from Scherer et al., 2005; reproduced from Environmental Geology, by permission of ©Springer Verlag).

a b c

Figure 29 Humbly Grove gas storage facility (courtesy Star Energy). a) site clearance (Feb 2004) and b and c) completed facility (Feb 2005).

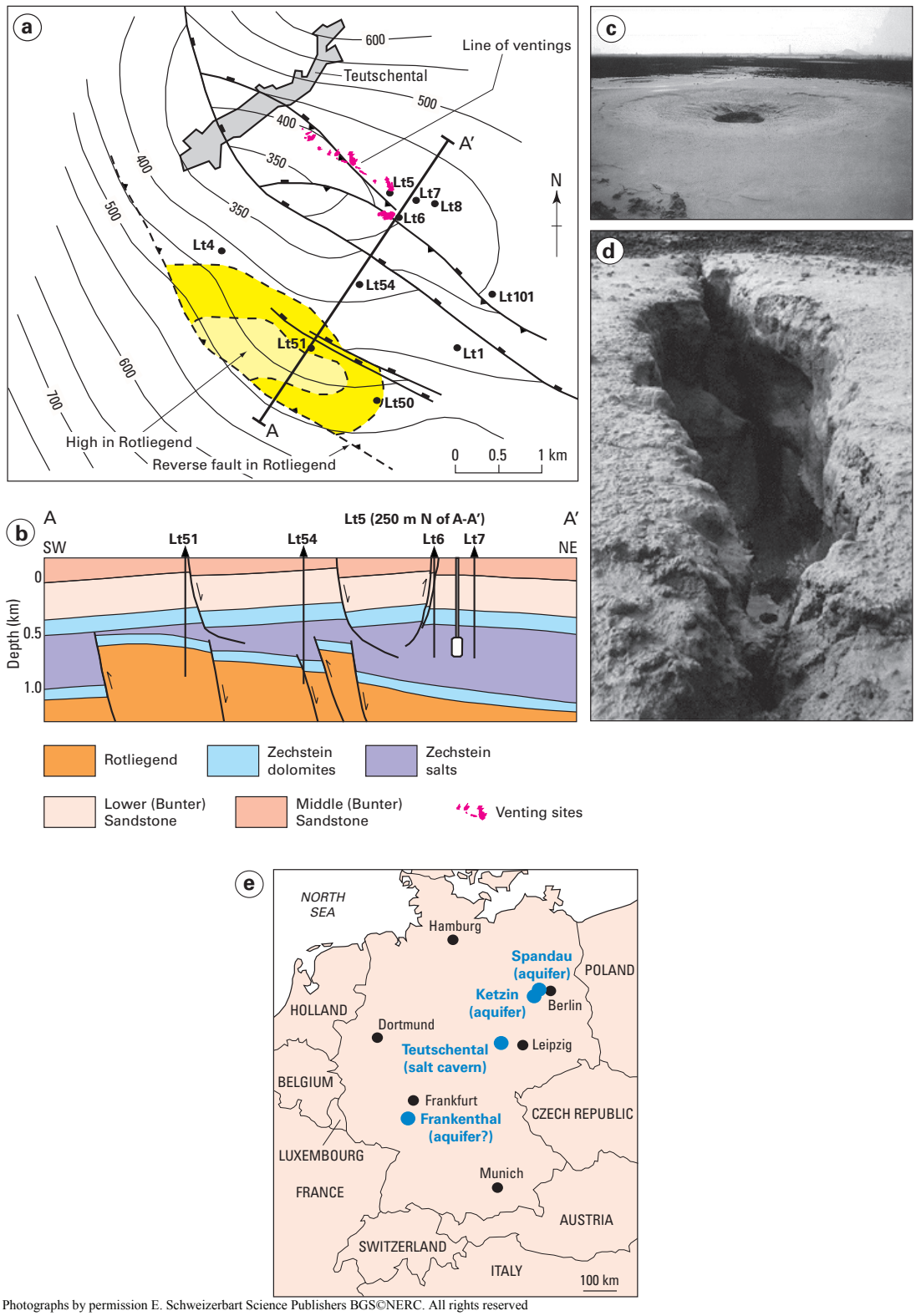

Figure 30. Details of the Teutschental (West Germany) site and ethylene escape (based upon Katzkung et al., 1996). a) structure contour map on top Zechstein halite, b) SW-NE cross section across the Lauchstädt structure and storage site area, c) and d) photographs of venting sites, from which a mixture of ethylene and water erupted, e) location map for UGS sites in Germany and referred to in text. Photographs reproduced by permission of E. Schweizerbart Science Publishers: http://www.schweizerbart.de/).

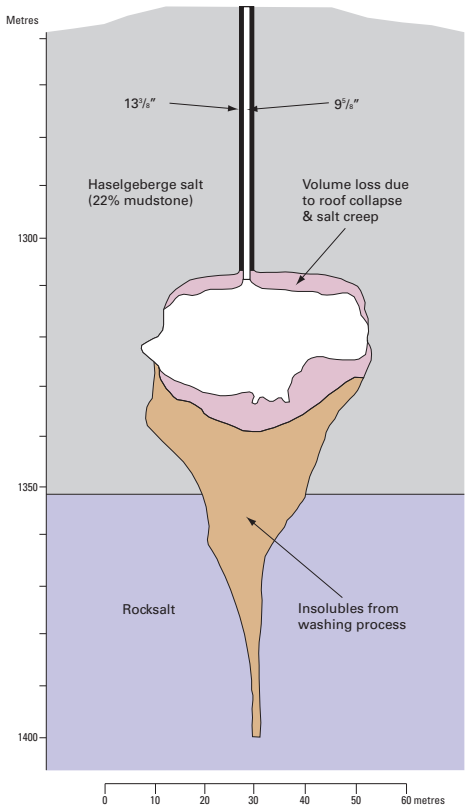

Figure 31. Detail of the Kiel storage cavern in Germany, illustrating volume loss due to insolubles, roof collapse and salt creep (after Bérest & Brouard, 2003).

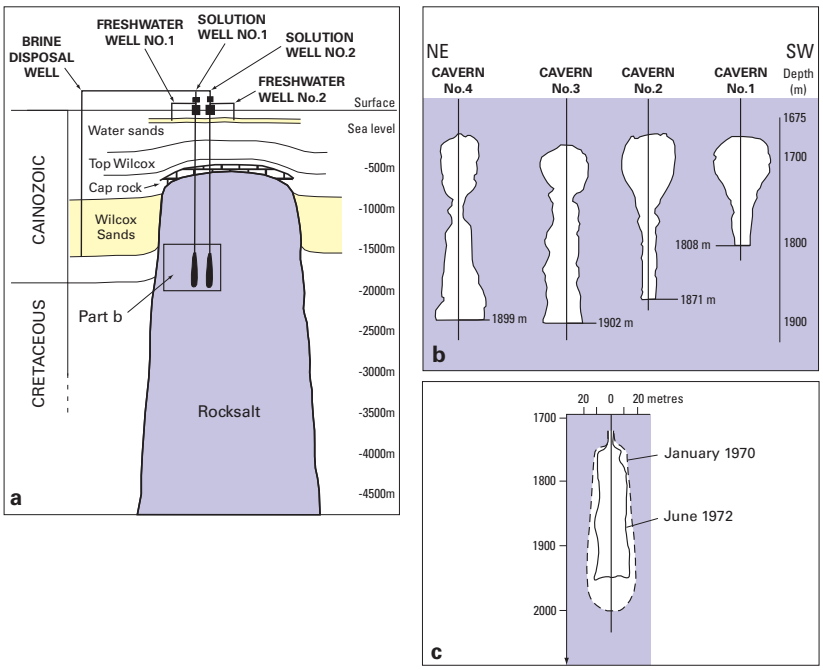

Figure 32. Details of the Eminence salt dome and storage facility (based upon Allen, 1972). a) cross-section of the salt dome with depth of caverns, b) detail of the depths and shapes of the four caverns constructed at Eminence c) illustration of the extent of salt creep and decrease in cavern size.

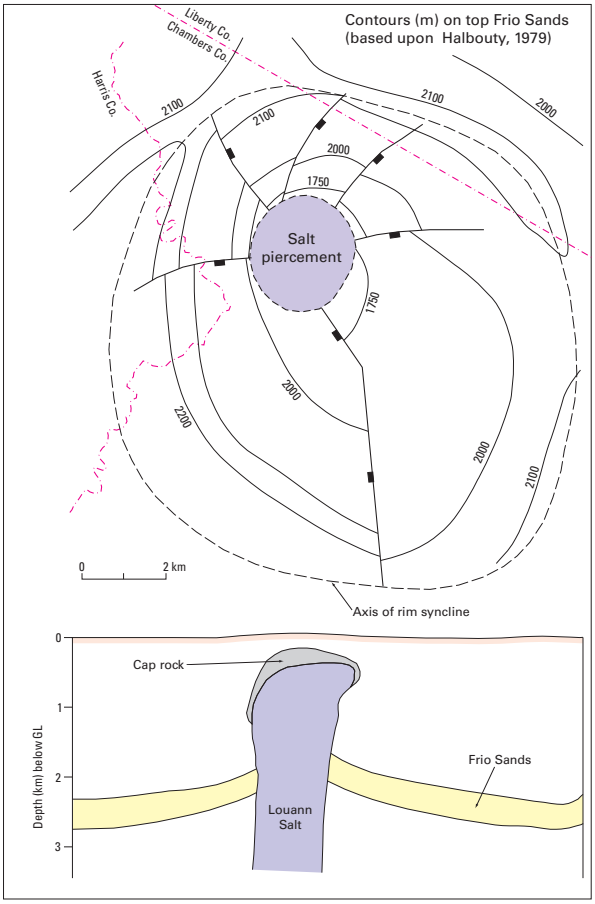

Figure 33. Details of the Mont Belvieu salt dome and storage facility a) structure contour map on the top of the Frio Sands showing area of salt piercement (after Halbouty, 1979), b) cross-section of the salt dome.

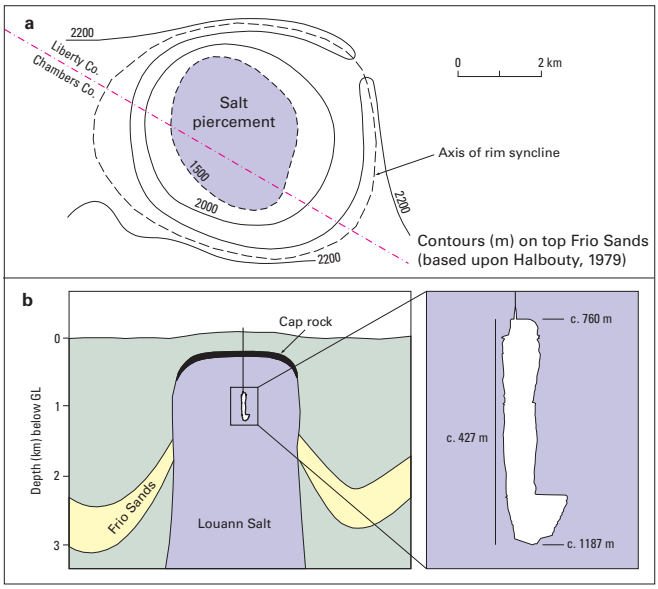

Figure 34. Details of the Moss Bluff salt dome and storage facility a) structure contour map on the top of the Frio Sands showing area of salt piercement (after Halbouty, 1979), b) cross-section of the salt dome illustrating the depth of the cavern and shape.

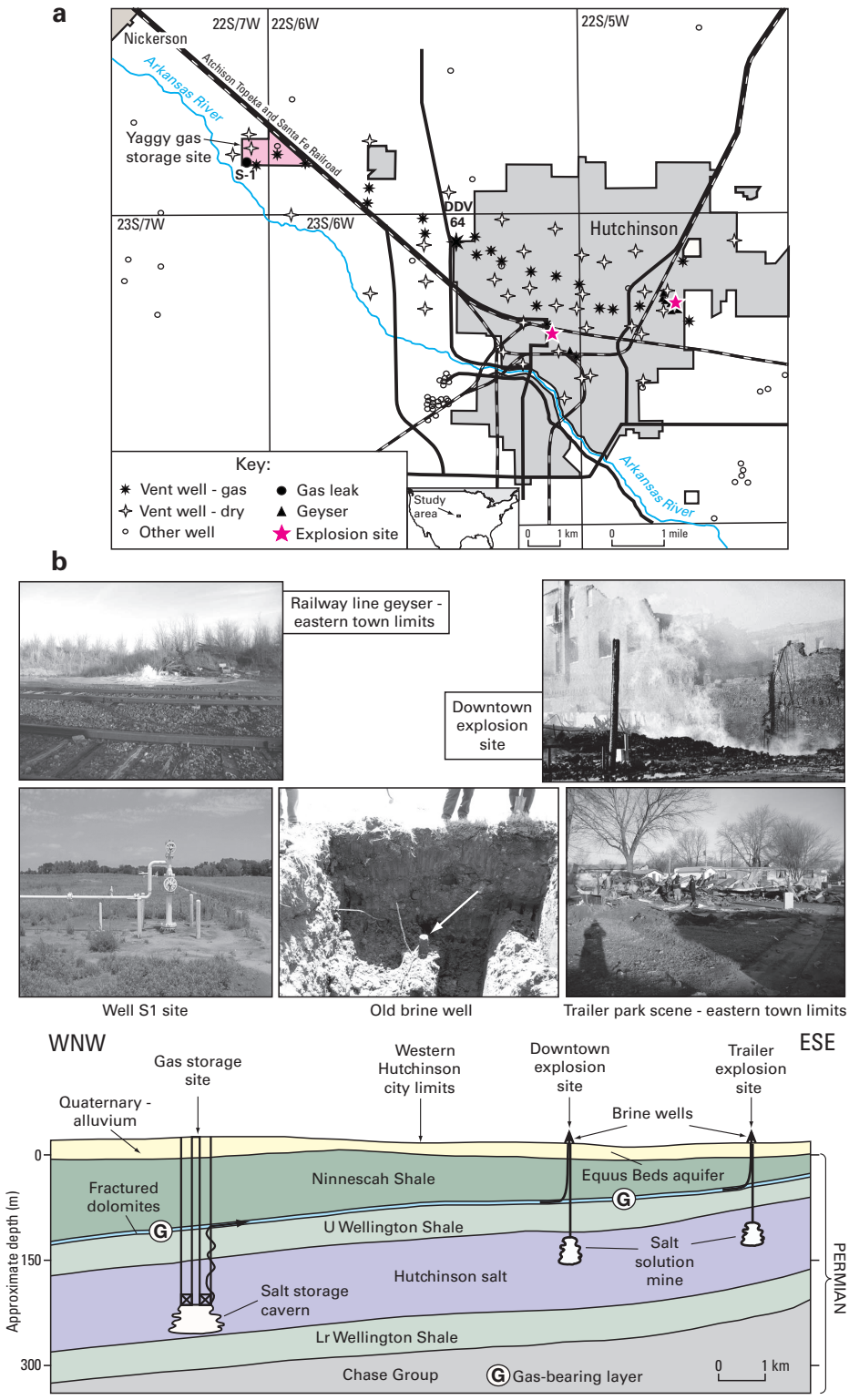

Figure 35. Details of the Hutchinson incident. (a) location map illustrating the site of the storage facility circa 11 km (7 miles) NW of the town of Hutchinson (b) WNW-ESE cross section showing the stratigraphy and structure of the area and the route taken by the gas from the storage cavern to the town (after Kansas Geological Survey). Images shown courtesy of Chief Forbes, Hutchinson Fire Department; Kansas Geological Survey; Kansas Department of Health and Environment, CUDD Drilling and Shannon Pope of RPC Inc.

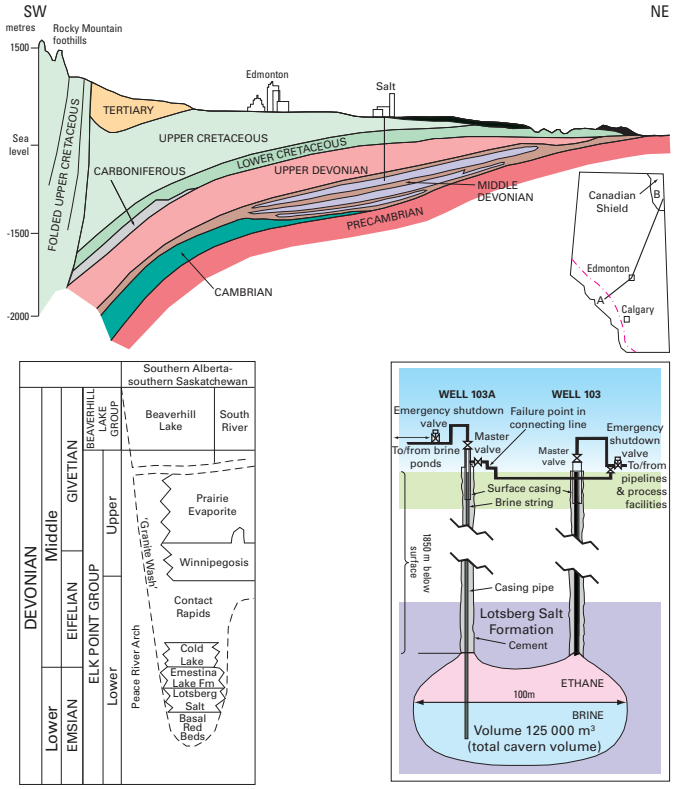

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Figure 36. Setting of the Fort Saskatchewan cavern storage facility, Canada. a) sketch cross section of the area, b) cross section of the cavern an infra-structure (after EUB, 2002).

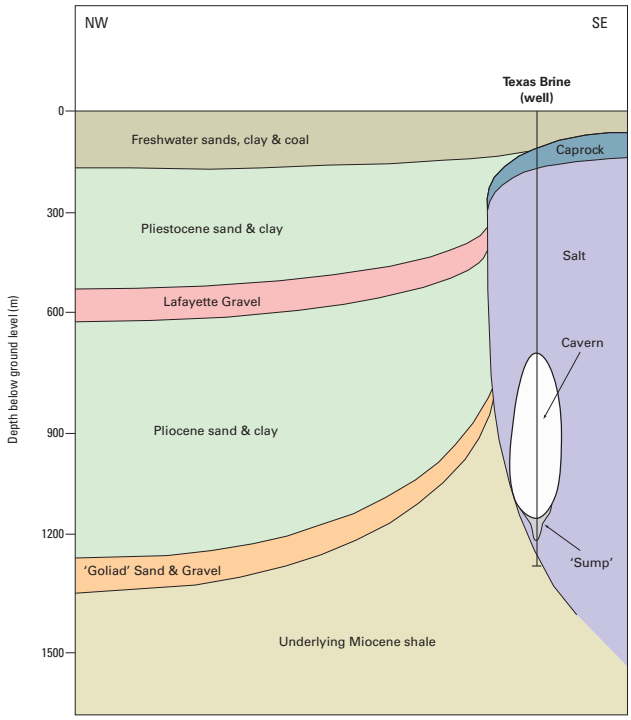

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Figure 37. Sketch section through the Napoleanville salt dome illustrating the situation when shale layers were encountered indicating that due to poor site characterisation, the sidewalls of the salt dome/stock had been intersected during brining operations (after Neal & Magorian, 1997).

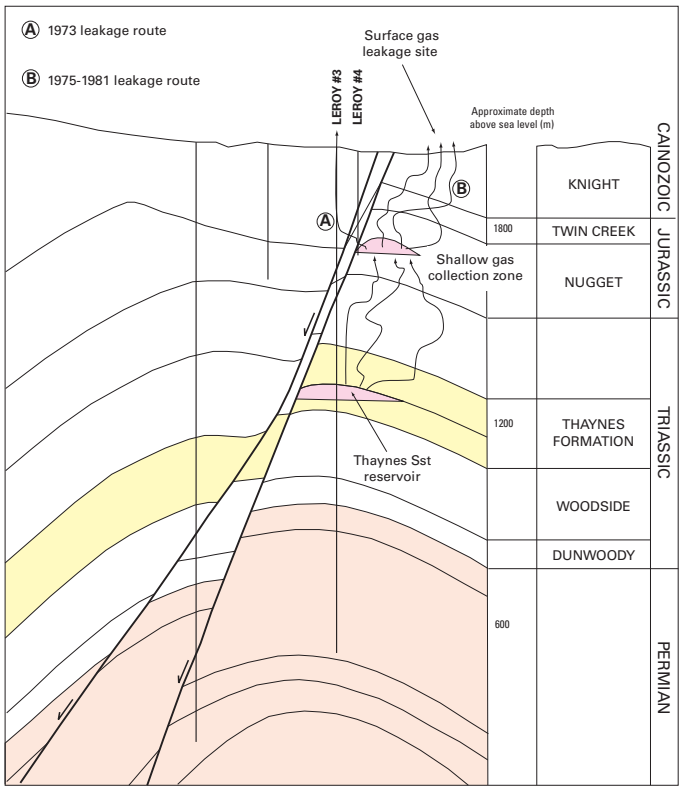


Figure 38. Stratigraphy, cross-section and leakage paths from the Leroy Gas Storage Facility, Wyoming (after Araktingi et al., 1984).

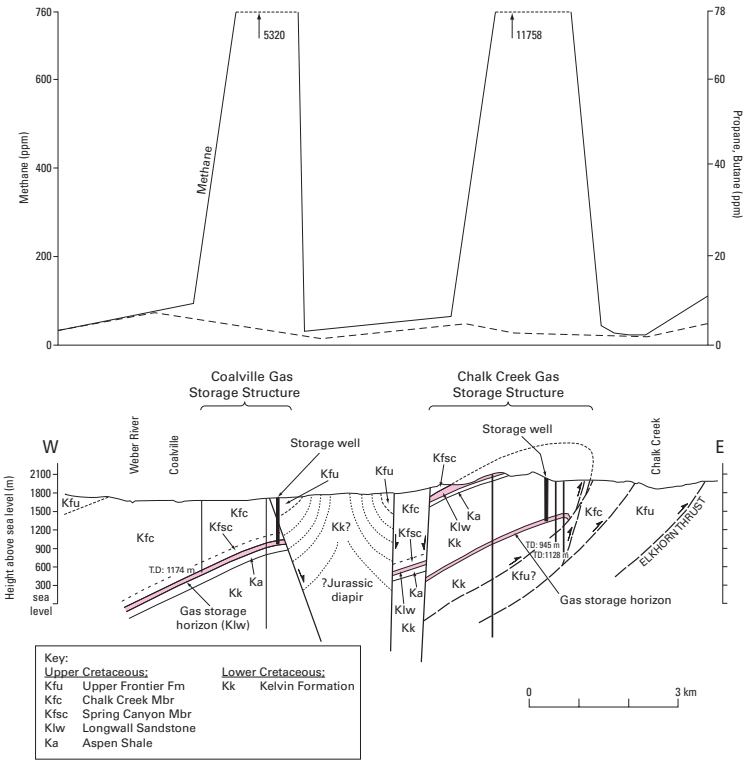


Figure 39. Stratigraphy and structural detail of the Coalville and Chalk Creek gas (aquifer) storage facilities, Utah, USA (after Morgan, 2004).

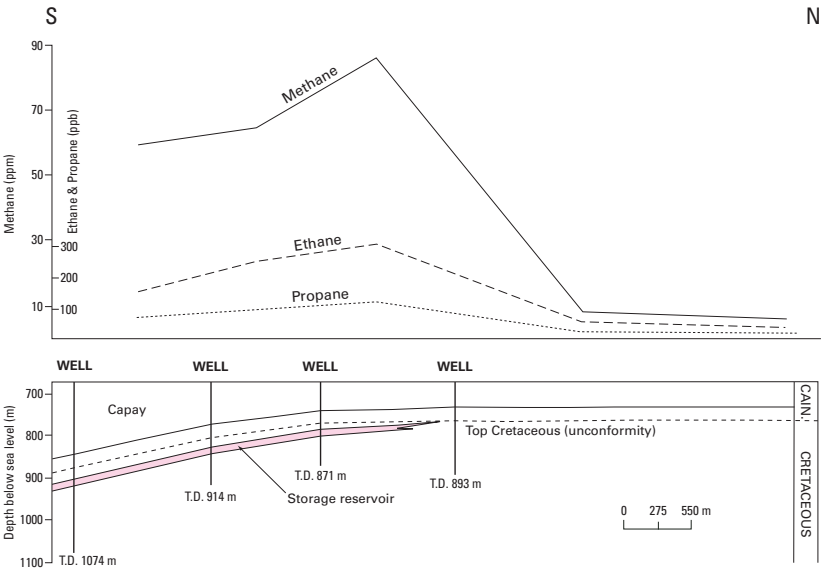


Figure 40. Cross-section of the Pleasant Creek gas (aquifer) storage facility in California (after Jones & Drozd, 1983). Also shown the soil-gas profiles showing leakage of the aquifer caprock.

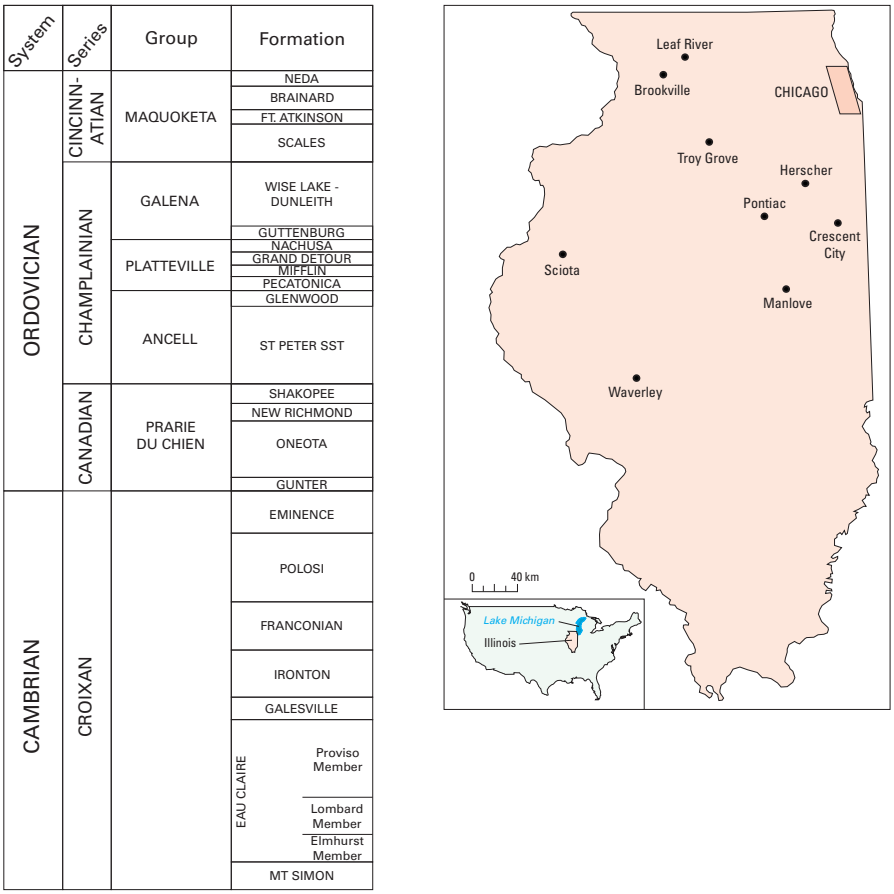


Figure 41. Stratigraphy of Illinois aquifer sandstones and location of the main gas storage sites having experienced difficulties, see Appendix 5 (after Collinson et al., 1988; Kolata & Wilson, 1991).

Figure 42. Structural contour map of the Weeks Island salt dome, Louisiana, illustrating the sites of the two sink holes in relation to the extent of salt mine workings (after Warren, 2006).

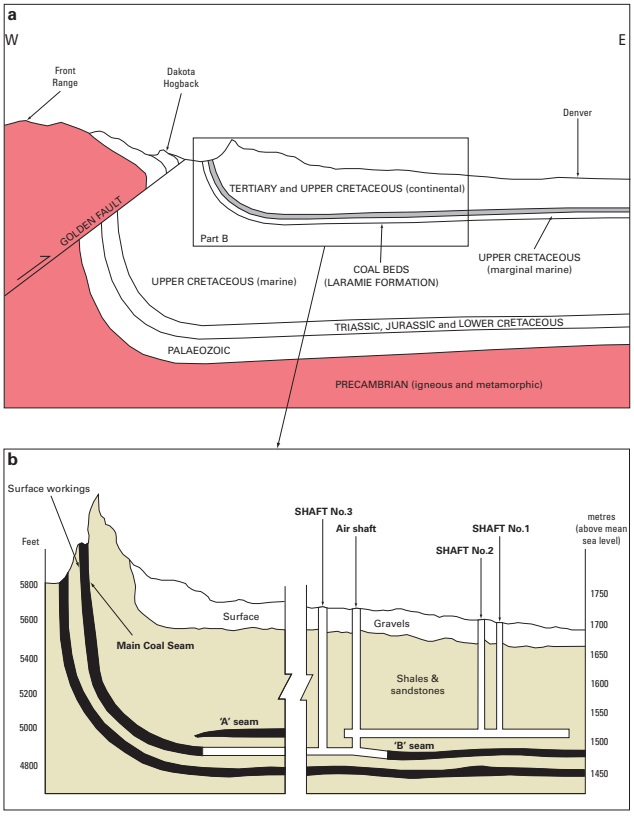
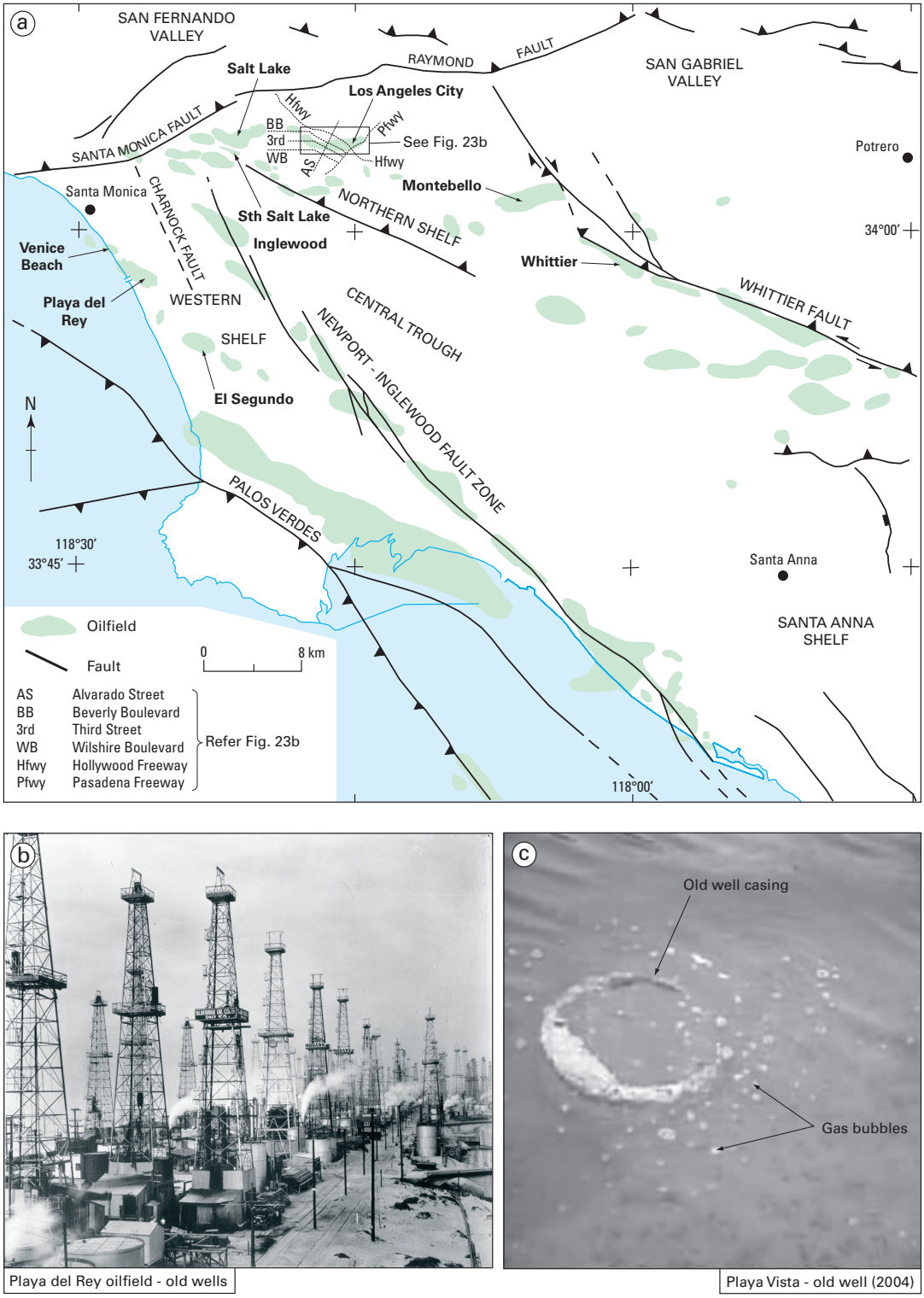


Figure 43. Detail of the Leyden Mine gas storage site, Colorado (after Raven Ridge Resources, 1998).



After Seaver Center for Western History Research, Los Angeles County Museum of Natural History Save Ballona Wetlands, Camp Dresser & McKee, Wright and Biddle

Figure 44. Map of the oilfields and main tectonic features in the Los Angeles Basin. a) Oilfields based upon Camp Dresser & McKee (2001) and Wright (1991), faults based upon Wright (1991) and Biddle (1991), b) oil derricks along the ocean front at Playa del Rey (after Seaver Center for Western History Research, Los Angeles County Museum of Natural History), c) gas bubbles emerging from old oil well in lagoon at Playa Vista, Playa del Rey oilfield (courtesy Jeanette Vosberg, Save Ballona Wetlands - see http://saveballona.org/techpages/well.html).

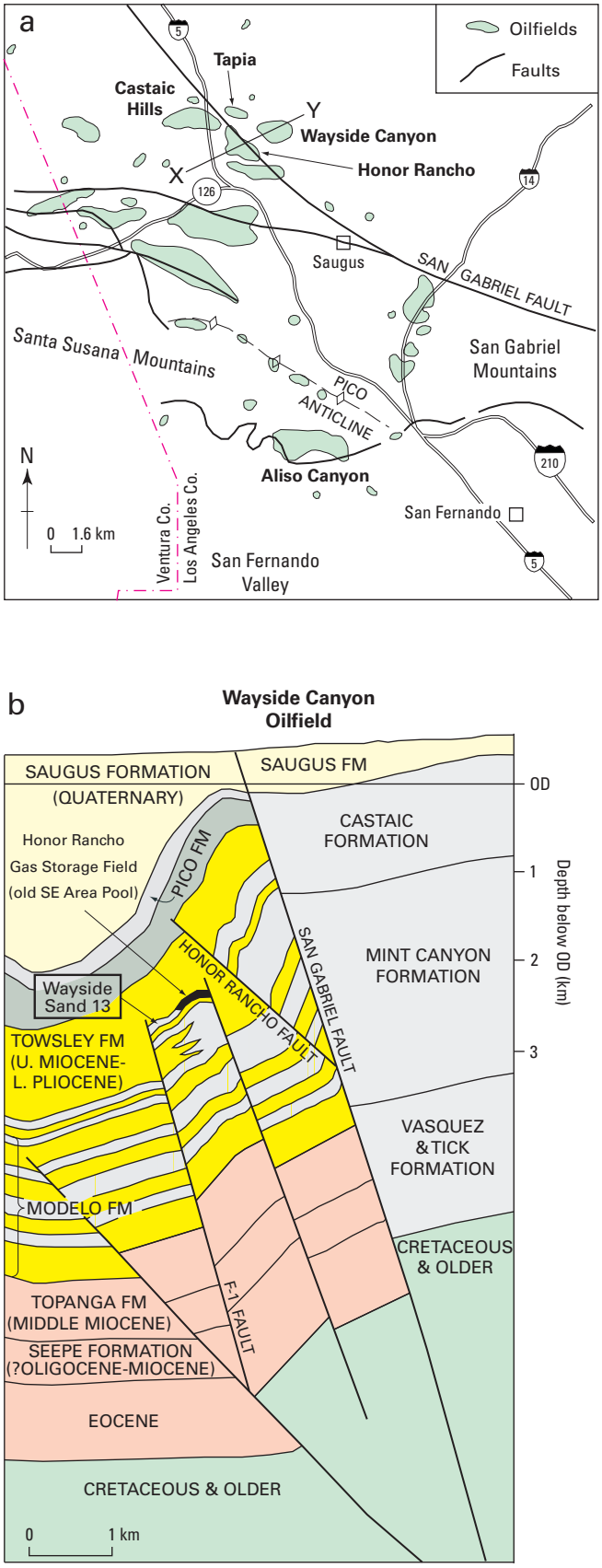


Figure 45. Castaic and Honor Rancho gas storage facilities. a) Location map, b) cross section of the Honor Rancho Oilfield (after Davis & Namson, 2004).

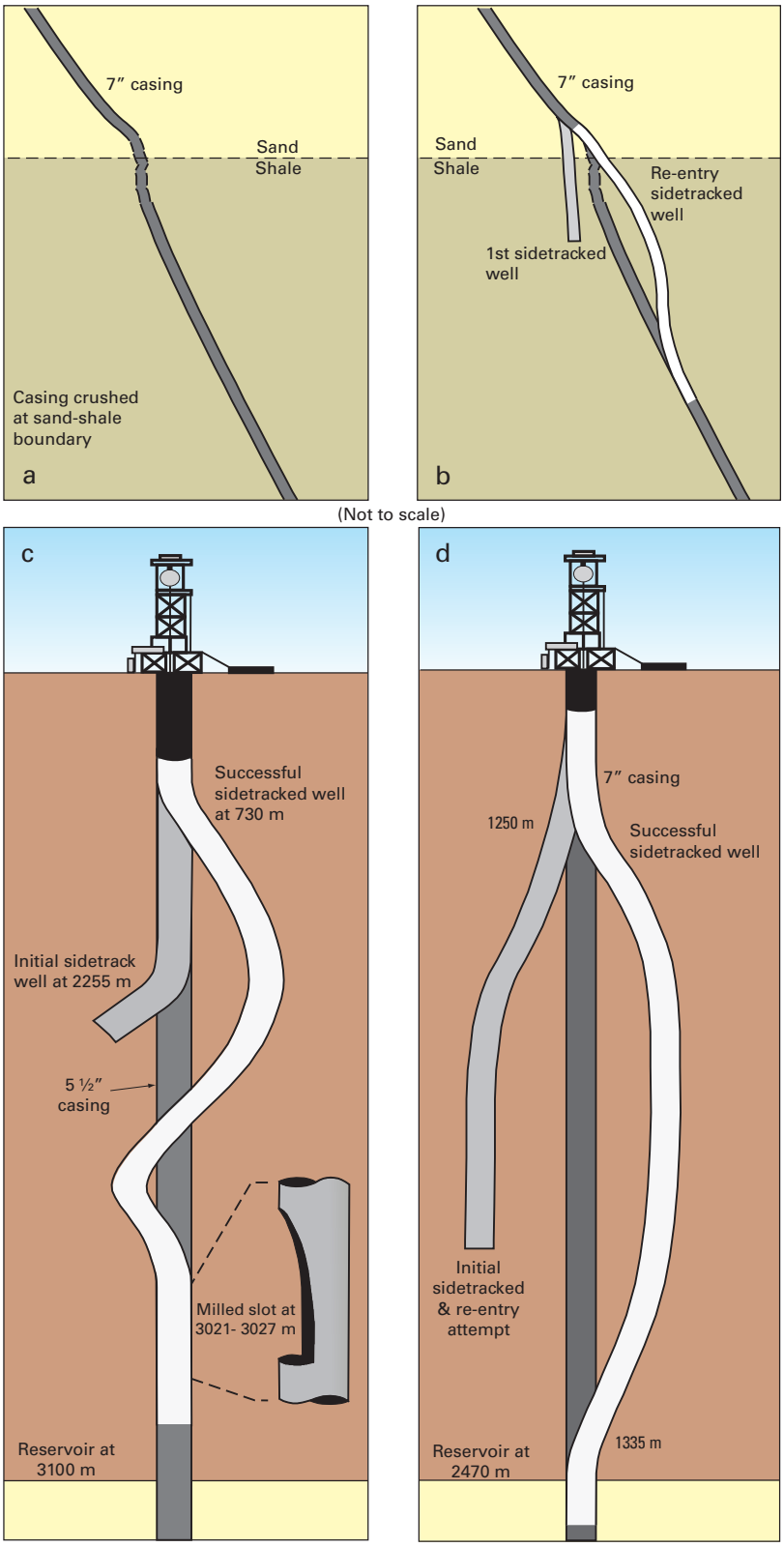


Figure 46. Sketch diagrams showing problems with and the repair of gas storage wells in California (after Vector Magnetics: http://www.vectormagnetics.com/ Case_HistoryO&G.html). a) and b) damage following an earthquake, c) inadvertent sidetracking of a well, d) inadvertent sidetrack due to corroded casing.

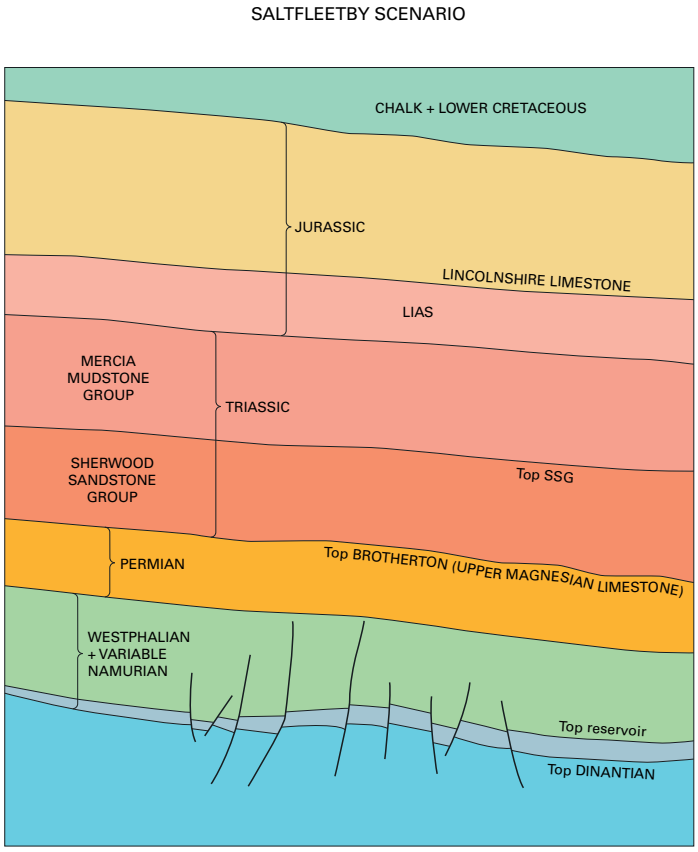


Figure 47. Sketch section illustrating the geological conditions likely to represent the 'Saltfleetby scenario' (based upon Hodge, 2003).

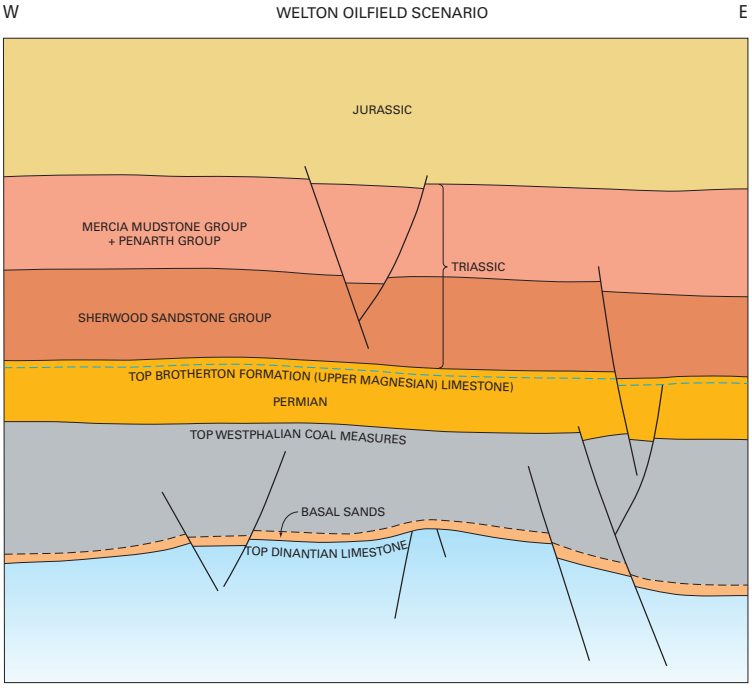


Figure 48. Sketch section illustrating the geological conditions likely to represent the 'Welton scenario' (based upon Rothwell & Quinn, 1987).

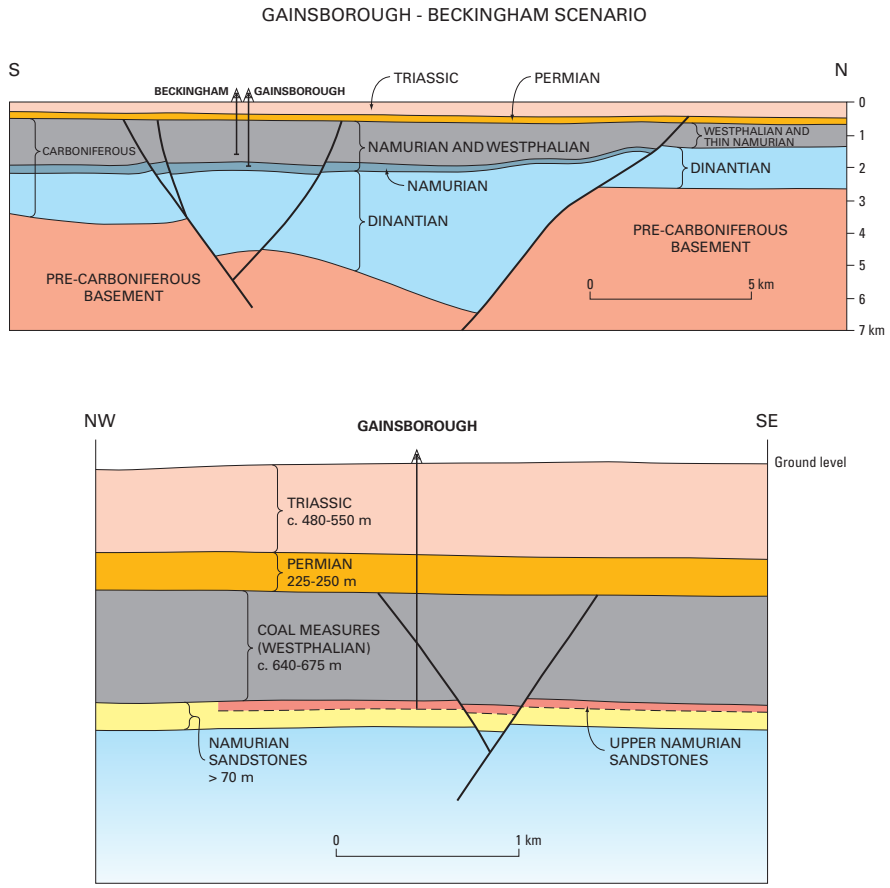


Figure 49. Sketch section illustrating the geological conditions likely to represent the 'Gainsborough-Beckingham scenario' (based upon Brunstrom, 1963; Fraser & Gawthorpe, 1990, 2003).

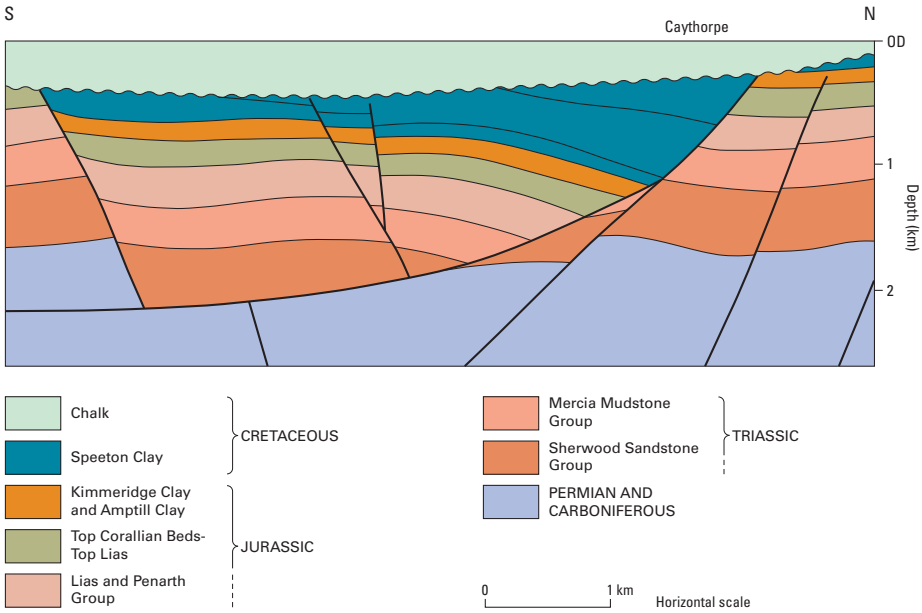


Figure 50. Sketch section illustrating the geological conditions likely to represent the 'NE England scenarios' (e.g. Caythorpe and Kirby Misperton gasfields – based upon Kirby & Swallow, 1987).

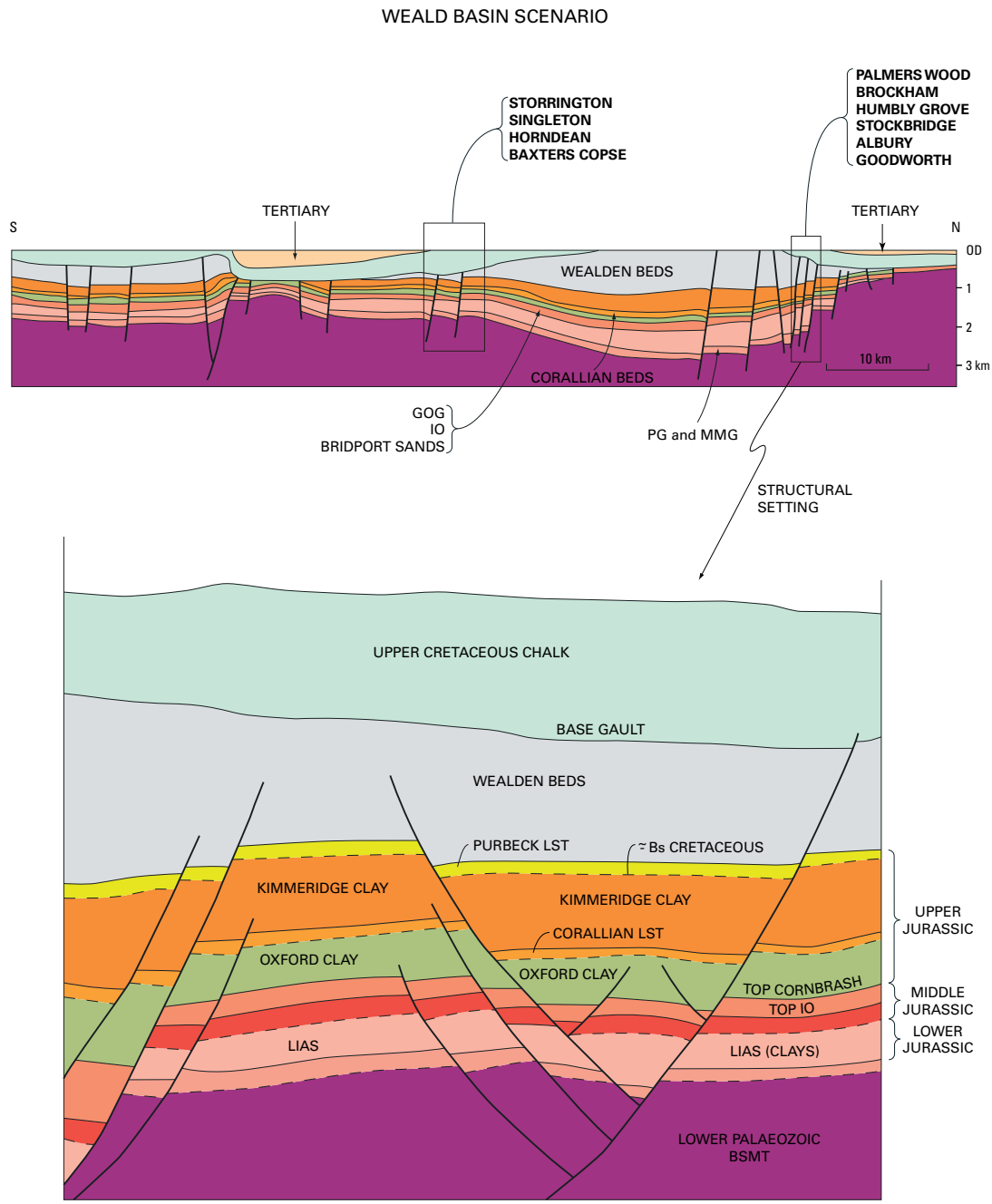


Figure 51. Sketch section illustrating the geological conditions likely to represent the 'Weald Basin scenarios' (e.g. Humbly Grove and Storrington – based upon Hancock & Mithern, 1987).

Age	Lithostratigraphy	Main rock type	Strength/Av. Porosity(%)	Approx. thickness (m)
Upper Cretaceous	Chalk	Chalky limestone	Moderately weak/ 10	183-213
	Upper Greensand	Sand		~30
	Gault Clay	Claystone	Weak rock 30-50	~76
Lower Cretaceous	Lower Greensand	Ferruginous sst	Weak rock	75-92
	Wealden	Sandstones and claystones	Moderately weak	192-232
	Purbeck	Siltstones, claystones, limestones	Weak rock	139-156
Upper Jurassic	Portland	Sst & siltst		52-62
	Kimmeridge Clay	Lsts,claystones siltstones	Weak rock/ 35	172-188
	Corallian	Ssts, marls claystones & silts		66-73
	Oxford Clay	Organic rich clays & silts	Weak rock/ 30	101-109
	Kellaways Beds	Fine sands & clays	Very weak rock/30	10-11
Middle Jur	Cornbrash Forest Marble & Gt Oolite Lst	Limestones & ssts	Weak to strong/ 9.6-16	60-70
	Fuller's Earth	Claystone, siltst	Very weak	17
	Inferior Oolite	Lst, clayst, siltst	Weak	30
Lower Jurassic	Upper Lias	Claystone	Weak	55
	Middle Lias	Siltst, fine sst	Weak/35	50
	Lower Lias	Organic rich claystones	Weak	~100
Rhaetic	Rhaetic Penarth Group	Lst, sst	Moderately strong	~10
Carb.	Carboniferous Limestone	Limestone		>10

Figure 52. Generalised stratigraphy for the Humbly Grove and northern Weald area. Abbreviations: Lst –limestone; Sst – sandstone; Siltst - siltstone.

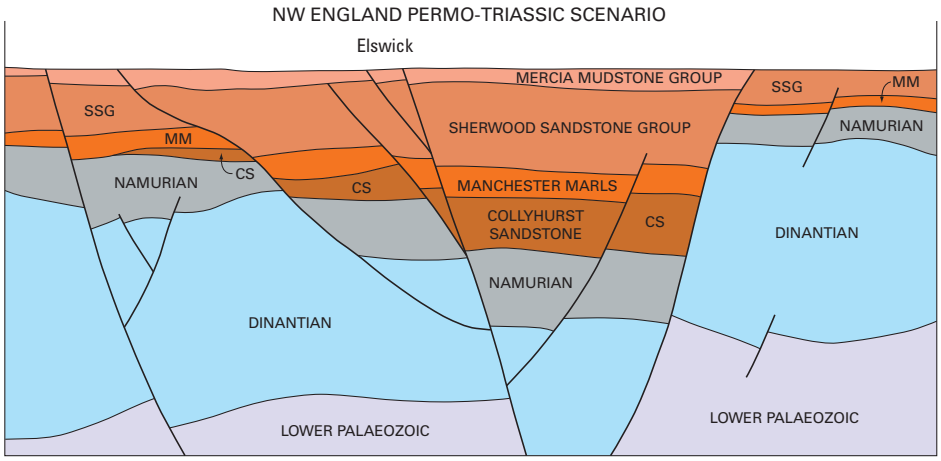


Figure 53. Sketch section illustrating the geological conditions likely to represent the 'NW England (Elswick) scenario' (based upon Aitkenhead et al., 1992).

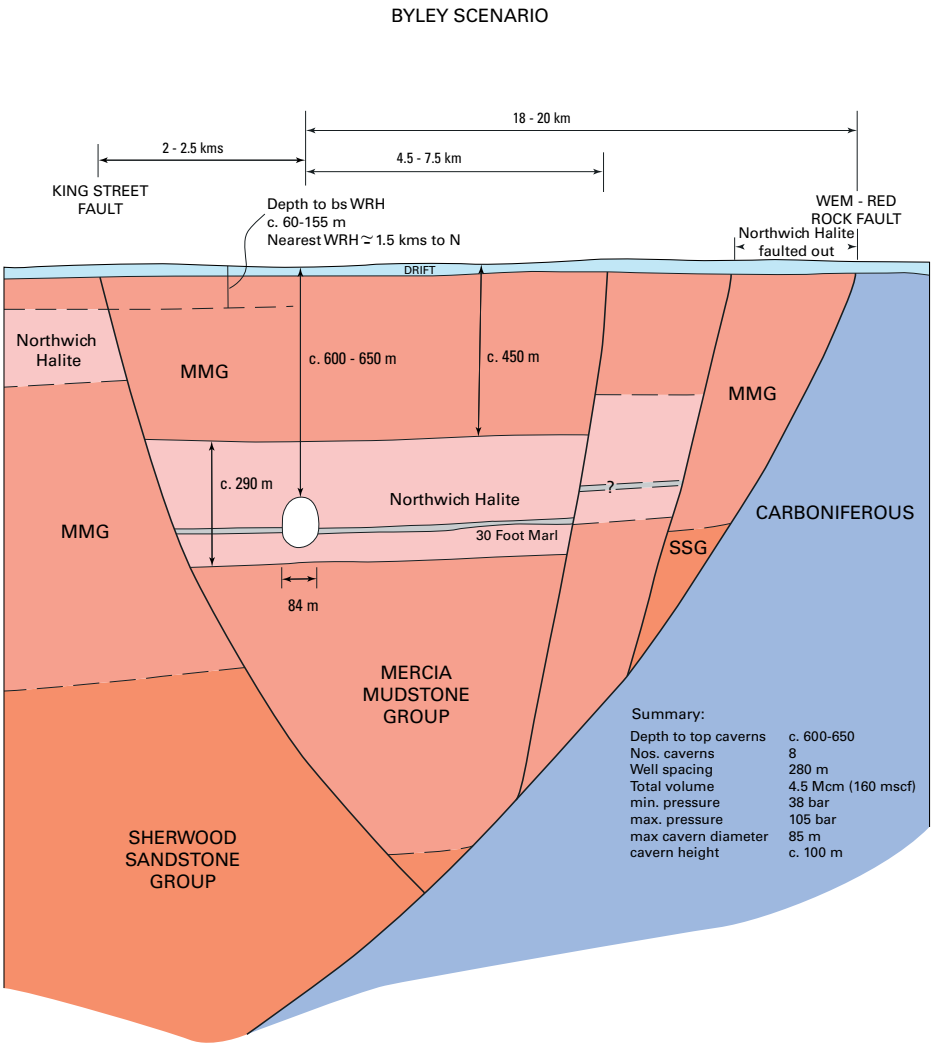


Figure 54. Sketch section illustrating the geological conditions likely to represent the 'Cheshire Basin scenario' – relating to the Byley, Hole House, King Street and Stublach sites.

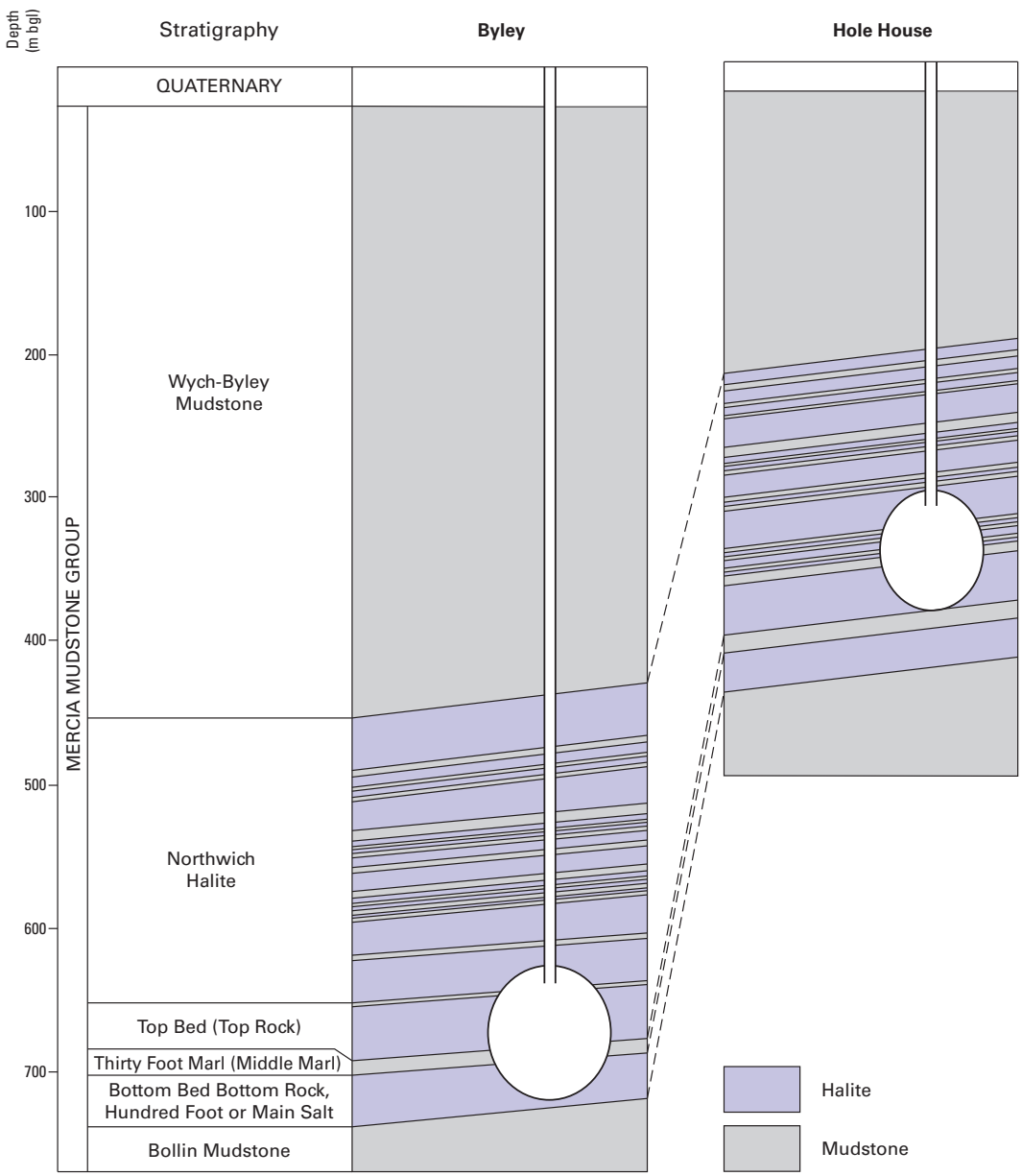


Figure 55. Sketch section illustrating the geological conditions likely to represent the 'Byley and Hole House scenarios'.

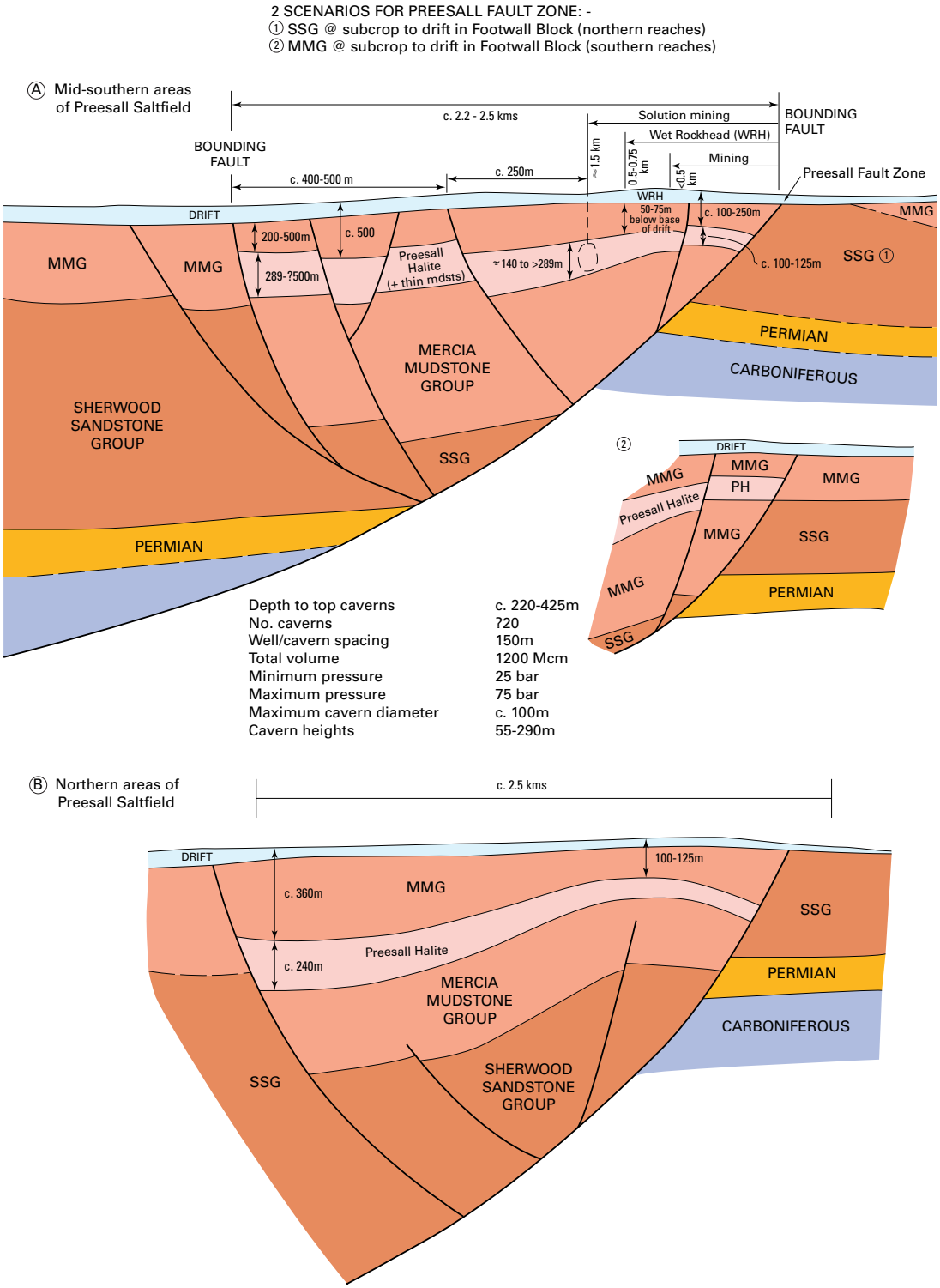


Figure 56. Sketch section illustrating the geological conditions likely to represent the 'Preesall saltfield scenario'. a) the southern areas of the saltfield (more intragrabenal faults), b) the northern areas of the saltfield (fewer intragrabenal faults).

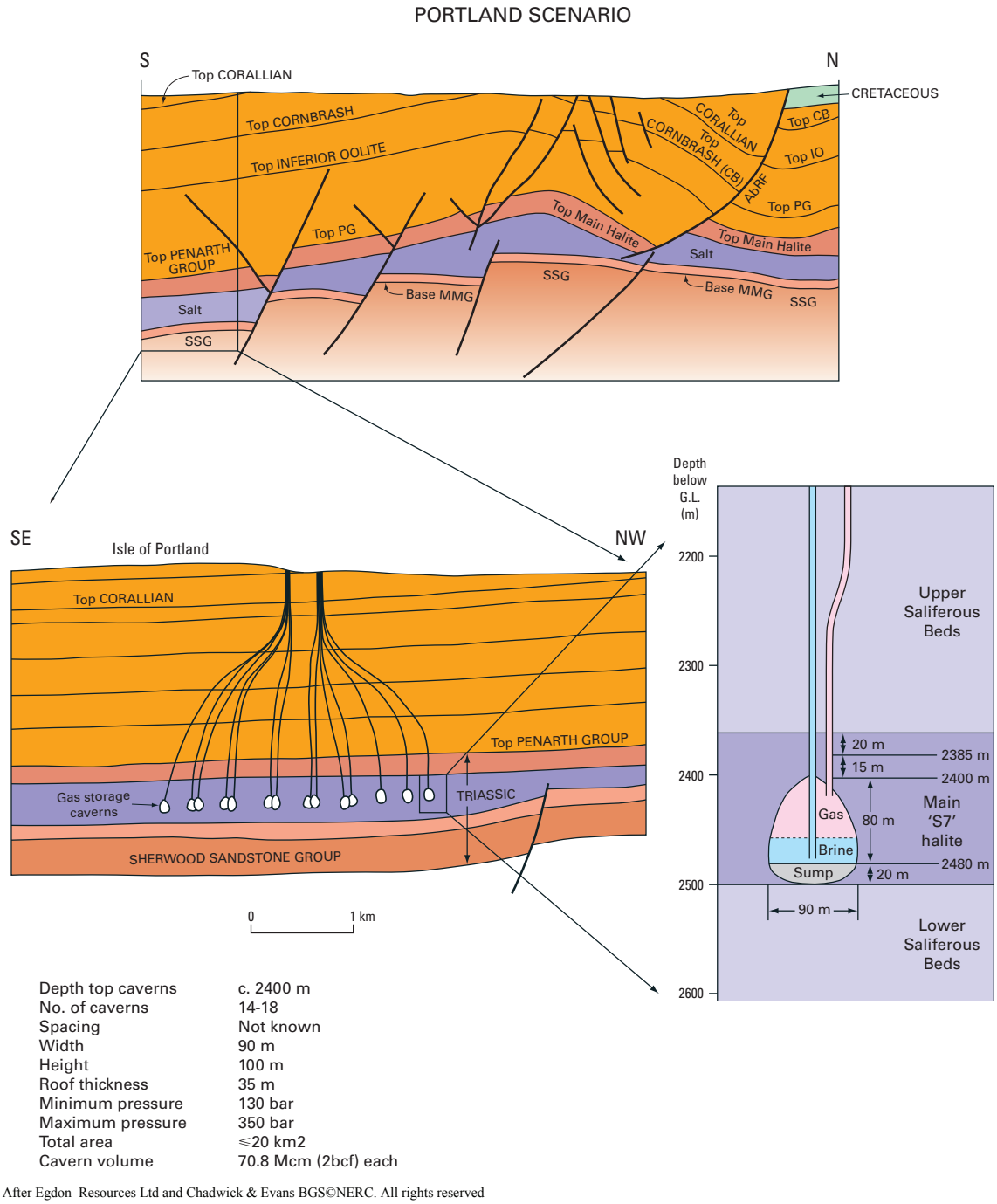
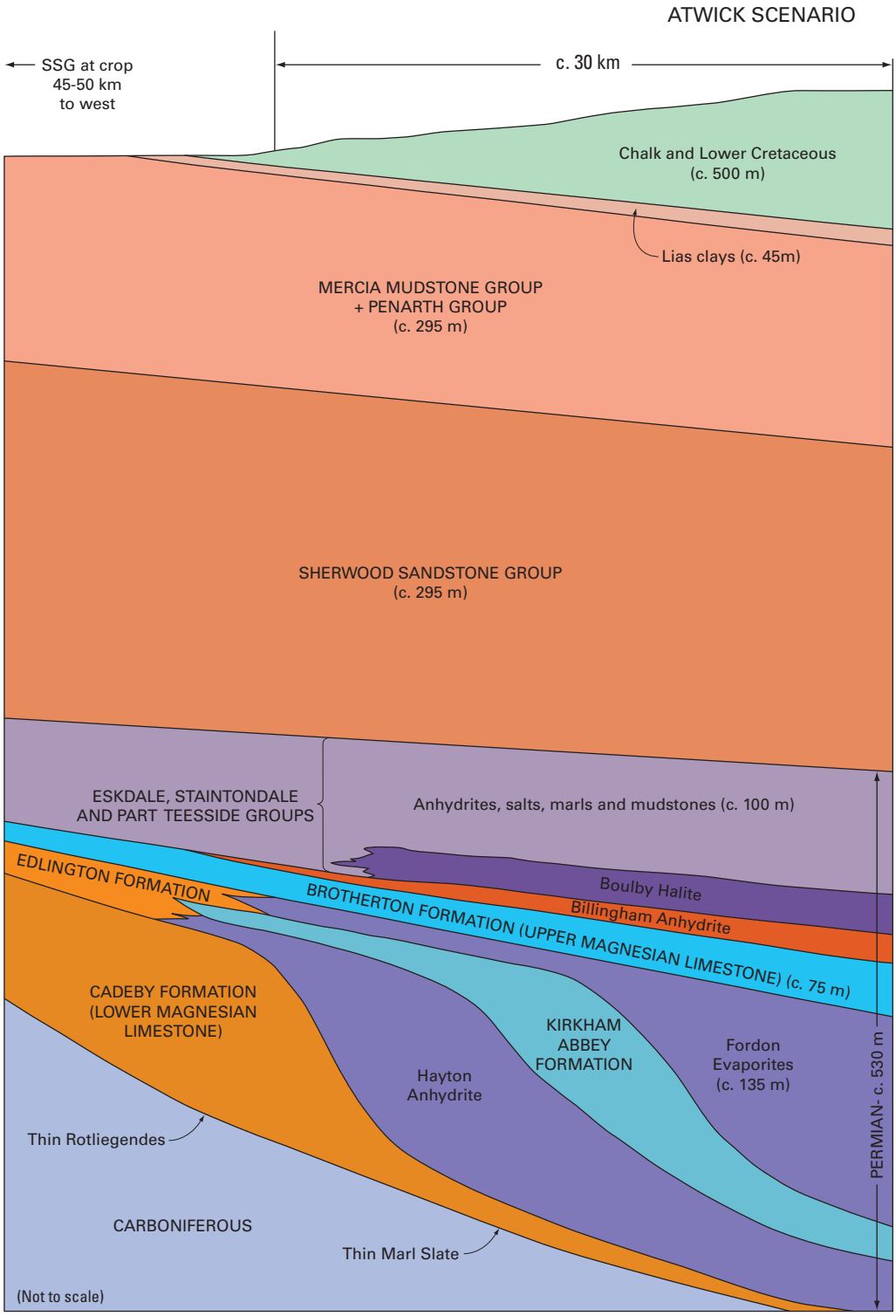


Figure 57. General setting of the Dorset Halite in the region of the proposed salt cavern storage facility beneath the Weymouth-Isle of Portland area. a) Line illustration of the thickening of the (Dorset) halite of the Wessex Basin in the Weymouth Anticline, based upon depth converted seismic reflection data (Chadwick & Evans, 2005), b) sketch of the level of proposed gas storage caverns and layout (after Egdon, 2006a).



Depth top caverns	c. 1670 - 1900 m	Minimum pressure	c. 120 bar
Nos of caverns	9	Maximum pressure	c. 270 bar
Spacing	not known	Maximum cavern diameter	not known
Total volume	c. 420 Mcm	Cavern heights	c. 60 - <100m

Figure 58. Sketch section illustrating the geological conditions likely to represent the 'NE England Permian scenario' (e.g. Hornsea/Atwick, Aldbrough).

Tables

Table 1 (following page). Summary of operational and planned underground gas storage facilities in Britain. Note: information regarding the caverns operational in the Teesside area and the product stored has been in part supplied by SABIC, whose assistance is gratefully acknowledged. This represents our most up to date information on the various caverns and stored products. However, more detail might become available with time.

[1] Note Table 2: DTI (2006a&b) figures, [2] Note Table 2: DTI (2006a&b) figure

Area	Site	Owner/operator	Storage capacity (Mcm)	Number of caverns (Chalk & salt storage)	Approx. depth of storage (top-bottom if known - m)	Comments
Operational facilities – depleted oil and gasfields						
Rough (offshore)	Southern North Sea	Centrica	2,832	N/A	c. 2743	Operational since 1985
East Midlands	Hatfield Moors	Edinburgh Oil & Gas	122	N/A	c. 427	Operational since 2000
Wessex-Weald Basin	Humbly Grove	Star Energy	280	N/A	c. 982	Operational since 2005
Planned facilities – depleted oil and gasfields						
East Midlands	Welton	Star Energy	435	N/A	c. 1360	Planning application refused, likely Public Inquiry. Commission 2008?
East Midlands	Saltfleetby	Wingas UK Ltd	600	N/A	c. 2234	Planning application submitted January 2005. Commission 2009?
East Midlands	Hatfield West	Edinburgh Oil & Gas	Not known	N/A	c. 396	Planned - feasibility studies 2004-2005
East Midlands	Gainsborough	Star Energy	227-240	N/A	c. 1375	Pre-planning stage
East Yorkshire	Caythorpe	Warwick Energy Ltd	Up to 210	N/A	c. 1829	Planning consent refused 22 June 2006. Public Inquiry due to start 24 April 2007.
Wessex-Weald Basin	Albury – phase 1	Star Energy	160	N/A	c. 625	Pre-planning stage, commission 2007/08?
Wessex-Weald Basin	Albury – phase 1	Star Energy	Up to 715	N/A	ditto	Pre-planning stage, commission 2010?
Wessex-Weald Basin	Bletchingley	Star Energy	Up to 900	N/A	c. 930-1143	Pre-planning stage, commission 2009?
Wessex-Weald Basin	Storrington	Star Energy	Not known	N/A	c. 1152	Pre-planning stage – application likely after feasibility studies.
Operational facilities – Chalk caverns						
North Lincolnshire	Killingholme	ConocoPhillips and Calor Gas	0.1 (liquid ≈ 60,000 tonnes of LPG)	2	180-?210	Two mined caverns in Chalk c. 180 m below ground level, operational since 1985
Operational facilities – salt caverns						
Cheshire Basin	Holford H-165	IneosChlor (formerly operated by NG (Transco), now Ineos	0.175	1	350-420	Planning approval granted 1983. Ten year inspection completed 2006. One of number of abandoned brine cavities with ethylene & natural gas storage since 1984.
Cheshire Basin	Hole House Farm (Warmingham Brinefield)	Energy Merchant (EDF Trading)	75	4	300-400	Planning approval granted 1995. 4 caverns, operation started in February 2001
East Yorkshire	Hornsea/Atwick	Scottish & Southern Energy	325	9	c. 1720-1820	Planning granted 1973, operating since 1979. 9 caverns planned.
Teesside	Saltholme	SABIC (formerly IneosChlor//Huntsman)	Up to 0.12-0.2	18 (plus 9 redundant)	350-390	Development in 1950s, storage started 1965-1982. 18 ex ICI caverns in operation. 1 'dry' cavity storing nitrogen; 17 'wet' storage cavities containing hydrocarbons ranging from Hydrogen to Crude Oil; 9 redundant storage cavities; 75 redundant brine wells/cavities never used for storage; 5 in service brine wells.
Teesside	Saltholme	IneosChlor/Northern Gas Networks	0.08	4	340-370	4 ex ICI natural gas cavities. Development started 1959-1983, storage started 1959-1983. Now owned by IneosChlor & operated by Northern Gas Networks for natural gas.
Teesside	Wilton	SABIC (formerly IneosChlor/Huntsman)	Up to 0.04	5 (plus 3 redundant)	650-680	Storage started from 1959 to 1983. 8 caverns leached, 5 operational cavities in total leached for storage purposes: 4 cavities storing Ethylene, 1 cavity storing Mixed C4's. 3 cavities redundant or never in service for storage
Teesside	Wilton	SembCorp/BOC	Not known	2	650-680	2 ex ICI cavities - operational & storing nitrogen (for BOC Nitrogen)
Planned facilities – salt caverns						
Cheshire Basin	Byley/Holford (southern end of Holford Brinefield - Drakelow Lane area)	Scheme initiated by Scottish Power, sold to E.On UK plc	160-170	8	630-730	Secretary of State reversed Public Inquiry decision. Under construction, commission 2008? Salt caverns to be leased from Ineos who own the salt & will construct caverns
Cheshire Basin	Stublach (Holford Brinefield between Drakelow Lane and Lach Dennis)	Ineos Enterprises Ltd	540[1]	28	550-560	Planning application December 2005, granted June 2006, fully consented August 2006. Government will not call in for Inquiry. Project progressing to design stage, commissioning 2009?
Cheshire Basin	King Street (Holford Brinefield)	King Street Energy (NPL Estates)	216	9	>400	Proposed construction of 9 cavities, each with a volume of 400,000 cubic metres, holding up to 216 Mcm of gas in total of which up to 126 Mcm will be working gas
East Yorkshire	Hornsea – Aldbrough N & S	Scottish & Southern Energy and Statoil	420	9	1800-1900	Planning granted 2000, 2 sites operational by Q3 2007?
NW England	Preesall	Canatxx Gas Storage Ltd	c. 1200[2]	20-24	245-510	Significant public objection to proposals. Public Inquiry held (October 05-May 06), Inspector's decision not expected before October 2007
East Yorkshire	North of Aldbrough	E.ON UK	420	Not known	c. 1800	Planning application submitted to East Riding of Yorkshire Council, January 2007. Subject to permission, work to start late 2007, first phase operational 2010, with completion 2013.
Wessex-Weald Basin, Dorset	Isle of Portland	Portland Gas Ltd. (subsidiary Egdon Resources)	990	14-18	2100-2300	Pre-planning stage, application due for discussion at County Council meeting March 2007.
Larne, N Ireland	Larne Lough	Portland Gas NI Ltd(subsidiary Egdon Resources)	Not known	Not known	1680	Feasibility study stage, seismic acquisition in October 2007

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	Type and Number of UGS facilities (2005)					Working Volume	Deliverability
Area	***Gas & Oil Fields***	***Aquifers***	***Salt Caverns***	***Other***	***Total***	***Bcm (10^9 m^3)***	***Mcm[a]/d (10^6 m^3/d)***
Europe	64	23	27	3	**117**	75	1,448
Former Soviet Union	36	13	1		**50**	110	983
U.S.A.	320	44	30		**394**	113.5	2,369
Canada	44		8		**52**	17	279
South America	2				**2**	0.2	2
Asia	7				**7**	2.6	14
Australia	5				**5**	1.0	10
Total (%age)	**478 (76)**	**80 (13)**	**66 (11)**	**3 (<1)**	**627**	**319.3**	**5,105**
Number of incidents in storage facilities	16	17	27	5			
Number of incidents in storage facilities as %age of number of facilities operational in 2005	3%	21%	41%	None operatio-nal, 2005			
Number of incidents in storage facilities involving casualties/ evacuations	3	2	9	5			
Number of incidents in storage facilities involving casualties as %age of number of facilities operational in 2005	0.63%	2.5%	13.6%	None operatio-nal, 2005			

UGS Figures for America 1997/2005

	Number of facilities - 1997	***Working Volume (Bcm) - 1997***	***Number of facilities - 2005***	***Working Volume (Bcm) - 2005***
Gas & Oil Fields	346	94.3	320	97.3
Aquifers	41	9.97	44	11.3
Salt Caverns	27	3.3	30	4.9
Total	**414**	**107.6**	**394**	**113.5**

Consumption and storage volumes

	***Total gas consu-mption (Bcm) - 1997* (BP, 2006)**	**Number of facilities - 1997**	***Working volume (Bcm) - 1997***	***%age gas storage/ consumption - 1997***	***Total gas consu-mption (Bcm) - 2005***	**Number of facilities - 2005**	***Working volume (Bcm) - 2005***	***%age gas storage/ consumption - 2005***
North America	769.3	414	107.6	14	775	446	130.5	16.8
Western Europe	341.3	75	53	15.5	427.4	117	c. 75	c. 17.6
Russian Federation	350.4	46	c. 80.5	c. 23	405	50	c. 110	c. 27.2
Total Europe and Russia-Eurasia	*936.1*	*138*	*Not available*	-	*1121*	174	*c. 187.5*	*16.7*
World Totals	**2249.7**	**580**	**262.4**	**11.7**	**2749.6**	**627**	**319.3**	**c. 11.6**

Table 2. Number of underground natural gas storage facilities, working volumes and deliverability, both worldwide and in the USA (based upon IGU, 2003; Favret, 2003; Plaat, 2004 & this volume; EIA, 2006).

[a] Mcm = million cubic metres (as used by DTI), equalling 10^6 m^3

Table 3. Calculated diffusive fluxes for the McClave Field (Nelson & Simmons, 1995)

	Cap rock porosity	
	5%	***10%***
Methane loss (m^3/yr)	521	2383
Methane loss (mcf/yr)	18.4	84.1
Replacement time (m.y.)	2.21	0.485

Table 4. Calculated methane losses for a 1737 m and a 39.6 m thick caprock (Smith et al., 1971)

	Calculated losses for fields with hypothetical gas production			
	1737 m thick caprock		**39.6 m thick caprock**	
	283.2 Mcm (10 bcf)	***2.83 Bcm (100 bcf)***	***283.2 Mcm (10 bcf)***	***2.83 Bcm (100 bcf)***
Methane loss (m^3/yr)	2,832 (0.0028 Mcm)	21,294 (0.0213 Mcm)	124,310 (0.124 Mcm)	934,455 (0.935 Mcm)
Methane loss (mcf/yr)	0.100	0.752	4.39	33.0

Table 5. Summary of the main hydrocarbon province characteristics and significant discoveries onshore UK.

Province	Typical hydro-carbon occurrence	Typical Reservoirs	Source(s)	Trap type	Examples
Wessex-Channel Basin (including the Weald Basin)	Oil and gas	Bridport Sands, Great Oolite (Jurassic), Sherwood Sandstone Group (Triassic)	Lower Lias (clays Jurassic)	Tilted fault blocks & Palaeogene inversion anticlines	Oil: Wytch Farm, Kimmeridge, Humbly Grove, Stockbridge, Wareham Gas: Albury
East Midlands	Oil and gas	Silesian sandstones & fractured Dinantian limestones (Carboniferous)	Silesian (Carboniferous) mudstones and coals	Variscan anticlines and stratigraphic traps	Oil: Eakring, Welton, Rempstone, Scampton, Gainsborough Gas: Hatfield Moors and Hatfield West, Trumfleet, Saltfleetby
Yorkshire/NE England	Gas	Permian limestones (e.g.Upper Magnesian Limestones)	Silesian (Carboniferous) mudstones and coal	Mesozoic folds	Malton, Marishes, Lockton, Eskdale
NW England	Oil and gas	Sherwood Sandstone Group (Triassic)	Silesian (Carboniferous) mudstones and coals	Variscan anticlines, stratigraphic – superficial deposits trapping oil	Oil: Formby Gas: Elswick
Midland Valley Scotland	Oil and gas	Silesian sandstones (Carboniferous)	Silesian (Carboniferous) mudstones and coals	Variscan (end Carboniferous-Permian) anticlines	Oil: Dalkeith, Gas: Cousland

Table 6. Tolerance of microbes to extreme environments (West & McKinley, 2001).

Condition	Example of organism	Limit of growth
High temperature	'Black smoker' bacteria	Reported to 113^0C.
Low temperature	*Sporotrichum carnis*	-20^0C
High pH	Nitrifying bacteria	12
Low pH	*Thiobacillus ferrooxidans*	0
High salinity	*Halobacterium halobium*	50% salt by weight
Low salinity	*Salmonella oranienburg*	70ppb dissolved salts
High pressure	*Desulfovibrio desulfuricans*	180MPa
Radiation	*Deinococcus radiodurans*	Single dose 5000 Gy
Chemical toxins e.g. $PbCl_2$	*Aspergillus niger*	67 mg ml^{-1}

		Storage Type				
		Depleted oil/gasfields	Aquifer	Salt Cavern	Abandoned mine	Total
Main processes attributed to leak/failure mechanism/abandonment of facility	well/casing problems/failure	5	4	11		20
	above ground infrastructure - valve/pipes/wellhead/compressor	3	1	7		11
	failed pressure test – facility never commissioned			1		1
	design/construction failure – facility never commissioned			3		3
	inadvertent intrusion	1	1			2
	during repair/testing/maintenance	2	2	1		5
	Overpressure aquifer/overfilling cavern		1	2		3
	migration from injection footprint	5				5
	cap rock – not gas tight		9		2	11
	cap rock - faulted	2	4			6
	salt creep			3		3
	cavern communication			1		1
	mine shaft				1	1
	wet rockhead/sinkholes			1	1	2
	seismic activity	1				1
	too shallow, facility abandoned		1			1
	loss of wellhead pressure			1		1
	not determined	1		2		3
	Unspecified product			2		2
	Natural gas/town gas	16	17	8	2 (coalmines)	43
	Propane/LPG			8	1 (coalmine?), 1 'unlined cavern'	10
	Ethane			1		1
	Ethylene			3		3
	Butane			1		1
	Crude oil			1	1 (saltmine)	2
Incidents by country/US state	California	11	1			12
	Illinois	1	8		1 (coalmine?)	10
	Texas			10		10
	Louisiana	1		5	1 (saltmine)	7
	Kansas			2		2
	Mississippi			3		3
	Rest of America (including Canada)	1	3	3	1 (coalmine?), 1 'unlined cavern'	9
	France		1	2		3
	Germany	1	3	2		6
	Belgium				1 (coalmine)	1
	Denmark		1			1
	UK	1				1
Fire/explosion associated with the incidents		4	1	10		15
Total number of incidents		16	17	27	5	65
Number of incidents involving casualties/evacuees (%age of incidents)		3 (≈19%)	2 (≈12%)	9 (≈33%)	None operational, 2005	
Total number of incidents as a %age of facility numbers in 2005 (facility numbers – Table 1)		≈3% (478)	≈21% (80)	41% (66)	None operational, 2005	
Human impact	Dead - America			8		9
	- Rest of World		1			
	Injured - America	3		48		c. 62
	- Rest of World	2	9			
	Evacuated - America	c. 52		6110		c. 6700
	- Rest of World	31	500			
	Total dead	0	1	8	0	9
	Total injured	5	9	48	0	c. 62
	Total evacuated (excluding village of Knoblauch, Germany – numbers not found)	83	>500	c. 6110	0	c. >6700

Table 7. Summary of main processes leading to leakage from and failure of underground hydrocarbon storage facilities.

Depleted Oil/Gasfield Storage						
Facility	**Operator**	**Product**	**Date**	**Description of event/fatalities/injuries**	**Reported cause/comment**	**Main reference(s)**
Incidents involving casualties/large evacuations						
Fort Morgan, Colorado, USA	Colorado Interstate Gas Co.	Gas	October 2006	Gas leak, halting storage operations. 13 families evacuated (c. 52)	Well leak – completion failed	State of Colorado (2006); (http://tonto.eia.doe.gov/oog/info/ngw/ngupdate.asp).
Rough Field, Southern North Sea, UK sector	Centrica	Gas	Feb 2006	Explosion and fire, 2 injured, 31 airlifted from platform	Catastrophic failure of a cooler unit in one of the four glycol dehydration units, leading to explosion in vicinity	Centrica (2006)
Southern Illinois, USA	Not available	Gas	Feb 7th 1997	Explosion & fire. 3 employees injured	Inadvertent strike of gas from UGS reservoir during drilling of oil well	Findlaw (2002)
Casualty Totals				***5 injured/c. 83 evacuated***		
Incidents where no casualties involved but financial or property loss or closure occurred						
Breitbrunn/Eggstatt Gasfield in Bavaria, Germany	Not available	Gas	2003	Pressure increase in the first annulus of borehole	Failure of the well completion	Bary et al., (2002) ; Überer et al., 2004
Playa del Rey, LA, California, USA	SoCal	Gas	April 2003	25 minute release of gas with a fine mist of oil	Valve in compressor unit broke	Peterson & Marquez (2003)
Castaic Hills & Honor Rancho, Calif., USA	SoCal	Gas	1975-present?	Gas migrating from Castaic reservoir to adjacent fields & thence to surface	Gas migrates to shallower Honor Rancho & Tapia reservoirs, via faults to surface killing oak trees	Davis & Namson (2004); Khilyuk et al., 2000)
Montebello, LA California, USA	SoCal	Gas	1950s-1980s	Storage gas lost over extended period	Storage gas migrated from injection area, injection ceased 1986, facility closed 2003	Benson & Hepple (2005); Chilingar & Endres (2005); EIA (2006)
Playa del Rey, LA, California, USA	SoCal	Gas	1940s-present day	Migration of stored gas	Stored gas has been migrating from Playa del Rey structure into Venice structure from earliest days, some fault related	Reigle (1953); Exploration Technologies Inc., (2000); SoCal, (2004); Chilingar & Endres (2005)
McDonald Island, Stockton, California, USA	Pacific Gas & Electric Co.	Gas	Oct 1993	Explosion, causing US $2 million damage.	Explosion in moisture extraction (gas conditioning) plant	Lee (1968); Delta Protection Commission (1997)
Epps, Louisiana, USA	Trunkline	Gas	1980s-1990s	Injected gas produced elsewhere in structure – from same reservoir	Gas migrated away from injection footprint – connection between traps. Facility remains operational	Coleman (1992); EIA (2006)
McDonald Island, Stockton, California, USA	Pacific Gas & Electric Co.	Gas	1974	Explosion, fire burned for 19 days, 0.42 Mcm gas consumed	Not available	San Joaquin County (1992)
East Whittier, California, USA	SoCal	Gas	1970s	Gas migrated from original injection site	Injected gas produced by other company, facility eventually closed in 2003.	Benson & Hepple (2005); EIA (2006)
El Segundo, California	Not available	Gas	Early 1970s	Gas migration - facility abandoned due to new housing	Gas migration from reservoir to surface. Abandoned for safety.	Khilyuk et al. (2000)
California, USA	Not available	Gas	Not available	Storage well damaged - crushed	Storage well damaged during earthquake	Vector Magnetics (http://www.vectormagnetics.com/ casehistories.pdf)
California, USA	Not available	Gas	Not available	Storage well damaged - casing shoe leak	Well inadvertently sidetracked during repair of casing shoe leak	Vector Magnetics (http://www.vectormagnetics.com/ casehistories.pdf)
California, USA	Not available	Gas	Not available	Corrosion of storage well casing	Well inadvertently sidetracked during repair of corroded casing	Vector Magnetics (http://www.vectormagnetics.com/ casehistories.pdf)

Table 8. Summary of documented incidents or problems reported at underground hydrocarbon storage facilities developed in depleting oil/gasfields, some of which have led to leakage and/or failure.

Aquifer Storage						
Facility	**Operator**	**Product**	**Date**	**Description of event/fatalities/ injuries**	**Reported cause/comment**	**Main reference(s)**
Incidents involving casualties/large evacuations						
Spandau, Germany	GASAG	Gas	April 2004	Explosion, 9 injured, 3 seriously, 500 evacuated in 1 km radius of incident	Explosion, perhaps linked to maintenance work, a defective seal, or work on the facilities contents gauges, destroyed the wellhead	Associated Press (April 23rd, 2004); F May (pers com (2004)
Ketzin (Knoblauch), Berlin, Germany	1960s not available, latterly UGS Mittenwalde	Town gas (1960s), natural gas (1970s-2000)	1960s-2000	1960s-gas migration from reservoir to surface, town of Knoblauch evacuated (permanently?). 1 fatality in house	Cap rock not gas tight – migration along faults in cap rock also thought likely. The 1 fatality linked to CO migrating up old well into house	http://www.mydeltaquest.com/english/archive-New-technology-would-store-carbon-underground; Juhlin et al. (2007); NJ Riley (pers com., 2007)
Casualty Totals				***1 dead, 9 injured, >500 evacuated***		
Incidents where no casualties involved but financial or property loss or closure occurred						
Stenlille, Denmark	Danish Oil and Gas Company (DONG)	Gas	1995	Gas in shallow aquifer and bubbled to surface	Casing leak	Laier & Øbro (2004 & in press)
Chémery, France	Gaz de France	Gas	Sept 1989	Major gas leak, no explosion. Flights diverted around gas cloud	During routine maintenance of well completion and replacement of a filter	NAWPC (1999); IAVWOPSG (2005);
Frankenthal, Germany	Saar-Ferngas	Gas	Sept 1980	Gas escape, no explosion, no casualties	Drilling into existing pipework?	AEA (2005)
Leroy, Wyoming, USA	Mountain Fuel Supply Co.	Gas	1973-mid 1980s	Numerous incidents of gas escaping	Corroded well casing & overpressuring of aquifer	Katz and Tek (1981); Araktingi et al. (1984); Nelson et al. (2005)
Pleasant Creek, California, USA	Not available	Gas	1972-1976	Soil gas surveys detect gas over storage area	Gas migrating up out of reservoir. Poor seal?	Jones & Drozd, 1983; Jones & Pirkle: http://www.eti-geochemistry.com/FinalVersion1.10.htm)
Sciota, Illinois, USA	Central Illinois Public Service Company	Gas	1971-1974	Testing and injection 1971-1972	Ineffective seal provided by caprock, facility was abandoned in 1974	Buschbach & Bond (1974); Coleman et al. (1977)
Pontiac, Illinois, USA	Northern Illinois Gas Company	Gas	1963-1974	Testing and injection with inert combustion gas 1970	Ineffective seal provided by caprock, facility was inactive in 1974	Buschbach & Bond (1974); Coleman et al. (1977)
Leaf River, Illinois, USA	Northern Illinois Gas Company	Gas	1968-1971	Water pump and injection tests reveal leak	Faulting, caprock leak, facility abandoned	Buschbach & Bond (1974); Coleman et al. (1977)
Chalk Creek & Coalville, Utah, US	Questar, still operational	Gas	1970s	Soil gas surveys detect gas over storage areas	Gas migrating up out of reservoirs – faults?	Jones & Drozd, 1983); Morgan (2004)
Brookville, Illinois, USA	Natural Gas Pipeline Company	Gas	1963-1966	Water pump and injection tests indicated leak from reservoir	Faulting, caprock leak, facility abandoned	Buschbach & Bond (1974); Coleman et al. (1977)
Manlove, Illinois, USA	Peoples Gas Light and Coke Company	Gas	1961-1963	Gas migrated from 2 upper reservoirs into glacial drift deposits	Reservoirs abandoned but 3rd, deeper one later developed	Buschbach & Bond (1974); Coleman et al. (1977)
Waverley, Illinois, USA	Panhandle Eastern Pipeline Company	Gas	1960s	Gas migration to shallower levels	Gas was either recycled into reservoir, or produced	Buschbach & Bond (1974); Coleman et al. (1977)
Troy Grove, Illinois, USA	(The then) Northern Illinois Gas Company	Gas	1957-1959	Gas migration from reservoir known since early development	Gas withdrawn from higher levels and re-injected at depth. Facility still operational	Buschbach & Bond (1974); Coleman et al. (1977); Hunt (2004)
Herscher, Illinois, USA	Natural Gas Storage Company of Illinois	Gas	April-July 1953	Gas found in shallow water wells within 5 weeks of operation	Injection ceased, relief wells drilled - withdraw water from periphery & injected into overlying formations pressure	Buschbach & Bond (1974); Coleman et al. (1977)
Northern Indiana, USA	Not available	Gas	Not available	Gas escape	Reservoir selected too shallow, number of water wells were affected by the intrusion of natural gas. Facility abandoned	Buschbach & Bond (1974); Perry (2005, 2007 pers comm.)

Table 9. Summary of documented incidents or problems reported at underground hydrocarbon storage facilities developed in aquifers, some of which have led to leakage and/or failure.

Table 10 (next page). Summary of documented incidents or problems reported at underground hydrocarbon storage facilities developed in salt caverns, some of which have led to leakage and/or failure.

Salt Cavern Storage						
Facility	**Operator**	**Product**	**Date**	**Description of event/fatalities/injuries**	**Reported cause/comment**	**Main reference(s)**
Incidents involving casualties/large evacuations						
Moss Bluff, Texas, USA	Duke Energy	Gas	August 19th-25th 2004	Fire & explosion, circa 360 evacuated, circa 169.9 Mcm (6Bcf) of natural gas released and burned. Fire allowed to self extinguish by burning off the remaining gas	Initial separation and breach of the 8 5/8-inch well string inside the cavern, pressure surge in well acted like 'water hammer', causing breach of corroded pipe above ground, escaping gas ignited, resultant fire caused wellhead to fail with blowout preventer successfully installed on 26th August.	Duke Energy (2004); (http://www.solutionmining.org/cmsFiles/Files /MossBluff_Part1ExecSum_&_IncidentDescrp.pdf)
Magnolia, Napoleanville, Louisiana, USA	Entergy-Koch (Gulf South)	Gas	Dec 24th 2003	Gas leak/evacuation. c. 9.9 Mcm gas released in few hours, 30 evacuated	Casing failure, crack in the casing of a well near the top of a cavern	Hopper (2004); http://www.txgt.com/sec/Pipelines%2010K%2012-31-05%20FINAL.pdf
Conway, McPherson County, Kansas, USA	Williams Midstream Natural Gas Liquids	Propane	1980s-2002	NGL's found in wells & local groundwater. 30 homes bought and c. 120 people relocated 1980-81.	Problems possibly related to effects of wet rockhead	Ratigan et al. (2002)
Hutchinson/Yaggy, Kansas, USA	Oneok	Gas	January 2001	Fire & explosion, 2 dead, 1 injured & ≥250 people evacuated	Casing failure – damaged during re-entry operations. $5.25 million punitive damages. Problem with radioactive tool during another minor incident, which was later cemented into cavern.	Allison (2001a&b), Kansas Geological Survey (2004) and website (http://www.kgs.ku.edu/Hydro/Hutch/)
Brenham, Texas, USA	Mapco	LPG (propane, butane, ethane)	April 1992	Fire & explosion, 3 dead, 23 injured, 50 evacuated, 26 homes destroyed within 1.5 miles of the explosion, damage to further 33 homes	Overfilling and valve failure. $5.4 million & $138 million punitive damages awarded	NTSB (1993a&b, 2006); Thoms & Gehle (2000); Bérest & Brouard (2003)
Mont Belvieu, Barbers' Hill, Texas, USA	Not available	Propane	Nov 5th 1985	Fire & explosion, 2 dead, 2000 evacuated	Casing failure	Bérest et al. (2001)
Mont Belvieu, Barbers' Hill, Texas, USA	Not available	Propane	Sept 17th 1980	Fire & explosion, 75 families evacuated (c. 300)	Casing failure - corrosion	Bérest et al. (2001)
West Hackberry, Louisiana, USA	SPR	Oil	Sept 1978	Fire, 1 dead. c. 72,000 bbls crude oil released	Packer failure during repair of casing	DOE (1980); Bérest & Brouard (2003)
Petal, Mississippi, USA	Not available	Butane	August 1974	Fire & explosion, 24 injured, 3000 evacuated	Overfilling of cavern	EIA (1995); Hirschberg et al. (1998); AEA (2005)
Casualty Totals				***8 dead/48 injured/c. 6110 evacuated***		
Incidents where no casualties involved but financial or property loss or closure occurred						
Odessa , Texas, USA	Huntsman Polymers	Propane/cavern	16 March 2004	100t (c. 116.5 m^3) natural gas liquids stored at 600 psi escaped from an underground storage cavern, between 8.30 pm and midnight. Ethylene being added to storage at time	Metal gasket in a wellhead flange failed, remaining gas flared off, no reported injuries	Hazardous Cargo Bulletin (June 2004); N Riley (pers com, 2007); http://www.accessmylibrary.com/coms2/summary_0286-17925865_ITM
Fort Saskatchewan, Alberta, Canada	BP Canada	Ethane	August 2001	Gas leak & fire. Established that 14,500 m^3 of ethane was lost over 8 days	Valve failure	EUB (2002)
Mineola, E. Texas, USA	Suburban Propane	Propane	1995 (1993?)	Casing leak, blow out & fire	Cavern operations led to connection between adjacent caverns, sudden pressure build-up and casing leak	Gebhardt et al. (1996); Bérest & Brouard (2003); Warren (2006); (http://www.wildwell.com/Firefighting/ff_na4.htm)
Stratton Ridge, Texas, USA	MG/Dow	Gas	1990s	Cavern failure	Leak – failed MIT	Hopper (2004)
Clute, Texas, USA	Dow Chemical Co. & S Texas Pipeline Company	Ethylene	1988/1989	$6 million of ethylene (7 million gallons) lost between December 1988 & March 1989. Escaped at 396 m depth. Collected beneath caprock to salt dome	Product escaped from casing leading to the cavern & related to movement in the salt dome? Relief well drilled and product burned off.	Kolmetz (2007: http://kolmetz.com/pdf/Ethylene-safety-incidents.pdf
Viriat, France	Not available	Ethylene	1986	Gas cloud	Rupture of separator unit	Nigel Riley (HSE 2005, pers com)
Mont Belvieu, Texas, USA	Not available	Propane	October 1984	Fire & explosion, several million $'s damage	Casing failure	Bérest et al. (2001)
Teutschental, Germany	Not available	Ethylene	March 1988	Ethylene leak & geysers.	Leak in the well/pipeline	Katzung et al. (1988); Kansas Geological Survey website (http://www.kgs.ku.edu/Hydro/Hutch/GasStorage/other.html)
Mississippi, USA	Not available	Natural gas/salt cavern	Early 1980's	Natural gas leakages, no reports of casualties	4 caverns at facility, wells of 2 found to be leaking due to poor cementing	Pirkle (1986); Pirkle & Jones (2004)
Elk City, Oklahoma, USA	Not available	Unspecified	Early 1970s	Surface eruptions, boulders thrown in air	Unspecified	Katz (1974)
Eminence, Mississippi, USA	Transco	Gas	April 1972	Lost capacity. Closed in the early 1980s, but volume had been regained and is presently operating	Salt creep – too low operating pressure range.	Allen (1972); Baar (1977; Bérest & Brouard (2003); Warren (2006)
Bryan Mound, Texas, USA	Not available	Unspecified gas	1950s	Loss of wellhead pressure	Caverns abandoned empty, 30 years later still stable	Warren (2006)
Goodyear Arizona, USA	Not available	Propane	Not available (Microseeps)	Several million cubic feet of propane lost	Corrosion hole in well casing at depth around 91 m below ground	Pirkle (1986); Pirkle & Jones (2004)
Kiel, Germany	AG	Town gas + hydrogen (60% - 65%)	1960s-present?	Lost capacity, cavern operated from 1968 to at least 1971. Town gas storage since 1971?	Salt creep	Coates et al. (1981); Padró & Putsche (1999); Bérest & Brouard (2003)
Tersanne, France	Gaz de France	Natural gas	1970-1979	Lost capacity, cavern still operational, having regained much of earlier volume loss	Salt creep	Bérest & Brouard (2003), Warren (2006)
Bayou Choctaw, Baton Rouge, Louisiana, USA	Not available	Empty cavern	1954	Collapse of overburden into the developing cavern number 7	Uncontrolled leaching operations	Coates et al. (1981); Neal & Magorian (1997)
Clovelly, Louisiana, USA	Not available	Empty cavern	Not available	Insufficient thickness of salt to act as a barrier	Cavern leaching in the salt overhang	Neal & Magorian (1997)
Napoleanville, Louisiana, USA	Not available	Empty cavern	Not available	Shale layers of salt dome side encountered in some caverns, leaving insufficient buffer salt	Salt dome edge and enclosing rocks had been encountered	Neal & Magorian (1997)

Abandoned Mine Storage						
Facility	**Operator**	**Product/type**	**Date**	**Description of event/fatalities/injuries**	**Reported cause/comment**	**Main reference(s)**
Weeks Island, Louisiana, USA	US Dept. of Energy	Oil/saltmine	1991-1994	Loss of salt mine cavern integrity at SPR facility	Sinkholes caused by leaching of salt and collapse of mined caverns	Neal & Magorian (1997); Warren (2006)
Anderlues, Belgium	Not available	Gas/coalmine	1980-2000	Leakage from coal mine. Operations ceased in 2000 due to connectivity with shallower mine levels such that gas escaped to overlying strata, very costly maintenance work on shafts and the high adsorption levels of the gas onto the coal seams	Caprock not gas tight, gas leaked out of mine workings	Piessons & Dusar (2003)
Leyden, Arvada, Colorado, USA	PSCo	Gas/coalmine	1960s-2000	Leakage from coal mine. $278,000 damages, facility closed 2001.	Caprock not gas tight, gas leaks out of mine workings	Raven Ridge Resources (1998)
Crossville, Illinois, USA	Not available	Propane/coal mine	mid 1960s - 2000	Leakage from mine. No reported casualties	Leakage from the shaft, once in overburden migration was pressure driven along faults, fractures and joints	Pirkle (1986); Pirkle & Price (1986); Jones & Burtell (1994)
Unlined rock cavern (salt?)						
Ravensworth, Virginia, USA	Washington Gas Light Company	Propane/ unlined rock cavern	24 Aug. 1973	Smell of gas reported, with gas bubbling up 300m from a residential area. Water injected around well to stem migration of gas in subsurface.	Not clear, but appears propane escaped from an underground unlined rock cavern	Berest (1989); N Riley, HSE pers com 2007

Table 11. Summary of documented incidents or problems reported at underground hydrocarbon storage facilities developed in abandoned mines, some of which have led to leakage and/or failure

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Table 12. Details of operating European UGS sites in MARCOGAZ survey of European UGS incidents to 2000 (from Joffre & LePrince, 2002).

Countries	Number of UGS sites	Number of active storage wells	Number of cumulated years of site operation	Average number of years of cumulative well operation
Austria	4	25	178	2225
Belgium	2	10	40	200
Denmark	2	25	20	250
France	13	355	294	52185
Germany	10	114	213	12247
Italy	9	307	215	33002
Spain	2	9	10	45
Totals	**42**	**845**	**970**	**100155**

Table 13. Breakdown of the information collected during the MARCOGAZ survey of European UGS incidents to 2000 (from Joffre & LePrince, 2002).

Substances involved	
Criteria	*Number of events*
Natural Gas	7
Oil	3
Solids	1
Total:	*11*
Immediate source of accident	
Criteria	*Number of events*
Storage (wells)	5
Surface process (compressor, treatment, piping)	6
Suspected Cause	
Criteria	*Number of events*
Human	3
Plant/equipment	8
Immediate Effects	
Criteria	*Number of events*
Injuries	2 (1 light) (1 severe + 2 light)
Material + release of gas	6
Not available	3
Emergency Measures Taken	
Criteria	*Number of events*
Well closed	1
Emergency plans activated	2
Checking process	1
None	1
Not available	6
Immediate Lessons Learnt	
Criteria	*Number of events*
Redundant blowout preventor installed	2
New design of installation	5
None	3 (unique accidents)
Not available	1

Table 14. Summary of main casualty figures from various oil, gas and petrochemical incidents in the USA and rest of the world. Figures relating to Office Pipeline Safety (OPS) and HSE for domestic gas supplies partly duplicate those pipeline figures in the USA summarised in Tables 15 & 16, which were the major incidents covered in NTSB reports.

Type of Incident/industry		Numbers reported dead	Numbers reported injured	Numbers reported evacuated
UFS[2]	USA – Tables 7-11	8	48	6,110
	Rest of world – Tables 7-11	1	14	c. 583 (excluding Ketzin)
Energy Supply Chain	Above ground storage tanks (world - 1951-2003; Persson & Lönnermark, 2004; Clark et al., 2001) – Table 20	778	426	>7,000
	Oil sector – (1986-2005; Hirschberg et al., 1998; Table 17)	15,695	20,276	274,746
	Gas sector (1986-2005; Hirschberg et al., 1998; Table 17)	2,233	5,210	105,011
	LPG sector (1986-2005; Hirschberg et al., 1998; Table 17)	3,701	21,120	961,776
	Railroad (USA) – Table 19 (NTSB reports; http://www.ntsb.gov/Publictn/R_Acc.htm)	9	5,441	10,452
	Petrochemical plants – world (Table 18; HSE, 1975; KAMEDO, 2000; Doyle, 2002; Marsh, 2003; Gruhn, 2003 & Macalister, 2005)	3,674	303,342	7,200
	OPS (USA) 1986-2006(part) - Transmission & distribution network & hazardous liquid pipelines (Table 15)	449	1,978	Not available
	HSE (UK) 1986-2005 domestic gas supply/use – Table 16 (figures in brackets = number from CO poisoning)	729 (576)	4,273 (3,346)	Not available

[2] UFS has been ongoing in the Canada and the USA since 1915 and 1916 respectively and in Europe since the 1950s (see section 2.2.4.2 of the main report). For storage utilising depleting oil/gasfields, incidents involving casualties have only been found reported since 1997, although migrating gas has been known in some Californian gas storage facilities since the 1940s. Although leakage has been known in some aquifer storage facilities since the early 1950s, the few casualties are reported, with 1 fatality in the 1960s and 9 injured in 2004. For salt cavern storage facilities problems and leakages have been reported since the early-mid 1950s, although casualties associated with this storage type have been found reported from 1974.

Table 15. American OPS statistics for reported incidents and casualties involving both hazardous liquids and gas supply for the period 1986-2006(part) – refer http://ops.dot.gov/stats/stats.htm).

Year		Hazardous Liquid Pipeline Operators			Gas Distribution Operators			Gas Transmission Operators	
	No. of Accidents	*Fatalities*	*Injuries*	*No. of Incidents*	*Fatalities*	*Injuries*	*No. of Incidents*	*Fatalities*	*Injuries*
1986	210	4	32	142	29	104	83	6	20
1987	237	3	20	163	11	115	70	0	15
1988	193	2	19	201	23	114	89	2	11
1989	163	3	38	177	20	91	103	22	28
1990	180	3	7	109	6	52	89	0	17
1991	216	0	9	162	14	77	71	0	12
1992	212	5	38	103	7	65	74	3	15
1993	229	0	10	121	16	84	95	1	17
1994	245	1	7	141	21	91	81	0	22
1995	188	3	11	97	16	43	64	2	10
1996	194	5	13	110	47	109	77	1	5
1997	171	0	5	102	9	67	73	1	5
1998	153	2	6	137	18	64	99	1	11
1999	167	4	20	118	16	80	54	2	8
2000	146	1	4	154	22	59	80	15	18
2001	130	0	10	124	5	46	87	2	5
2002	147	1	0	102	10	44	82	1	5
2003	131	0	5	141	11	58	97	1	8
2004	144	5	16	175	18	41	123	0	3
2005	137	2	2	170	14	38	182	0	7
2006 (part)	86	0	0	102	11	19	107	1	3
Totals	3,679	44	272	2,851	344	1461	1,880	61	245
Total no. incidents	8,410								
Total no. fatalities	449								
Total no. injuries	1,978								

Table 16. UK gas safety statistics illustrating known incidents relating to supply and use of flammable gas for the period 1986-2005 and which resulted in fatalities/injuries (based upon published Health & Safety Executive figures). The cause of incidents resulting in death or injury and which were not known (or related to suicide) are not included here. Note: the HSE fatalities refer to the gas distribution system and use of gas and not the transmission system.

	1986/ 1987	**1987/ 1988**	**1988/ 1989**	**1989/ 1990**	**1990/ 1991**	**1991/ 1992**	**1992/ 1993**	**1993/ 1994**	**1994/ 1995**	**1995/ 1996**
Total number of incidents (resulting in fatalities/ injuries)	131 (60/71)	148 (71/77)	126 (45/81)	130 (68/62)	121 (43/78)	139 (50/89)	138 (35/103)	179 (47/132)	146 (35/111)	146 (42/104)
Explosion/fire (number of fatalities/ injuries)	12/58	12/72	6/42	15/67	11/48	8/63	3/39	9/52	4/35	6/51
CO poisoning (number of fatalities/ injuries)	35/85	48/76	41/94	34/88	30/131	33/184	41/176	29/252	30/198	29/141
Totals (fatalities/ injuries)	***47/143***	***60/148***	***47/136***	***49/155***	***41/179***	***41/247***	***44/215***	***38/304***	***34/233***	***35/192***
(Based upon HSE figures – HSE, 2005, 2006)										

	1996/ 1997	**1997/ 1998**	**1998/ 1999**	**1999/ 2000**	**2000/ 2001**	**2001/ 2002**	**2002/ 2003**	**2003/ 2004**	**2004/ 2005**	**2005/ 2006 (part**	**Sub totals**
Total number of incidents (resulting in fatalities/ injuries)	143 (40/103)	164 (45/119)	151 (37/114)	174 (56/118)	174 (38/136)	154 (44/110)	114 (33/81)	127 (34/93)	147 (37/110)	151 (31/120)	2903 891/2012
Explosion/fire (number of fatalities/ injuries)	9/35	8/43	11/30	10/61	8/36	5/47	5/38	5/43	2/42	4/25	153/927
CO poisoning (number of fatalities/ injuries)	31/156	27/189	33/194	23/228	25/265	22/169	20/138	11/171	18/203	16/208	576/3346
Totals (fatalities/ injuries)	***40/191***	***35/232***	***44/224***	***33/289***	***33/301***	***27/216***	***25/176***	***16/214***	***20/255***	***20/233***	***729/4273***

Table 17. Summary of casualty figures for varying stages of the energy chain. Based largely upon the ENSAD (severe accidents) database for oil, gas and LPG production and supply for the period 1969-1996 (from Hirschberg et al., 1998).

Category	Casualty Figures - sector				
		Oil	*Gas*	*LPG*	*Totals*
Not known	Fatalities	813	22	88	*923*
	Injured	1,224	445	147	*1,816*
	Evacuees	22,000	15,710	303,900	*341,610*
Exploration/extraction	Fatalities	1,502	158	5	*1,665*
	Injured	4,453	61		*4,514*
	Evacuees	1,000			*1,000*
Transport to refinery	Fatalities	5,839			*5,839*
	Injured	883			*883*
	Evacuees	20,240			*20,240*
Long distance transport	Fatalities		987	828	*1,815*
	Injured		1,857	1,578	*3,435*
	Evacuees		82,525	3,501	*86,026*
Refinery/processing	Fatalities	399	8	164	*571*
	Injured	1,966	345	393	*2,704*
	Evacuees	23,430		161,000	*184,430*
Regional distribution	Fatalities	7,142	226	1,988	*9,356*
	Injured	11,750	936	11,523	*24,209*
	Evacuees	208,076	300	477,365	*685,741*
Local distribution	Fatalities		600	330	*930*
	Injured		1,349	7,199	*8,548*
	Evacuees		4,476	1,900	*6,376*
Heating/industrial	Fatalities		232	298	*530*
	Injured		217	280	*497*
	Evacuees		2,000	14,110	*16,110*
Totals	***Fatalities***	***15,695***	***2,233***	***3,701***	***21,629***
	Injured	***20,276***	***5,210***	***21,120***	***46,606***
	Evacuees	***274,746***	***105,011***	***961,776***	***1,341,533***

Table 18 . Significant petrochemical plant accidents involving death or injury.

Petro-chemical industry incidents						
Location	**Information source**	**Operator**	**Type**	**Date**	**Description of event/fatalities injuries**	**Reported cause**
Coliseum, Indianapolis	KAMEDO (2000)	Not available	Gas	1963	Explosion, 66 dead, 436 injured	Functional fault at refrigeration plant, gas release and explosion
Flixborough, N Lincolnshire, England	HSE (1975), Marsh (2003)	Nypro (UK)	Cyclo-hexane	1st June 1974	Explosion and fire, 28 dead, 104 injured, 3000 evacuated	Bypass pipe failed during a pressure surge, releasing product which formed a cloud that exploded (unconfined vapour cloud explosion)
Bhopal, India		Union carbide	Chemical plant - Methyl isocyanate	3rd Dec 1984	Major leak, 3500 dead, over 300000 injured	Major leak from holding tank with stored MIC overheated and released toxic heavier-than-air MIC gas, which rolled along the ground through the surrounding streets. The gas may ultimately have injured between 150,000 to 600,000 people, at least 15,000 of whom later died
Pasedena, Texas		Phillips	Chemical	23rd Oct 1989	Explosion and fire, 23 dead, 130 injured	Release of highly flammable process gases during regular maintenance operation. Vapour cloud ignited.
Deer Park, Texas		Arco Chemical Co		1990	17 dead	Not available
Belpre, Ohio	Doyle (2002)	Shell	Chemical storage	27th May 1994	Fire and explosion, 4 dead, 1700 evacuated	Fire at chemical plant spreads to nearby storage tanks, with loss of millions of gallons of chemicals
Port Neal, Iowa	Marsh (2003), Gruhn (2003)	Terra Industries	Chemical plant	13th Dec 1994	Explosion, 4 dead, 18 injured, 2500 outside plant evacuated	Explosion in ammonium nitrate process area, destroying the main seven-storey process building and creating a crater about 10 m across. In addition, the explosion broke windows of buildings over 25 km away in Sioux City and was felt 48 km away.
Deer Park, Texas	Doyle (2002), Marsh (2003)	Shell	Chemical plant	22nd June 1997	Explosion and fire, blast felt 25 miles away. 30 receive medical help.	Flammable gas leak led to fire and explosion
Wuppertal, Germany	Marsh (2003)	Not available	Chemical plant	8th June 1999	Explosion, 50 injured including 20 local residents	Human error – wrong chemical added to tank during production of insecticide
Pasedena, Texas	Marsh (2003)	?Phillips	Chemical/plastics	27th Mar 2000	Explosion and fire, 1 dead, 69 injured	Chemical reaction caused explosion and fire during cleaning
Birkenhead, UK	Marsh (2003)	Not available	Polyacrylates	16th May 2001	Fire destroyed plant, 2 injured	Major release and fire destroys the polyacrylates plant
Toulouse, France	Marsh (2003), Macalister (2005)	Total	Fertilizer plant	21st Sept 2001	Explosion, 30 dead, 2500 seriously injured.	France's worst industrial accident, but cause never established
Geismar, Louisiana	Doyle (2002)	Shell	Chemical plant	12th Feb 2002	Explosion and flash fire, 1 dead, 1 injured	Not available
Totals					***3674 dead/303342 injured/7200 evacuated***	

Railroad incident	Information source	Operator	Type	Date	Description of event/fatalities/injuries/evacuations	Reported cause
Bogalusa, Louisiana	NTSB (1995)	Vicksburg Chemical Company	Derailment, hazardous leak	23rd Oct 1995	Ruptured freight tank, 4710 people treated in hospitals, 81 admitted, 3000 evacuated	Derailment led to rupture of freight tanks and leakage of nitrogen tetroxide, forming vapour cloud
Sweetwater, Tennessee	NTSB HZB/98-02	Norfolk Southern Railway Company	Freight tank fracture	7th Feb 1996	Circumferential fracture on freight tank, 4 injured, c. 500 residents evacuated	Freight car fractured in two, releasing flammable 8000 gallons of toxic material
Tennessee Pass, Colorado	NTSB RAB/98-08	Southern Pacific Lines	Derailment hazardous leak	21st Feb 1996	Derailment, 2 drivers dead, 1 injured, 4 families evacuated	Runaway train led to derailment, rupture of freight tanks and major spillage
Selkirk, New York	NTSB HZB/98-03	Consolidated Rail Corporation	Freight tank fracture	6th Mar 1996	Circumferential fracture on freight tank, 1 injured, no evacuations	Catastrophic failure of freight tank releasing liquefied propane that ignited in large fireball
Alberton, Montana	NTSB RAB/98-07	Montana Rail Link	Derailment, hazardous leak	11th April 1996	Ruptured freight tank, hazardous chemical leak, circa 1000 evacuated, 1 dead on train, 350 treated for gas inhalation, 123 serious	Derailment led to rupture of freight tanks and spillage of chlorine and potassium hydroxide solution
Memphis, Tennessee	NTSBHZB/98-04	Illinois Central Railroad	Crack in tank	2nd April 1997	Crack and release of hazardous material, c. 150 (26 houses) evacuated from ½ mile radius	Hydrogen-assisted crack in repair weld led to release of corrosive liquid and vapour cloud
Crisfield, Kansas	NTSB/RAR-00/01 PB2000-916301	Burlington Northern & Santa Fe Railway Co.	Derailment, hazardous leak	2nd Sept 1998	Ruptured freight tank, release hazardous material, c. 200 evacuated within 5-mile radius	Derailment led to rupture of freight tanks and release of hazardous materials and fires
Louisville, Kentucky	NTSBHZB/00/02	Matlack Inc	Freight incident	19th Sept 1998	Hazardous material release, 2400 evacuated from factory, 600 remain indoors, 7 minor injuries	Chemical reaction during cargo transfer, human error.
Whitehall, Michigan	NTSB HZB/00/03	Quality Carriers Inc	Chemical reaction	4th June 1999	Chemical reaction, 1 dead, 1 injured, 11 evacuated from the plant	Chemical reaction during cargo transfer, human error.
Riverview, Michigan	NTSB/HZM-02/01 PB2002-917002	ATOFINA Chemicals Inc	Pipe fracture, gas leak & explosion	14th July 2001	Pipe fracture, releases poisonous, flammable gas, 3 dead, injuries and c. 2000 residents evacuated	Unloading line of a railroad tank car fractured and separated, with release of methyl mercaptan, a poisonous and flammable gas. Gas ignited, fire ball
Minot, North Dakota	NTSB/RAR-04/01 PB2004-916301	Canadian Pacific Railway	Derailment, hazardous gas leak	18th Jan 2002	Rupture freight tank and release of gas and vapour cloud, 1 resident dead, 11 seriously injured, 322 minor injuries, 11600 people affected by vapour cloud	Train derailed, catastrophic rupture of freight tank and release of ammonia gas and vapour plume
Freeport, Texas	NTSB/HZM-04/02 PB2004-917003	BASF Corporation	Freight tank rupture	13th Sept 2002	Rupture of freight tank, 28 injured, residents within 1.5 miles evacuated for 5 ½ hours	Catastrophic rupture of freight tank and explosion at transfer station release hazardous waste. Major damage, with loss of transfer station and buildings
Tamaroa, Illinois	NTSB/RAR-05/01 PB2005-916301	Canadian National Freight Train	Derailment, hazard material	9th Feb 2003	Derailment led to leak and fire, no injuries, 850 residents evacuated	Derailment causing leak of methanol from freight tanks, which ignited. Acid released from other tanks
Calamus, Iowa	NTSB/HZM-04/01 PB2004-917001	River Valley Corporation	Cargo tank	15th April 2003	Tank rupture, 1 dead, 1 injured	Sudden failure of cargo tank rupture releasing corrosive liquid/gas. Poor welding & inspection found.
Middleton, Ohio	NTSB/HZB-0401	Amerigas Corporation	Cargo tank	22nd Aug 2003	Freight tank failure, 5 treated, circa 100 evacuated from plant	Cargo tank fracture releasing poisonous and corrosive gas
East St Louis, Illinois	NTSB/RAB-05/04	Alton & Southern Railway Company	Train collision, hazardous release	21st Sept 2004	Hazardous materials release, c. 140 evacuated, no injuries reported	Remote control collision in yard and hazardous materials release
Pico Rivera, California	NTSB/RAB-05/02	Union Pacific Railroad	Derailment, hazardous release	16th Oct 2004	Derailment, freight tanks strike houses, circa 100 people evacuated. No injures reported	Derailment of freight cars, some hitting homes, rupturing tanks and releasing diesel fuel
Totals					***9 dead/5441 injured/10452 evacuated***	

Table 19. Significant American hydrocarbon related railroad accidents/incidents involving death or injury (based upon NTSB figures refer website).

Table 20. Above ground storage tank incidents between 1951-2003 resulting in fatalities and/or casualties (based upon Persson & Lönnermark, 2004 but including Clark et al., 2001).

Location	Date	Facility	Ignition source	Casualty Figures
Santurca, Bilbao, Spain	1967	Crude oil storage tanks	Rail tanker exploded	1 dead, 8 injured
Amsterdam, Netherlands	20/11/1969	Petrol storage tank	Not available	1 injured
Czechowica, Poland	26/6/1971	4 crude oil storage tanks involved	Lightning	33 dead (most firefighters)
Spain	1972	Gasoline storage tank	Smoking	1 dead
Ras Tamura, Saudi Arabia	22/8/1979	Aramco refinery storage tank exploded and was followed by fire	Not available	Fire burned for one day. 2 dead, 6 injured
Heide, Germany	20/9/1979	Refinery tank	Not available	1 injured
Amsterdam, Netherlands	29/9/1979	½ full storage tank in port area	Not available	1 dead, 2 injured
Cork, Ireland	1/3/1981	2 fuel storage tanks	Operator sampling	1 dead
Tacoa, Caracas, Venezuala	19/12/1982	2 heating oil storage tanks	Not available	150 dead
Bogata, Columbia	23/12/1982	3 gasoline/kerosene storage tanks	Not available	1 dead 15 injured
Corinto, Nicaragua	30/7/1983	8 oil storage tanks	Maintenance	3 dead.
Philadelphia, USA	5/10/1983	Naptha storage tank	Explosion	4 injured
Cologne, Germany	May 1985	Several storage tanks	Not available	Area evacuated.
Naples, Italy	1985	Aviation fuel storage tank	Overfilling	5 dead, 170 injured
Pretoria, S Africa	21/5/1985	Petrol tank	Not available	3 firemen dead, 7 injured
Chicago, USA	23/12/1986	Gasoline storage tank	Explosion	1 dead
Lyon, France	1987	14 tanks diesel storage tanks	Not available	2 dead
Chicago, USA	14/9/1987	Fuel storage tanks	Explosion	2 dead, 3 injured
Port Arthur, Texas, USA	1988	4 gasoline storage tanks	Not available	8 dead, 8 injured
Sines, Portugal	27/8/1988	3 tanks	Maintenance	2 dead, 3 injured
Qingdao, China	12/8/1989	Oil depot, 6 tanks	Lightning	16 dead, 70 injured
Sandwich, Mass, USA	5/8/1989	2 fuel oil tanks	Maintenance	2 injured
Oklahoma, USA	1980	3 tanks	Worker	Worker using lighter ignited fuel, 3 tanks badly damaged. 3 dead.
Port of Tampa, Florida, USA	May 1990	Gasoline tank	Explosion	1 dead
Houston, Texas, USA	8/7/1990	2 tanks	Explosion	17 dead, 5 injured
New Orleans, Louisiana, USA	1992	Crude oil storage tanks	Not available	2 dead
Texas, USA	1992	Not available	Human	1 dead, 4 injured
Wyoming, USA	8/8/1992	More than 100 tanks	Not available	4 injured
Nanjing, China	21/10/1993	Gasoline storage tank	Overfilling	2 dead
Delaware City, USA	17/7/1994	2 oil tanks	Lightning	6 firefighters injured
Ueda, Nagano, Japan	11/10/1994	Petrol storage tank explodes, igniting 3 other tanks	Not available	1 dead
Dronka, Egypt (Clark et al., 2001)	2/11/1994	Aviation fuel storage tanks	Lightening	469 residents of village killed (Ash, 2006; Clark et al., 2001)
Addington, Oklahoma, USA	11/6/1995	Crude oil storage	Lightning	2 dead
San Juanico, Mexico	11/11/1996	2 gasoline storage tanks	Faulty valve	4 dead
Hyderabad, India	Sept 1997	LPG, kerosene & petroleum storage tanks	Explosion	34 dead, 100 injured
Israel	Nov 1997	Diesel storage tank at refinery	Explosion	Diesel storage tank blew up at refinery. 1 dead
Calgary, Canada	9/8/1999	Oil, diesel fuel, jet fuel, propane storage tanks	Fire	2 dead
Kansas, USA	4/9/2001	Oil tank	Human	1 dead
Duson, LA, USA	30/11/2001	Crude oil storage tank	Explosion, cause not determined	1 boy badly burned
Dexter, KS, USA	7/6/2002	2 oil storage tanks	Explosion	1 injured
Turkey	28/7/2002	9 LPG tanks	Not available	5000 evacuated
Dunbar, S Africa	17/10/2002	Fuel storage tanks at bitumen factory	Not available	1 dead, 6 injured
Gdansk, Poland	3/5/2003	Gasoline tank	?mobile telephone	3 dead
Buncefield, Hertfordshire, UK	11/12/05	Fuel storage depot	Overfilling	43 injured
Totals				***778 dead, 426 injured, >7000 evacuated***