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Preservation of Artifacts in Salt Mines as a Natural Analog for the Storage of Transuranic Wastes at the WIPP Repository

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Introduction

Use of nature's laboratory for scientific analysis of complex systems is a largely untapped resource for understanding long-term disposal of hazardous materials. The Waste Isolation Pilot Plant (WIPP) in the USA is a facility designed and approved for storage of transuranic waste in a salt medium. Isolation from the biosphere must be ensured for 10,000 years. Natural analogs provide a means to interpret the evolution of the underground disposal setting. Investigations of ancient sites where manmade materials have experienced mechanical and chemical processes over millennia provide scientific information unattainable by conventional laboratory methods. This paper presents examples of these pertinent natural analogs, provides examples of features relating to the WIPP application, and identifies potential avenues of future investigations.

Subterranean systems, such as salt mines and natural caves, are characterized by inherent micro-meteorological effects that involve slow, steady air and moisture flows that give rise to associated geochemical processes. Salt mines are particularly germane to our

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investigations as rock mechanics response and engineering material properties have led the scientific community to advocate use of salt deposits for safe disposal of a variety of hazardous wastes. Therefore, to initiate these studies of natural analogs, we have identified promising sites in Austria, Germany, Poland, and England. This paper only cites examples of analogical information pertaining to the Hallstatt salt mine in Austria and Wieliczka salt mine in Poland. This paper intends to develop an appreciation for the applicability of natural analogs to the science and engineering of a long-term disposal facility in geomedia.

Background

International consensus suggests deep geologic disposal is the best option for containing high-level and transuranic (TRU) wastes over long time periods (10,000 years and longer). The WIPP repository, located near Carlsbad, New Mexico, USA, began as a research and development project of the United States Department of Energy (DOE) and was certified on May 13,1998, by the Environmental Protection agency (EPA) to dispose of TRU waste. The WIPP is a full-scale, mined geologic repository designed to demonstrate the safe management, storage, and disposal of TRU radioactive wastes (Figure 1).

Shown schematically in Figure 2, the repository is located at a depth of approximately 2150-ft. (650-m.) in the Salado Formation, a Permian evaporite sequence. The Salado Formation is composed mainly of halite (salt) with some anhydrite and clay layers interspersed and has not been disturbed by post-depositional processes. The halite, impermeable in its natural state, is considered an ideal medium for the disposal of wastes. Further, excavation of disposal rooms creates a deviatoric stress state that plastically deforms the surrounding salt into the opening. The salt will continue to creep as long as the stress difference exists. The creep process will eventually close the storage rooms completely, as shown in the artist's renditions in Figures 3 through 6. If the rooms are undisturbed by inadvertent human intrusion, complete encapsulation of the stored material is ensured.

The WIPP is required to comply with regulations under Title 40 of the *Code of Federal Regulations* Parts 191 and 194 (40 CFR 191, 194). These regulations require that performance assessment demonstrate the ability of the disposal system to contain wastes for 10,000 years in accordance with 40 CFR 191.13. These evaluations are based on computer predictive performance models that reflect how modelers believe the waste and the repository will behave in the natural environment over time. These performance models are developed from collections of data and observations of the chemical, geological, and physical laws applicable to the site. Uncertainty of future conditions requires that numerous parameters be evaluated over a broad range of conditions using computer codes. The abilities of modeling codes to represent future conditions can be evaluated against complex natural analog systems in which the processes of interest are or have been operative.

At present the processes modeled for the WIPP performance assessment include corrosion and degradation of waste by geochemical and biological processes thought to be relevant to the repository's future behavior. These processes are conservative assumptions. Passivation of metals and encasement of waste and canisters by salt are relevant processes that are not included in performance assessment calculations with any consequence or probability of occurring. Creep closure of the surrounding formation is included in the models, but not as a means for waste preservation.

Creep closure of salt formations is one of the reasons that the National Academy of Sciences recommended bedded salt as a preferred medium for permanent disposal of nuclear waste. Salt creeps readily into deep underground openings, thereby compressing and entombing waste emplaced in the excavations. The geometric progression of room closure is illustrated as a function of time in Figure 7 a-d (Itasca Consulting Group, 1996). Compaction of room contents (as depicted in cartoons) continues until the stress-state reestablishes equilibrium. Closure is rapid at first and asymptotically diminishes, but the waste will be mechanically compressed before any potential degradation can be advanced.

Waste degradation gases can be generated by two processes: (1) hydrogen gas by anoxic corrosion of iron, iron alloys, and aluminum, and (2) carbon dioxide and methane by anaerobic microbial degradation of waste containing cellulose, rubber, or plastic. Present day laboratory experiments for the corrosion rates of metals indicate relatively rapid degradation in the high ionic brine environment of the WIPP. Metal artifacts recovered from ancient salt mines demonstrate the subjective uncertainty in the values obtained by laboratory experiments. These artifacts have been well preserved in many cases without specially designed man-made barriers. Such evidence of chemical and biological inactivity stands in marked contrast to the assumption that materials in the waste at WIPP will corrode or decay due to chemical reaction with the brine.

Natural analogs can be important information sources because: (1) laboratory experiments can last for only a few years, at most, while repository performance must be assured for 10,000 years and (2) the heterogeneity and complexity of natural systems can not be adequately reproduced in a laboratory experiment. Slow but significant reactions are only observed over the long term. Studies of ancient salt mines as an analog for the WIPP can add an important measure of confidence to the validity of waste encasement and preservation for predictive performance models, if sites of sufficient age are employed.

Sometimes, field scale tests are not a viable option for testing the validity of assumptions or predicted outcomes. In such instances other validation techniques have been acceptable to regulatory agencies. The Nuclear Regulatory Commission (NRC) rules (10 CFR Part 60) recognize that (a) evaluation of the efficacy of specific waste-isolation designs and (b) identification of processes and events significant to repository performance over 10,000 years may be augmented by supporting studies of *analogous systems* (natural analog).

Analogous systems for the preservation of non-geologic materials may also be found in various subterranean sites. Subterranean systems (human made subsurface structures like quarries, water wells, road and railway tunnels, underground aqueducts, catacombs, military underground defense systems dwellings, and natural caves) are characterized by inherent micro-meteorological effects that involve slow, steady air and moisture flows, and associated geochemical processes (especially dissolution and precipitation processes). It is well known that these processes have interacted with archeological artifacts stored within these settings for periods measured in millennia, encased almost hermetically, and preserved intact.

Subterranean systems whether manmade or natural serve as repositories that chronicle the characteristics and results of past climates, past geomorphic processes, past geochemistries, past vegetations, and other processes associated with the ancient presence of animals and humans (Gillieson, 1996).

Salt Analogs

Salt is part of man's philosophical and religious history. Salt as a commodity is interwoven with the advancement of human civilization. Ancient salt workings located in various locales around the world contain prehistoric artifacts uncovered during modern-day mining activities. Salt tunnels containing stone hammers and axes have been found at sites in Asia Minor, Armenia, South America, Austria (Hallstatt, Hallein and Halle) and near the Salt River civilization in Arizona. The Hallstadt salt mines in the Austrian Alps and the Italian mines in Lungro, Cosenza, and Etruscan Volterra supported prehistoric communities forming important centers of inland civilization.

In modern times, during World War II, the Germans took advantage of the benign underground setting of salt mines in Austria and Germany to store a large part of the looted art from conquered nations. One positive attribute of the underground (with respect to potential for long-term preservation) is a relatively constant temperature. The temperature of the Alt Aussee mine in Austria averaged 47°F in the summer and 40°F in the winter (Howe, 1946). The Merkers salt mine in Germany is shown in Figure 8.

Named after the richest location of prehistoric finds north of the Alps, the Early Iron Age (800 to 400 BC), was called the 'Hallstatt Period.' The salt mines at Hallstatt in the Salzkammergut and Dürrnberg near Salzburg in Austria began as salt mines as early as 1000 BC (3000 years ago) when the Celts were mining salt (Figure 9). Equipped with simple wooden, bronze, and iron tools, the prehistoric miners entered the mountain to depths reaching 300 meters. A review of salt mine artifacts from the Hallstatt mine and literature located at the Natural History Museum in Vienna, Austria, demonstrates that extremely good preservation of both metal and organic artifacts occur at the Hallstatt. Organic materials such as leather, clothing, and wooden tools emplaced for thousands of years are found in excellent condition due to 'preservation' in the salt (Figure 10).

In the years 1573 and 1616 in the salt mine on Dürrenberg Mountain, prehistoric miners' bodies were found. Documents state that the skin of the miners was intact and only tinged brown from the effects of salt. Another 'Man in Salt' is assumed to be present in the Hallstatt salt mine and three more bodies are thought to be located near the tunnel walls in the Dürrenberg mine. These ancient bodies and the ancient bronze and iron artifacts dating back 3000 years show the over-riding potential for preservation in a natural geologic system.

In Poland the Wieliczka salt mine is the oldest continuously operational salt mine in Europe that has a working, documented history of more than 700 years. It is believed that salt was taken out of Wieliczka as early as 3500 BC (Wieliczka Salt Mine Marketing Department, 1998). This site offers the investigator the unique ability to observe two analog types, the ancient archeological artifacts uncovered and the effects of the modern mechanical ventilation system. The mine includes 7.5 million square meters of post-excavator space on 9 levels; each between 64 and 327 meters with passages that total more than 320 km (Wieliczka Salt Mine Marketing Department, 1998). Ancient mine works, wooden structures, machines, and equipment hundreds of years old can be seen within the mine site and at the exhibition of Cracow's Salt Mine Museum (Wieliczka Salt Mine Marketing Department, 1998).

The mine is noted for the many carvings, even churches, and altars carved out of the rock salt within the mine. With the introduction of mechanical forced ventilation at the end of the last century, high summer humidity has been pulled into the mine for nearly 100 years. Many of the salt carvings are now eroding. The surfaces of the sculptures are showing the effects of dissolution such as in the 17th-century St. Anthony Chapel (Figure 11). A study headed by Glenn Cass (Salmon et al., 1996) of the California Institute of Technology has found that air pollutant deposition enhances the water vapor condensation problem within the mine. The authors found that air pollutant concentrations, such as SO_2, within the Wieliczka mine compared to those outside were removed quickly and thoroughly from the ventilation air within the mine by deposition to the interior mine surfaces. When the relative humidity exceeds 75% in the salt mine, the salt deliquesces, dissolving the surface. The introduction of pollutants, SO_2 and others, lowered the relative humidity point at which a water film began to form, by a process related to the Clausius-Clapeyron phenomenon.

The quantity and source of brine in the WIPP waste disposal areas is a major concern. Brine, if available in the waste regions after closure, will accelerate the degradation of the waste and the waste containers producing gas by-products. The Wieliczka ventilation problem indicates that a source for some brine now observed in the WIPP may be the combined effects of pollutant introduction from the surface by the mechanical ventilation system and the exhaust from underground equipment; in effect, lowering the deliquescence point at which a water film forms on the mine walls. The sorption of particulate matter and/or gases to the mine walls could increase brine quantities and lead to a false conclusion that the source of all brine is flow from the surrounding bedded rock salt. The Wieliczka salt mine offers an applicable analog useful for demonstrating that liquid water accumulation due to pollutant deposition to surfaces of the mine is a relevant mechanism for anthropogenic brine. Once the WIPP is closed and backfilled, this source for brine would be eliminated.

Conclusions

It is through the use of natural analogs that we can identify and confirm that a process occurs in nature as well as in a laboratory or in theory. Subterranean systems, such as the salt mines, provide unique readily accessible media in which to observe the effects of inherent geological processes on foreign materials placed within them. Indeed, subterranean settings, both ancient and modern, provide a source of relevant data on the required time scales, albeit analog data. Systematic investigations of the present composition of artifacts from a variety of known settings and the processes affecting their preservation would provide useful data on, and insight into, the long-term processes affecting waste emplaced in mined geologic repository sites such as the WIPP.

Both the ancient and modern sites offer valuable insights into the interactions of the complex geological systems. Adequate knowledge for geodisposal requires the integration of information from a wide variety of disciplines.

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National Archives and Records Administration item 239-PA-6-34-2, Storage in salt mine in Merkers, Germany. Photo credit: Cpl. Donald R. Ornitz, photographer, April 15, 1945.

"Wieliczka" Salt Mine, Marketing Department, 32-020 Wieliczka, Park Kinga 1, Poland, phone (0-12) 78-68-00, fax (0-12) 278-42-46, September 2, 1998.

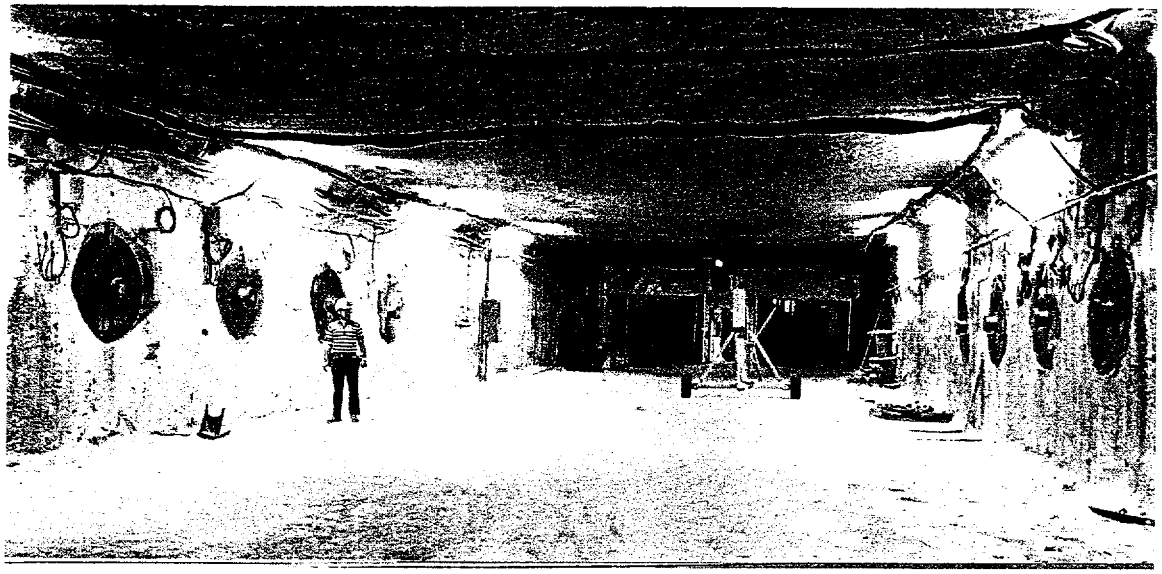


Figure 1. Room T at the WIPP. (Photo credit: Jim Conklin, in Matalucci, 1998)

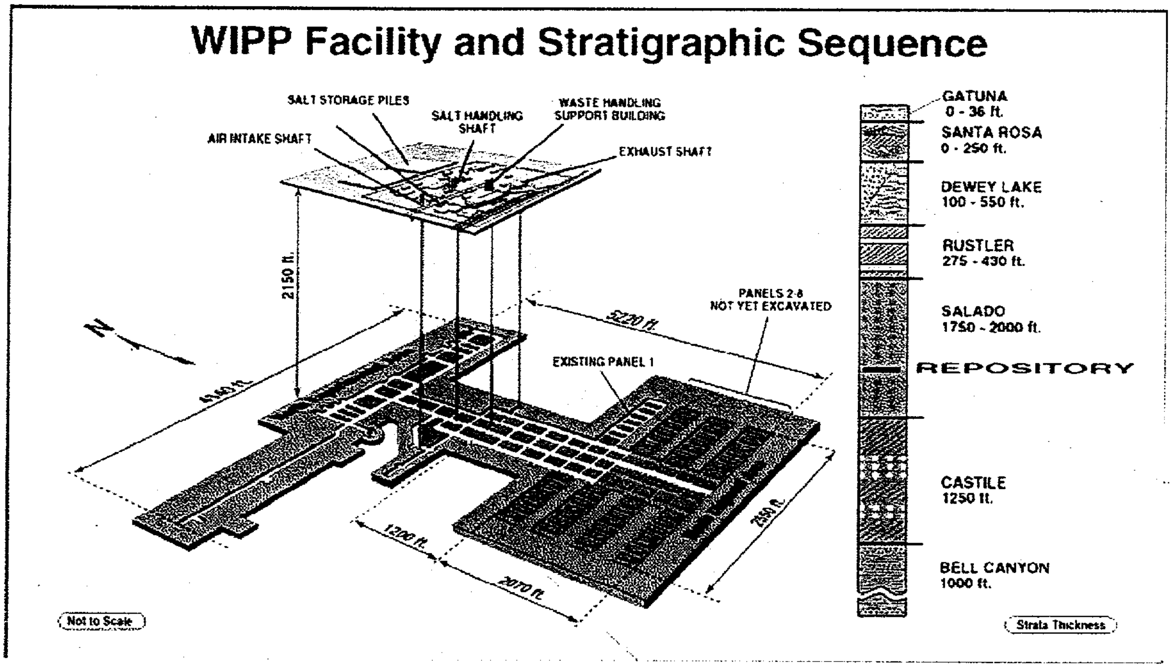


Figure 2. The WIPP Facility and Stratigraphic Sequence.

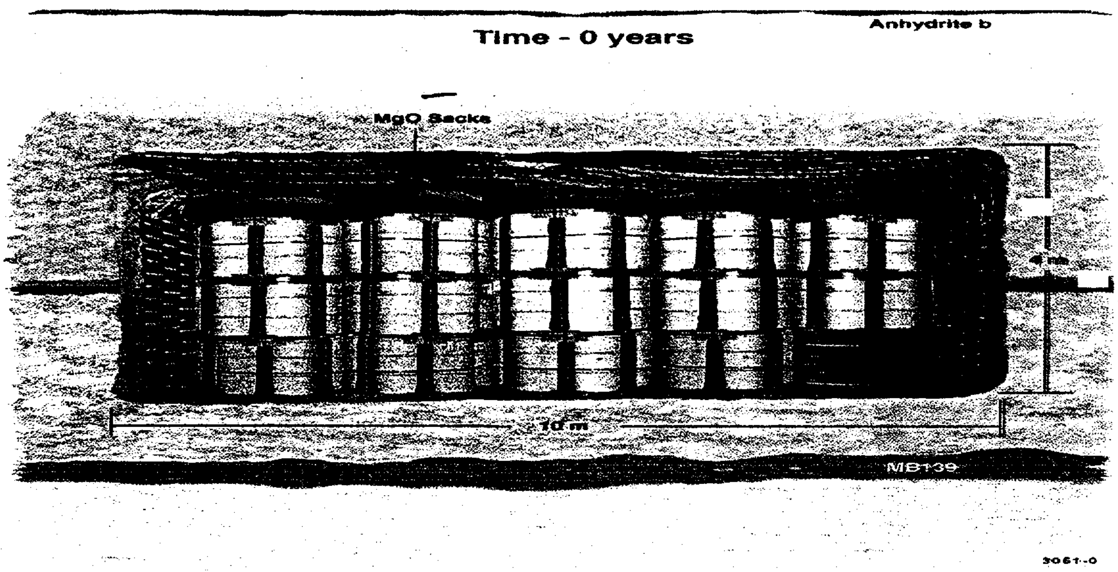


Figure 3. WIPP Disposal Room: 0 years.

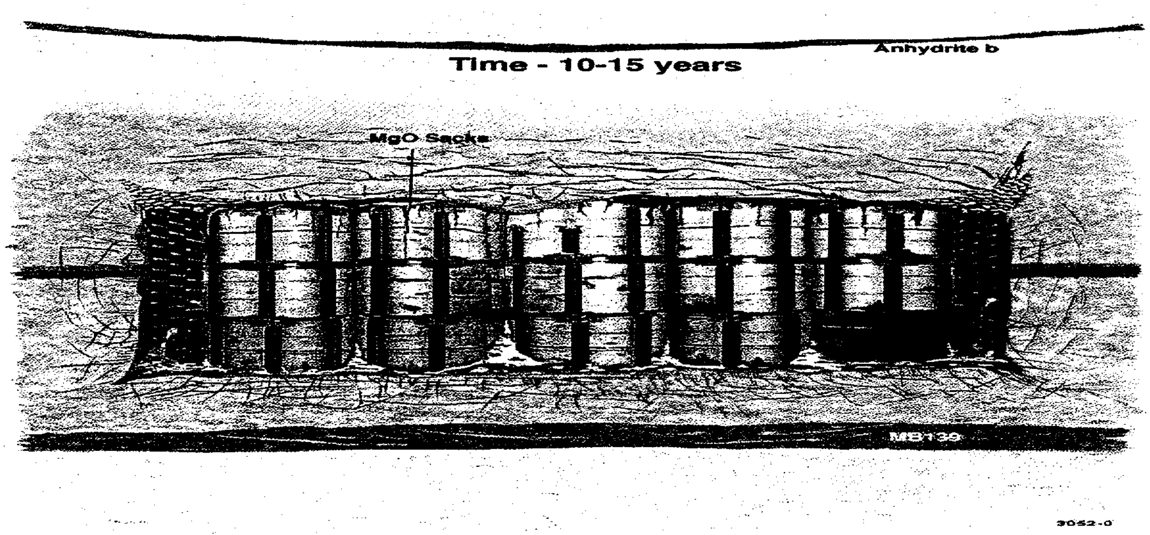


Figure 4. WIPP Disposal Room: 10-15 years.

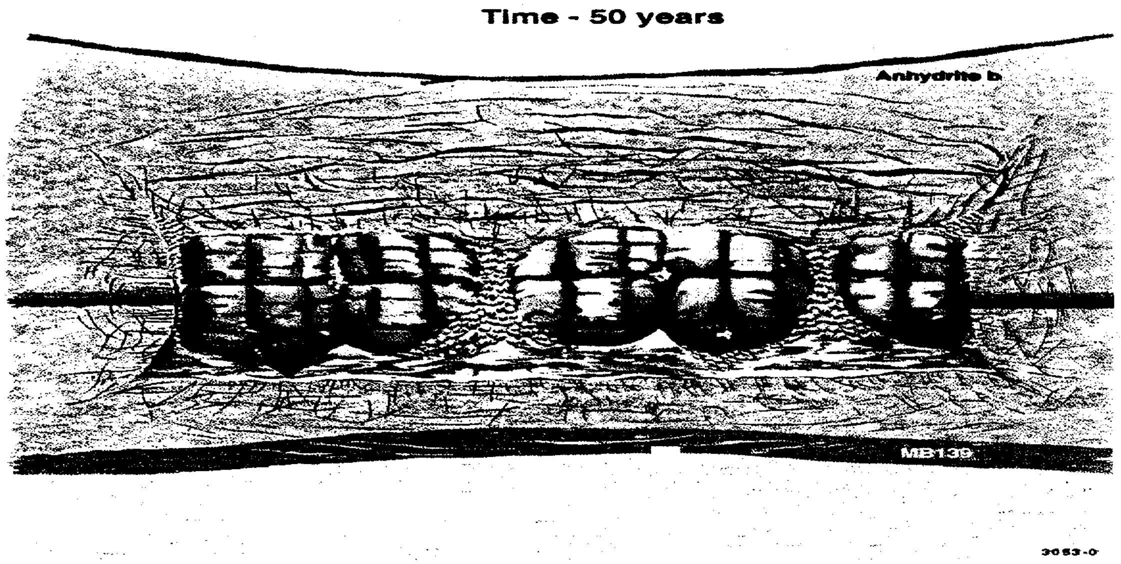


Figure 5. WIPP Disposal Room: 50 years.

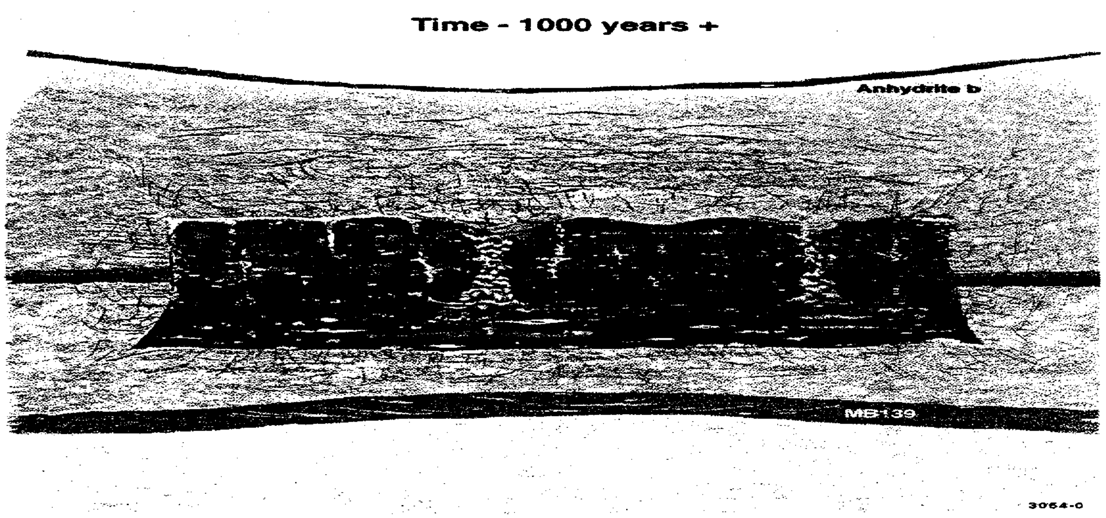
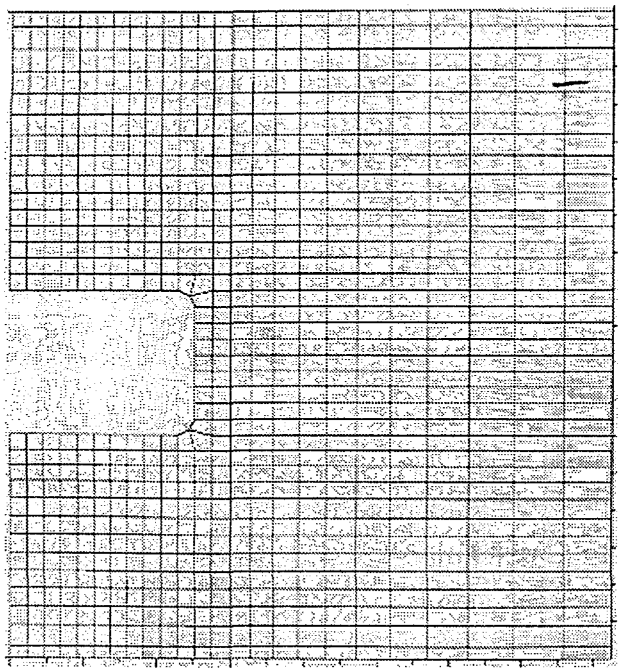
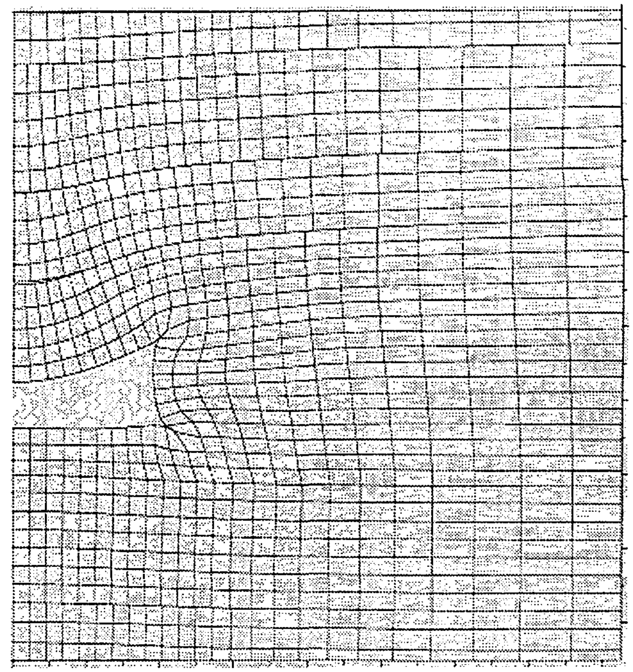


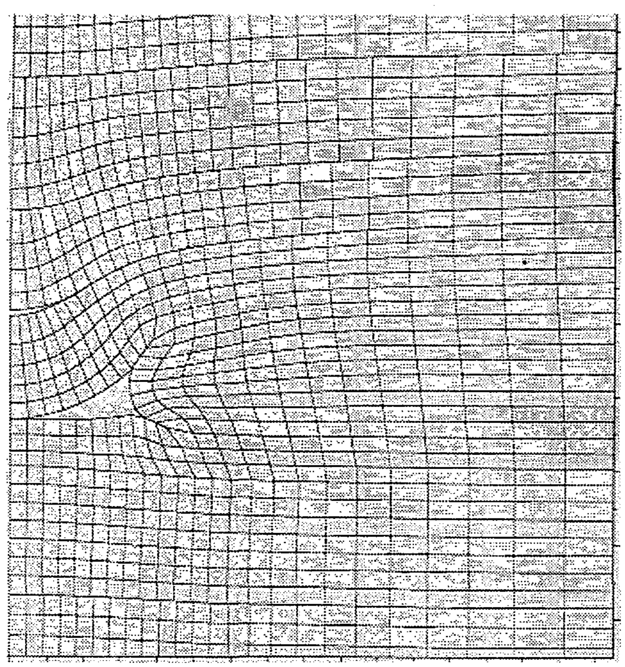
Figure 6. WIPP Disposal Room: 1000 years +.



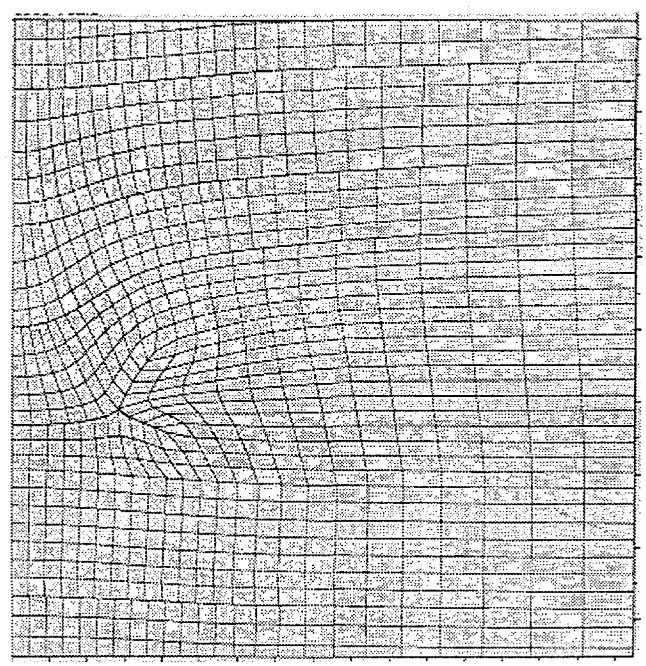
a. T = 0 Years



b. T = 50 Years



c. T = 100 Years



d. T = 1000 Years

Figure 7 a-d. Computer Model Simulation of Room Closure.

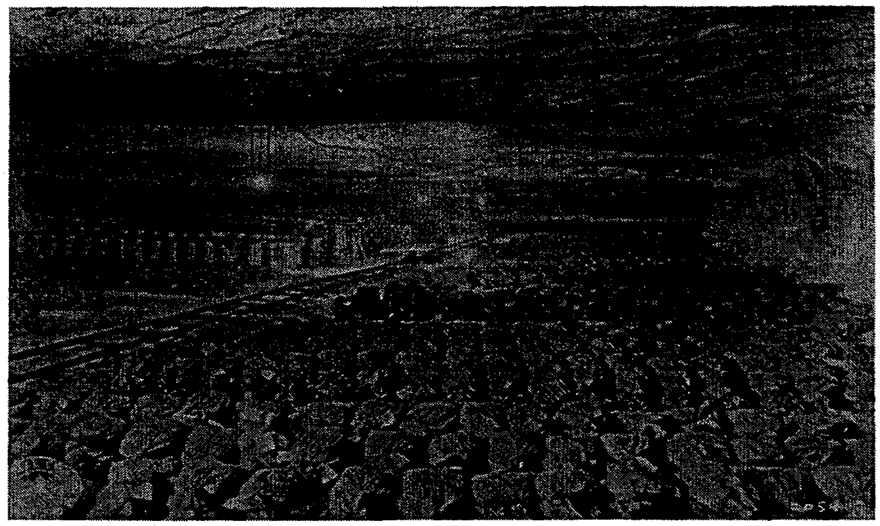


Figure 8. **Reichsbank wealth, SS loot, and Berlin museum paintings that were removed from Berlin to a salt mine in Merkers, Germany. (Photo credit: U.S. National Archives, 1945)**

Figure 9. **Map of Europe showing approximate location of the salt mines Hallstatt and Wieliczka.**

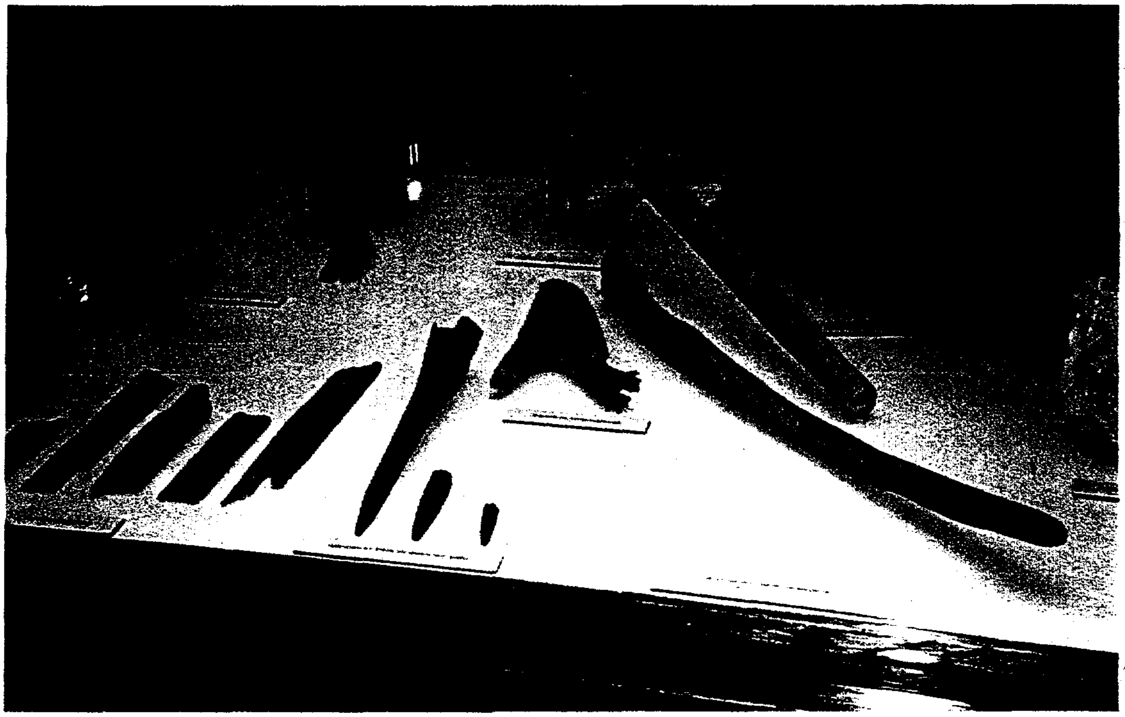


Figure 10. Vienna Natural Historical Museum (Prehistoric Section). Three bronze picks are found in the front center of the display case. The pick on the left is essentially complete. (Photo credit: Fairhurst, 1997)

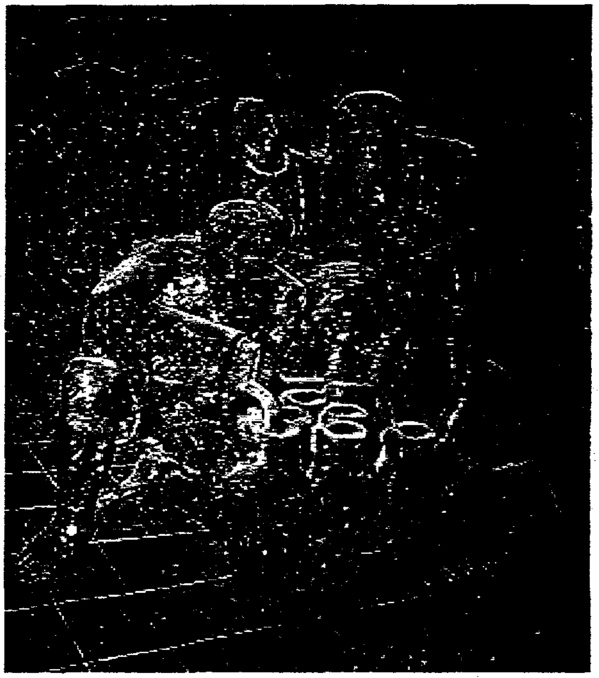


Figure 11. Salt carving in Wieliczka mine. (Wieliczka Salt Mine Marketing Department, 1998)