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Review of Geologic Factors Affecting Underground Limestone Mining in the U.S. and an Overview of Underground Limestone Mining in Nebraska

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ABSTRACT

Underground limestone mining in the United States, an increasingly important activity, is affected by intrinsic geologic factors, the important attributes of a mined limestone unit in itself (including its depositional and diagenetic history), and extrinsic geologic factors, which involve geologic entities outside the realm of that single unit (tectonics and crustal stress, joints, faults, folds, fractures, regional geohydrology, etc.).

Intrinsic factors determine the overall quality and amount of reserves of a limestone, whereas intrinsic and extrinsic factors in concert determine the design parameters and operational procedures of an underground mine. Both extrinsic factors and external factors (weather and air humidity) act upon intrinsic factors during the life of a mine, contributing to the instability of the mine's roof.

Three distinct areas of underground limestone mining can be identified in the U.S: the Midcontinent, Midwestern, and Appalachian mining regions. Although there are other, outlying districts where limestone has been mined underground, these three regions are major concentrations of mining that can be related directly to regional geologic patterns.

The Midcontinent mining region (Nebraska-Iowa-Missouri-Kansas) is characterized by shallow, single-level mines in relatively thin Upper Pennsylvanian cyclothem limestones. Strata are essentially horizontal, making mining easier in some respects, but strong stratigraphic constraints are imposed on mining not only by the thinness of limestone units, but also by underlying and overlying shales, which can present engineering problems in themselves. The Midwestern mining region (Iowa to Ohio, southward to Kentucky) can be considered the fundamental core region of American underground limestone mining. In this region, generally thicker, essentially flat-lying, relatively high-quality Ordovician-Mississippian limestones are mined. Typically, the maximum depths below land surface in these mines are greater than in the Midcontinent. In the Appalachian mining region (Pennsylvania, West Virginia, Maryland, Virginia, Tennessee, Alabama), Cambrian-Mississippian limestones are mined at maximum depths of as much as 2000 ft (610 m). Dipping strata and excessive horizontal stresses are common problems.

Underground limestone mining in the Weeping Water District of southeastern Nebraska, at the northwestern edge of the Midcontinent mining region, has become an important contributor to the state's mineral economy since 1980. The Plattsmouth-Kereford interval (Oread Formation, Upper Pennsylvanian) is mined extensively in N-S- and E-W-trending, regular, room-and-pillar mines at depths of as much as 156 ft (48 m) below the land surface. The Plattsmouth-Kereford interval is distinguished by common, large karst depressions, local solution brecciation ("popcorn" rock), and what appear to be phylloid-algae-framed carbonate mud mounds. Stone mined in the Weeping Water District is used for aggregate, agricultural lime, calcium phosphate production, and, indirectly, for Portland cement production. The single greatest geologic concern in the Weeping Water mines is

the necessity of extensive roof-bolting into the soft, weak Spring Branch Limestone Member.

INTRODUCTION

Limestone easily places among the five most essential nonfuel mineral resources consumed by modern societies. Crushed stone and portland cement, the summed production of which was valued at $15.6 billion in 2003 (U.S. Geological Survey, 2004), rely heavily, if not fundamentally, on limestone mining. The production values of these two commodities have been prominent for many years, and there is every indication that they will remain in high demand. Demands should also continue for other limestone-derived products such as agricultural lime, chemical lime, fillers, fluxes, and flue-gas desulfurizers.

The public perception of limestone mining fixates on an image of large-scale surface quarrying, even though underground limestone mining has been carried out at least since Roman times, and huge subsurface works have existed for centuries in northwestern Europe (Price and Verhoef, 1988; Edmonds et al., 1990). Underground mining in the U.S. began at least as early as the 1880s and became an important component of the nation's limestone industry by the period 1920-1950 (Dean et al., 1969; Ault et al., 1974; Scotese et al., 1981). The number of underground stone mines fell during the 1970s (Kendorski, 1998), but at the beginning of the 21st century it appears that underground stone mining will increase in importance through the next few decades, in not farther into the future. Head (1996) predicted that by 2015, 15percent or more of the total amount of stone mined in the U.S. will be mined underground.

Underground limestone mines are major capital investments that should be viewed in terms of a minimum 25-year life span, yet they can prove to be both efficient (extraction ranges as much as 70-85percent in the Midcontinent region) and profitable. Truly bold local developments in underground limestone mining, however, can accrue major risks for companies and investors if site investigation, exploration/resource characterization, and mine design programs are insufficient. Nonetheless, it can also be cost-ineffective to carry out highly detailed core drilling and sampling (Lewis and Moran, 1990), and therefore there is a very finte limit to the amount of risk reduction that can be practiced in the early stages of mine development.

The practice of underground limestone mining in the U.S. is heavily influenced by, in approximate rank order: (1) geological factors, dominated by the impracticability of surface mining in areas of thick Quaternary sediments or otherwise relatively deep carbonate rock reserves; (2) economic factors, amounting mostly to the presence or absence of aggregate local to regional market conditions favorable to a major investment of capital; (3) regulatory factors dealing with safety, health, and environment (cf. Bernardos et al., 2001), which apply to underground mining in general (e.g., regulation of diesel particulate emissions relative to mine air quality); (4) miscellaneous legal factors, such as planning, zoning (e.g., Lee and White, 1993), leasing, and the mitigation of geologic hazards (e.g., ground collapse over mined areas), as well as the limitations presented by pre-existing infrastructures (oil, water, gas lines) and other immobile assets not owned by a mining concern (cf. Marksberry, 2002); and (5) social factors, particularly public perception and aesthetic concerns about surface mining, but also including other aspects such as the characteristics of the local work force and any local history or tradition of limestone mining.

With respect to economic factors, it must be emphasized that certain mitigating conditions can spur the investigation and development of otherwise "uneconomic" subsurface limestone resources. For example, the pre-existence of infrastructure constituting a major capital investment, such as cement kilns and attendant facilities, at a site, combined with the ever-present limitation of freight costs, might lead operators to choose the underground mining of deep resources on or near that site over the far off-site relocation of surface mining operations. Likewise, if local markets for aggregate, a very low unit value product, would otherwise be dependent on long-distance transport of material from distant sources (Lewis and Moran, 1990), a sizeable investment in underground mining may be deemed appropriate. Limestone mining, especially in the crushed stone market, is strongly location-dependent (Lewis and Moran, 1990). Thus, large capital investments in mine and plant infrastructure only add momentum to that location dependency.

Intangible social and emotional ties between companies and communities can certainly influence a decision to keep operations in a given area. On the other hand, regulatory and legal factors can halt mining at any development stage or "artificially" render it unprofitable or impractical even if all other factors are favorable.

GEOLOGIC FACTORS

Geologic Factors and Mine Evolution

This paper identifies geologic factors as being the most crucial of all factors affecting underground limestone mining. Multiple geologic factors exert influence at each of the four evolutionary stages of an underground limestone mine: conception, design, operation, and post-use (figure 1). The conception stage, at which the feasibility of mining is determined, is influenced mostly by the presence or absence of a suitable limestone resource in a given area. The design and operation stages, in comparison, are affected mostly by: (1) the spatial continuation of resource quality and quantity as it has been determined by depositional and diagenetic history, and (2) aspects of physical failure in mines. The post-use stage, which includes abandonment, reclamation, or commercial utilization of mined space (as in the Kansas City, Missouri-Kansas metropolitan area), is affected primarily by long-term engineering stability.

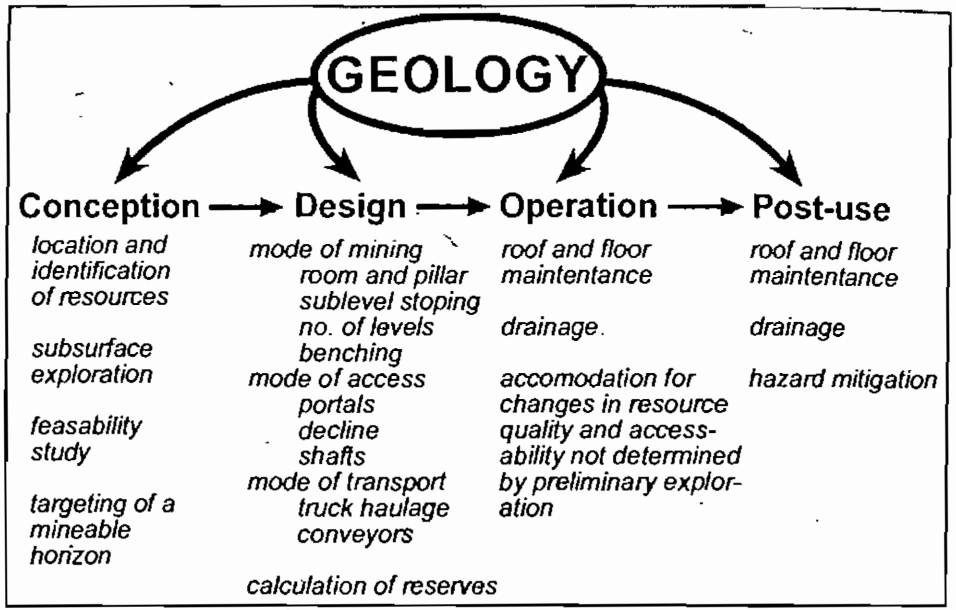


Figure 1. Evolution of an underground limestone mine and the influence of geology at all stages. Post-use includes either abandonment or utilization of mined space for non-mining uses (business, storage, etc.).

Failure in Underground Limestone Mines

Failure, to mining engineers the most significant effect of geologic factors, can occur in the three basic structural parts of an underground stone mine (roof, floor, and pillars: figures 2, 3) as a result of the interaction of specific geologic factors (jointing, stress, bedding characteristics, geohydrology, etc.). Not surprisingly, roof problems are invariably considered to be a high-ranking issue in underground limestone mine design (table 1). Roof problems emerge over time throughout the life of a mine and, disconcertingly, can continue long after the mine has been abandoned. They also exert major capital costs: the necessity for extensive artificial support of a limestone mine roof (bolting) can increase the final price of aggregate by as much as 15percent. Floor problems can influence roof stability through their influence on mine pillars. Pillars typically do not pose major problems in themselves (e.g., failure under excessive loading), but the probability of long-term stability decreases if overburden is very thick, layout is irregular, pillars are thinned by mining practices, pillars include geologic discontinuities

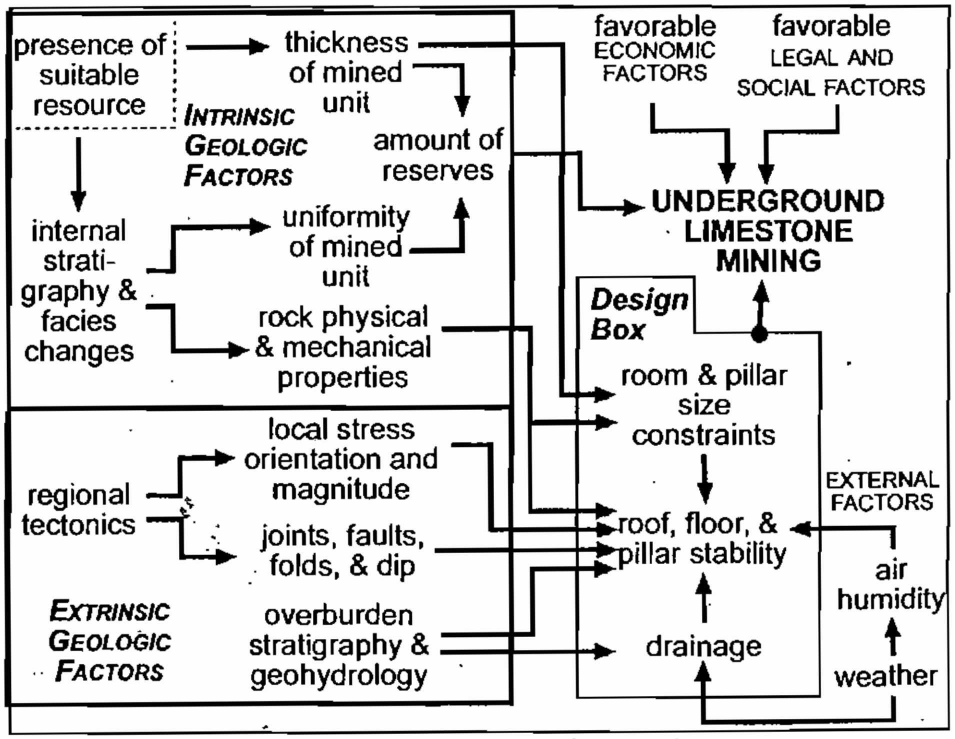
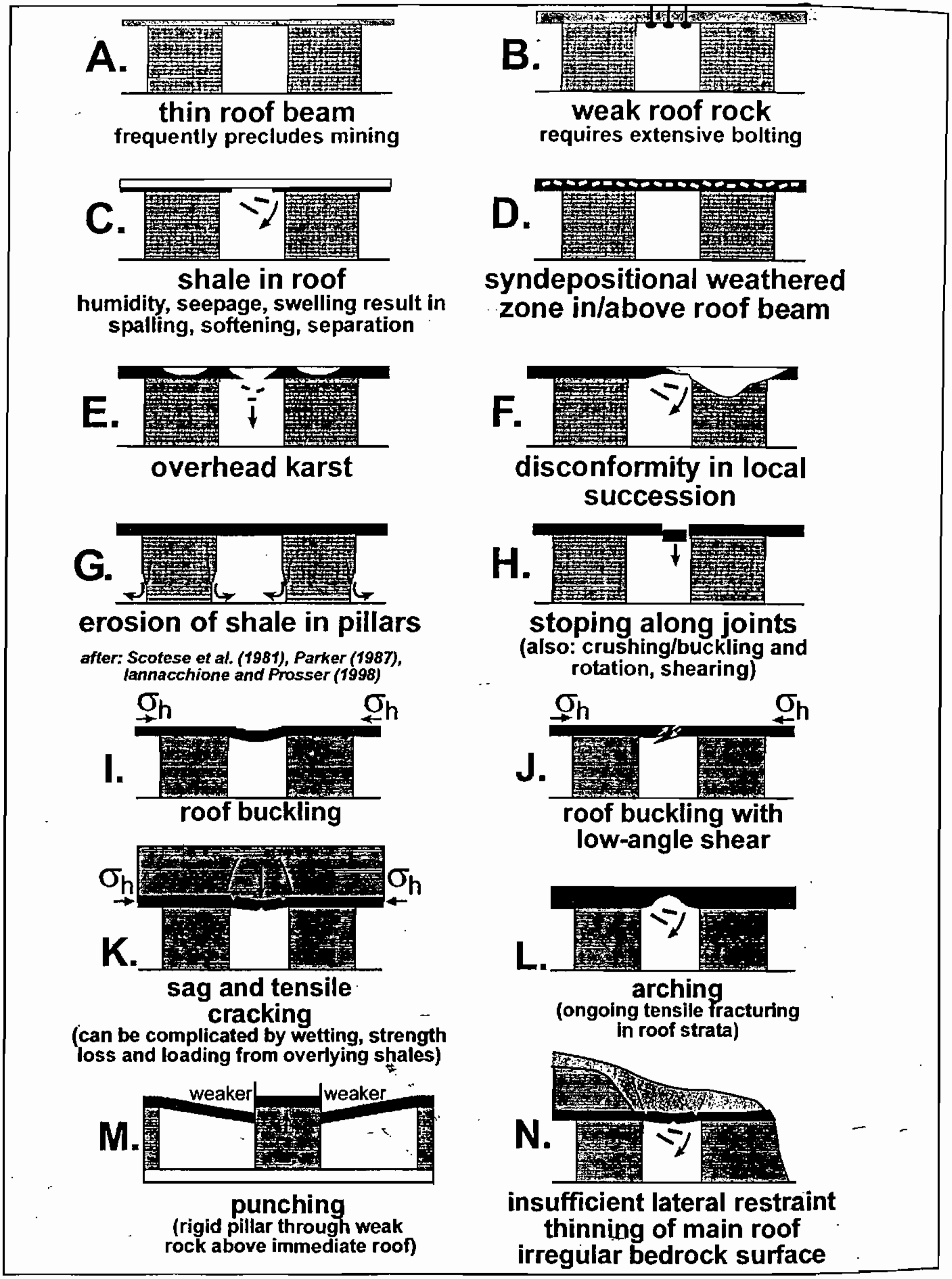


Figure 2. Graphic summary of floor problems in underground limestone mines.



A. **thin roof beam**
frequently precludes mining

B. **weak roof rock**
requires extensive bolting

C. **shale in roof**
humidity, seepage, swelling result in spalling, softening, separation

D. **syndepositional weathered zone in/above roof beam**

E. **overhead karst**

F. **disconformity in local succession**

G. **erosion of shale in pillars**

H. **stoping along joints**
(also: crushing/buckling and rotation, shearing)

after: Scotese et al. (1981), Parker (1987), Iannacchione and Prosser (1998)

I. **roof buckling**

J. **roof buckling with low-angle shear**

K. **sag and tensile cracking**
(can be complicated by wetting, strength loss and loading from overlying shales)

L. **arching**
(ongoing tensile fracturing in roof strata)

M. **punching**
(rigid pillar through weak rock above immediate roof)

N. **insufficient lateral restraint thinning of main roof irregular bedrock surface**

Figure 3. Graphic summary of roof problems in underground limestone mines.

Table 1. Responses from questionnaire circulated to underground limestone mine operators. Operators were asked to rank their three top geological concerns about particular mines. Number of total picks for a given concern are provided (total), along with number of picks for that concern as being greatest concern of three provided (greatest).

Geologic concern	total picks	greatest
A. Midcontinent Mining Region (7 responses)		
Roof conditions	6	5
Joints	4	1
Shale in mined unit	3	
Thickness of mined unit/mine height	2	1
Uniformity and quality of mined unit	2	
Humidity/moisture effect on back	2	
Depth of overburden	1	
Post-use development	1	
Amount of reserves	1	
Floor problems	1	
B. Midwestern Mining Region (23 responses)		
Uniformity and quality of mined unit	13	7
Roof conditions	10	5
Fractures/joints/faults	6	4
Depth of overburden	6	3
Mine drainage	3	
Karst	3	
Amount of reserves	1	1
Lack of surface resources	1	1
Shale in mined horizon	1	1
Horizontal stress	1	1
C. Appalachian Mining Region (13 responses)		
Dip of beds	7	4
Uniformity and quality of mined unit	4	2
Joints/faults/fractures	4	2
Roof conditions	4	1
Ventilation	2	2
Horizontal stress	2	
Bentonitic partings	1	1
Depth	1	1
Karst	1	
Floor conditions	1	
Mine drainage	1	

(dipping bedding planes, faults, joints, etc.), or if multilevel mining is practiced (Iannacchione, 1999).

Intrinsic, Extrinsic, and External Factors: Definitions

Geologic factors can be grouped into intrinsic factors, or those determining the fundamental properties of a mined limestone unit in itself, and extrinsic factors (regional supra-limestone stratigraphy, post-depositional tectonics, and geohydrology). Factors can be shown in flow-chart fashion because they are interrelated and have very specific hierarchical relationships, which are indicated by the direction of arrows in the chart (figure 4).

External factors are defined as factors that have natural origins and lie outside of the geologic realm (figure 4), yet have demonstrable relationships with geologic factors. Weather, which determines the humidity of both outside air and mine air, as well as shallow groundwater conditions on a yearly to decadal time scale, is the chief example. Ventilation in stone mines is particularly difficult because of the massive volumes of air involved and their relatively slow circulation through mine works. High humidity and the interaction between incoming outside air and mine air leads to condensation (fog banks are typical occurrences in some underground stone mines), which, by moisture addition and swell-

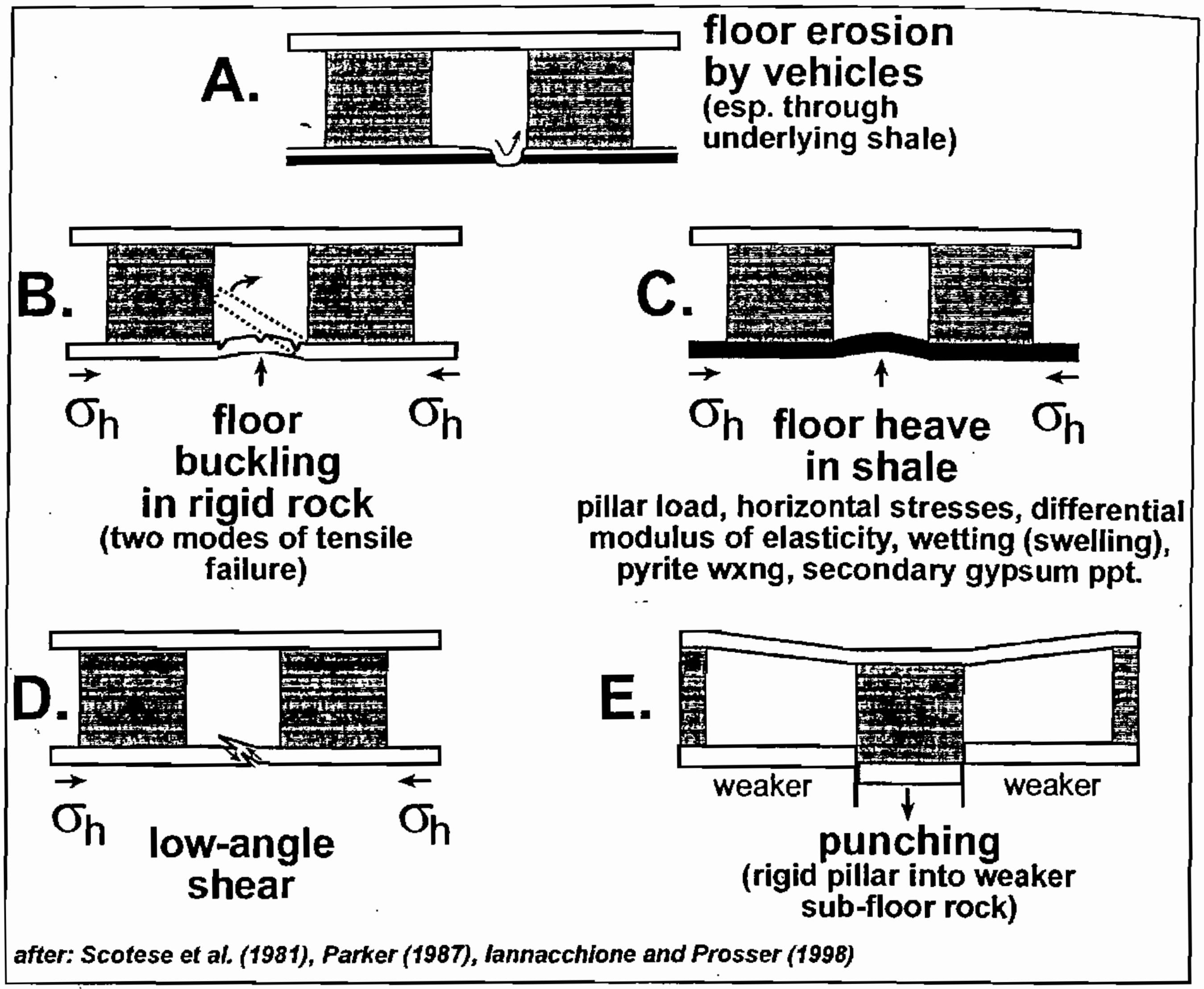


Figure 4. Flow-chart model of geological factors affecting underground limestone mining in the U.S. Note importance of "Design Box" as a "circuit" through which these factors influence the practicability of underground mining.

ing, activates planes of weakness along shale seams in the ceiling ("back") of a mine. Subsequent roof failures, typically seasonal (summer) in nature, are highly problematic in mine operation. The careful regulation of mine air, by increasing its flow or by precondensing humidity and pumping out the water thus produced, can mitigate such problems.

Extrinsic or external factors typically activate intrinsic factors. The relationships between intrinsic and extrinsic factors are particularly intimate, to the point that distinctions between them sometimes verge on the artificial. Nonetheless, distinguishing between types of factors constitutes an important problem-solving tool for rationalizing the geologic occurrence of mineable limestones, and it also assists the organization of diverse information relevant to mine design, mine operation, and case studies of mine successes and failures. In engineering applications, the effects of multiple intrinsic and extrinsic geologic factors (compressive strength, rock quality designation, discontinuities, geohydrologic conditions) are collectively considered in the Geomechanics Classification or Rock Mass Rating System (RMR) of Bieniawski (1989).

INTRINSIC FACTORS

Presence of a Suitable Resource

The sum total of local to regional geologic history determines the existence of a specific limestone deposit that satisfies a particular demand: in essence, this is the "time dimension" of the geologic factors scheme (figure 5). The geologic history of a deposit is immense in magnitude, and it may seem inappropriate to relegate it to the status of an intrinsic factor, but in the actual exploitation of resources, the net effect of history is distributed

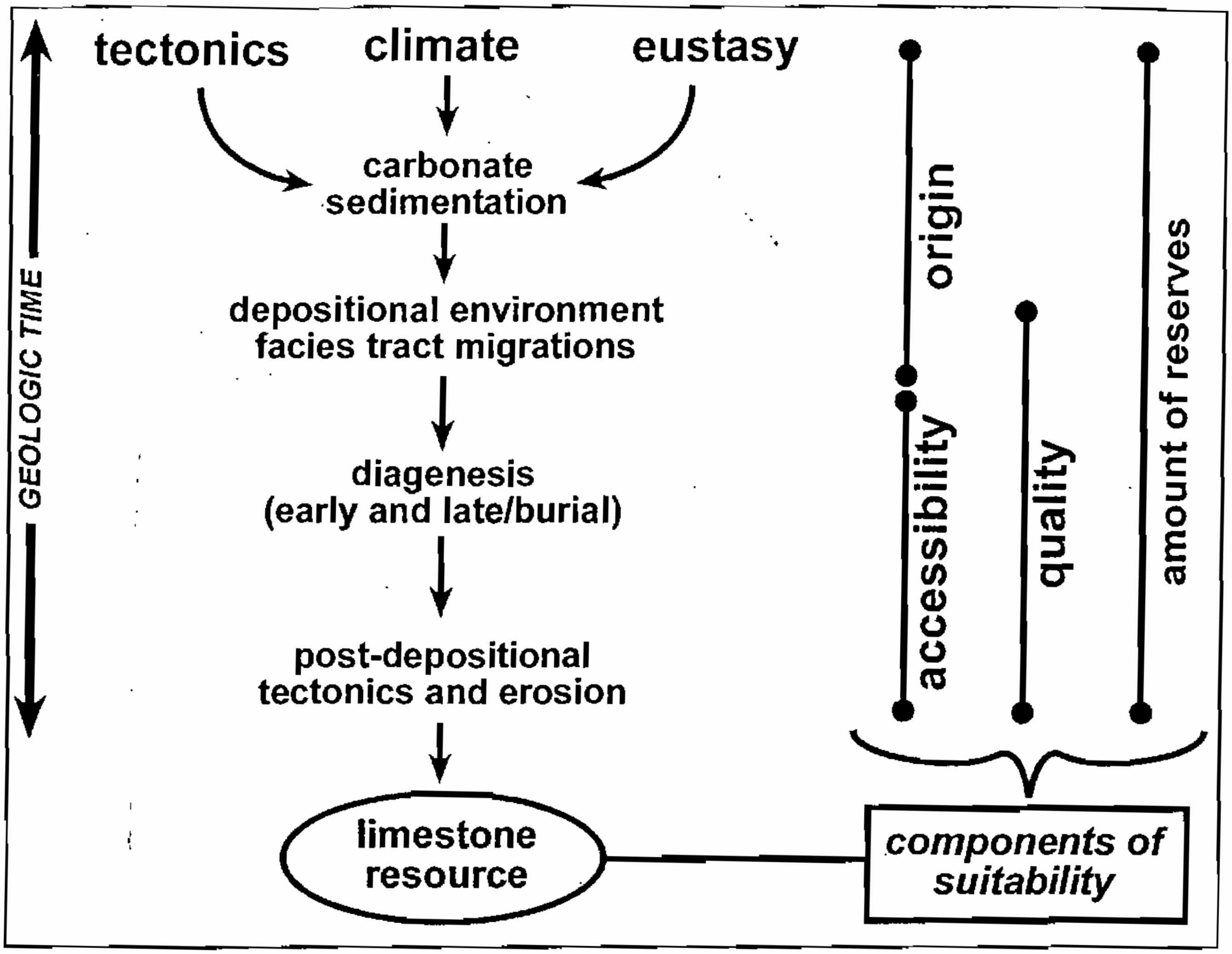


Figure 5. Time dimension of limestone resources. Hierarchical events and processes over geologic time determine the suitability of any given limestone deposit for particular uses.

very diffusely, and its role is usually considered to be more implicit than explicit. Moreover, understanding the geologic history of a limestone requires the application of esoteric disciplines (sedimentology, petrography, sequence stratigraphy, diagenesis, geochemistry, and tectonics) that, although ultimately important, are peripheral to the immediate concerns of economic geology. Important geohistorical considerations will be summarized only in a cursory fashion.

At a very large scale, there are definite trends in the modes, geographic extent, and eventual volume of carbonate deposition over geologic time. These trends result from plate tectonics, eustatic sea-level change, global climate change, and biotic evolution. The Phanerozoic evolution of continents and ocean basins (including changes in their sizes, shapes, bathymetry, and distribution) greatly reduced the total area of global shallow-water tropical shelf carbonate deposition from its Cambrian maximum, but this reduction in area is most prominent after the Permian (Walker et al., 2002). Thus, the Ordovician-Mississippian succession in the cratonic and craton-marginal terrains of the U.S. is distinguished by common and relatively thick limestones and dolomites (Bunker et al., 1988; Collinson et al., 1988; Fisher et al., 1988; Johnson et al., 1988; Milici and DeWitt, 1988) because optimum or near-optimum climatic (latitudinal), physiographic, and oceanographic conditions for carbonate deposition existed there during much of that time. During the Pennsylvanian, in contrast, numerous sea-level cycles deposited multiple, thin, mudrock-bound limestones in the interior of North America (Heckel, 1986, 1994).

Global accumulation rates of carbonate sediment did not vary significantly during the Phanerozoic and net carbonate accumulation in cratonic settings was controlled mostly by regional subsidence rates (Wilkinson et al., 1991), a conclusion instrumental in explaining the widespread nature of Paleozoic carbonate strata on the North American craton. By the late Jurassic (~150 Ma), however, the diversification of carbonate-producing plankton and the effect of falling eustatic sea-level on the position of carbonate compensation depth (CCD) had forced a permanent global shift to a system in which the usually deeper-water deposition of planktonic ooze. This shift became increasingly important in the global carbonate budget and resulted in the widespread Cretaceous deposition of chalky limestones (Boss and Wilkinson, 1991), which have been mined underground in northwestern Europe but not in the U.S.

At a smaller and more applicable scale, the facies compositions and geometries of individual limestone units, as well as the stratigraphic distribution of weathering surfaces that developed during a depositional cycle or between successive cycles (resulting in "preweathered" limestone), diagenetic trends, and intercalated clastic strata can be usefully rationalized by sequence stratigraphy (see Harris et al., 1999). Sequence stratigraphy aptly demonstrates the essential interplay of sea level rise and fall at 10^4-10^6 annum scales and local to regional facies tract migrations in the determination of limestone characteristics (e.g., Smith and Read, 1999). Sea-level-dependent facies tract migrations determined whether carbonate sediment was deposited at a specific place during a particular time interval, as well as its texture and many, but not all, aspects of its fabric and cementation (matrix content, mud or neomorphic microspar; biological binding or framing, as in reeflike organic buildups, bioherms and biostromes; grain content, packing, and orientation; intergranular, fenestral, shelter, and framework porosity: see Tucker and Wright, 1990, p. 1-27). Early diagenesis is also extremely important in determining the eventual properties of limestones. Carbonate depositional cycles on cratons are estimated to be only 3-30percent complete with respect to their actual representation of short-term geologic time (Wilkinson et al., 1991), implying that most of the total time represented by a package of strata is actually in the form of depositional hiatuses during sea-level falls (subaerial exposure), sediment bypass, and similar events. The significance of this "missing time" is great because it is the locus of some of the diagenesis that is more-or-less unique to carbonate rocks (Harris et al., 1999): dolomitization, dissolution, recrystallization, and certain types of porosity (moldic, channel, vug, cavern, stylolitic), and cementation. These processes have a large, and perhaps underappreciated, impact on the quantity, quality, and physical properties of mined rock. Thus, the enlightened application of sequence stratigraphy to the economic geology of limestone resources, now essentially unheard of, could prove to be very beneficial in the future.

Rock Physical and Mechanical Properties

Rock physical and mechanical properties, in this sense, include bedding characteristics, density/specific gravity, hardness, compressive strength (which range widely, about 28-207 MPa or 4,000-30,000 psi: Scotese et al., 1981), tensile strength (also wide-ranging: 3.5-14 MPa or 500-2,000 psi: Scotese et al., 1981), modulus of rupture, modulus of elasticity (usually high, as much as 41.4 GPa or 6×10^6 psi: Iannacchione et al., 1998), point-load strength, etc. Physico-chemical and geotechnical properties considered specifically in the engineering use of mined materials (alkali-silica reactivity and deleterious chert content, freeze-thaw susceptibility, slaking behavior) and abrasion resistance fall under this category, because from a geologic standpoint they are genetically related to the other properties. Even color, as in the case of limestone mined for high-brightness products, should be included. All of these properties develop as a result of the depositional and diagenetic history of limestones discussed above, which together produce important rock characteristics such as clastic sediment (particularly clay mineral and iron oxide) content, porosity, degree of cementation, microfabric, mineralogy (calcite vs. dolomite), isotropy or anisotropy in overall rock fabric, and degree of pre-existing dissolution or weathering.

Rock mechanics are important in a general sense in underground limestone mining (for example, horizontal stresses measured in-situ in mines may exceed limestone tensile strength and be of the same order of magnitude as compressive strength), but a specific consideration of planes of weakness (particularly bedding and joints) in the entire rock mass is of much more immediate importance in mine design (Scovazzo, 1996). The bedding characteristics of roof-beam strata constitute a very important consideration in mine design. Ideally, strata making up the roof beam, as well as strata directly above, should be thickly-bedded carbonate rock, in order to minimize loading of the roof by anything but gravity (concept of an immediate roof: Merrill, 1957; Obert et al., 1960). Bedding planes and indeed any other features (fractures, faults, fissures, joints, slickensides) that make rock inhomogeneous and anisotropic also decrease the strength of the roof rock (Merrill, 1957; Obert et al., 1960; Iannacchione et al., 1999): in fact, according to Merrill (1957) and Obert et al. (1960, p. 23), the ratio of mine opening/roof beam span to the thickness of beds forming the roof roughly determines the stress regime in the system. Usually, bedding planes in limestone roof rock produce roof beams 6-39 inches or 15-100 cm thick, and the minimal thickness of competent limestone normally necessary for safe roof is, in fact, about 100 cm (Iannacchione and Prosser, 1998; Iannacchione et al., 1999). Roof-beam deflection ("sagging") occurs when a beam separated by bedding planes deforms under stress within a mine (Iannacchione et al., 1999).

Even slight variations in the geometry of bedding planes affect mine design. A wavy or irregular shale seam (or any other bedding surface) chosen as a roof line makes the actual driving of mine headings much more difficult than would a smooth, horizontal bedding plane. Horizontal strata exactly parallel to the top and bottom of mine openings are the ideal case for mine development. Tectonically deformed strata (dipping or folded beds, see discussion below), however, can be highly problematic. Secondary bedding surfaces may have an angular orientation to mine openings, regardless of the overall regional dip of the entire limestone unit containing them. Cross-strata and higher-order (bounding) surfaces, if present in limestone being mined, promote the development of loose rock as roof slab falls (where cross-strata meet the roof line at an angle greater than the horizontal), and as scale on the mine walls (Grau and Prosser, 1996). Other non-horizontal depositional surfaces (e.g., beds with primary depositional dips off of mud mounds, platforms, banks, reefs, and even the syndepositional draping and compaction of strata around early-cemented carbonate phases) are likely to present similar challenges in underground mining, although their potential roles have not been investigated thoroughly in published literature.

It must be stressed that the bedding phenomenon in carbonate rocks is more complex than it is in siliciclastic rocks. Bedding in carbonates can certainly be of primary depositional origin alone, but much of what is perceived as bedding in limestones and dolomites is either primary bedding strongly enhanced by post-lithification pressure dissolution, or secondary bedding actually created by pressure dissolution. Simpson (1985) called attention to stylolitic pseudobedding, which can be seen to cut across primary bedding. Both stylolites and unsutured dissolution seams (Wanless, 1979) must determine a large amount of the bedding, parting, and stress response of limestones. Thin clastic partings or stringers, or seams (ranging from "hairline" thickness to a few centimeters) delineate bedding in many limestone deposits, and range in origin from the concentration of thin bands of insoluble residue along dissolution planes to true pulses of clastic deposition during a period of overall carbonate deposition. Petrographic observations indicate that many such partings could have originated from a combination of both processes.

Merrill (1957, p. 3) observed that the weakening of mine-roof rock over time ("time deterioration") included "a change in the number of layers" in roof rock under stress. It is logical to assume that stylolites and dissolution seams, previously identifiable only in thin sections, are the progenitors of such post-excavation stress responses, and Merrill's (1957, figure19) time series of stratascope photographs seem to support this explanation. Therefore petrographic examinations, while perhaps requiring outside geologic expertise and an additional small economic expenditure, could greatly augment a mine-design program.

Aside from design concerns, some mine operators also express the opinion that the presence of regular bedding planes through a limestone unit, whether primary or diagenetic, makes mining easier in certain applications.

Internal Stratigraphy and its Lateral Facies Changes

The internal stratigraphy of a mined horizon and its lateral facies changes influences the quality and mineable tonnage of a limestone resource as well as the procedure of underground mining. Limestone units that are unbroken by significant beds of shale, bentonite, or other siliclastic sediment throughout an economically-mineable horizon (one that can be mined at an opening size sufficient for optimal production relative to regional market conditions) have the greatest theoretical value in the production of lime-specific products (cement, fillers, quicklime, agricultural lime, chemical lime, etc.).

Mine operators maintain that laterally-consistent shale seams in the upper part of a mined horizon, can be desirable in the establishment of a roof line because they facilitate excavation of the mine's back or ceiling. Scaling (removal of thin sheets of rock susceptible to falling from the roof), however, is a necessity when multiple thin shale seams or interbedded thin shales and limestones are present at the roof line.

Shale strata in the base of a mined horizon or just below it will cause problems in a mine's floor if not treated properly. Softening and shrink-swell associated with wetting (if drainage is insufficient) cause floor heave, and pyrite oxidation, perhaps facilitated by microbes, followed by sulfate-mineral (gypsum or epsomite) precipitation (Parker, 1987) contributes to overall degradation of the floor. Poor mining procedures, such as excessive floor erosion by vehicles and "robbing" the floor for stone, exacerbate floor failure and should be avoided. Excessive settlement occurs over Argentine Limestone Member mines in the Kansas City (particularly Lenexa, Kansas) area if insufficient limestone is left in the mine floor, allowing the shales of the underlying Lane Formation to deform by creep, which eventually leads to roof failure and collapse (T. Wanless, personal communication, February 2, 2002). Such shales also slake rapidly in water and lose strength rapidly (Zipf and Schmuck, 1996).

Chert occurs frequently in Paleozoic limestones. Small amounts of chert distributed throughout the rock mass, or in discrete, thin horizons have a negligible effect on production and product use, although excess wear on crushing equipment has been attributed to chert nodules. Larger quantities of imperfectly crystalline, reactive chert can render a limestone deposit unsuitable for aggregate applications because it contributes to alkali-silica reactivity (ASR) in the finished concrete.

Lateral facies changes include in-mine transitions from desirable limestone into: (1) limestone with a higher siliciclastic sediment content or, even worse, purely siliciclastic sediments (such transitions include minor disconformities: cf. Kendorski, 2002); (2) preweathered and brecciated facies, especially those associated with paleokarstification; and (3) facies-dependent dolomitization (see Tucker and Wright, 1991), a well-documented phenomenon that needs to be considered in rock-resource assessment. Lateral facies changes have proven to be mildly problematic in the least and a mine-limiting factor at the most. In the Midcontinent, the Pennsylvanian Raytown Limestone Member shows localized lateral increases either in the number of discrete shale seams or in the amount of detrital clay minerals dispersed throughout the rock matrix. This increase translates to a rise in the alkali content of cement kiln feed that may be intolerable under specified operating conditions. In the Bethany Falls Limestone Member, also in the Midcontinent, the same type of trend appears to decrease the durability of stone mined for aggregate. These two cases represent more "stealthy" manifestations of facies change that may not be predicted unless a comprehensive program of geologic and geochemical analysis precedes mining. Other facies changes occur at a large scale and are immediately obvious. In the East Fairfield Coal Company's Petersburg Mine at Petersburg Ohio, for example, sandstone "horsebacks" or small channel fills, appearing lateral to and below the uppermost strata of the Vanport Limestone, cause a roof-stability problem (T. Miller, personal communication).

Thickness of Mined Unit, Uniformity, and Amount of Reserves

Phanerozoic cratonic carbonate rock cycles, which average about 8 m (26 ft) in thickness (Wilkinson et al., 1991), a figure perhaps not coincidentally similar to the scale of headings in many mines. Again, sequence stratigraphy can ultimately be called upon to account for a major part of the total mineable thickness of limestone deposits, because it relates rates of deposition, erosion, sea-level rise and fall, and accommodation space, whereas compaction, mostly a syndepositional phenomenon itself, accounts for the rest.

Accounting for extraction ratios, optimal ranges of equipment size, and, generally the return on capital investment, a general rule for the absolute minimum profitable thickness in modern underground limestone mining is around 15 ft (4.6 m). Many mines, especially outside of the Midcontinent region (see discussion below), have works that operate in a mineable horizon two to seven times as thick. Obviously, the thickness of a mined unit directly determines the amount of reserves available. The uniformity of desirable characteristics in a mined unit is a consequence of depositional history (lateral facies distribution and migration), diagenetic history, and weathering history, as discussed previously.

EXTRINSIC FACTORS

Extrinsic factors are factors that do not emerge simply from the on-site depositional history or properties of the mined rock, but nonetheless have major impacts. Regional tectonism determines the magnitude and orientation of stress fields, as well as local geologic structure (joints, faults, folds, and dipping strata), either of which can render a mining operation infeasible.

Overburden Stratigraphy and Geohydrology

The stratigraphy of rocks and sediments above the level of a mine affects mining in several different ways. The presence of competent rock, particularly strong and thickly-bedded limestones, directly above the immediate roof of a mine supports the load of overlying materials, and where such strata are absent, roof failure is much more likely (figure 3A-H; see discussion below). If there are thick, soft shales and sandstones, as well as unconsolidated sediments, above a targeted limestone horizon, the construction of a truck-access decline with optimal grade and geotechnical stability may be prohibitively expensive (cf. Marksberry,

2002) or technically impossible, even if the depth to limestone is not excessive. In mines that lack valley-side access or where the construction of a decline is problematic, the amount of overburden determines the depth of shaft excavation that will be necessary to reach a target horizon, and therefore in large measure determines the scale of initial capital investment.

The main effect of thick overburden is that it is the driving force behind underground mining in the first place. As stripping ratios exceed the generally accepted 2:1-3:1 ratio range, mining is all but forced underground if capital is available. Thick overburden definitely increases the load on mine pillars, but effective design typically compensates for such effects during the operating life of a mine. The thinning of overburden and "loss of lateral restraint" (Parker, 1987; figure 3N) atop mine works at hillsides or approaching outcrops probably contributes to roof collapses more readily (Kendorski and Hambley, 1992).

Most limestone mines in the U.S. are relatively dry mines: drainage problems within a mine horizon are most likely to occur when mining has to be carried out downdip in steeply dipping or "rolling" strata. Groundwater in overburden can facilitate roof failure when it facilitates weathering roof-rock weathering, reduces the strength of soft or preweathered roof rock, or seeps through joints or fractures in a mine roof (Hasan, 1996). Drainage out of overlying strata, even if it has no effect on a mine's roof rock, can promote falls around portals (particularly with freeze-thaw cycles) and generally create a nuisance. Sprayed concrete and mesh, attached by rock bolts or pins, can minimize rock fall around portals, while surface drains, sumps, and pumping systems can control drainage.

Local Stress Orientation and Magnitude

Definite extant patterns in stress produced by plate tectonics have been documented across the eastern half of the U.S., where most underground limestone mining has been carried out (actually, stresses are even more prominent have more complicated patterns in the more tectonically-active West). Eastern North America has a long history of far-field tectonic stress: in distant Paleozoic times, compressive stresses from the Appalachian and Ouachita-Marathon orogenies were transmitted through cratonic carbonates at least as far as 800 km away from the respective orogenic fronts (Craddock and van der Pluijm, 1989). As a general rule, the interior of modern North America is characterized by uniform, horizontal or subhorizontal (±15°) compressive stresses and a thrust and strike-slip faulting regime (Zoback, 1992). More specifically, a NE-SW to ENE-WSW compressive stress field dominates in the central U.S., shifting to nearly E-W compression just westward of the Appalachian foldbelt in eastern Ohio-western Pennsylvania-northern West Virginia and east-central Tennessee, although stress orientations in the Valley and Ridge province are "locally contradictory" to this overall trend (Zoback and Zoback, 1980, figure 5).

The dynamic balance of vertical and horizontal stress can actually maintain the stability of a mine, but such a balance may not exist. Excessive horizontal stresses (14-70 MPa or 2,000-10,000 psi), at least two times the local vertical stresses, are particularly problematic in the eastern U.S. and can cause roof buckling (Iannacchione and Prosser, 1998; Iannacchione et al., 1998). According to Gividen (1996) the optimal design for a mine in an area of high horizontal stresses is to have a wide (50-60 ft or 15.2-18.3 m) main entry aligned parallel to the principal horizontal stresses and the narrower (25-30 ft or 7.6-9.2 m) minor entries at 90° to the main. High horizontal stresses are usually presented as being characteristic of Appalachian region mines (see discussion below), but mines in other areas can have significant horizontal stress problems as well if there are major vertical differentials in rock characteristics. For example, directly below a thick, mined limestone (Bethany Falls Member) in the Kansas City area, lies a thin shale (Huchpuckney Member) with a low modulus of elasticity, which, in turn, is underlain by a thin limestone (Middle Creek Limestone Member) with a much higher modulus of elasticity. Under these conditions of relatively great vertical differentials in rock properties, stresses as high as 11 MPa or 1,600 psi have been measured in the Middle Creek (J. Parker, personal communication, February 2, 2002).

Joints, Faults, Folds, and Dip

The small- to medium-scale physical manifestations of crustal stresses and tectonism, which would include joints, faults, folds, local and regional dip, slickensides, and similar features, all have an effect on underground mine design and operation.

Over 95percent of all stone mines in the U.S. mine strata with dips of 10° or less (Iannacchione at al., 1998), and therefore conventional room-and-pillar mining is applicable. In the Appalachian region, however, mined strata can approach a vertical orientation, requiring the application of different techniques (see discussion below).

Vertical or near-vertical joints in particular, which usually occur in two distinct sets at any one place, are considered to be signatures of the current plate tectonic stress field (Scheidegger, 1993). The type of material infilling a joint or fracture, its shear strength, the weathering condition of a joint or fracture, hydrogeologic conditions (whether groundwater moving through the feature and, if so, at what rate), and scalar dimensions (length, width, and spacing of joints/fractures relative to similar features) will together determine its behavior and net effect on mining (Scovazzo, 1996). The presence of joints can lead to multiple manifestations of roof failure, including slippage, crushing and rotation, buckling and rotation, and shearing between corners (Potts et al., 1979). Wedge failures will occur in mine roofs if joints intersect a mine roof at an angle (Iannacchione et al., 1999, figure 5).

Driving mine headings and cutting rectangular pillars at an angle (-45°) to major statistical groups of joints ("master joints") is a common "compromise" that minimizes the exposure of joints in the mine roof, theoretically minimizing roof rock falls and preventing roof failure (Kendorski, 1998). Not all mining engineers agree that this is a uniformly applicable solution (J. Parker, personal communication, February 2, 2002).

Other

Methane gas leakage is a problem in deep mines in the Kansas City area. In these cases, mines penetrated Lower Pennsylvanian strata that have produced economic quantities of hydrocarbons farther west. Gas leakage problems in mines can be very difficult and very expensive to remediate.

REGIONAL PATTERNS

Limestone resources can be found over most of the U.S., and, indeed, underground calcium carbonate (limestone and marble) mines have operated from California to Maryland. Thick, relatively flat-lying Paleozoic carbonates in the eastern half of the U.S. (east of ~96° W), however, have been the targets of most operations. Non-geological influences such as population density, demand, infrastructure distribution and development, and industrial history have also determined this geography of limestone mining. Even more specifically, a number of underground mining operations are concentrated in the Central Lowlands Province, where Paleozoic strata are nearly horizontal. Generalized regional patterns in the geologic aspects of underground limestone mining can be identified within the U.S. There are three major mining regions in the U.S. east of the Rocky Mountain front (figure 6), as well as outlying operations. Historically, these regions have been discrete geographic entities, but in a larger sense they also reflect the depth and age of limestones mined, ranges of mine design techniques applied, as well as the predominant geological conditions.

Midcontinent Mining Region

The Midcontinent mining region (figure 6) is a narrow belt of underground limestone mines in Upper Pennsylvanian cyclothems (UPC) limestones. It encompasses parts of southeastern Nebraska, southwestern Iowa, northeastern Kansas, and northwestern Missouri, but for practical purposes it consists of separate districts wherein mining was or is highly concentrated, such as Weeping Water (Nebraska), Atchison-Leavenworth (Kansas), and Kansas City. These districts are in or near population clusters exceeding 500,000 persons, specifically the Omaha-Council Bluffs-Lincoln (Nebraska-Iowa) and greater Kansas City metropolitan areas. There are outlying mining operations as well, such as the Schildberg Construction Company mine at Atlantic, Iowa, which has supplied aggregate markets in southwestern Iowa. As a rule, Quaternary cover (loess, glacial till, alluvial, and glaciofluvial-glaciolacustrine sediments) is thick in the region, and therefore, mining has proceeded largely from valley-side access to bedrock along major drainages. Much of the Paleozoic limestone production in the Midcontinent, whether mined in the subsurface or at the surface, has come from UPCs of the Kansas City to lower Shawnee groups. With respect to underground mining, only three limestone units within this interval are particularly important: the Bethany Falls Member (Swope Formation), the Argentine Member (Wyandotte Formation), and the Plattsmouth and Kereford members (Oread Formation). Some past underground production derived from the Spring Hill Member (Plattsburg Formation) and from the Stoner Member (Stanton Formation), both in the Lansing Group.

Midcontinent region mines are relatively shallow, with maximum depths below the land surface of d•60 m (typically d•30 m). Mining is stratigraphically limited to a single-level of headings in limestone units that are almost always less than 10 m thick. Stratigraphic limits present serious roof ("back")-height constraints upon truck size and haulage: some recently active Argentine Limestone Member mines in the greater Kansas City area had ceilings as low as 12 ft (3.7 m). Even today, mine operators may find themselves desiring a mere 2-2.5 ft (0.6-0.76 m) of additional overhead clearance in order to use larger equipment underground. Constraints on reserves have sometimes been encountered as a consequence of shallow mining under highly-dissected terrain or encountering incised stream channels infilled with Quaternary sediments (Parker, 1987).

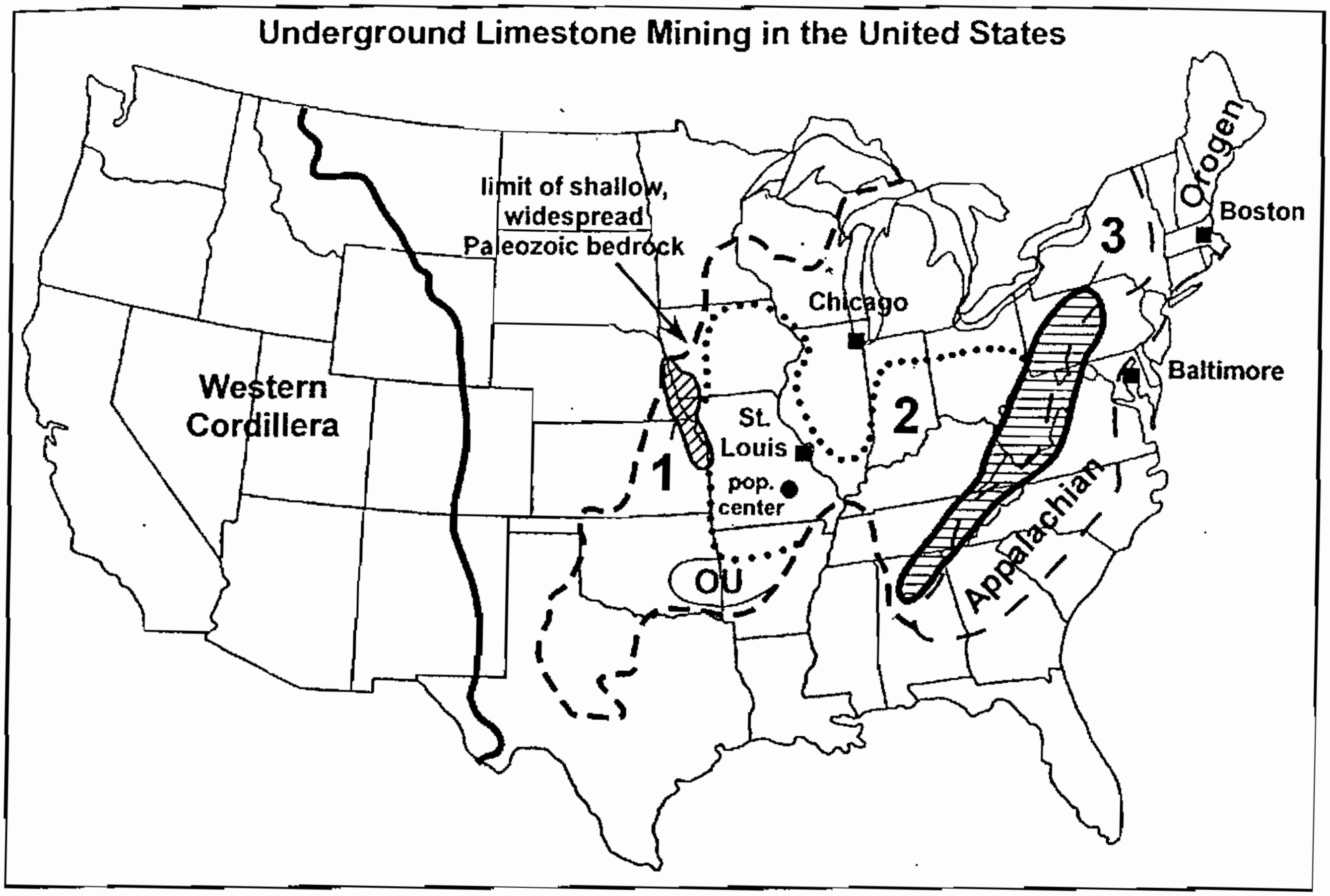


Figure 6. Underground limestone mining in the U.S. Three historically-distinct regions are Midcontinent (1), Midwestern (2) and Appalachian (3) mining regions. Position of orogenic belts (Western Cordillera and Appalachian Orogen) determines nature of geologic structure, particularly as it affects mining practice and availability of limestone units for surface mining. Midwestern (2) and Appalachian (3) mining regions overlap most of "North American Core Region" defined by the cities of Chicago, Boston, Baltimore, and St. Louis, as well as Montreal, Canada (not shown), which encompasses the concentration of traditional manufacturing activity on the continent, as described by geographers (DeBlij and Muller, 2000). Note position of U.S. population center in southeastern Missouri, the migration of which will gradually affect markets for limestone products, particularly aggregate. OU= Ouachita Mountains.

The inherent stratigraphic heterogeneity of UPCs (see Heckel, 1986), specifically the intercalation of shales and mudstones with limestones, creates major vertical contrasts in rock properties such as shrink-swell, slaking, overall strength, and modulus of elasticity (which, theoretically, could differ by two or more orders of magnitude between successive shales and limestones). In almost every case, Midcontinent UPC limestones deposited during the regressive stage of a depositional cycle (Heckel, 1986, 1994) show subaerial exposure and weathering features. These features including teepee structures, cracking in thinly-bedded peritidal strata, brecciation (informally called "peanut" or "popcorn" rock or "buckshot"), rooting, and micro- to macrokarst, to depths of greater than 2 m in some cases (Joeckel, 1989, 1994, 1995, 1999). Paleosols developed in mudrock units directly above these weathered zones are in many cases riddled with sets of large pedogenic slickensides (Joeckel, 1994, 1999), which must be viewed as potential pre-existing failure planes. These observations indicate that a sequence stratigraphic approach to understanding limestone resources adds a welcome element of predictability to mine conception and design.

Potential floor problems and roof-beam instability (figures 2A, C, 3A-D, G, H: erosion of thin or irregular limestone floors down to underlying shales, excessive stresses on sub-floor shales, creep, floor heave, possible rock bursts, etc.) are extremely important considerations in Midcontinent mines (Dean et al., 1969; Hasan, 1996). The almost ubiquitous presence of preweathered limestone in the upper parts of mined units forces operators to leave a thicker roof beam, further limits mine ceiling, and sometimes necessitates the use of artificial roof support (figure 3D). Extensive roof bolting (figure

3B), for example, is required in the Plattsmouth-Kereford limestones in southeastern Nebraska (see discussion below). Lateral variations in limestone facies, syndepositional weathering, and the subsequent effect on rock quality pose significant problems at several sites. Joint/fracture orientations have typically been taken into consideration in the design of modern (post-1950) mines, resulting in rooms and pillars that are oriented at an oblique angle to major features; joints planes, however, are typically nearly normal to bedding (see figure 3H). Many mines are essentially dry, and where drainage problems exist they are more the result of design inadequacies rather than any single, overwhelming geohydrologic phenomenon. In the latter cases, localized wetting of particular sub-floor shale strata in abandoned mines, subsequent loss of strength, and failure is a probable contributor to pillar weakening and roof collapse.

Shaly strata or thin shale partings and medium-scale bedding are common in mined UPC limestones, as is stylolitic/dissolution-seam pseudobedding (see discussion of mining in Nebraska below). At the Schildberg Construction Quarry Atlantic (Iowa) Mine, below the uppermost, preweathered 1.2 m (3.9 ft) of the Bethany Falls Limestone, and extending downward to its basal contact with the Hushpuckney Shale, exploratory cores show over 30 thin (0-12 cm, but usually <3 cm) fine shale-lined partings, calcareous shales seams, or zones of fissile, shaly limestone spaced at intervals of approximately 10-120 cm (though almost always at 10-30 cm, a range that corresponds to bedding expressed in the actual mine). Several of these features are laterally consistent, and therefore, there were two viable choices for the placement of the roof line; the lowest of the two seams (3.3 m or 10.8 ft below the top of the Bethany Falls) was eventually used in order to minimize the necessity of roof bolts through the weak, preweathered uppermost limestone. In comparison, older mines in the Bethany Falls in the Kansas City area had a 4-8 ft- or 1.2-2.4 m-thick immediate roof (Scotese et al., 1981). About 18 in (46 cm) of limestone are left for the mine floor (similar to the 24 inches or 61 cm left in Argentine Limestone floors: Zipf and Schmuck, 1996), considering the problems encountered with Bethany Falls Mines in the Kansas City area (Parker, 1987), but finding a consistent parting there is more difficult than in the roof. Table 1 (A) summarizes the results of a survey of Midcontinent mines.

Schildberg Construction Company's Atlantic (Iowa) Mine experienced excessive drainage from Quaternary sands at one corner of the excavation for its decline. In the short term, temporary collapse of the excavation followed, and in the long term, a potential for nuisance drainage on the mine face was perceived. The property owner retained water rights, and a novel solution was arrived at by which drainage water was collected and sold to a local golf course (figure 7).

The predominant uses for mined limestone in the Midcontinent region are construction, concrete, and asphalt aggregates, but agricultural lime and limestone for Portland cement are also produced, as well as small quantities of limestone for the manufacturing of agricultural-grade calcium phosphate. There is considerable potential for mine development in UPC limestones outside the core Midcontinent districts, but capital investment in mine works (especially shafts in areas where valley-side access is impossible) may be too great relative to present market conditions.

Midwestern Mining Region

East of the Midcontinent, older Paleozoic limestones are mined over a very broad area south of the Great Lakes, from the Missouri-Mississippi drainage divide eastward to the edge of the Appalachian Plateau, including central and eastern Iowa, central and eastern Missouri, Illinois, Indiana, western Ohio, and northern Kentucky (figure 6). Mines are loosely clustered around the Lexington (Kentucky), St. Louis (Missouri-Illinois), and Indianapolis (Indiana) metropolitan areas. The Midwestern region is the core region or "heartland" of underground limestone mining in the U.S. and encompasses all or parts of such major structural features as the Michigan Basin, Illinois Basin, Iowa Basin, Ozark Dome, Nashville Dome, and Cincinnati Arch.

Underground mines in the Midwestern region are moderately deep, usually 40-150 m, but as much as 350 m below the land surface at maximum depth. Mined units are in most cases thick Ordovician (in the southern and southeastern parts of the region) and Devonian or Mississippian (in Iowa, Missouri, Illinois, and Indiana) limestones (e.g., Burlington, Camp Nelson, Davenport, Eagle City, Gilmore City, Iowa Falls, Keokuk, Maynes Creek, North Hill, North Vernon, Oregon, Otis, St. Louis, St. Genevieve, Salem, Spergen, Spring Grove, Tyrone, Wassonville). The Silurian Salina Group has been mined for limestone in Ohio. The greater mined horizon thickness in Ordovician-Mississippian carbonate units of the Midwestern region presents significantly less of a constraint than in the Midcontinent Pennsylvanian mining region.

In most cases, a lack of suitable near-surface resource and comparatively large depths to useable stone are the fundamental issues in the decision to mine underground, but in at least one case in Kentucky, an underground site is being converted to

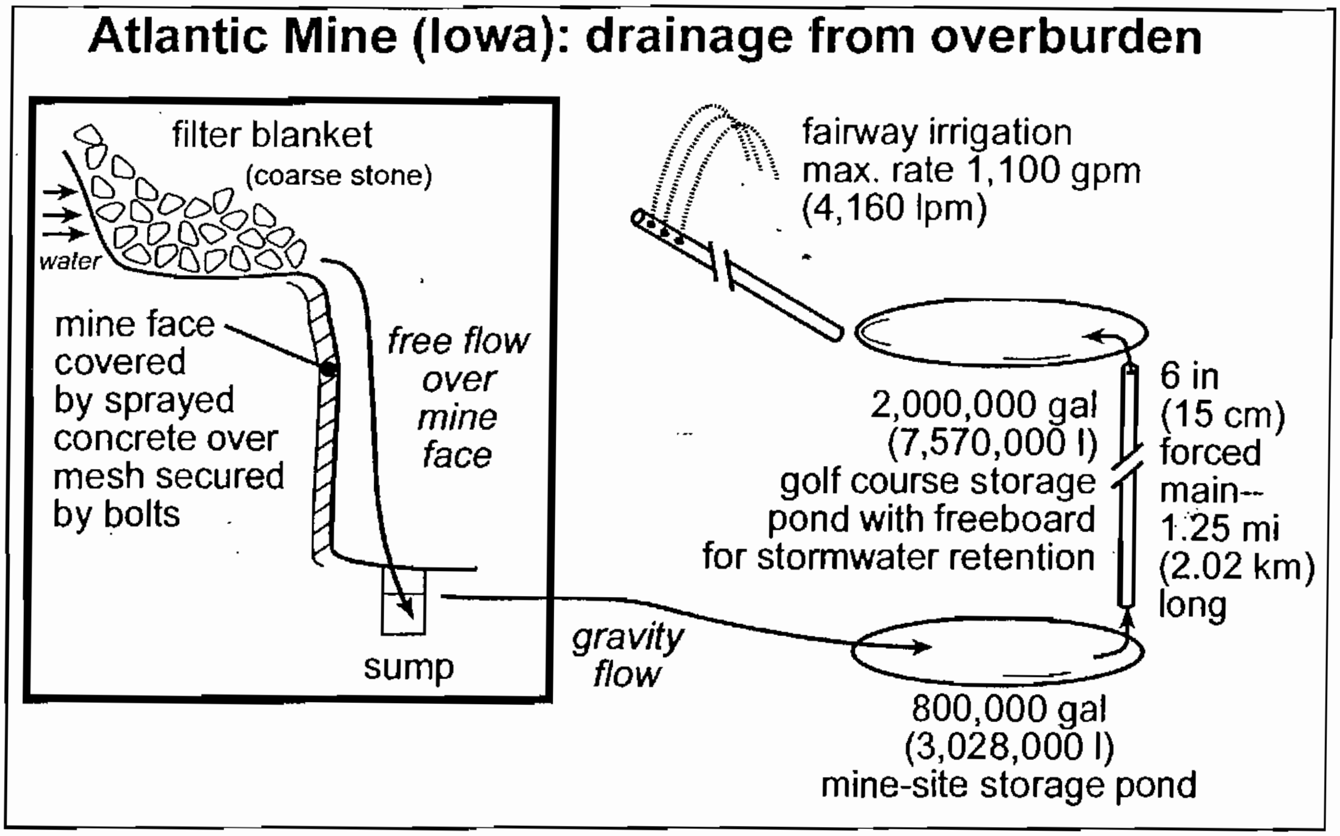


Figure 7. Drainage water management at Schildberg Construction Company's Atlantic (Iowa) Mine.

open-pit mining. One or more benches are typically (although not always) used in Midwestern region operations; there are also multilevel mines. The Jefferson County Mine (Rogers Group, Inc.) at Louisville, Kentucky mines the Tyrone Limestone at 450 ft (137 m) depth and the Camp Nelson Limestone at 1,150 ft (350 m) depth (J. Torres, personal communication, April 13, 2002). There are three multilevel mines in Iowa: the Linwood Mine (Linwood Mining and Materials, Inc., Davenport: J. Rhodes, personal communication) and the Ames and Durham Mines (Martin Marietta) at Ames and Knoxville, respectively. The Durham Mine has three levels and produces both gypsum (from a 15 ft or 4.6 m opening in the Spergen Limestone) and limestone (Eagle City-Wassonville in a 20 ft or 6.1 m opening, and North Hill in a 20 ft or 6.1 m opening: J. Stafne, personal communication, March 7, 2002).

Roof selection and roof stability in the Midwestern region are complicated by the presence of chert bands and/or shale seams in some strata. Modern and ancient karst pipes, sinkholes, and similar features, which degrade rock quality, have removed mineable rock entirely, or (when above the mine level) weaken roof beam strength, constitute a far more widespread problem in the Midwestern region than in the Midcontinent. Paleo-erosion surfaces (which thinning or completely removing limestones) also limit resources in specific cases, and major facies changes weaken some mine roofs (Malcom Mine: J. Stafne, personal communication, March 7, 2002). Lateral variability in facies/rock quality and jointing/fracturing are locally problematic, particularly when joint planes have a <90° relationship to bedding, thereby promoting wedge failures in roofs. Problems in mine stability resulting from excessive horizontal stresses have been reported in Kentucky. The Durham Mine (Knoxville, Iowa) is a deep (397 ft or 121 m) Mississippian mine with some drainage problems (J. Stafne, personal communication, March 7, 2002). Table 1 (B) summarizes the results of a survey of Midwestern mines.

The uses of limestone mined underground in the Midwestern region are more varied than in the Midcontinent, reflecting the quality of individual mined units, diversity of regional needs, and proximity to certain markets. Construction aggregate, road base stone, concrete and asphalt aggregate, agricultural lime, riprap, portland cement, flue-gas desulfurizers, glass flux, and chemical lime are produced. The more widespread use of Midwestern-mined limestone in cement and chemical lime makes the lateral variability in rock chemistry an important concern.

Appalachian Mining Region

The Appalachian mining region includes parts of the Appalachian Plateau (including the Cumberland Plateau) and the Valley and Ridge provinces (figure 6). Eastern Maryland, western to central Pennsylvania, West Virginia, Virginia, east-central Tennessee, and northern Alabama are included. Mined units range from Cambrian to Mississippian in age and include the Five Oaks/Mosheim, Greenbrier (Loyalhanna), Kinzers, Monteagle, and Valentine limestones.

Dipping strata (commonly *e*•10º), joint planes oblique to bedding, faults, locally excessive horizontal stresses (>27.6 MPa: Iannacchione and Prosser, 1998; Iannacchione et al., 1998), and generally more pervasive and complex geologic structure set the Appalachian region apart from the two regions previously discussed. High horizontal stresses have been recorded in eastern Kentucky, West Virginia, western Pennsylvania, and Virginia (Iannacchione et al., 1998). Appalachian region mines commonly have maximum depths below land surface of at least 350 ft (107 m). High-relief terrain and steep dip (30º) make one of the mines in the Appalachian region, Chemical Lime Company of Virginia's Kimballton Mine at Ripplemead, Virginia (opened in 1947), the deepest known active limestone mine in the U.S. at some 2000 ft (610 m) maximum depth below land surface. A 100 ft (30.5 m)-thick interval is mined at Kimballton Mine through benching in three passes, leaving 80 ft (24.4 m)-wide pillars (R. Roeder, personal communication, March 12, 2002). Even more steeply-dipping strata (70-90°) of the Valentine Member (Linden Hall Formation, Ordovician) at the formerly-active Graymont, Inc. Bellefonte (Pennsylvania) Mine necessitated the exceptional employment of sublevel stoping methods (two upper drill subs and one lower loading drift with drawpoints) at depths of as much as 1000 ft (305 m) below land surface. In another mine in the Valentine Member at Pleasant Gap, Pennsylvania, bentonite (altered volcanic ash) partings decrease the stability of the mine roof, probably significantly more than typical illitic shale seams would because of the extreme shrink-swell of smectitic clays (D. Hite, personal communication, March 20, 2002; see Rones, 1969).

Procedurally, strongly dipping strata (commonly, but not always the case in this region) are more difficult to mine than are horizontal strata. Therefore, additional staff training and expertise are needed in comparison to an operation in horizontal strata. Drainage can be a problem in mines that excavate dipping strata because of the downslope orientation of mine works. A modified room-and-pillar layout with barrier pillars is used in Franklin Industrial Mineral's Crab Orchard Mine (Anderson, Tennessee) to improve ventilation in deep mine works (R. Freas, personal communication, March 6, 2002). Table 1 (C) summarizes the results of a survey of Appalachian region mines.

The uses of mined limestone from the Appalachian region include road base, concrete and asphalt aggregate, chemical lime, high-brightness products, high-quality quicklime, and fillers. Higher-value products depend heavily on the mineralogical/chemical purity of certain deposits. Poorer-quality stone in terms of chemical purity (the Loyalhanna Limestone Member may contain as much as 50 percent silica in Pennsylvania) is limited to use in aggregate applications.

Other Operations

Other active and abandoned underground limestone mines are located across the U.S., outside of the major mining regions described above. Furthermore, certain operations that lie within one mining region have similarities with mines in an adjacent mining region.

The East Farfield Coal Company opened the Petersburg Mine in the Pennsylvanian Vanport Limestone at Petersburg in northeastern Ohio in 1996. The mine is a single-level mine with eleven entries 18 ft high and 40 ft wide (5.5 x 12.2 m) and a maximum depth of 240 ft (73 m) below land surface (T. Miller, personal communication). Although it lies at the margin of the Appalachian limestone mining region, this mine has features in common with Midcontinent region mines: single-level mining from headings, a relatively thin mineable horizon, mixed lithologies in the enclosing stratigraphic succession, an approximately horizontal attitude of strata, and roof problems related to preweathering of limestone and lateral facies changes.

In the past 25 years, there have been multiple attempts at mining Mississippian limestones at great depths in the Kansas City area. Similarly, a private company made initial investigations into the deep mining of Mississippian limestones about 10 km south of the Omaha metropolitan area in the early 1970s, although no deep mining has yet been initiated in that area. Lafarge North America's Sugar Creek Mine in the Kansas City area, commissioned in 2001, currently mines the Mississippian St. Louis Limestone at 680 ft (207 m) depth, and will probably mine at a second level (the Devonian Callaway and Cooper limestones), about 400 ft (122 m) deeper, in the future (Marksberry, 2002). The quality of the St. Louis (chemical composition for cement manufacturing) was the primary geologic concern at the inception of the mine, along with the great depth to the target horizon. Early in the mine construction stage, however, another problem emerged: the Pennsylvanian-Mississippian unconformity, which completely removes the St. Louis Limestone in part of the mine, limits reserves and is forcing a change in mining plans. Another, even deeper (Devonian) limestone mine operated in the Kansas City area in the late 1970s, but has since been abandoned. These deep mines have more in common with mines in the Midwestern region than they do with the typical Midcontinent Pennsylvanian limestone mines described in this paper. Deep mining of quality Mississippian limestone will probably increase in the next several decades in the Midcontinent as easily-accessible supplies of Pennsylvanian limestone dwindle and as suburban expansion limits surface access in major metropolitan areas.

Some mines have lesser similarities to the modal types in the mining regions identified in this paper. Global Stone St. Clair operates a single-level mine in the Silurian St. Clair Limestone at Marble City, north of the Ouachita Front in east-central Oklahoma. Stone quality is the chief geologic concern; clastic seams and partings are absent in the mined unit, but roof bolting is not employed (W. Farris, personal communication, April 4, 2002). J.M. Huber Company operates a single-level underground mine (Michel Mine) in the Ordovician Honeycutt Formation at Marble Falls, Texas, for the production of plastic filler, and a benched mine (Miss Linda Mine) in the Cambrian Murphy Marble at Marble Hill, Georgia for materials used in plastics and floor tiles (C. Joyce, personal communication). Both the Miss Linda Mine in Georgia and the Global Stone St. Clair mine in Oklahoma have been operating since the 1950s. Geologic factors affecting the Michel Mine are, in order of effect, brecciation of the mined rock, joints/fracturing, and rock quality (chemistry). The Miss Linda Mine is chiefly affected by faluting, joints/fractures, and rock quality (mineralogy).

Scotese et al. (1981, figure 1.1) showed circa-1970 underground stone mines in California, Utah, Wyoming, Arkansas, Alabama, New York and Vermont. Little additional information supports these accounts, and it is thus assumed that some of these reports may be erroneous, while others are by now long-defunct. In California, underground mining operations definitely existed, and employed shrinkage stoping and block caving methods as well as traditional room-and-pillar mining (Bowen, 1957).

UNDERGROUND LIMESTONE MINING IN NEBRASKA

Context and History

Nebraska is a comparatively stone-poor state and typically ranks in the lower half or lower quarter of U.S. states in overall industrial minerals production. Shallow limestone bedrock (UPCs and the Upper Cretaceous Greenhorn and Niobrara formations) is accessible only in the eastern quarter of the state, and along the incised Republican River drainage in south-central Nebraska (figure 8). Dozens of quarries and mines have operated in the past, but by 2002, production was almost completely accounted for by UPC limestone mining at three surface quarries (near DuBois, Louisville, and Ft. Calhoun) and four underground mines (Weeping Water). Small agricultural lime operations surface mine the Niobrara Formation at Nelson in Nuckolls County and, up until recently, the Greenhorn Limestone at Garland in Seward County. Underground mines alone account for much of the total volume of limestone produced in Nebraska. Additional underground limestone mining ventures in eastern Nebraska are likely to appear within the next two decades as both the constraints on surface mining and the demand for materials increase.

Underground mining of UPC limestones began in Nebraska surprisingly early, in the 1920s. Archival photographs indicate that by 1927, National Stone Company had extensive underground works on both sides of the Platte River at Louisville, south of Omaha. The main mined unit was miscorrelated as the Ervine Creek Limestone by Condra (1927), and has since been called the Argentine Limestone Member in Nebraska Geological Survey publications, although it is almost certainly the Raytown Limestone Member (Heckel et al., 1979). Both surface and subsurface limestone-mining operations in eastern Nebraska have long been concentrated in the lowermost Platte River Valley in Sarpy and Cass counties, the valley of Weeping Water Creek in Cass County, and along the Missouri River bluff line from Blair, Nebraska southward. In the Platte and Weeping Water valleys, valley-side outcrop access facilitated relatively easy quarry or underground mine development. Today, Kerford Limestone, Martin Marietta, and PCS Phosphate companies mine the Plattsmouth Limestone and the thinner, overlying Kereford Limestone (hereafter P-K: figure 9) of the Oread Formation (Shawnee Group, Virgilian) underground in the Weeping Water district. In this district, underground mining began in the mid-to late-1960s, and then intensified in the mid-1980s.

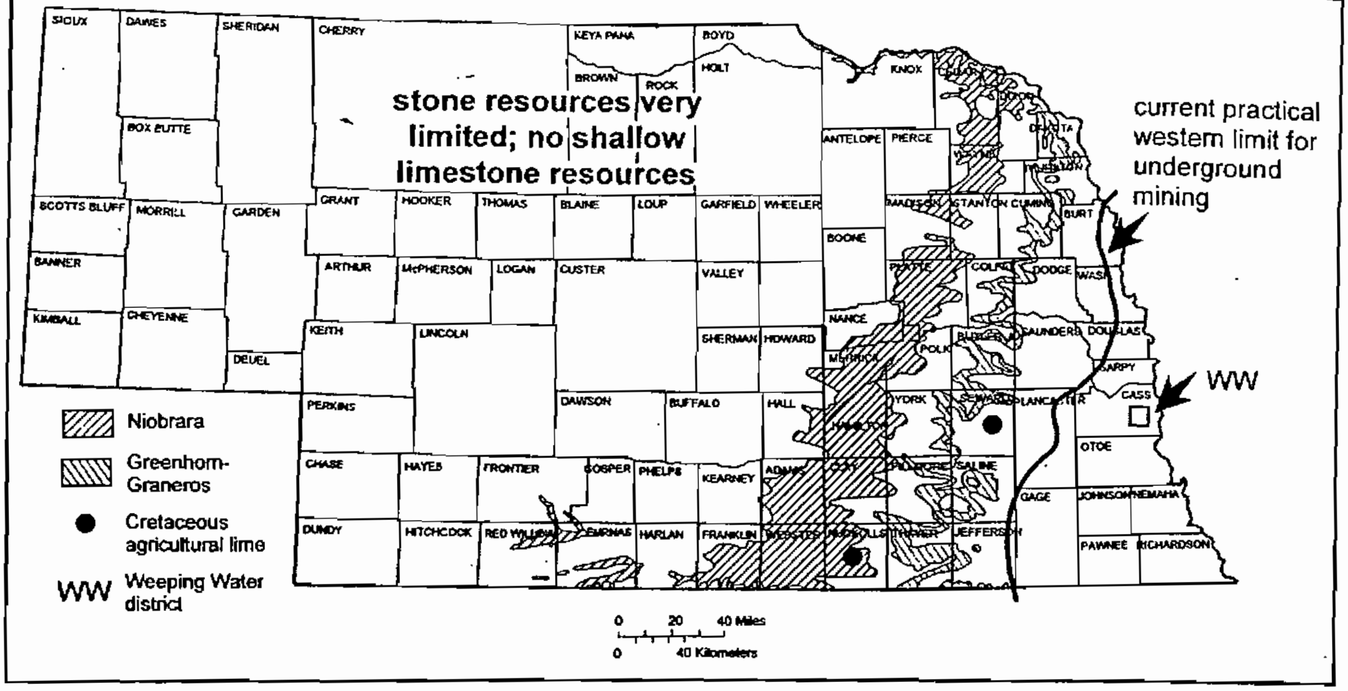


Figure 8. Limestone resource distribution in Nebraska. Upper Pennsylvanian and lowermost Permian limestone-bearing cyclothems are bedrock in southeastern part of the state (east of limit line shown on map). Mississippian limestones and Devonian limestones and dolomites are also accessible at depths of >100 m in this area. Upper Cretaceous Greenhorn and Niobrara formations (distribution as bedrock shown) are at shallow depth only locally, and are currently mined for agricultural lime at two small operations. Bedrock stone resources suitable for crushed stone, aggregate, riprap, etc., are absent over most of the state.

Geology and Mine Design

In the area of the mines, the Plattsmouth-Kereford interval varies in thickness between 5 and 10 m. Maximum mining depth below land surface is 48 m. The regular room-and-pillar plans of the Weeping Water mines have N-S and E-W orientations, designed to be oblique to the roughly NE-SW and SW-NE regional orientation of joints. Typical pillars are about 35 ft x 35 ft. Mines work both updip and downdip (<1°), and there are no major drainage problems. The P-K interval and enclosing strata "roll" gently, about 30-60 cm (2-3 ft) every 21 m (70 ft), and the mines are excavated accordingly, where necessary. In parts of the Weeping Water mines, there is also a total of 2 m (7ft) difference in floor elevation across several cross-cuts due to variability in the lower part of the Plattsmouth. Floor softening and gouging by loaders are problems in certain parts of the mines.

Mining proceeds from valley-side portals and declines under the uplands. Under the uplands, the Ervine Creek Limestone Member, a thick limestone upsection from the Plattsmouth Limestone, bears some of the load of unconsolidated Quaternary overburden and Pennsylvanian rocks above mine level. Kerford Limestone Company is unique in its employment of an extensive 60-inch (152 cm) conveyor with a 54-inch wide (137.2 cm) belt that moves 1,000 tons/hr (1,100 mt/hr) from the mouths of two mines to the plant.

The design and operation of the Weeping Water area mines have been most strongly affected by problems with the roof rock, the Spring Branch Limestone, a soft, laterally-variable, partially shaly carbonate mudstone that loses as much as 50 percent of its strength with wetting and drying. The use of 6-14 ft (1.8-4.3 m) resin-grouted bolts, as well as 8-inch-wide 18-gauge steel straps, is ubiquitous in the securing of roofs. Condensation of atmospheric humidity within the mines, resulting from seasonal differences in temperature and humidity between mine air and outdoor air, causes ongoing "peeling" from the base of the Spring Branch Limestone, which, in turn, may necessitate rebolting in order to prevent roof falls. Some mine personnel also blame the Spring Branch Limestone for the clogging of dust collectors because it is so soft and argillaceous. The bolting process itself is not particularly problematic, although slow seepage of water through, and subsequent softening of, newly drilled bolt holes is a minor inconvenience.

Less obvious or immediate geologic factors, which nonetheless ultimately have appreciable impacts, result from the internal stratigraphy and depositional/exposure history of the P-K interval. Although the two limestones are nearly indistinguishable and all but stratigraphically continuous in much of the total mined area, the upper contact of the P-K interval varies considerably in character over distances of several tens to a few hundred meters. A thin (1-20 cm), highly discontinuous, and locally very irregularly bed of calcareous shale (Heumader Shale Member) frequently appears between the Plattsmouth and Kereford limestones. Shale in the Heumader appears to merge with the mud infillings of large karst voids, where the latter are present (figure 10). Of much greater concern in the mining process, however, is the occurrence of large, reddish-mudstone (paleosol)-filled sinkhole-like depressions in the upper P-K interval (figure 10). Karstic depressions are not visible in natural surface outcrops, which are very limited in extent. In the many kilometers of underground mine faces, though, several karstic depressions are preserved in place because they impede, if not halt, mining at particular points. The depressions are filled with blocky reddish-brown mudstone containing rounded, clay-sheathed limestone fragments and common, large (>1 m^2) slickensides. The largest of the depressions are as much as 2 m deep (below the top of the P-K interval) and may be as much as 50 m in diameter. Large depressions are underlain by fissured and brecciated limestone, large (>20 cm wide) mud-filled voids, and collapsed bedding (5-10º from the horizontal). Rare, smaller depressions (about 3 m in diameter and < 75 cm deep) appear to have little association with similar dissolution/collapse features. Although collapsed beds in the karstified upper P-K interval have discordant relationships with underlying horizontal strata, the overlying Clay Creek Limestone Member is clearly divisible as a separate, thin (20-25 cm) bed above the mudstone-filled karstic depressions. Thus, stratigraphic relationships indicate that there is a widespread, planar marine erosion surface at the base of the Clay Creek, a weathering surface atop the P-K interval, and, possibly, some localized weathering at the P-K contact (as evidenced by the characteristics of the Heumader Shale).

At least 10 percent and perhaps as much as 25 percent of the P-K limestone in the Weeping Water district is a facies referred to by miner personnel as "popcorn" rock: dense carbonate mudstone separated into centimeter-scale masses or nodules by pervasive, irregular, very thin shale partings (many of which appear to be pressure dissolution seams, or shale layers enhanced by dissolution), slickensided, clastic-mud-filled fractures, and strongly grooved, clay-lined stylolites. Most of this fabric can be attributed to exposure (preweathering) during the Pennsylvanian. The origin of the fabric of "popcorn" rock is partially depositional and partially late-diagenetic. Carbonate and smaller quantities of clastic mud were deposited nearly simultaneously, and that the clastic mud dewatered and compacted more than the carbonate mud during early diagenesis. Later, during burial diagenesis, localized pressure dissolution occurred.

"Popcorn" rock disaggregates automatically within the mine through atmospheric wetting and drying within two weeks after it is mined due to the shrink-swell of clay minerals (specifically illite-smectite) in shale seams/stylolites, and also, it appears, due to the precipitation of unknown sulfate or carbonate minerals from water seeping out of the rock face. "Popcorn" rock sometimes appears in direct association with large (>50 cm deep), subvertical, mud-filled fractures, enlarged horizontal, mud-filled cracks or shale seams, irregular, mud-filled vugs, and collapsed bedding. The co-occurrence of these features underscores the interpretation that some of the nodular aspect of "popcorn" rock is related to Pennsylvanian karstic weathering.

The lower half of the Plattsmouth consistently contains many thin (0.2-2 cm) shale seams, many of which are directly associated with dissolution seams and stylolites. These shale seams degrade overall rock quality, but not significantly enough to seriously affect product marketability. Seams are frequently at 2-20º to the horizontal and define lens-like masses, laterally-overlapping strata, and mound-like packages of nearly horizontal strata of carbonate mudstone-wackestone (dominant) and packstone (figures 9, 11). The geometry of shale seams suggests that any discordant relationships to horizontal strata result from: (1) the buildup of carbonate in phylloid-algae-framed mud mounds, and (2) selective syndepositional cementation of some zones and subsequent differential compaction of surrounding, softer carbonate sediments prior to the development of supra-Plattsmouth karst and the production of the sub-Kereford marine erosional surface. Much of the depositional and early diagenetic history of the P-K interval in the Weeping Water district are currently unknown, but future research may produce information relevant to limestone mining, use, and processing.

Uses of Mined Material

The P-K interval is mined primarily for concrete and asphalt aggregate (roughly 75 percent of output), and also for agricultural lime (including locally-produced pellets) and calcium phosphate production. Half or more of the mined volume of the so-called "popcorn" rock is waste, although some is added to the crusher run of normal rock. Ash

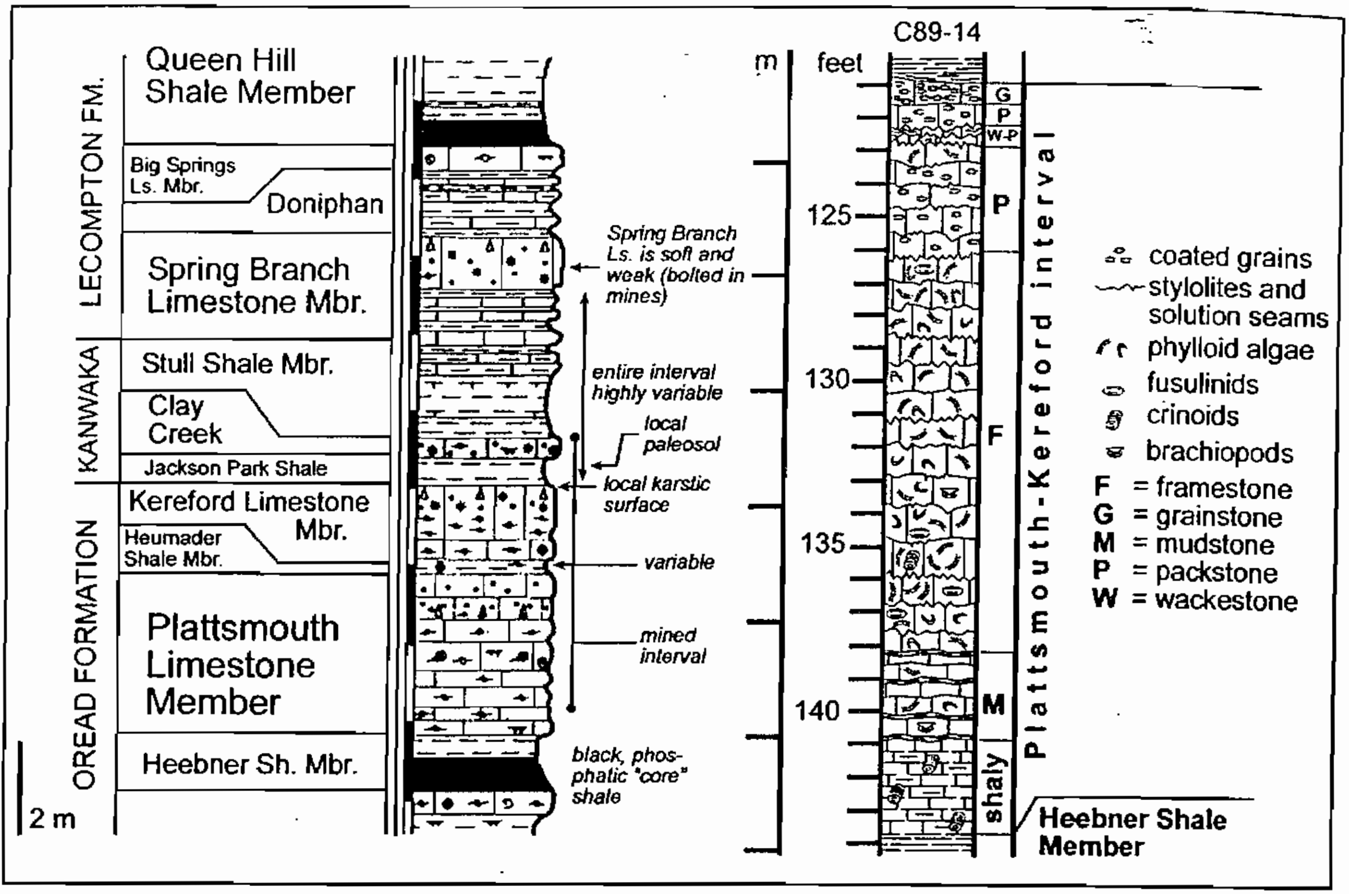


Figure 9. Stratigraphy of the Plattsmouth-Kereford interval in southeastern Nebraska. Column at left (after Nebraska Geological Survey Publications) shows enclosing strata, including Heebner Shale, "core" black phosphatic shale of cyclothems according to Heckel (1986, 1994). Column at right shows typical Plattsmouth-Kereford limestone interval in one core from Weeping Water area.

Grove Cement Company (Louisville, NE), which operates the only cement plant in the state but does not currently mine underground, obtained a permit to screen and reclaim waste fines from one of the limestone aggregate mining operations at Weeping Water in 1998. These waste fines are now trucked 10 mi (15 km) to the Louisville plant as an important source of low-magnesium limestone for cement kiln feed. Their removal from the Weeping Water site also facilitates reclamation. A total of 1,226,673 tons (1,351,794 mt) of fines had been reclaimed by the end of May, 2002, and 1,147,878 tons (1,264,962 mt) have actually been incorporated into the cement manufacturing process. The existing 78,795 ton (86,832 mt) limestone fines inventory (May, 2002) at the Louisville plant will eventually be consumed, as will the remaining estimated 500,000- 1,000,000 tons remaining at the Weeping Water site.

Geologic Hazards

Collapse of abandoned or active mined works and resulting surface subsidence have occurred at least twice in the Weeping Water area in the past two decades. On a separate occasion, older (mid-1980s) mine works formerly operated by another company were encountered by active mining and found to be filled with water, resulting in an unanticipated 3,000,000 gallon (11,300,000 l) drainage into the operating mine.

The most recent mine collapse (July, 2000) in the Weeping Water area occurred at one of the two Kerford Limestone Company mines after multiple rain events in an area near the floodplain of Weeping Water Creek, where the Ervine Creek Limestone Member is absent above the P-K interval. The preweathered condition of the upper Plattsmouth (see discussion below) and its weakening effect probably contributed to the collapses. Kerford's collapse was rapidly repaired with 90 wooden cribs, and the affected mine continues to operate. Hasan (1996) attributed a collapse over a Kansas City-area mine to progressive water percolation, which led to roof-rock weathering and weakening.

The hazards of underground mining in the Weeping Water district are in some ways yet to be

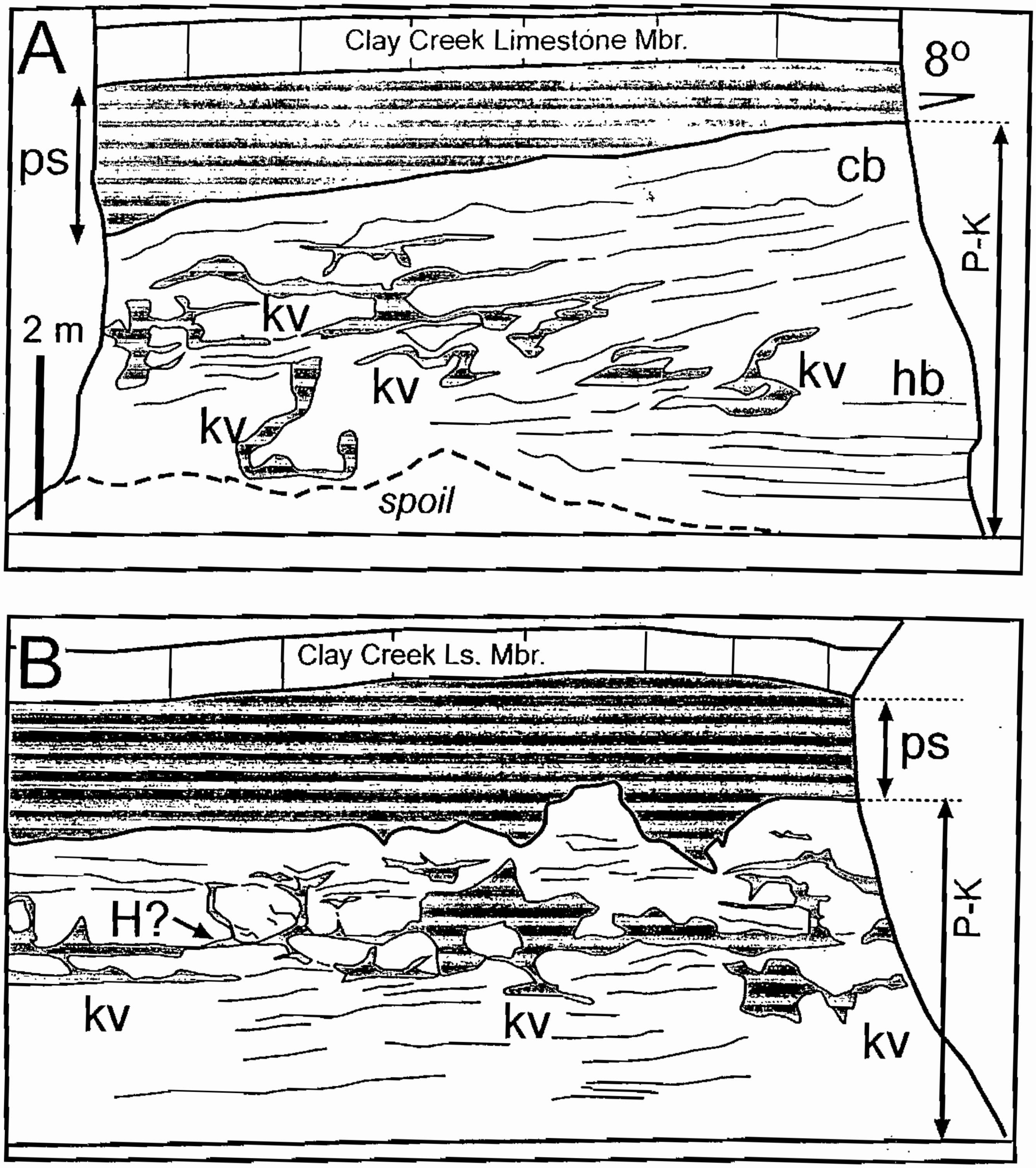


Figure 10. Partial view of approximately 50 m-diameter karstic depression at top of Plattsmouth-Kereford (P-K) interval, Martin Marietta mine, Weeping Water, Nebraska. A. End-view of pillar showing paleosols (ps) developed in red clastic mustone and karstic voids (kv). Weathered upper surface of P-K interval dips about 8° toward axis of depression. B. Partial longitidunal view of same depression, at right angles to A above (A articulated at the right-hand side of B). Note red clastic mustone and karstic voids (kv), as well as probable Heumader Shale Member (H?) merging with mud infillings of voids.

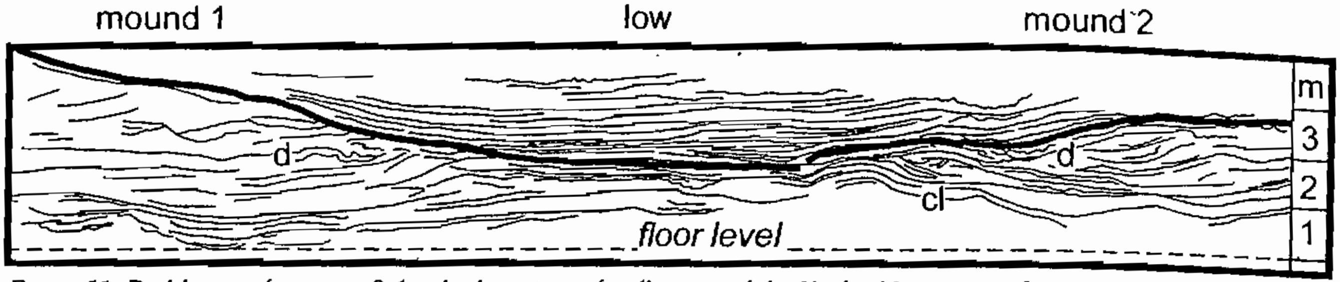


Figure 11. Bedding surfaces in a 3-4 m-high section of wall in one of the Kerford Limestone Company's mines at Weeping Water, Nebraska. Note apparent mounds, probable syndepositionally-cemented lens with draped laminae around it (cl), and what appear to be deformed, possibly slumped, laminae (d).

demonstrated. Speculatively, the low-angle bedding surfaces so common in the lower part of the Plattsmouth Limestone could present future mine stability problems (cf. Grau and Prosser, 1996; Iannacchione, 1999), but these surfaces never appear to intersect the roof line, and thus their potential effect is minimal. Karstic depressions over the Plattsmouth, however, will eventually prove to be a more significant problem in future roof control, as may the large slickensides within the mudstone (paleosols) fills of these depressions.

In the spring of 2002, Cass County, Nebraska officials discussed the potential of ground collapse under county roads that cross over present mine works in the Weeping Water area. Both the Conservation and Survey Division (Nebraska Geological Survey) and a local mine operator were queried about this potential, and in the end, the mine operator and the county tentatively agreed that selective, pre-emptive backfilling of works under existing roads would be a mutually-agreeable preventative solution.

CONCLUDING COMMENTS

Geologic factors that affect underground limestone mining are easily defined and constitute a limited set of entities. When and where many of the problems prove to be problematic, established engineering procedures can be applied as solutions. Even very deep mining operations, although still unproven in the Midcontinent, can prove to be profitable if planned and managed correctly. Thus, underground mining should be seriously considered as a viable option in many areas where surfaces resources are limited, suburban sprawl is increasing, public reaction to surface mining is negative, and yet the demand for limestone products will continue (cf. Lee and White, 1993; Bernardos et al., 2001). Underground mining should now be considered an important aspect of planning for supply and demand over 20-50 year time scales in most of the eastern half of the U.S. The historical regionality of techniques, modes, and target horizons of underground limestone mining, as described in this paper, is already breaking down in the Midcontinent because of such changes. Barring unforeseen economic or technological developments, further change is certain.

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