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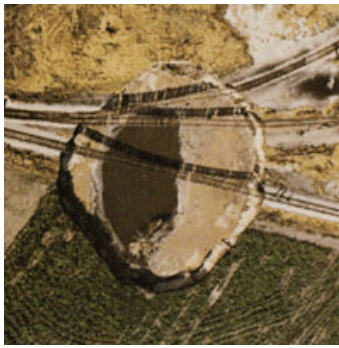

Sinkhole Formation

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U.S. DEPARTMENT OF ENERGY | NNSA

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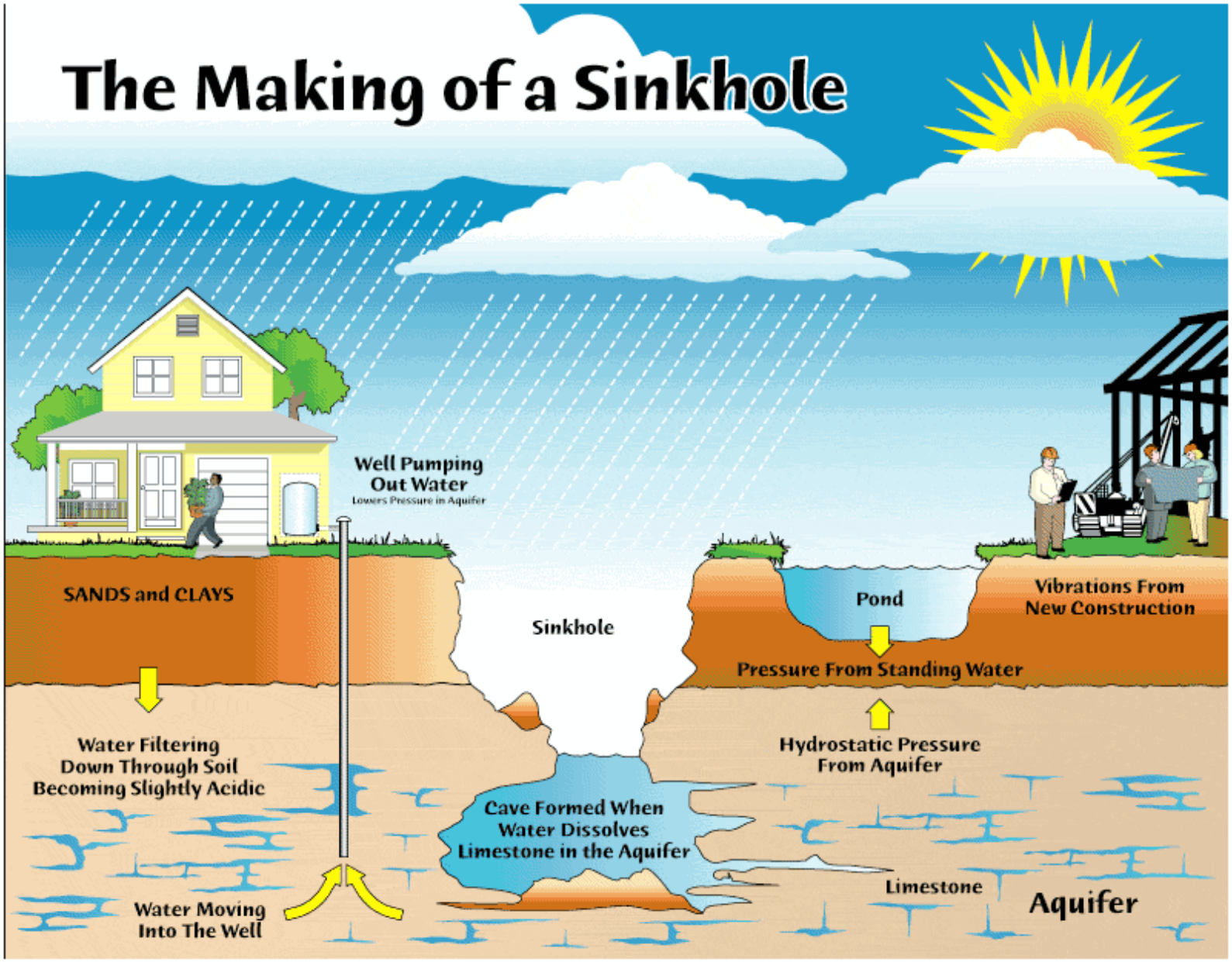
Sinkhole Overview

- A sinkhole, (also known as a sink, shake hole, swallow hole, swallet, doline or cenote), is a depression or hole in a land surface formed by the dissolution and collapse of a cavern roof
- Sinkholes are typically cylindrical or funnel-shaped
- Sinkholes may vary in size from less than a meter to several hundred meters both in diameter and depth
- They generally occur in evaporite rock regions, especially limestone, and are connected to subterranean passages
- They form gradually or suddenly
- They are found worldwide



[Used by permission from Southwest Florida Water Management District]

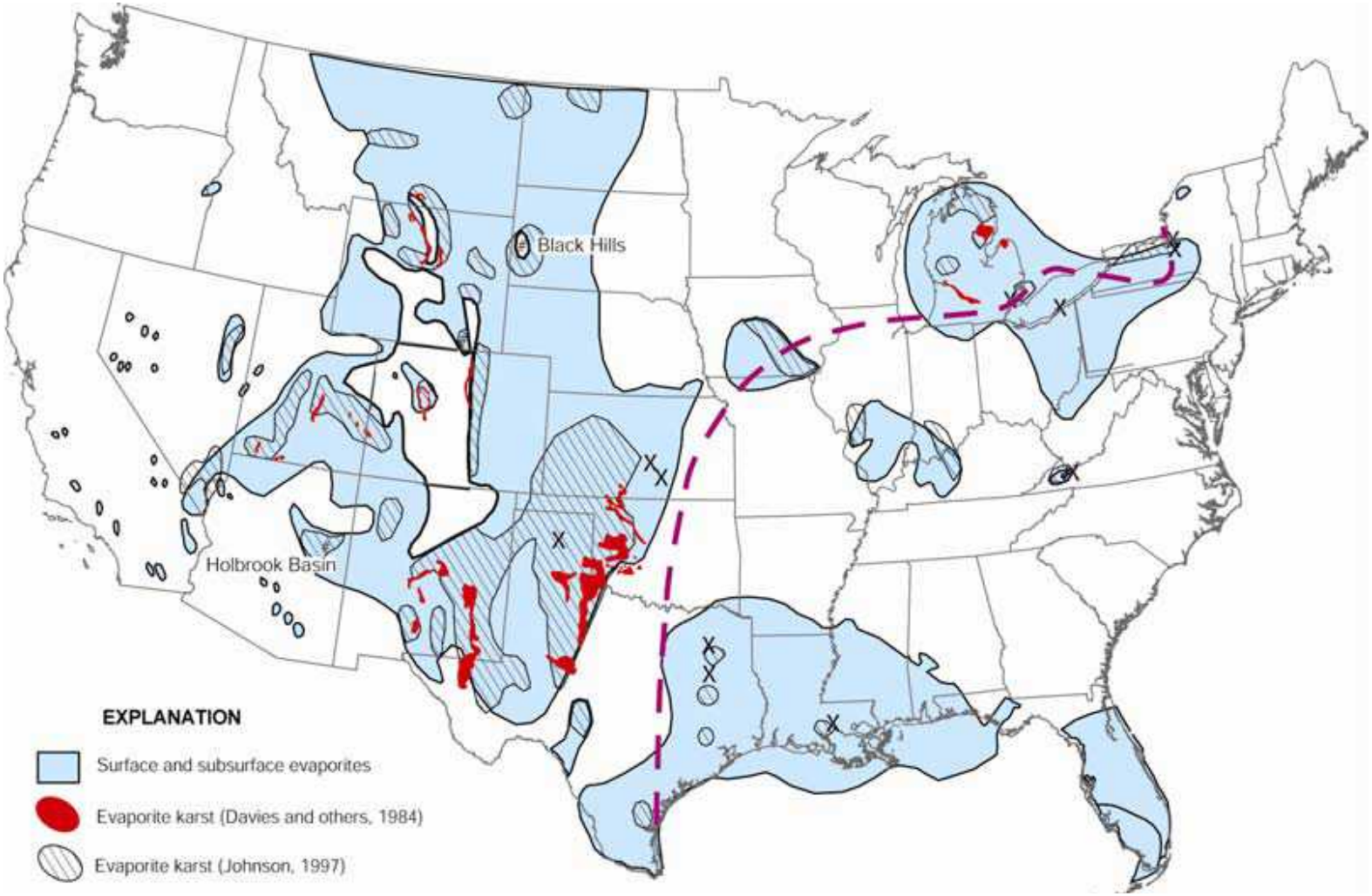
Evaporite Rocks

- Sinkholes may appear anywhere rock dissolves easily
  - Evaporite rock – a water-soluble mineral sediment – have the highest solubility of common rocks
  - Such high solubilities enable subsurface dissolution cavities or channels to form in a matter of days, weeks, or years

Mineral class	Mineral name	Chemical Composition
Chlorides	Halite Sylvite	$NaCl$ KCl
Sulfates	Anhydrite Gypsum	$CaSO_4$ $CaSO_4 \cdot 2H_2O$
Carbonates	Calcite Dolomite Magnesite	$CaCO_3$ $CaMg(CO_3)_2$ $MgCO_3$

- Evaporite rocks underlie more than 20% of the world's land surface and about 35-40% of the US's

Prevalence of Evaporite Rock in US

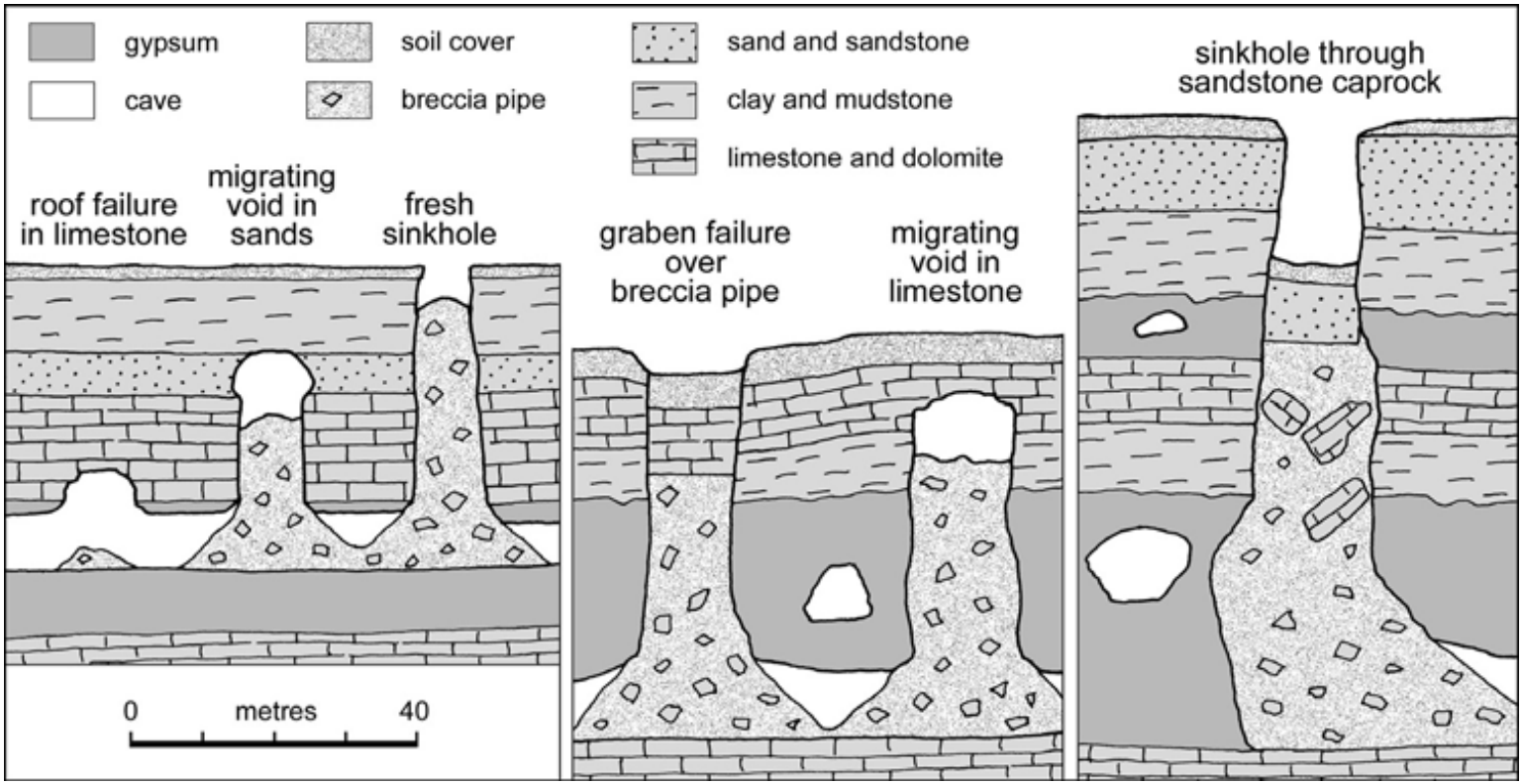


Distribution of outcropping and subsurface evaporite rocks in the United States (USGS, 2005)

Sinkhole Formation Generalized

- Sinkholes in or above evaporite rocks can form as the result of either natural processes or human activities
- In 1986, it was estimated there are more than 5000 breccia pipes (naturally formed) in North America
  - Diameters range up to 1000 m
  - Known to propagate from depths of 1200 m
- The mining of evaporite rocks and/or the drilling of boreholes into or through evaporites have accidently created a number of sinkholes in Louisiana, Texas, Kansas, Michigan, New York, and New Mexico

Sinkholes Formation over Gypsum in Ukraine and England



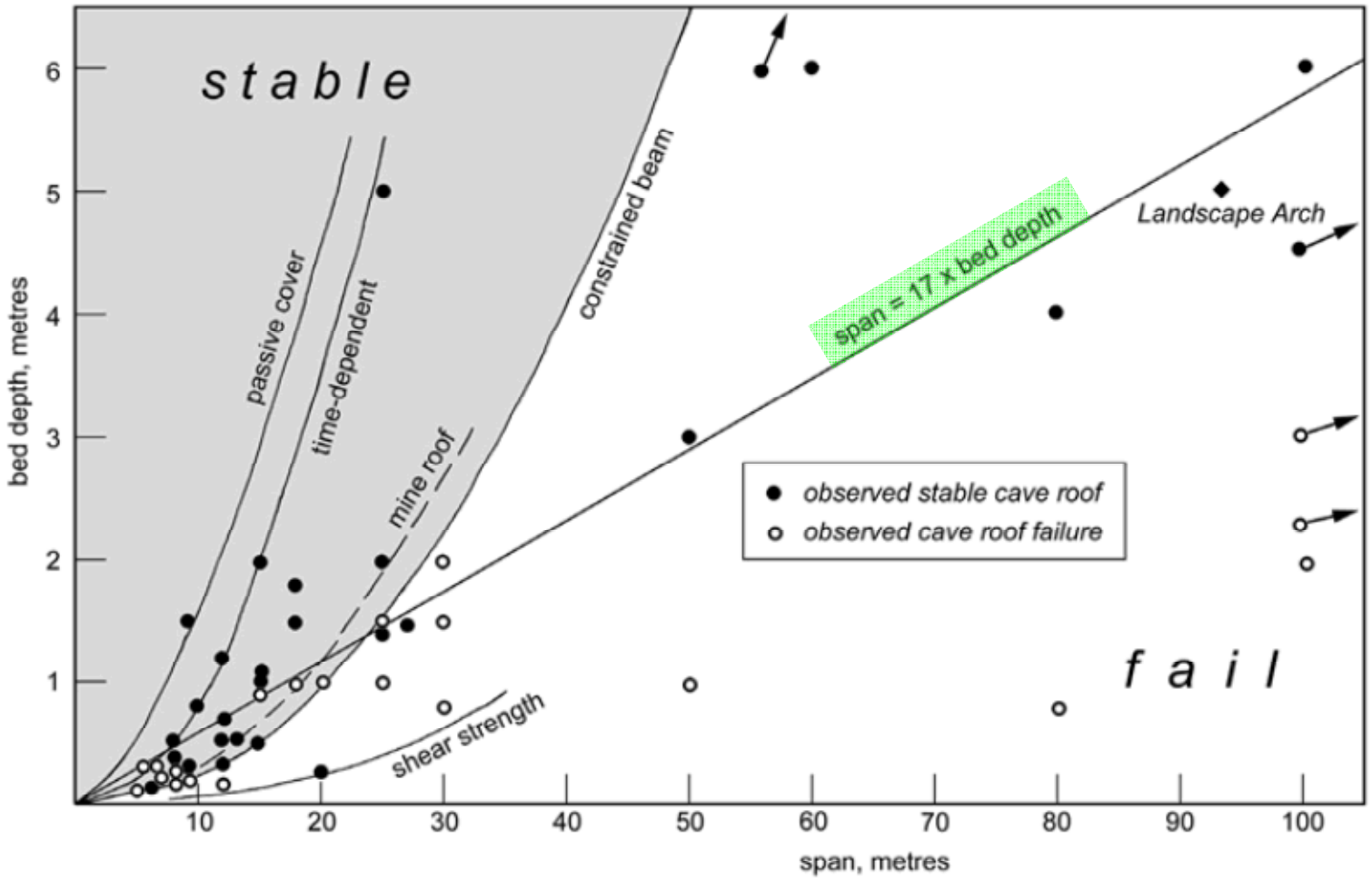
Other Examples of Sinkholes

- McCauley Sinks, Arizona – twenty sinkholes each > 100 m across and 30 m deep formed in sandstone by discrete cavity migration and breccia pipe formation. Depth to evaporite ≈ 300 m
- Meade, Kansas – Initial sinkhole 52 m across and 27 m deep. Caprock thickness ≈ 150 m
- Berezniki Potash Mine, Russian Urals – Breccia pipe migrated through 400 m caprock in 7 months (last 100 m in 12 days). Sinkhole was 150 m deep, 40×80 m across
- Crater Lake, Saskatchewan, Canada – Sinkhole 300 m across formed by ring fault. Extent of breccia pipe development at depth unknown. Depth to evaporite ≈ 900 m

Modeling Roof Failure

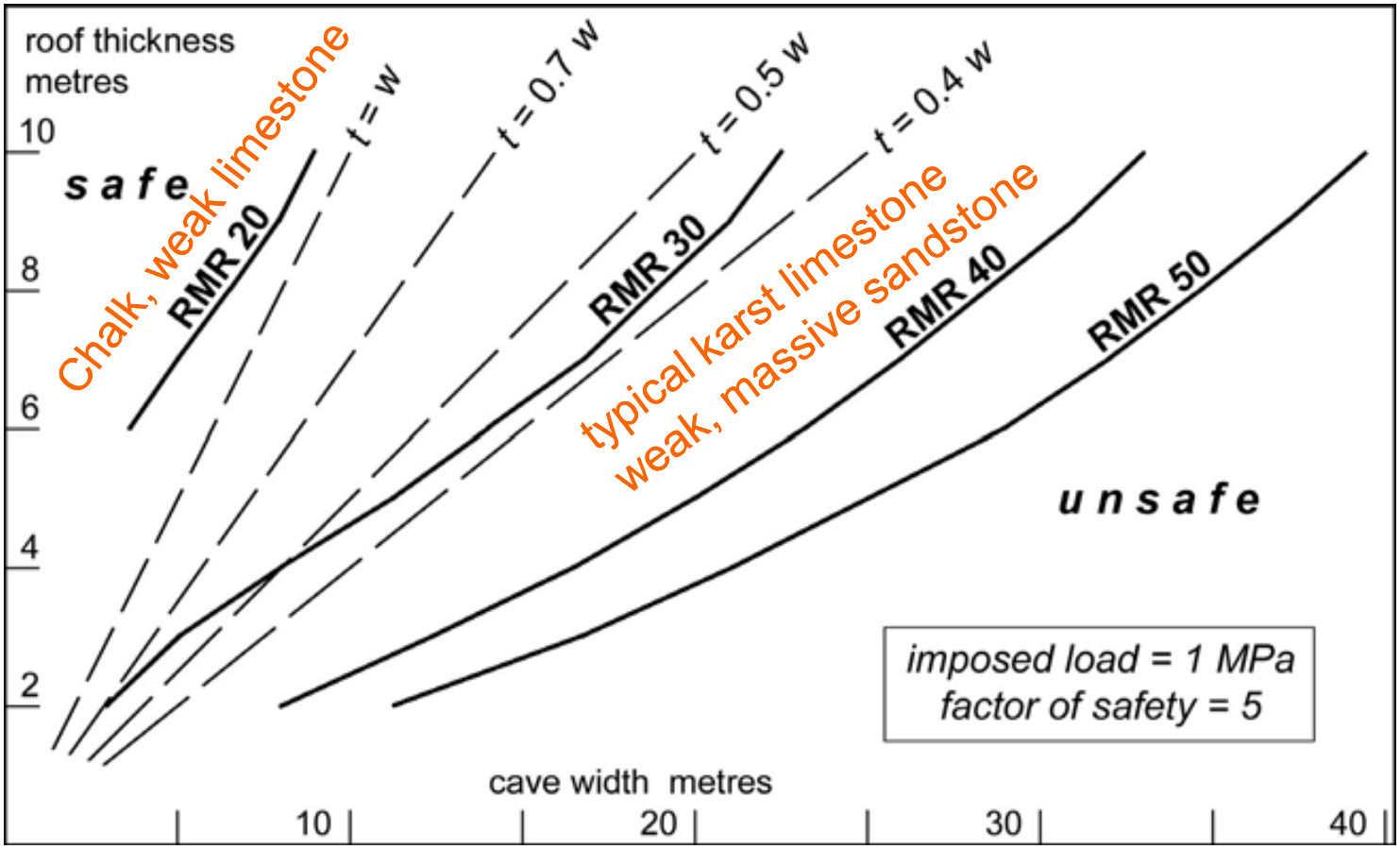
- Stability is often expressed as a function of thickness of (intact) roof, width of the cavity, rock mass strength, and stress condition in the ground
- Structural analysis of a cave roof is often treated as a beam under flexural stress or an arch in compression
  - Bearing capacities are less for rock beams than for compression arches
- Rock mass strengths are negligible in tension, but high in compression
- Rock mass strength is notoriously difficult to assess
- Any justification or refinement of the thickness-to-width cover ratios is limited in defining the rock mass strength
  - Roofs typically cannot be regarded as unbroken slabs or beds of intact rock
  - They must be regarded as a fractured rock mass

Correlation Between Bed Thickness and Cavity Span with respect to Failure of Intact Beams



Waltham et al, "Sinkholes and Subsidence," Springer, 2005, p. 54

Correlation between Roof Thickness, Cavity Span, and RMR



- Rock Mass Rating (RMR) rock strength, drill core quality, groundwater conditions, joint and fracture spacing, and joint characteristics
- Unpublished data from L. Zhengxin (cited in Waltham et al., p. 148)

Karimi-Jafari et al. (2008)

- A popular rule of thumb:

  "Cratering does not occur when the ratio between cavern diameter and cavern depth is significantly smaller than: $d/h \approx 2/3$"

Subsidence, Sinkholes and Craters above Salt Caverns.
M. Karimi-Jafari, P. Bérest, and B. Brouard.
Solution Mining Research Institute
Spring 2008 Technical Conference.

Rock Mechanics View of Caving

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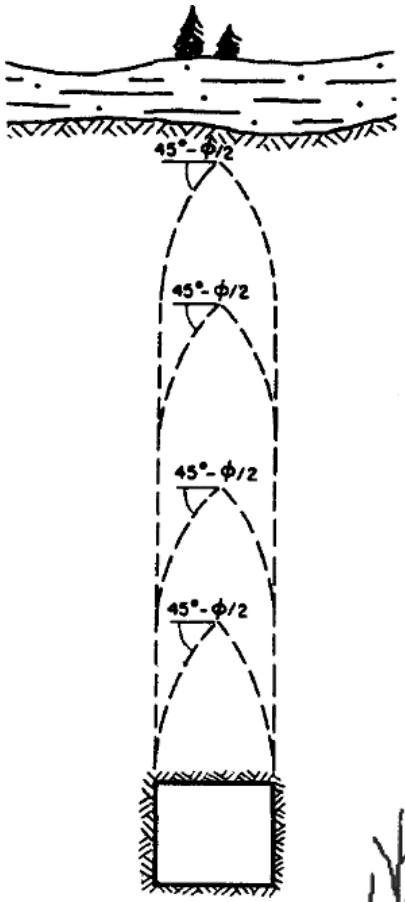
Brady and Brown (Rock Mechanics for Underground Mining, 3rd ed., 2004) identified three distinct caving mechanisms, each associated with different geological environments

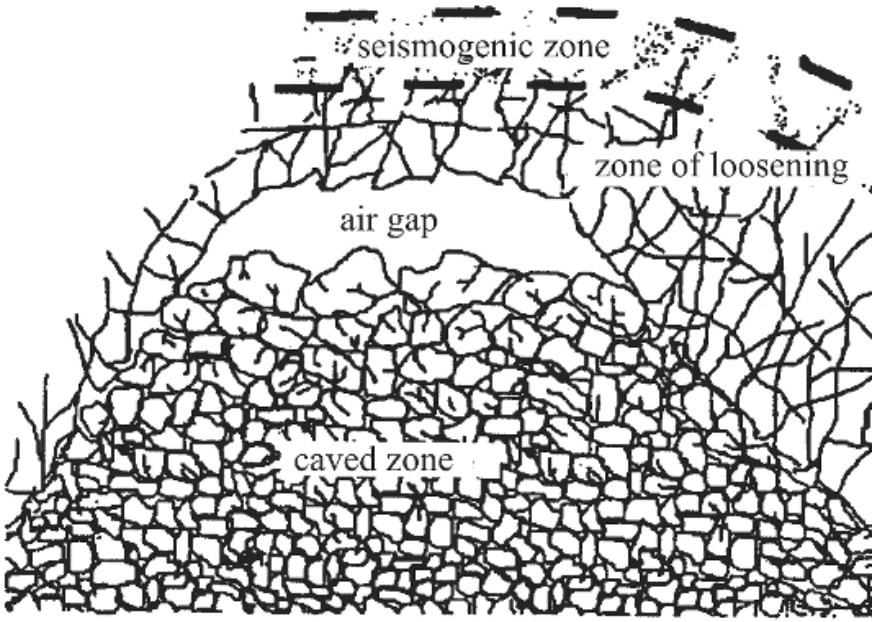
1. Progressive failure of stope roof in weathered or weak homogeneous rock
2. Block caving due to the unraveling of a discontinuous rock mass. Failure is controlled by the regular discontinuities in the rock mass
3. Plug subsidence, which is controlled by one or more structural features which provide low shear strength surfaces on which the plug of an undercut rock may slide under the influence of gravity

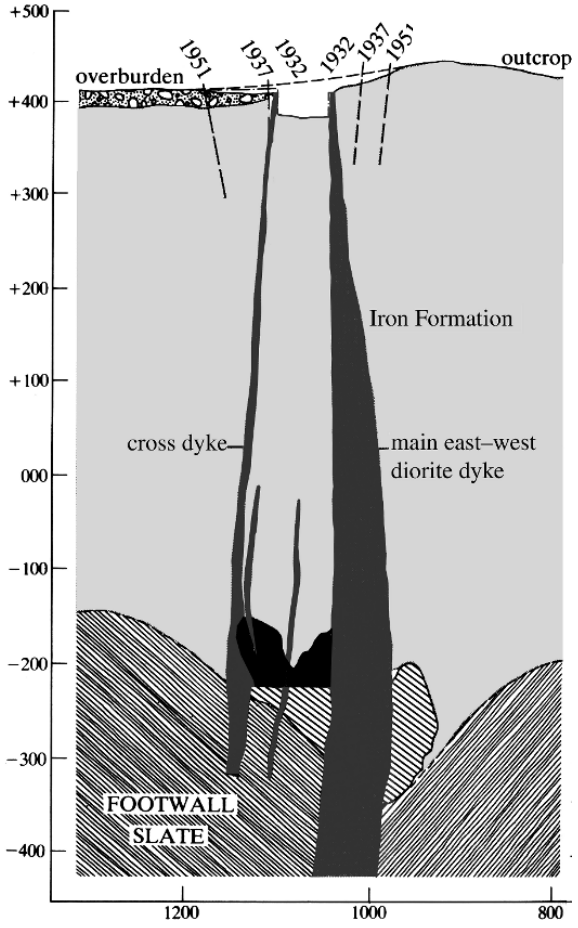
Rock Mechanics View of Caving (cont.)



Chimney failure

Block Caving





Plug failure

General Mitigation Recommendations

- Sinkholes can be prevented in most cases by not permitting unsaturated water to flow into or through the evaporite rock
- This can best be accomplished by a combination of
  - Detailed geologic mapping of the subsurface
  - Accurate assessment of the hydrogeology of the area
  - Designing engineering systems that prevent the unintended penetration of mines or cavities in the bedrock
  - Proper design, construction, and maintenance of solution mines and room-and-pillar mines to prevent roof collapse
  - Proper casing or sealing off of beds when boreholes are drilled into or through evaporite formations

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THE END

Questions?