Lithification of Clastic Sediments—Part I: Significance, Processes, and Modeling

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Abstract

Lithification is important to diluvial geology and the mineral industry, especially petroleum. Lithification can be used to determine the amount of eroded overburden, which we apply to North Central Montana. There are also five other ways to determine erosion and, using these, secular scientists have estimated immense continental erosion. We delve into the variables affecting lithification, emphasizing diagenesis and, in particular, mechanical and chemical compaction of sandstone. Despite many difficulties, the study of lithification has produced some data useful in inferring burial depths for sandstones from compaction microtextures.

Key Words: lithification, sandstone, burial depth, erosion, compaction, cementation

Introduction to Lithification

Sedimentary rocks are a powerful witness for the Genesis Flood (Oard and Reed, 2017). They come in layers that sometimes stretch thousands of kilometers in one direction, and in vertical sequences that show very little if any erosion between and within layers. The big picture defies the uniformitarian principle upon which all secular geology is based. Erosional features on the Earth's surface show numerous features difficult to explain by uniformitarianism, such as planation surfaces, long transported resistant rocks, tall erosional remnants, pediments, water gaps, and submarine canyons (Oard, 2008, 2013).

Sedimentary rocks cover about 70% of the continents and can range from zero to over 20,000 m (66,000 ft.) thick in some deep basins. For instance, the 350 by 550 km (220 by 345 mi.) South Caspian Basin has 26–28 km (85,000–92,000 ft.) of sediment, 12–14 km (39,000–46,000 ft.) of which is dated as Cenozoic (Knapp et al., 2004)! The top 3 km (10,000 ft.) of this sediment is dated Quaternary (Richardson et al., 2011). However, sedimentary rocks still present questions for creation scientists, as well as uniformitarian scientists.

Once sediments accumulate, they need to be lithified, i.e., cemented to form sedimentary rocks. We commonly see sedimentary rocks on the surface below a thin soil layer and sequences of various types of sedimentary rocks in cliffs that are almost always cemented. How did they get cemented? Was it during the Flood? Were near-surface sediments cemented after the Deluge? Or can it be both? Some creation scientists suggest that the topmost of the diluvial sedimentary rocks were commonly unlithified right after the Flood (Whitmore, 2013). Whitcomb and Morris (1961, p. 153) stated that the sediments in the Grand Canyon area "were still comparatively soft and unconsolidated." Unlithified sediments play into the idea that the Cenozoic strata were laid down

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by postdiluvial catastrophes with great erosion and redeposition of unlithified or poorly lithified diluvial sediments, amounting to 1,000 m or more (Whitmore, 2013).

Unlithified sediments likely occurred on top of the sediment pile at the peak of the Biblical Flood since cementation requires mechanical and chemical compaction, as we will describe in this paper. Then why are surficial sedimentary rocks mostly lithified, as shown by large structures resting on solid foundations (Figures 1 and 2)? Such lithification requires hundreds of meters of overburden to provide pressure overburden that is now missing. This erosion was not from post-Flood catastrophes (Oard, 2019), but occurred at the Recessional Stage of the Deluge when about 1,900 m of sediments were eroded off the continents forming the continental shelf and slope (Oard et al., 2023).

Economic and Scientific Importance of Lithification

The degree and nature of lithification is of great economic and scientific importance. Geotechnical engineering focuses on geology as the interface with manmade structures, and the differences in response between soils and rock in bearing capacity, deformation, and seismic performance can be dramatic. Failure to recognize the importance of geotechnical factors can lead to failure of buildings, bridges, and other structures. Mining, both surface and underground, must take into account the geotechnical properties of the earth materials in order to be both safe and economical. Both degree and manner of lithification have important ramifications for petroleum reservoir rocks. Degree of lithification is also of great importance to the construction industry, which is dependent on earth materials.

Figure 1. The foundation for the 6,000-ton catalytic cracker in the center of this picture is founded 13.7 m (45 ft.) into upper Kootenai Formation sedimentary bedrock to prevent even a few millimeters of differential settlement. The bedrock consists predominantly of claystone with sandstone interbeds (fine-grained, argillaceous sandstones).

Lithification impacts classification (e.g., sand, sandstone, and quartzite) and understanding of possible depositional and diagenetic processes. The resulting hardness, strength, and abrasion resistance are relevant to resistance to erosion, which is not only important to civil and geotechnical engineering, but also to explanation of topographic development and geomorphology, including development of the landscape surfaces on which we live. The rheological properties dramatically impact geomechanics and the potential for deformation of the strata.

Lithification Can Imply Eroded Overburden

When sediment is laid down, it has a relatively high porosity. As more sediment is laid down, the pressure of the sediment above, the lithostatic pressure, squeezes out the air or other fluid between the framework grains. The increased pressure causes changes in the framework grains and matrix as porosity decreases. Then cementing chemicals, or cement, are added to the grains to cement them together, and this reduces both the porosity and permeability. If all the variables can be estimated,

Figure 2. This 30-year-old reinforced stone foundation was built with upper Kootenai sandstone quarried 135 years ago, refaced, and reused. While the reinforced concrete piers and grade beams it sits on have an unconfined compressive strength of 5,000 psi (34 MPa), the sandstone averages 11,000 psi (75 MPa). The primary stone is a medium-bedded arkosic sandstone (immature, fine-grained to medium-grained subarkose) with minor iron cement; some of the stone is argillaceous (sublitharenite) but it still exhibits a strength of at least 7,000 psi (48 MPa).

then a rough estimate of the amount of overburden can be calculated, a major goal of this research project. If the sedimentary rocks are located at the surface, then this procedure will also give us a measure of the amount of erosion. Since many areas, such as the plains, do not have other means to estimate the eroded overburden, the lithification characteristics of surficial sandstones would be a useful tool to infer the amount of erosion.

North Central Montana Erosion

Our study area is in North Central Montana, an area important to historical geology. The amount of erosion over the plains of Central Montana with its isolated mountain ranges was first estimated to be "immense" by William Morris Davis of Harvard University, who proposed his famous "cycle of erosion" or "geographical cycle" in the late 1800s based on this area (Oard, 2013). He first threw out the Genesis Flood for an explanation of geology and geomorphology and assumed uniformitarianism. He surmised extensive erosion in the area that planed the land down into several erosion surfaces or peneplains. He recognized as much as 1,500 m (4,900 ft.) of erosion in the area based on erosional remnants of dikes and sills and on the igneous rocks in the Highwood and Crazy Mountains of Central Montana (Chorley et al., 1973).

Estimating the Amount of Erosion

In a subsequent paper, we will be estimating the amount of erosion in North Central Montana by several methods, including the features of sandstones at or near the surface. We will briefly examine some of the many methods for estimating the amount of erosion (and thus burial depth of a particular stratum) in a region. Some of them are indirect, such as chemical methods that rely on radiometric dating, which in turn are based on many uniformitarian assumptions. We will not use these. But there are five more direct methods.

One of these methods is based on the height of erosional remnants. This gives a minimum estimate because we do not know how thick the sediments originally were above the top of the erosional remnants. Since erosional remnants are often sedimentary rocks, and the rock is often cemented, we can safely assume hundreds of meters more of eroded sediments above the top of the erosional remnants in many cases (see below), since overburden is required to provide the pressure to compact and, for some important processes (Table I), to cement the sediments to rock. This method is illustrated in Figure 3.

A second method is to measure the erosion from an eroded anticline or dome which rose by the bowing up of sedimentary rocks. When anticlines uplift, the top is stretched and cracked. Thus, the center of the anticline would have been much more vulnerable to erosion, especially with Floodwater moving at high velocity above it. So, the top of the anticline would have been eroded, leaving the sides or limbs more intact. Measuring the amount of erosion at the center of the anticline is relatively easy using trigonometry. One projects the dip of the sedimentary rocks found along the sides of the eroded anticline up toward the top of the anticline and then estimates the thickness of the missing rock. This calculation assumes

Table I. Sources of Silica

Source	Process	Significance
pressure solution	localized stresses induce silica to enter solution and precipitate nearby	minor to major source of silica; proximate, so no transport problem
feldspar dissolution	dissolution of feldspar produces silicic acid and cations	minor to major source of silica depending on parent material
physil (clay mineral and mica) transformation	silica released during transformation from kaolinite to smectite and illite, and from smectite to chlorite	produces additional free silica from altered feldspars and volcanic ash
mudstone fluid expulsion	silica-rich fluids expelled from consolidating sediments	minor source, limited transport distance
fluid transport	silica dissolved elsewhere transported in ground water or hydrothermal fluids	fluid transport limits effectiveness, deposition is negative feedback
volcanic ash	dissolution of feldspar, glasses	amount of silica depends on ash mineralogy and environment
biogenic silica	dissolution or opalization of sponge spicules, radiolaria, diatoms	minor source of silica but sometimes observed

the thicknesses of the sedimentary layers were the same over the top of the anticline (i.e., a *concentric* fold), but sometimes the layers were thinner (a *similar* fold). So, the amount of erosion may be overestimated, especially if exposures are too few to ascertain whether concentric or similar folds are present. And since rock units commonly thin and thicken with distance, caution must be used when estimating any volume eroded over great distances. This geometric method is shown in Figure 4 and was the one we used for estimating 4,200–5,100 m (13,800–16,000 ft.) of erosion over the San Rafael Swell of the northwest Colorado Plateau (Oard and Klevberg, 2008). This erosion is close to the estimated average of 2,500 to 5,000 m (8,200–16,700 ft.) that has occurred over the *entire* Colorado Plateau, an area of 337,000 km^2 (130,000 mi.^{2})!

Note also that the top formation is the Green River Formation (GRF). Some creation scientists believe the GRF was deposited in a postdiluvial lake (i.e., Whitmore, 2006). However, Oard and Klevberg (2008) pointed out that the area of the GRF is 40,000 km^2 (15,600 mi.^{2}) and averages 2.5 km (1.56 mi.) deep. The amount of oil in the shale is enough to supply all the oil needs of the United States for 100 years! Tropical and subtropical fossils, such as palms and crocodiles, are found in the GRF at a continental interior site straddling the continental divide at about 2,100–2,400 m (7,000–8,000 ft.) above sea level (asl). How can the GRF be from a postdiluvial

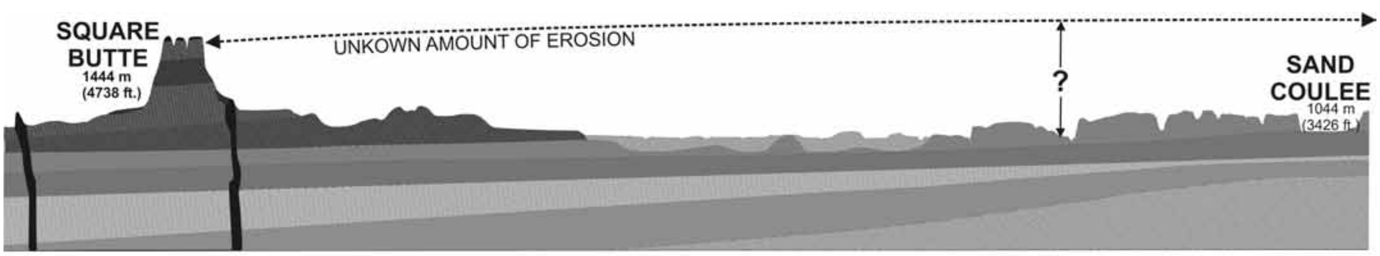

Figure 3. Cross section of formations south of Great Falls, Montana, showing interpolated line for estimating the amount of overburden eroded from an arbitrary sample location. Section is 50 km long, and vertical exaggeration is 10:1. Data are plentiful and deformation minor, but the uncertainties in the estimate are still significant.

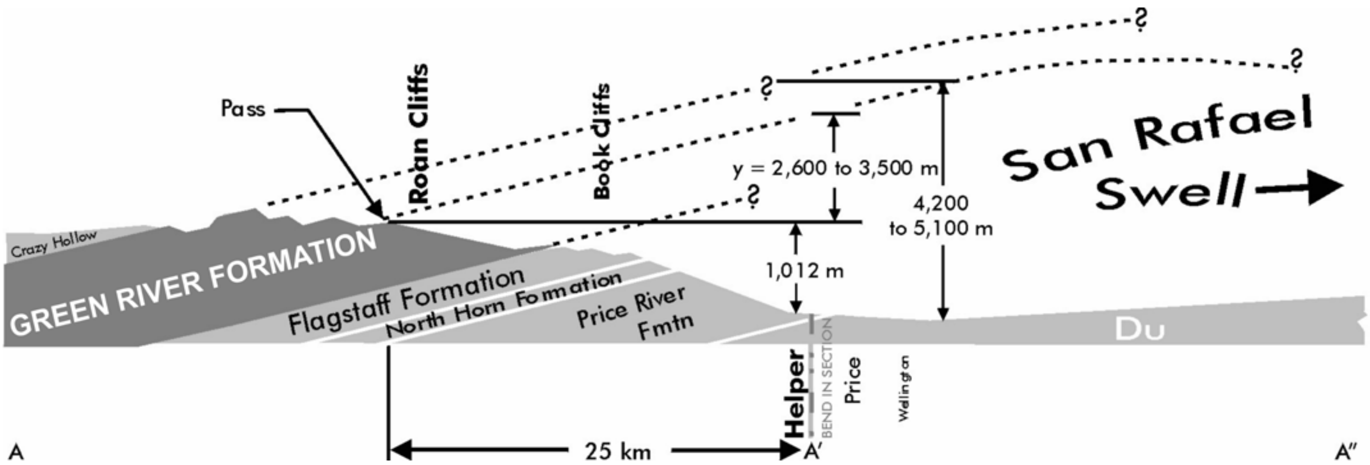

Figure 4. Estimating eroded cover from geometry of a fold. Modified from Figure 2 in Oard and Klevberg (2008).

lake? Just considering the erosion of the San Rafael Swell, those who believe the GRF is postdiluvial must believe that the GRF was laid down over the area, a huge anticline uplifted with 4,200–5,100 m (13,800–16,700 ft.) of erosion of the center, and the erosional debris not found at the edge of the anticline but apparently swept totally off the continent.

A third method of estimating the amount of erosion is by the rank of coal found at or near the surface. The formation of coal from plant material is generally related to the temperature (Thomas, 2013). Coal is made up of four ranks: lignite, sub-bituminous, bituminous, and anthracite, going from lowest to highest rank, with subdivisions within each of these. The hotter the temperature, the higher the rank. Thus, the rank of coal is typically related to the depth of burial and heating from the resultant thermal gradient. On this basis, coal near the surface indicates hundreds to thousands of meters of erosion of sedimentary rocks in the area. The amount of erosion depends upon assumptions, such as possible heating from a nearby heat source, the change in temperature with depth (i.e., thermal gradient), the existence of catalysts that can speed up the change, etc. So, like inferences about natural history typically are, coal rank estimates of erosion are educated guesses. The rank of bituminous and anthracite coal gave an estimate of about 4.0– 6.4 km (2.5–4 mi.) of sedimentary rock eroded from the Valley and Ridge Province just west of the Blue Ridge Mountains (Oard, 2011, 2013).

A fourth method of estimating the amount of erosion is to deduce the amount of continental margin sediments and assume that they originated from the adjacent continent. This estimate can be in error due to possible lateral input of sediments and a poor estimate of the offshore sediments. Based on this method, Oard (2013) estimated about 6,000 m (20,000 ft.) of erosion for the central Appalachians, about the same as the coal rank method. He also estimated about 2,400 m (8,000 ft.) of erosion from southwest Africa (Oard, 2017). A recent estimate of the amount of sediment in the oceans, especially the thick continental margin, has recently been made (Straume et al., 2019). If all the continental margin sediments resulted from diluvial runoff and 50% of sediments in the deep ocean, diluvial erosion during the Recessional Stage averaged about 1,900 m (6,230 ft.), as indicated on Figure 9 (Oard et al, 2023).

A fifth method of estimating burial depth is stratigraphically. The position of a given stratum relative to formations up-section can be used to estimate the amount of material previously overlying the subject stratum. This method is dependent on available outcrop and subcrop, along with additional geophysical data. It is also dependent on the veracity of correlation. Problems in stratigraphy have been pointed out by various authors (Klevberg, 1999, 2000a, 2000b; Berthault, 2002b, 2010; Oard and Reed, 2006), and this method is best suited to local or small regional application; application at a large regional extent may require many local studies integrated over the entire region.

Continental Erosion Was Immense

Evolutionary scientists have also made estimates in this range in local areas or regions. A total of more than 2,000 m (6,500 ft.) of strata has apparently disappeared from the Rocky Mountains and foothills of southern Canada (Schmidt, 1989; Osborn et al., 2006). Similar erosion has likely occurred on other continents, especially mountainous areas (King, 1983; Pazzaglia and Gardner, 2000). For example, 6,000 m (20,000 ft.) of rock probably was removed from the Flinders Range in South Australia (Chorley et al., 1984; Twidale and Campbell, 2005)! An estimated 3,000 m (10,000 ft.) of rock has been eroded from the Welch Mountains of the United Kingdom (Small, 1978). Partridge believes that more 1,000–3,000 m of rock has been removed from southern Africa since the Cretaceous Period in the uniformitarian timescale (Partridge, 1998). A total of 8,000–11,000 m (26,000–36,000 ft.) of sedimentary rocks are believed to have been removed from above the Vredefort impact crater, South Africa, while 5,000 m (16,500 ft.) was erased from above the Sudbury impact crater in southern Ontario (Senft and Steward, 2009).

These values of erosion reinforce the deduction by Oard et al. (2023) that an average of 1,900 m (6,320 ft.) of continental erosion occurred during the Recessive Stage of the Genesis Flood. The Recessive Stage was a powerful erosive mechanism that scoured the continents leaving behind unique landforms that are very difficult to impossible to explain by uniformitarianism. It also tells us that the sediments at or near the surface would most likely be lithified and unable to mass waste (Whitmore, 2013) during hypothetical postdiluvial catastrophes (Oard, 2019). Moreover, this 1,900 m (6,320 ft.) must be added back onto the continent to obtain a true picture of the amount of sediments collected on the continent at the peak of the Deluge. Adding 1,900 m (6,320 ft.) to the sedimentary rocks left on the continents will give us further insights into the powerful mechanisms of erosion, transport, and deposition during the Inundatory Stage.

Table II. Sediment Classification

Sediment Type	Description	Size	Resulting Lithologies
clastic	boulder	>256 mm	conglomerate
	cobble	64 – 256 mm	
	pebble	4.75 – 64 mm	
	sand	75µm – 4.75 mm	sandstone
	silt	5 – 75 µm	siltstone
	clay	<5 µm	mudrocks (various)
chemical	ions	dissolved	carbonates, precipitates

The Nature of Lithification

Deposition, diagenesis, and erosion in the past have produced what we observe in the present. Deposition explains the extent and magnitude of sedimentary rock bodies. Depositional structures and fabrics have led increasingly to semi-quantitative and quantitative inferences of depositional environment (fluid mechanics and energy), especially since the salient work of Berthault (2002a). Deposition, particularly lateral extent, and stratigraphy have been important emphases in the diluvialist renaissance following publication of *The Genesis Flood* (Whitcomb and Morris, 1961).

Diagenesis has received less attention and is the focus of this paper. It describes the changes occurring within a sediment body after deposition and includes compaction and cementation. As diagenesis affects rheological properties, it also impacts the timing and mechanisms of folding versus faulting. The problem specifically addressed here is whether burial depth can be estimated from diagenetic changes in a sedimentary stratum.

Geomorphology has received increasing attention in recent years (Oard, 2008, 2013; Whitmore, 2013). Based on the historical account presented in Genesis, an extensive erosion surface can be anticipated to dominate the continents. Geomorphology is therefore a key area of research for diluvialists. It also provides one variable in the quest for a means of estimating burial depths.

Analyzing Lithification

Sediments are classified as clastic or chemical and further distinguished by particle size or the type of dissolved ions from which they precipitated (Table II). As shown in Table II, gravel lithifies to form conglomerate, a lithology very important as an indicator of a high-energy depositional environment, but not especially common in the rock record. Sandstone, siltstone, claystone, and shale are much more common. Limestone is an example of a chemical sedimentary rock. Clastic sedimentary rocks respond to pressure and temperature during diagenesis and thus may be useful as burial-depth indicators. We are unaware of any corresponding properties in chemical sedimentary rocks.

The ideal lithology for use as a burial depth indicator would be a clastic sedimentary rock that would respond readily and predictably to overburden pressure. A well-sorted (poorly graded) gravel or sand would transmit the overburden loading immediately via particle-to-particle contact. Mudrocks, with their fine-grained matrix, would tend to be affected by pore pressures and would therefore respond much more slowly to overburden pressure. Sandstones are much more common than breccias and conglomerates and, being finer grained, provide a smoother response statistically to loading (Bjørlykke, 2014). As important petroleum reservoir rocks, sandstones have received much attention from the petroleum industry as well; thus, our attention is primarily on the use of sandstones as depth indicators. Coal has also received some study, however, and we will therefore include information from the literature on coal rank versus depth.

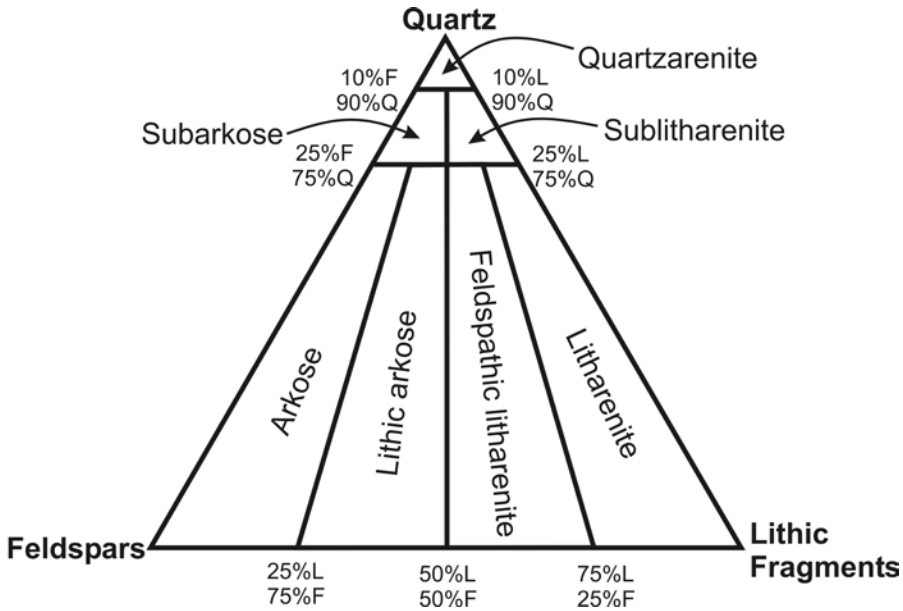

Figure 5. The commonly used Folk (1974) sandstone classification system was used in this study. *Mature* sandstones have well sorted (relatively uniform size), well rounded grains. Because of the resistance to physical and chemical weathering exhibited by quartz, mature sandstones tend to move toward the apex of the triangle (i.e., become more quartzose).

Ideal Lithology

In regard to sandstones, the ideal lithology would respond measurably to overburden pressure and exhibit the fewest possible potentially confounding variables. Finding an ideal quartzose sandstone, such as quartz arenite (also spelled "quartzarenite"), would greatly help in determining the amount of eroded overburden, but many sandstones are more complicated than this ideal (Figure 5). As a result, a nonideal sandstone presents innumerable complications, and other variables enter the process of mechanical and chemical compaction (i.e., cementation) that result in a cemented sedimentary rock (Pettijohn, 1975; Pettijohn et al., 1987). In these cases, it is almost impossible to infer the applied stress from overburden that would have been required to lithify the sediment. To more realistically estimate burial depth requires a lithology approximating this simpler "ideal" sandstone.

Mudrocks

Mudrocks make up about 50% of sedimentary rocks (Boggs, 2012), although estimates have varied. Mud is a mixture of silt and clay. Mudrocks include mudstone, shale, siltstone, and claystone. Mudstone is cemented mud without fine laminations, while shale is a mudrock with fine laminations (Neuendorf et al., 2005). Siltstone is a cemented silt, which is composed of over 50% silt-sized particles without laminations (Neuendorf et al., 2005). Claystone is consolidated clay that has more than 67% clay-sized particles (Neuendorf et al., 2005). Examples are shown in Figure 6.

Processes of Diagenesis

Mechanical compaction is an important step in the lithification process. It may include mineral transformations. In general, mechanical compaction appears to dominate the early (shallower, cooler) stage, while cementation dominates the later (deeper, hotter) stage. As conditions change, equilibrium may favor different minerals, and mineral transformations will occur whenever activation energies are not too high. To estimate burial depths in the past from lithologic properties in the present, it is important to be able to distinguish compaction effects from cementation effects. The latter can interfere with the former.

Mechanical Compaction

Several important variables affect mechanical compaction of sands (Table III). Cementation ("chemical compaction") creates bonds between particles and hinders compaction. Mechanical compaction and cementation reduce porosity and thus the space to accommodate transmission and storage of water or hydrocarbons. Another diagenetic process, dissolution, can counter these processes and increase porosity (Cox, 1985; Taylor et al., 2010), but since our concern in this paper is lithification, we will concentrate on compaction and cementation. This is a very large and complex field of study, but Table

Figure 6. Examples of the sedimentary rocks referred to in Table III. A) Conglomerate, Cypress Hills Formation. B) Sandstone and shale, probably Greyson Formation, Belt Supergroup. C) Siltstone and claystone, probably Spokane Formation, Belt Supergroup. D) Clay and claystone, Tullock Member, Fort Union Formation. E) Limestone, Helena Formation, Belt Supergroup.

Table III. Factors in Sandstone Mechanical Compaction

Factor	Effect on Sand Compaction: Low Pressure*	Effect on Sand Compaction: High Pressure*	References
grain size	more for large grains	reduced effect (crushed grains)	6,7
mineralogy, breakage	$CaCO_3$ > SiO_2	reduced effect for $CaCO_3$	3,7
mineralogy, deformation	more for lithic grains	greatly reduced effect	5
mineralogy, dissolution	more if feldspars dissolved	reduced, feldspars → SiO_2	1
grain shape	more for angular grains	reduced effect (crushed grains)	7
sorting	more for well sorted	reduced effect (crushed grains)	2
matrix	enhanced by matrix	reduced by matrix	7
temperature	reduced if >80°C - silica available, creates overgrowths		4
pressure solution	may increase for $CaCO_3$	increased for $CaCO_3$, SiO_2 also	4
grain coatings	hinder cementation, so greater compaction		4
cements	reduce compaction	little effect (already compact)	1
anhedral, large quartz	fast quartz overgrowth until crystals become euhedral		3,6
polycrystalline quartz	hinder cementation, so greater compaction		3,6

*Approximately 0–25 MPa for low and 25–50 MPa for high, but inflection point varies greatly between deposits.
1 Bjørlykke, 2014
2 Sun et al., 2020
3 Prajapati et al., 2020
4 Oye et al., 2020
5 Xia et al., 2020
6 Lander et al., 2008
7 Chuhan et al., 2003

III provides an overview of these factors. For example, shallower burial (lower pressure) results in more compaction for large sand grains than small ones. As the grains crush, the smaller particles fit between the bigger ones and reduce the stress on individual grains. By the time the stratum is deeply buried (high pressure), it is much more resistant to further compaction. As shown in the second row of the table, mineralogy also influences this. If there is more calcite than silica ($CaCO_3$>SiO_2), then the weaker calcite grains will break more quickly and result in faster compaction, but by the time deep burial (high pressure) is reached, they will have already filled in voids and begun to resist additional compaction.

An idealized (simplified) pattern of sandstone cementation begins with continuous deep burial. At first the sand is compacted with a beginning porosity of 40 to 45%, depending upon a number of variables (Paxton et al., 2002). Simple mechanical compaction with increasing pressure causes the grains to change arrangement by slipping and sliding past one another, fracturing, undergoing minor pressure solution, and deformation of compressible grains, resulting in a more compact arrangement with less porosity (Brzesowsky et al., 2014; Xia et al., 2020).

Porosity decreases by mechanical compression down to 26%, which is reached at about 2,000 to 2,500 m (6,650–8,200 ft.) (Stricker et al., 2016b; Therkelsen, 2016) as long as no other cements are added before these depths. This corresponds to a lithostatic pressure of 20 to 25 megapascals (MPa). There is generally no further porosity loss due to mechanical compaction below this depth, where the temperature is usually around 70°C (158°F) assuming an average geothermal gradient as observed today of 20 to 30°C/1,000 m. However, mechanical compaction can continue down to 5,000 m (16,000 ft.) in basins with a low geothermal gradient (Fawad et al., 2011), such as in the Gulf of Mexico (Taylor et al., 2010). It is the *temperature* that determines the depth of effective mechanical compaction.

After mechanical compaction, so-called chemical compaction takes over (the term "chemical compaction" is entrenched but unfortunate wording, for while porosity generally decreases, it is often not the result of a reduction in volume but rather deposition of cement). Cementation can occur during mechanical compaction, such as the addition of calcite cement at shallow burial depths or other diagenetic effects, but for the idealized example, we are assuming a pure silica sand with no additions during mechanical compaction. More heterogenous or fine-grained sediments may deviate significantly from this example, particularly mudrocks.

Mudrocks are formed primarily by compaction rather than cementation, which is different from sandstone. It seems that mud is easier to cement internally than sand, although some mudstones and other mudrocks also have silica cement. Most mudrocks are largely cemented by the physils (i.e., clay minerals and micas—not all clay is composed of micas or *clay minerals*) that dominate the mineral composition (Table IV). Some researchers believe that quartz cement for mudstones is mostly from an open system, such as is argued for the oil-bearing Wilcox mudstone of the Gulf of Mexico and Texas coastal area (Day-Stirrat et al., 2010). First the mud is mechanically compacted: "…mechanical compaction dominates initially with grains becoming more closely packed together through slippage, rotation and breakage" (Goulty et al., 2016, p. 703). Mechanical compaction commonly goes down to about 2,000 m (6,650 ft.) before chemical compaction (i.e., recrystallization and/or cementation) starts (Peltonan et al., 2009). Provided enough potassium is available, commonly from feldspar dissolution and transformation of smectite to illite at 65–70°C (149–158°F), mud changes to mudstone. It appears that the potassium must come from an open system (Day-Stirrat et al., 2011). The pore water

Table IV. Common Cements

Cement Type	Process	Strength	Dominant Bonding
clay	grain coatings	low	Van der Waals
iron	grain coatings, pore filling	low – medium	ionic
carbonate	grain contacts, pore filling	medium	ionic
silica	grain overgrowths	high	covalent

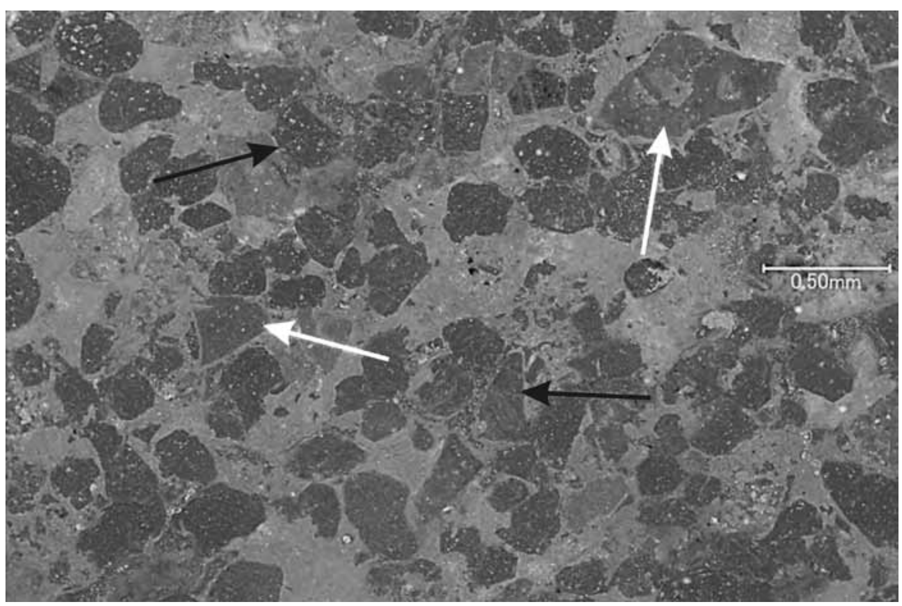

Figure 7. Cementation may occur during diagenesis, as shown by the iron cement in this sandstone sample from North-Central Montana. Black arrows point to detrital quartz grains, white arrows point to polycrystalline lithic fragments, and light gray between them is iron oxide cement (actual color is yellow ocher to orange).

must be released, or the mud becomes overpressurized and, with interbedded sand, the pore water is mostly expelled into the sandstones during compaction (Bjørlykke, 2011). The permeability of mudstones varies by 10 orders of magnitude, with the biggest differences in shallow environments, those less than approximately 500 m (1,600 ft.) depth (Mondol et al., 2008).

Chemical Cementation

There are various types of cement (Table IV). The strongest type is silica (silicon dioxide). Other types of cement are carbonates, iron oxides, and various types of clay minerals (Cui et al., 2017). Silica is the most common cementing agent for sandstones (McBride, 1989; Walderhaug and Bjørkum, 2003), and it is an especially strong cement. Carbonates are weaker cements and break down from chemical reactions, especially with acids. Cements can also change type during diagenesis, such as calcite being replaced by dolomite. Cements can be deposited during diagenesis (Figure 7), but they can also dissolve during diagenesis.

Above 70°C (158°F), silica cementation starts (Oye et al., 2020). In the simplest case, the cement consists of silica that is added to the study volume. Silica cementation depends upon the temperature and various kinetic effects (Molenaar et al., 2007; Xi et al., 2015; Niazi et al., 2019). The solubility of quartz increases exponentially above 70°C (158°F). Kinetic effects are overcome with increasing temperature and a high-silica supersaturation (Bjørlykke, 2014). One kinetic effect is the lack of surface area on the quartz grains because of a clay coating. Silica is added by several sometimes-controversial internal mechanisms (Table I) and one external mechanism, fluid flow (Oye et al., 2018; Wang et al., 2020).

A sand can be partially or totally cemented at depths shallower than 2,000 to 2,500 m (6,650–8,200 ft.) during mechanical compaction, especially by carbonate cement (Bjørlykke, 2014; Cui et al., 2017). The most common type of carbonate cement is calcite, but dolomite sometimes is the cement (Taylor and Machent, 2011). The carbonate cement can originate from a variety of mechanisms, such as dissolution of shallowly buried mud (Wang et al., 2016). Its solubility depends upon temperature, pressure, and pH. It is common to have interbeds of mudstone or carbonate within sandstone bodies, so it is not difficult for carbonate cement to originate nearby. The amount of carbonate cement can range up to about 30% of the intergranular volume, which is the sum of voids, matrix particles, and cement within the sediment.

If cement is added before the maximum mechanical compaction is reached in sandstones, then researchers know that cementation occurred *during* mechanical compaction. One can sometimes tell how deeply buried sandstones were by calculating the amount of the mechanical compaction above 26% porosity in these situations—or at least the *minimum* overburden to achieve the observed degree of compaction. The size and shape of quartz sand crystals also has a major impact on cementation rates and resulting porosity (Lander et al., 2008).

Grain coatings can greatly inhibit silica cementation because of a lack of bonding sites to the quartz framework grains (Busch et al., 2017), resulting in continued high porosity. So, the inhibition effect depends upon how much of the surface area of framework grains is covered (Busch et. al., 2020). Thus, the grain coating is an important variable for oil and gas accumulation (Busch et al., 2017; Hansen et al., 2017). For instance, clay, microquartz, mica, and hematite on sandstone grains retard quartz cementation (Harwood et al., 2013; Stricker et al., 2016b; Wang et al., 2017). The quartz cement cannot nucleate from coated quartz framework grains, and so porosity remains higher than expected (Hansen et al., 2017). This is one of the reasons why some deep sandstones are uncemented, such as some North Sea sands 2,500 m (8,200 ft.) deep (Therkelsen, 2016). This is also the reason why some North Sea sands have high porosity, up to 35% at 3,500 m (11,480 ft.) (Stricker et al., 2016a, 2016b, 2017; Maast, 2017). Such sandstones make ideal reservoirs for hydrocarbon accumulation.

Clay minerals (physils) are very common as cements in mudrocks, but in sandstones they often interfere with precipitation of the much stronger silica cement that is the primary diagenetic cement. Three phyllosilicate minerals are especially effective in coating quartz sand grains: chlorite (Taylor et al., 2010; Dowey et al., 2012), illite (Hansen et al., 2017), and mixed smectite-illite (Busch et al., 2020); see also Table I. Chlorite commonly comes from low grade metamorphism and the diagenesis of volcanic fragments, while illite mostly originates from the dissolution of feldspar grains, first changing to smectite clay that transforms into illite clay at temperatures of 65 to 70°C (149 to 158°F) (Goulty et al., 2016). Clay coatings depend upon the available clay, the amount of fluid flow, and the subsequent diagenetic pathway (Busch et al., 2020). Microquartz, which likely originated by the smectite-to-illite diagenetic reaction (Thyberg et al., 2010), retards quartz cementation because it creates a kinetic barrier (Taylor et al., 2010). Generally, the more the surface area of the quartz framework grains, the easier it is to add quartz cement (Walderhaug and Bjørkum, 2003). The lack of quartz cement is not a function of the amount of quartz in the pore water, which can be substantial at high temperatures, but on kinetic factors, such as the available surface area of quartz (Hansen et al., 2017; Emmanuel et al., 2020). Early carbonate cementation and clay coatings result in a wide range in cementation, porosity, and permeability for a given lithostatic pressure (Wang et al., 2017).

[To simplify analysis of the lithification process, we will start off with the ideal (fewest variables) cementation of a pure quartz sand into a sandstone with no matrix. Cementation of other sandstones and other types of sedimentary rocks is far more complex. A wide literature exists on sandstones and the cementation process, mainly because hydrocarbons are especially found within their pores and these are areas of active research by the oil and gas industry. There are two main types of simultaneous processes during the time cementation occurs: mechanical compaction and cementation ("chemical compaction")—they are not mutually exclusive. Mineral transformations may also be important.]

Authigenic Minerals

Numerous other diagenetic effects can occur during the cementing process, some of which are mentioned in Table I, often simultaneously (Stroker et al., 2013; Yuan et al., 2015; Li et al., 2017; Sun et al., 2020). As a result of feldspar dissolution, several physils can form and even change from one to another, releasing silica (Paxton et al., 2002; Peltonen et al., 2009). Cements can form and be dissolved or partially dissolved (Monsees et al., 2020). A sandstone can be cemented by more than one cement. Even some of the framework grains can be dissolved and replaced by cement (Taylor and Machent, 2011). The timing of each step in the cementation process can sometimes be discerned by cross-cutting relationships as seen in thin sections. Fluid inclusions in the rock can sometimes tell us the chemistry and temperature during diagenesis (Busch et al., 2017). Authigenic minerals which are produced by diagenesis are very common in sandstones, making up 13 to 59% of the rock, with the average about 26% (Therkelsen, 2016).

Figure 8. The laboratory at Norges Geotekniske Institutt (the Norwegian Geotechnical Institute) as it appeared from the mezzanine during Klevberg's visit in 2009. Cutting edge testing for the oil industry has occurred in this facility.

Modeling Lithification

There is a need to develop an effective model of sedimentary lithification to be used in a Flood model. To be useful, a lithification model must be more than speculation about natural history; it must be as quantitative and empirical as possible.

Need for a Lithification Model

Many of the concepts surrounding formation of sedimentary rocks are beliefs based on worldviews, sometimes with little or no scientific research behind them (Reed, 2001; Mortenson, 2004; Rudwick, 2005; Klevberg, 2014). Where economic interests rule, however, a more realistic approach is often developed to meet practical needs. We have previously proposed researching the equations of state for lithification directly through laboratory experimentation, but this represents a significant outlay of time and money (Figure 8). Thankfully, the oil industry has been willing to invest in some of this nascent lithification experimentation (Bjørlykke, 2014), and since sandstones are important reservoir rocks, much of the attention has centered on sandstones.

Tas Walker (1994) developed a natural history model based on the events recorded in Genesis. Walker's Biblical geological model has an Inundatory Stage, in which the water rises to a peak, followed by the Recessive Stage, in which the water runs off the uplifting continents and mountains and into the ocean basins and valleys

(Psalm 104:8) (Barrick, 2018; Barrick et al., 2020). These two stages are similar in all floods, especially flash floods, and Walker has divided the two stages into five phases. Thick sediments would have been deposited on the continents during the Inundatory Stage, which peaked at about Day 150 (Boyd and Snelling, 2014; Johnson and Clarey, 2021). Reed (personal communication, 2023) is in the process of estimating the amount of sedimentary rocks left on North America. Preliminary estimates are in the ballpark of 1,500–2,000 m (4,900–6,600 ft.). If we add 1,800 m (6,000 ft.) to the average amount of erosion during the Recessive Stage, we estimate that approximately 3,700 m (12,100 ft.) was deposited at the peak of the Deluge (Figure 9).

Estimating Conditions

The diagenetic processes in sandstones listed in Table I require certain ranges of temperature and pressure or solution chemistry. Evidence for these processes may be inferred from thin sections or other data. How the sediments came to be exposed to these conditions and the duration of that exposure may hinge on Earth history assumptions. For example, it is common to assume the average present geothermal gradient and then employ computer programs such as PetroMod® or BasinMod® to infer a burial history, but these models depend on uniformitarian assumptions, a clear case of begging the question (circular reasoning). Experimental data to determine equations of state and rates of lithification (Figure 10) for various lithologies would be invaluable to break out of this circular reasoning problem.

Coal rank appears to be more closely linked to temperature than pressure (Thomas, 2013; Klevberg and Oard, 2022), and usually the average current geothermal gradient is used in the calculations. The current geothermal gradient, of course can be either lower or higher than what it was in the past. If lower, coal rank can provide an estimate of maximum burial depth. If higher, coal rank would be a minimum burial depth.

Discussion: The State of Lithification Modeling

A model is only as good as its inputs. Accurate scientific modeling requires determination of the equations of state that govern mineral and rock stability. As a first step in this direction, the authors designed experimental apparatus and conducted a lithification pilot study in 2014 (Klevberg, 2014). The pilot study was conducted on the clay–claystone transition due to the simplicity of lithification governed by mechanical compaction. This transition was reached in 29 weeks at an applied pressure equal to 300 m (1,000 ft.) of overburden (Figure 11). Still unknown are compaction curves for other applied pressures, limitations of pore pressure reductions based on stratum thickness and lateral extent of sandstone interbeds, and similar variables. This present paper has therefore leaned heavily on industry-financed progress made in sandstones using expensive apparatus and labor beyond our means (Figure 8). Pioneering work by Bjørlykke and colleagues have greatly advanced our knowledge of lithification.

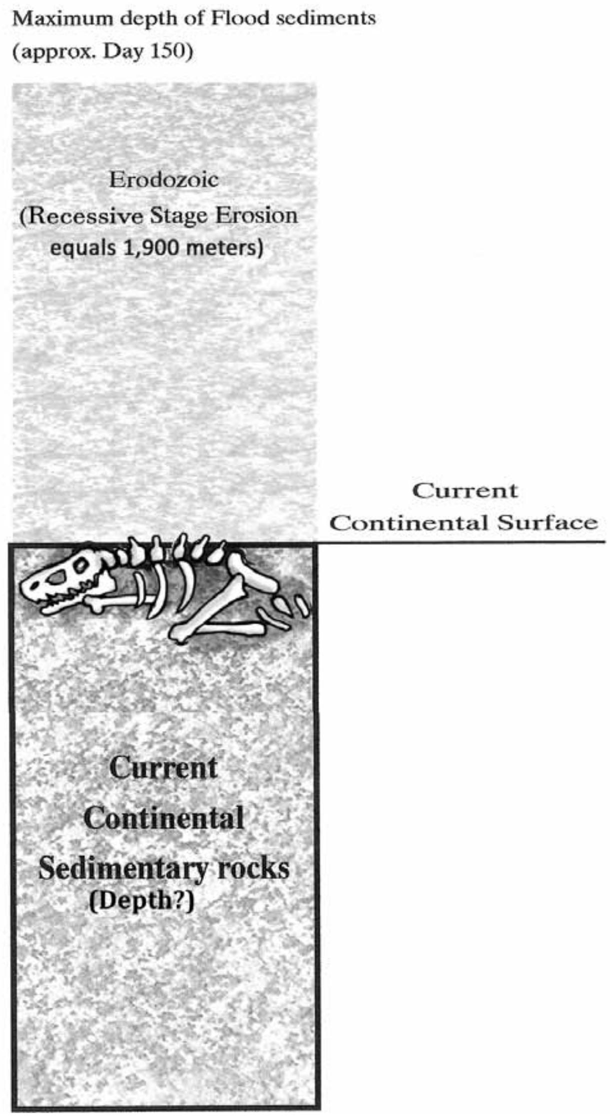

Figure 9. An estimated 1900 m (6,200 ft.) of sediments on average have been eroded off the continents to expose the present land surface. The term "-zoic" refers to life, and the late Roy Holt dubbed this period of erosion the "Erodozoic," probably because numerous buried organisms and fossils would be *eroded* and pulverized during the Recessive Stage.

Our goal has included correlating coal rank and inferred sandstone burial depths for North Central Montana. There may be some general patterns (Figure 12), but too many variables

State of the system:

$$S = f\,(M, T, P, pH, EH, SC\,...)$$

Rate of lithification:

$$\partial S/\partial t = \partial f\,(M, T, P, pH, EH, SC\,...)/\partial t$$

Figure 10. Equations of state include the variables needed to describe the state of a system. For a given parent material (M, including a defined grain size distribution and mineralogy), principal variables would be pressure (P), temperature (T), pH, EH, specific conductivity (SC), and possibly other chemical variables if the latter three commonly used ratios are not sufficient to define the state of the system. Taking the time (t) derivate of the equation obtains the rate at which equilibrium is reached, i.e., the rate of lithification.

are involved in coal rank—it is not just a function of overburden pressure. Sandstones, problematic as they may be, appear to be better burial depth indicators.

Methods of interpreting sandstone thin-section data are beyond the scope of an article such as this, but it is sometimes possible to determine whether stages in diagenesis overlapped. If there is evidence that matrix or cement interfered with mechanical compaction, then that particular unit may not be useful in estimating burial depth. However, it may be possible to determine a *minimum* burial depth and thus minimum amount of erosion, recognizing that actual burial depth may have been deeper due to these interferences.

In a subsequent article, we will present a field study of sandstones in the Kootenai and Blackleaf Formations of North Central Montana, some of which are associated with coal seams.

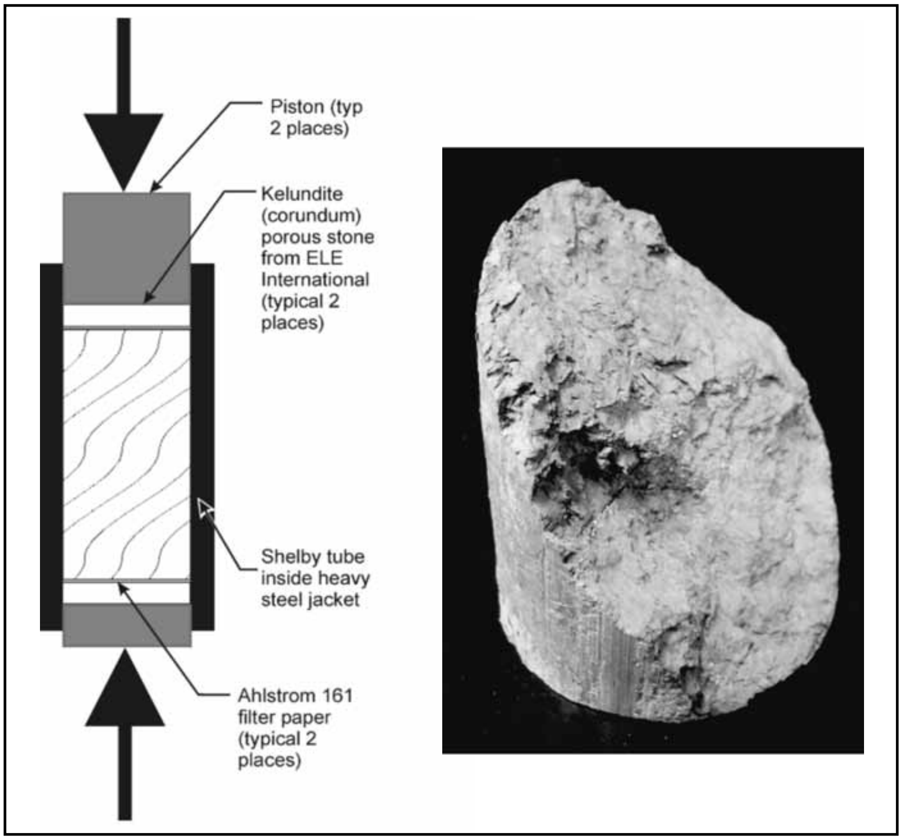

Figure 11. Schematic of test apparatus and photograph of resulting incipient claystone. A sample of fat clay was subjected to 900 psi (6 MPa) pressure, representing 300 m (1,000 ft.) of overburden, for 29 weeks. At the end of the period, it had consolidated to the borderline of unlithified sediment and rock.

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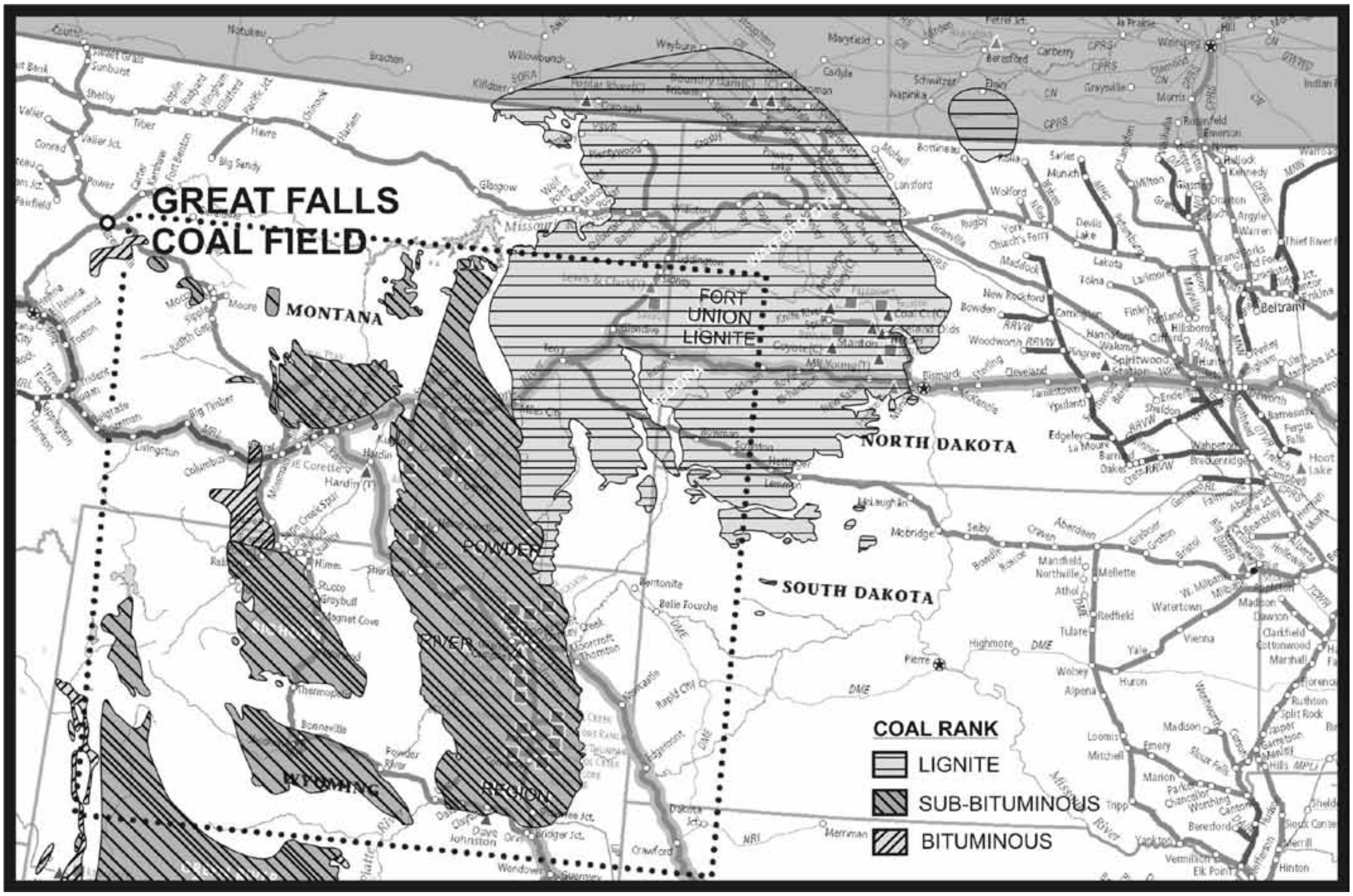

Figure 12. Map of extensive coal deposits of the north-central U.S.A. modified from Burlington Northern Santa Fe Railway figure. The generally higher rank of coal to the west and lower to the east corresponds to an inferred thinning of sedimentary cover (overburden) from west to east. Sandstone competence or hardness generally matches this gradient, but with many local exceptions. Square of dotted lines is area of primary commercial production (Powder River Basin).

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