Environment of Deposition of Permian Salt in the Williston and Alliance Basins[1]

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ABSTRACT

Evaporites, including halite, were deposited on the craton in the northern mid-continent region during Permian time as a result of a favorable combination of climate and geography.

Paleomagnetic data suggest that the region lay between 0° and 10°N. paleolatitude. The climate probably was warm in this equatorial belt. The Phosphoria sea, lying not far to the west, probably contributed little atmospheric moisture to the region. Upwelling currents, believed to have prevailed in the Phosphoria sea, brought cold waters to its surface, and consequently little moisture was evaporated. Furthermore, the prevailing winds from the north would have been unfavorable for distribution of this evaporated moisture eastward to the craton. The ancestral Rocky Mountain system further served to isolate the low-lying craton from the Phosphoria sea, except in central Wyoming where a transverse trough permitted the craton to be flooded from the west.

The restricted and shallow sea on this part of the craton and the warm, arid climate contributed to the environment favorable to the formation of the evaporites that accumulated in the intracratonic Williston and Alliance basins. Thick deposits of halite formed over a wide area in the Williston basin in western North Dakota and immediately adjacent parts of Montana and South Dakota. Much thinner halite deposits formed in the smaller Alliance basin and are distributed in a much smaller area in western Nebraska and adjacent parts of Wyoming.

INTRODUCTION

The Williston and Alliance basins are located respectively in western North Dakota and in western Nebraska. The Black Hills of South Dakota and Wyoming presently lie between these two basins; but in Permian time this was a region of low relief. Early in the Permian these areas were part of a larger basin; but late in the Permian these two basins were separated by an intervening positive area, having several tens of feet of relief, approximately coincident with the Black Hills. The locations of Williston, North Dakota, and Alliance, Nebraska, in respect to present-day geographic features are shown on Fig. 1; the basins are shown in relation to other paleogeographic features on Fig. 3. Until the last two decades, when oil tests were bored in these areas, little was known about the region's Permian rocks and the halite they contain.

Many of the conclusions presented here were derived from interpretation of stratigraphy and correlation of these rocks. Some of the basic data and evidence for these conclusions are available in a report on the Permian system in the U. S. Geological Survey's Paleotectonic Maps of the United States (McKee, Oriel, and others, in press). Additional stratigraphic details are presented by MacLachlan and Bieber in these proceedings on the Second Symposium on Salt. The

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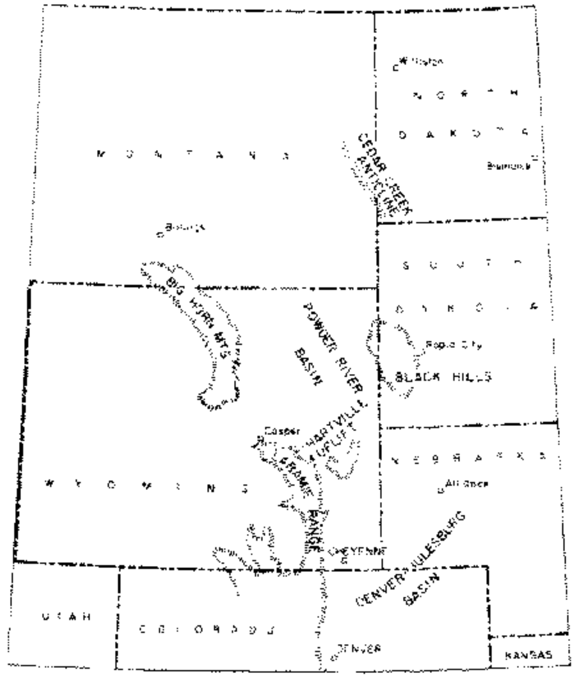


Figure 1. Locality index.

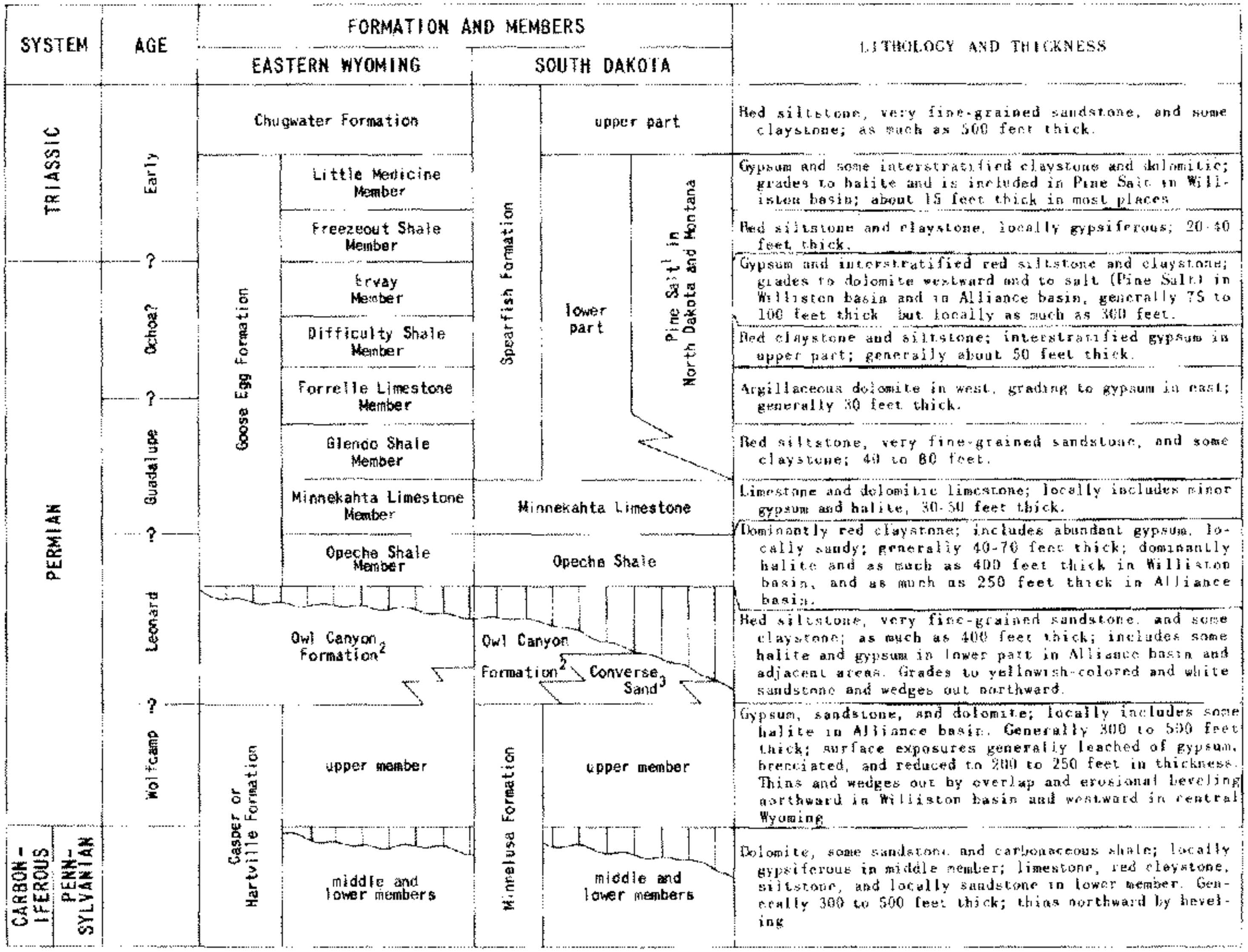
writer is especially indebted to R. P. Sheldon, E. R. Cressman, and M. R. Mudge, who contributed basic data and ideas that are incorporated into this report.

Marine water from the Phosphoria sea in western Wyoming flooded the nearby craton to the east in mid-Permian time. Access of this water to the craton was through a relatively narrow trough in central Wyoming bordered by the ancestral Front Range highland on the south and a broad uplift centered in Montana on the north. The low-lying craton east of these positive elements, however, was inundated over many hundreds of square miles. This shallow cratonic sea, believed to lie in the hot, arid climate of the paleoequatorial belt, was subject to much evaporation, concentration of brine, and consequent precipitation of salts. The denser brine, having higher specific gravity, sank and accumulated in the intracratonic basins where halite and possibly other salts were precipitated. Anhydrite and gypsum were precipitated at the margins of these basins and upon the craton from water of lower specific gravity. Dolomite was precipitated in water of near-normal marine salinity near the Phosphoria sea, and limestone formed in the Phosphoria sea itself.

STRATIGRAPHY

A summary of the stratigraphy (Fig. 2) is presented on the following page to briefly describe and identify the rocks considered in this report. Stratigraphic terminology, for the most part, is extended from exposures in eastern Wyoming and the Black Hills of South Dakota to adjacent subsurface strata of this region, including North Dakota and western Nebraska.

Minnelusa, Hartville, and Casper are names applied to equivalent formations of Pennsylvanian and early Permian age in different parts of eastern Wyoming and the Dakotas. These formations are composed of strata of essentially the same age, sequence, and lithology. Equivalent rocks in western Nebraska generally are referred to by informal Pennsylvanian and early Permian age names extended into this area from Oklahoma, eastern Kansas, and adjacent areas, and these names may be correlatives of the provincial series of west Texas. Minnelusa and equivalents are used herein for convenience to identify the Pennsylvanian and lower Permian rocks throughout this region.



1 Of Zieglar (1955)
2 Of Condra, Reed, and Scherer (1940)
3 Of subsurface geologists

Figure 3. Nomenclature and lithologic summary of Permian and enclosing rocks in eastern Wyoming, South Dakota, and adjacent areas.

The Minnelusa Formation and equivalents rest unconformably upon Mississippian or older rocks. These strata can be correlated with each of the mid-continent provincial series of the Pennsylvanian as well as lower Permian rocks of Wolfcamp age. Many details of the Minnelusa and equivalents have been recently described by MacLachlan and Bieber (1963), Mompers (1963), Hoyt (1963), McCauley (1956), and Foster (1958). In general, they are increasingly evaporitic upward, and some halite that formed in the central part of the Alliance basin in Wolfcamp time is included near the top.

The Owl Canyon Formation of Condra, Reed, and Scherer (1940), the next younger stratigraphic unit, extends southeast of a zero edge coinciding approximately with a set of linear structures extending from the central part of the Laramie Range into the southern part of the Black Hills. In general, the Owl Canyon is well-stratified red siltstone and very fine-grained sandstone. Near the zero edge the Owl Canyon Formation is increasingly sandy and loses most of the red color. The sandy facies of the Owl Canyon is informally named the Converse sand by subsurface geologists in the Lance Creek area north of the Hartville uplift. Well-developed equivalent sandstone is recognized in the southern Black Hills (C. G. Bowles, oral commun., 1962). At other places, however, this sandstone facies is not differentiated from the Minnelusa, Casper, or Hartville. A comparatively thin stratum of evaporite rocks is included in the Owl Canyon in the subsurface of northeastern Colorado and adjacent states. This stratum is correlated with the Stone Corral Formation of Nebraska, Kansas, and Colorado. Locally, as in the Alliance basin, this stratigraphic horizon includes poorly developed halite.

The Opeche Shale unconformably overlies the Owl Canyon Formation in the Alliance basin and the Minnelusa Formation farther north in the Williston basin and the intervening platform area. Westward in Wyoming, the Opeche is included in the Goose Egg Formation as the basal member (Burk and Thomas, 1956; Privrasky and others, 1958; Maughan, 1964). The rocks are dominantly red claystone, but in the basins the Opeche includes abundant evaporites. Halite dominates in parts of the basins where the sediments are thickest, and anhydrite, gypsum, and some dolomite dominate the areas where the sediments are relatively thin. Near the Chadron arch on the east and the ancestral Front Range on the west, the claystone grades into sandstone; and strata equivalent to the Opeche are identified respectively with sandstone that may be the same as the Cedar Hills Sandstone of Kansas (O'Connor, 1963) and with an upper tongue of the Lyons Sandstone. Gypsum and equivalent beds of halite in the lower part of the Opeche have been correlated across Nebraska and Kansas to the Blaine Gypsum in Oklahoma. Westward, the Opeche is correlated with the Meade Peak Phosphatic Shale Member of the Phosphoria Formation, one of the principal phosphate-rich horizons in western Wyoming, eastern Idaho, and adjacent areas.

The Minnekahta Limestone is in gradational contact above the Opeche. The Minnekahta also is included as a member of the Goose Egg Formation in most of eastern Wyoming. The Minnekahta is composed mostly of limestone and varies little in thickness over many hundreds of square miles. Locally, it includes some anhydrite or gypsum, and in a few places includes minor amounts of halite.

The Spearfish Formation overlies the Minnekahta in South Dakota and adjacent areas. The lower part of this formation is composed of an alternating series of red beds and gypsum or anhydrite beds. In Wyoming equivalent strata of this lower part of the Spearfish Formation are included in the Goose Egg Formation and are divided in ascending order into the Glendo Shale Member, Forelle Limestone Member, Difficulty Shale Member, Ervay Member, Freezeout Shale Member, and Little Medicine Member. Equivalent lithologic units in the lower part of the Spearfish can be recognized and are correlated with each of these members of the Goose Egg. The boundary between the Permian and the Triassic is placed between the Ervay and Freezeout Members.

The upper part of the Spearfish Formation lying above strata equivalent to the Little Medicine Member of the Goose Egg Formation is composed of well-stratified red siltstone, claystone and very fine-grained sandstone and is without interstratified evaporite deposits. In Wyoming equivalent strata are named the Chugwater Formation.

The gypsum beds of the lower part of the Spearfish are widespread. In the western part of the region, these beds include dolomite and are gradational to carbonate rocks in central Wyoming. In the Williston and Alliance basins and in several smaller basins in this region, these gypsum beds thicken and grade into halite. The most notable of these halite deposits is the Pine Salt (Zieglar, 1955; Maughan, in McKee, Oriel, and others, in press, in the Williston basin. It is stratigraphically equivalent to the Ervay Member of the Goose Egg Formation, and in some places may also include strata equivalent to the Forelle, Difficulty, Freezeout, and Little Medicine Members.

PALEOGEOMORPHOLOGY

The distribution of sediments and their facies relations suggest the location of land areas and depositional basins that were important elements of Permian geography (Fig. 3). Land areas were present southwest of the craton in two masses -- parts of the ancestral Rocky Mountains

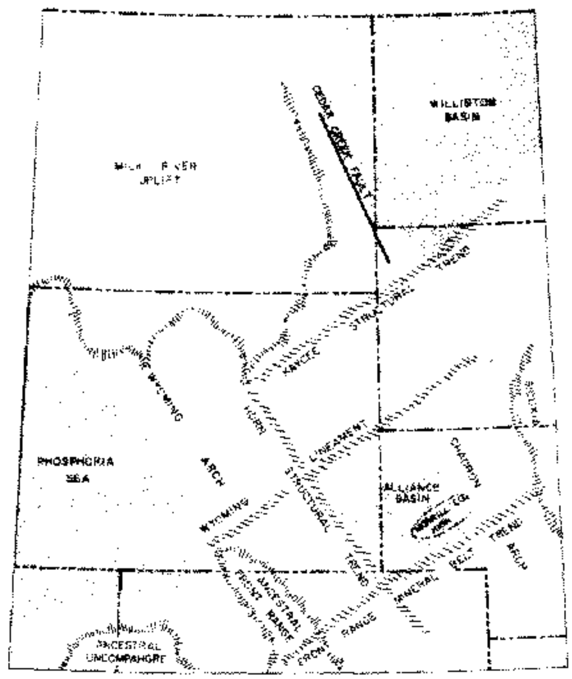


Figure 3. Mid-Permian land areas, basins, and related structural features.

known as the ancestral Front Range highland and the ancestral Uncompahgre highland. Northwest of the craton another larger landmass, the Milk River uplift, occupied most of what is now Montana. The craton itself was partly submerged, but the eastern part of the craton, Siouxia, lay above the level of the sea. These land areas are shown on Fig. 3.

The land areas probably were of low relief and barely stood above sea level in mid-Permian time. The ancestral Front Range and Uncompahgre land areas had been dominant features throughout the late Paleozoic. They had reached their greatest prominence in middle Pennsylvanian and early Permian time. The Milk River uplift did not come into existence until latest Pennsylvanian or earliest Permian (Maughan, in McKee, Oriel, and others, in press). This land was a relatively stable area that persisted with only minor tectonic activity through the Permian and seems to have continued at least through most of the Triassic. On the other hand, Siouxia, the land area to the east, seems to have persisted throughout the Paleozoic and Mesozoic, although its borders shifted appreciably from time to time.

The depositional areas below sea level included an arm of the Cordilleran geosyncline in the west, and east-west transverse trough in central Wyoming, and a part of the craton encompassing eastern Wyoming and Colorado, western North and South Dakota, and western Nebraska. This submerged cratonic area also included both the Williston and Alliance intracratonic basins in the east.

The Cordilleran geosyncline extended into a basin in eastern Idaho and western Wyoming, and was occupied by the Phosphoria sea. The east-west trough lay in central Wyoming as a low area between the ancestral Front Range and Uncompahgre land areas on the south and the Milk River land area on the north.

The Williston basin was a relatively shallow but slowly subsiding area in western North Dakota. This basin was bounded along its western edge by a fault or sharply folded monocline coincident with the present Cedar Creek anticline. A less well-defined structural belt that trended east-northeast in southwestern North Dakota bounded the deeper parts of the basin on the south and separated it from the craton. The northern and eastern edges of the Williston basin in Permian time are unknown because of beveling prior to deposition of Jurassic strata. How far north and east Permian sediments may have been deposited originally is not known, but it is estimated that in areal extent about one-half to two-thirds of the rocks originally formed in this basin are preserved here.

The Alliance basin in western Nebraska and eastern Wyoming was similar to the Williston basin, though smaller. It, too, seems to have been relatively shallow and subsided slowly. Its western margin was a moderately well-defined, north-northwest-trending linear structure which farther northwest in the Big Horn Mountains is approximately coincident with the Horn Fault. The eastern margin was formed by the Chadron arch. Less well-defined structures trending east-northeast formed the north and south boundaries. The northern margin of the Alliance basin coincided approximately with the Wyoming lineament. The southern margin of the basin was bounded by structures trending parallel to the Wyoming lineament that apparently extended east-northeast along the trend of the Front Range mineral belt. The Morrill County high is a probably anticlinal structure near the southern edge of the Alliance basin that is parallel with this Front Range mineral belt trend, but that formed after deposition of middle and upper Permian rocks.

The structural elements that define the land areas and basins described above suggest a rectilinear system of faults and folds (Fig. 3). The underlying crystalline rocks are believed to have broken into large blocks that moved differentially along these linear trends. Repeated movement of these basement blocks affected older and younger sedimentary rocks as well as Permian rocks.

PALEOLATITUDE

The region about the Alliance and Williston basins probably was within the equatorial belt in Permian time. This inference is based on paleomagnetic evidence, much of which has been summarized by Cox and Doell (1960). The equatorial belt suggested by the position of the virtual geomagnetic pole in Permian time (Cox and Doell, 1960, Figs. 33 and 34, pp. 758, 759) probably shifted from northwest of this region in Pennsylvanian and early Permian time to south of this area in late Permian and Triassic time. This shift may have resulted from polar wandering, continental drift, or both, but these theories, as well as the dynamo theory, are under investigation by many others and are beyond the scope of this report. Theories regarding the coincidence or lack of coincidence of the earth's magnetic and rotational axes are not considered here, but it is assumed that these axes approximately coincided in Permian time as they do at present, and that the magnetic field was dipolar then as now.

Sheldon (1964) demonstrated the coincidence between geographic elements, including latitude, of recent and ancient sites of phosphorite deposition. He (1964, p. C111) plotted the position of the paleoequator relative to the average position of the Leonard virtual geomagnetic pole (pole E55 of Cox and Doell, 1960, table 1, Fig. 25) in the northern mid-continent region (Fig. 4). The Alliance basin was within 2°-3° of the equator in Leonard time, and the Williston basin was within 10°. A hot and arid climate favoring the deposition of evaporites (Landes, 1963, p. 7) is consistent with the location of the region in low latitudes at or near sea level.

WIND DIRECTION

Prevailing wind in this region in Permian time probably was analogous with prevailing northeasterly trade winds common around the earth today in the subtropical anticyclonic belt of the northern hemisphere. Crossbedding in eolian sandstone of Permian age (Fig. 4) indicates

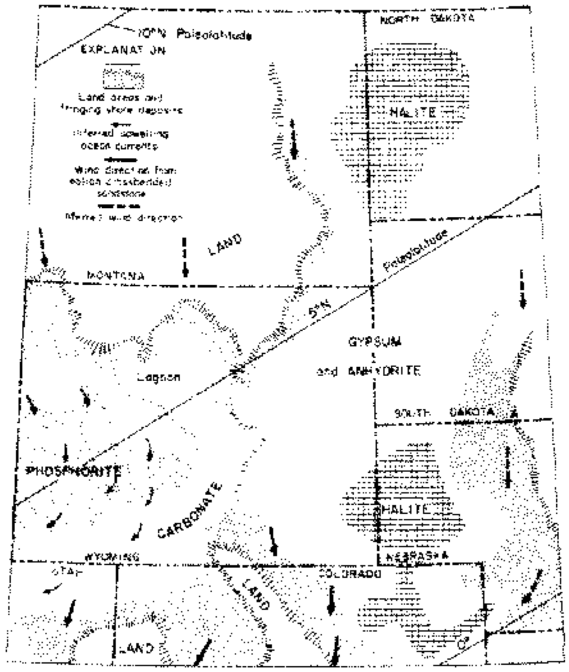


Figure 4. Halite and phosphorite deposits relative to early Permian (late Leonard) paleogeographic features modified from Sheldon (1964, Fig. 8, p. C111).

a generally north-to-south direction in respect to the present geographic poles. Measurements of crossbeds indicate a slight easterly component to the paleowind in northern Colorado (R. F. Wilson, oral commun., 1959) and in northeastern Utah (Poole, 1964, Fig. 7, p. 402). The paleowind in southern Wyoming was directly from the north or slightly west of north. Reorientation of this northerly wind in respect to the Permian paleomagnetic pole gives a northeasterly paleowind consistent with the prevailing northeasterlies of the subtropical anticyclone. The subtle differences in orientation noted in the Wyoming, Colorado, and Utah measurements suggest that eastward rotation of the earth deflected the paleowinds as they approached the paleoequator.

The comparison of ancient and modern trade winds is extended further with the assumption that the paleowind over the northern mid-continent region was arid. If land existed across central Canada in Permian time, it would have had a similar drying effect on the paleotrade wind as the present-day Eurasian landmass has on the modern trade wind in North Africa. Probably upwelling of cold water to the surface of the Phosphoria sea (Sheldon, 1964) and consequently reduced evaporation may have contributed further to aridity of these trade winds.

FORMATION OF EVAPORITE DEPOSITS

Halite was formed in the Williston and Alliance basins by processes similar to those outlined by K. K. Landes (1963) in the first proceedings volume of the Salt Symposium. Figure 5 is a diagrammatic cross section into the Williston basin that illustrates the relation of evaporites. The diagram shows the long fetch across the craton in central and eastern Wyoming where saline water from the open ocean was evaporated in the presumed hot and arid climate and concentrated to low-density brine. Dolomite and sulfate rock were deposited in this area. High-density brine that formed from further evaporation sank, because of its higher specific gravity, into the deeper water areas of the subsiding basins where halite was deposited. Some of the brine, including the more soluble salts, may have been flushed from these basins by reflux circulation. Thus far, of the series of readily soluble evaporites halite is the only mineral reported from this region, suggesting that more soluble salts such as polyhalite and sylvite did not form. However, these salt

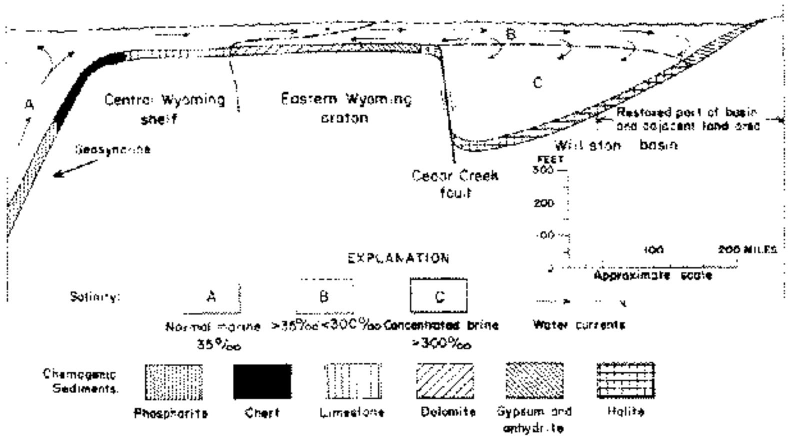
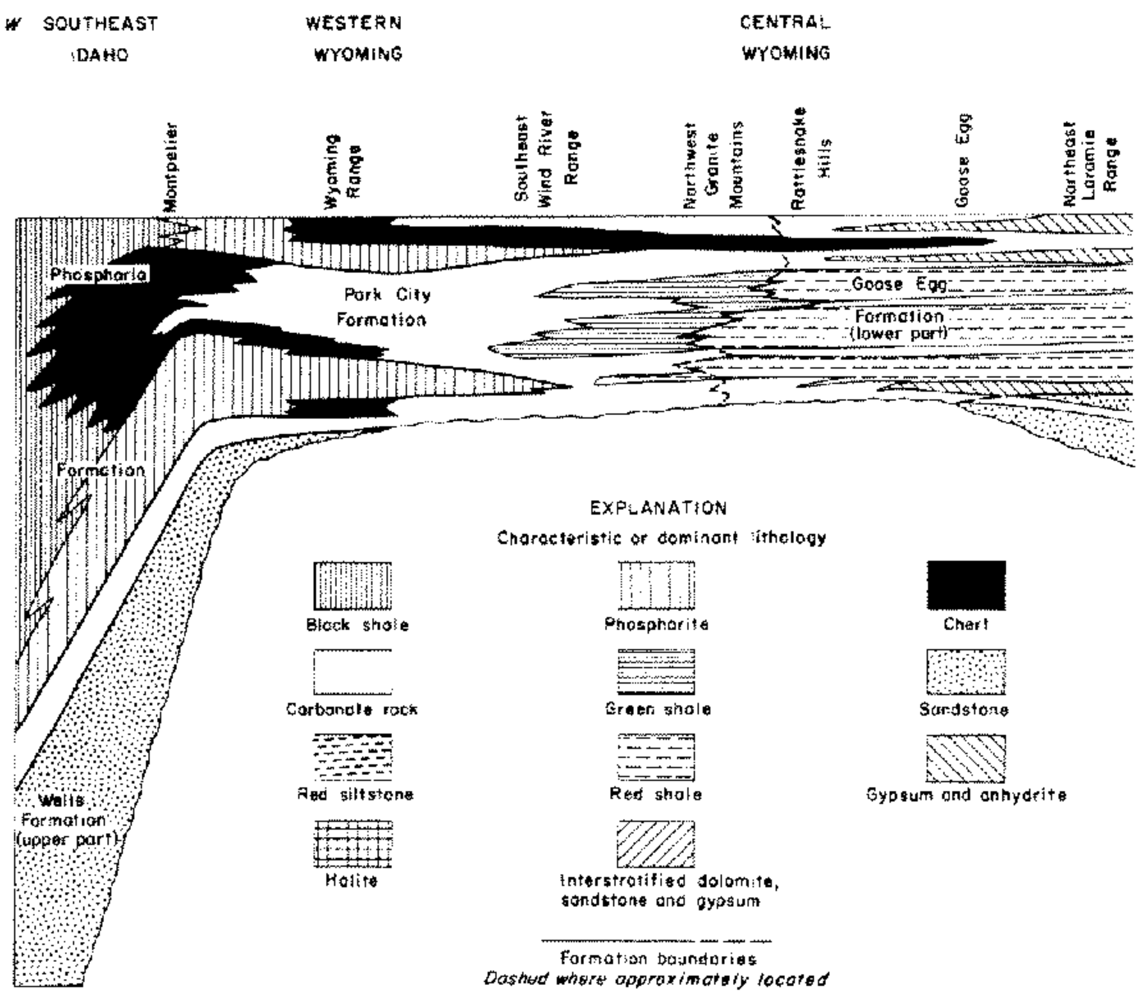


Figure 5. Diagrammatic relations of salinity and structure to deposition of Permian evaporites in Williston basin.

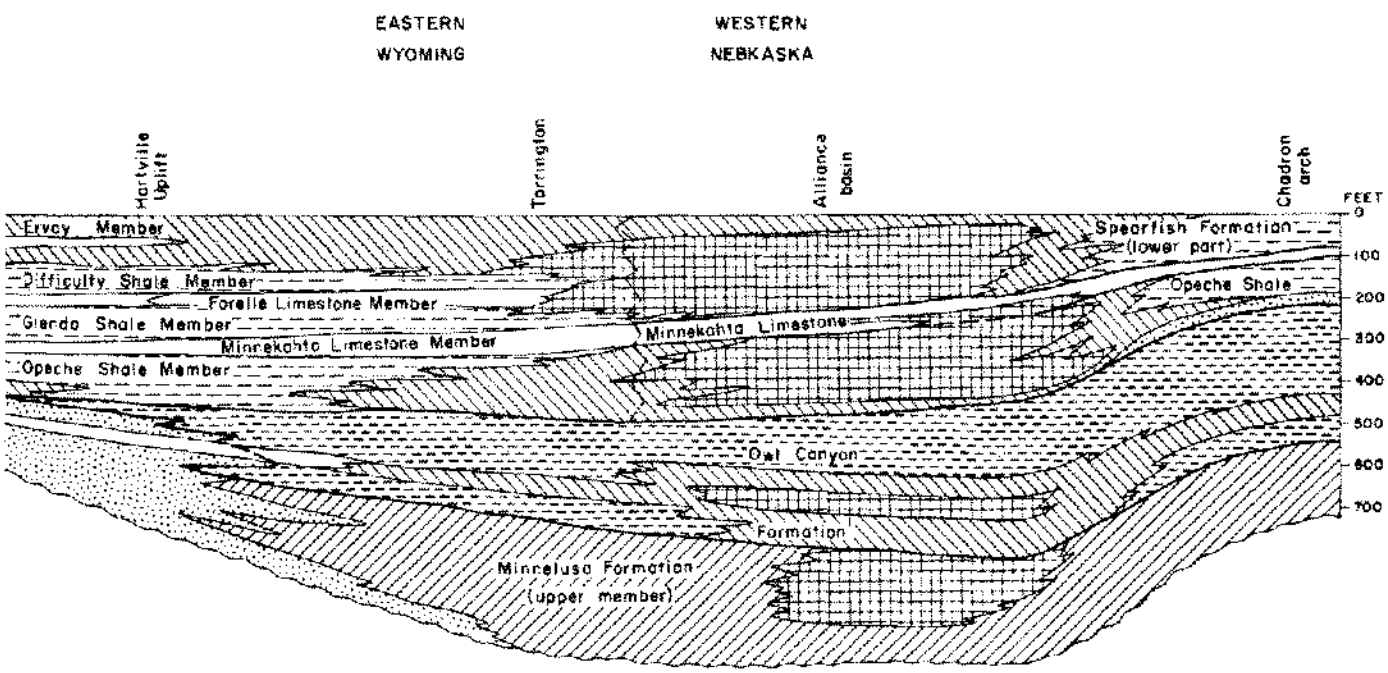
deposits have not been thoroughly examined for the presence of the more soluble evaporites. As dolomite, sulfate, and halite were being deposited in these areas, phosphorite, chert, and limestone were formed in the Phosphoria sea.



FACIES DISTRIBUTION

Halite occurs in Permian rocks principally at four stratigraphic positions (Fig. 6). The lowest is in the upper member of the Minnelusa Formation -- especially near the top of this member -- in a small part of the Alliance basin. Halite in the Owl Canyon Formation is closely related areally to that in the Minnelusa. The halite of the Opeche is abundant in both the Williston and Alliance basins, but is more widely distributed in the Williston. The Pine Salt is stratigraphically the highest halite deposit in Permian rocks and may include some strata of early Triassic age as well. This upper salt stratum is present in about the same areas as the halite in the Opeche, but is less well developed. The salt deposits in the Minnelusa, Opeche, and the Pine Salt are discussed in more detail below.

The upper member of the Minnelusa Formation of early Permian age includes halite beds in a few scattered places in western Nebraska. At time of deposition of these sediments, the Alliance basin, as defined herein, had not formed or was only incipiently formed. The evaporites were deposited in the southern part of a larger basin centered near the present Black Hills. This basin was isolated from the Cordilleran sea, and influx of saline waters was principally from the mid-continent sea which may have been separated from the basin by limestone reefs in northeastern Colorado and adjacent parts of Nebraska and Kansas. The existence of similar reefs adjacent to the Chadron arch has been suggested by Barr and Bieber (1961). The evaporite rocks are dominantly anhydrite or gypsum, and dolomite is abundant. Halite seems to have formed only in localized deeper parts of this regional basin, but may have originally been deposited more widely and subsequently leached. Collapsed breccias in exposures of these rocks in the Black Hills, Hartville uplift, and northern part of the Laramie Range probably were formed by



[1]Condra, Reed, and Scherer (1940)

Figure 6. Diagrammatic cross section of Permian rocks in Idaho, Wyoming, and Nebraska. Modified in part from McKelvey and others (1959).

dissolution of this salt as were the anhydrite and gypsum as suggested by Love, Henbest, and Denson (1953).

Further details of this lower Permian salt are not considered in this report.

The Opeche Shale is composed dominantly of red beds and evaporites, and locally includes significant beds of halite. The red beds are mostly fine-grained detrital sediments believed to have been washed onto the submerged part of the craton from adjacent low-lying land areas.

The distribution of detrital and evaporite facies of the Opeche (Fig. 7) suggests broad channels across the shallowly submerged craton. The central parts of the channels are indicated by

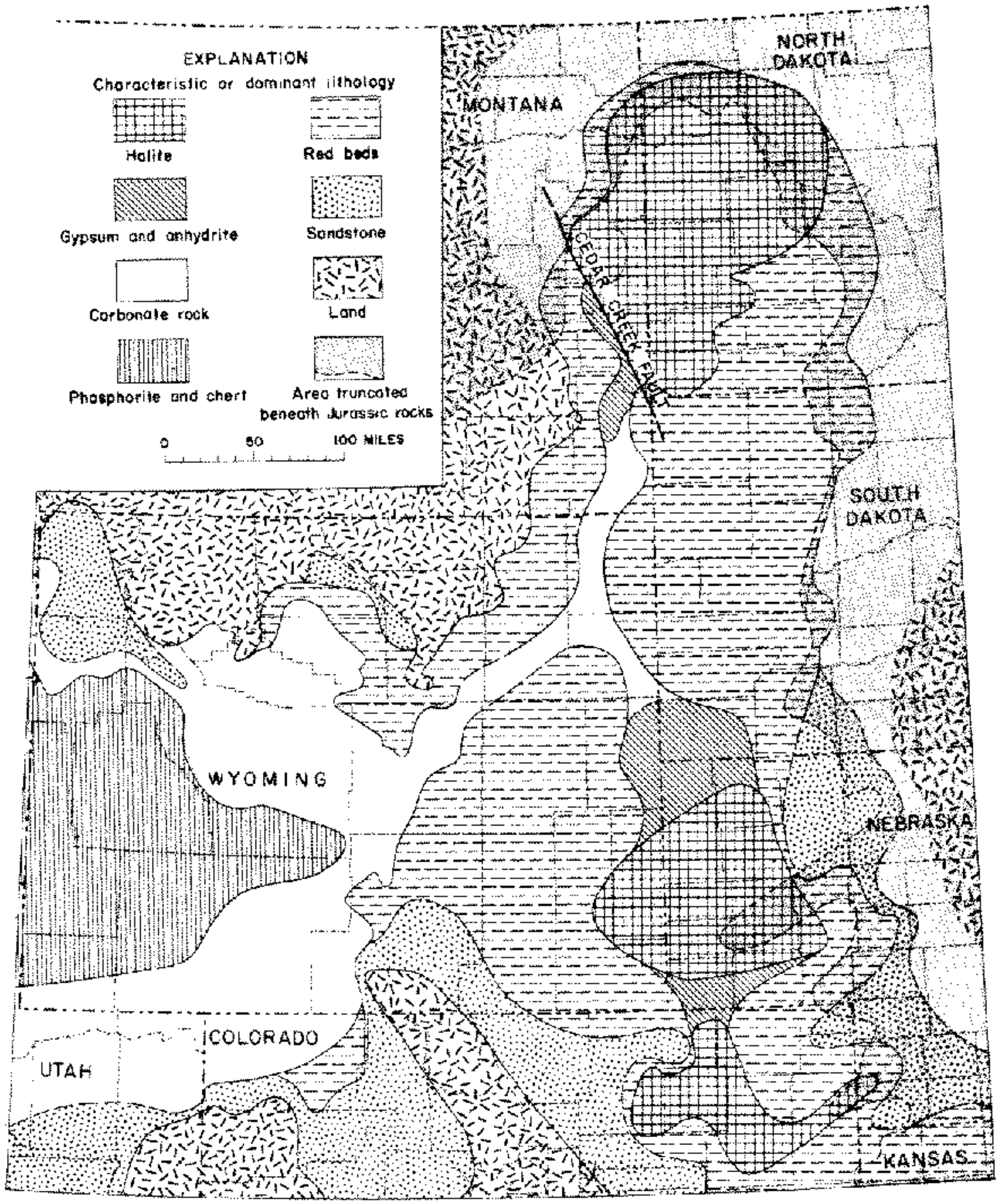


Figure 7. Generalized lithofacies at time of deposition of Opeche Shale and associated halite (late Leonard).

lithofacies where nonclastic rocks predominate over clastic rocks. The main channel extended sinuously from near Casper, Wyoming, across the present-day Powder River basin and opened into the Williston basin across the Cedar Creek structure that separated the western part of the relatively stable craton from the subsiding basin. A branch of this channel extended southeastward from near the center of the Powder River basin and opened into the Alliance basin across structural elements associated with the Wyoming lineament (Fig. 3).

Halite-bearing sediments are as much as 400 feet thick in the Williston basin; but according to Sandberg (1962, p. 74) the maximum thickness of relatively pure salt in the Opeche is about 180 feet. About 250 feet of sediments containing halite accumulated in the Alliance basin. In both

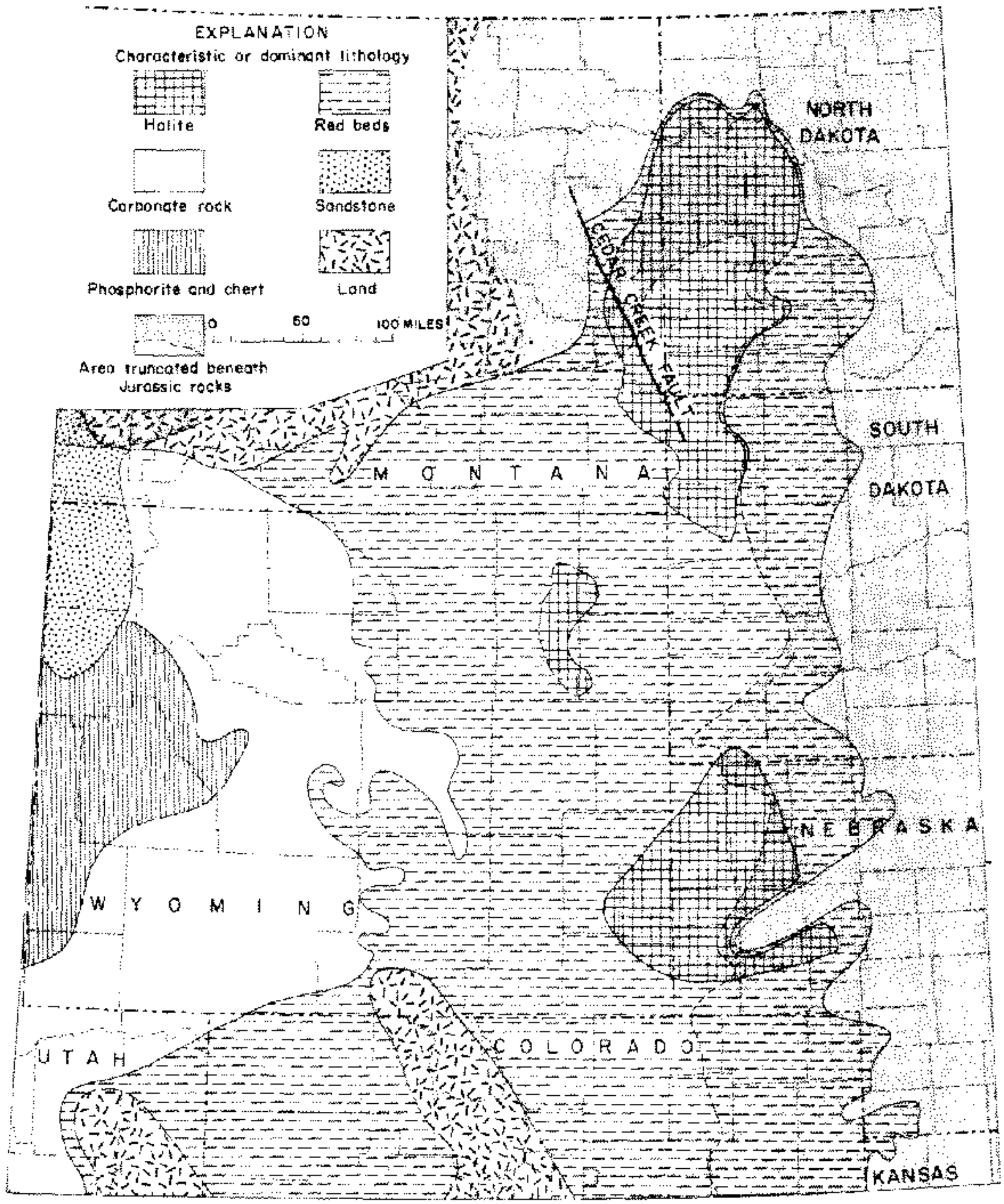


Figure 8. Generalized lithofacies at time of deposition of lower part of Spearfish Formation and associated Pine Salt (Guadalupe and Ochoa?).

areas individual beds several tens of feet thick are indicated by data collected at many oil test borings. The salt is less pure toward the margins of the basins where it intertongues with gypsum and anhydrite as well as with detrital sediments that thicken shoreward.

The Pine Salt in the Williston basin and equivalent halite beds included in the lower part of the Spearfish Formation in the Alliance basin seem to have been formed similarly as the halite beds in the Opeche. The distribution of the dominant or characteristic lithologic facies of these upper Permian rocks is shown in Fig. 8.

A maximum of about 380 feet of halite-bearing sediments accumulated in the Williston basin at this time (Sandberg, 1962, pp. 77-79), but only about half this thickness contains relatively pure salt. About 200 feet of relatively pure salt accumulated in the Alliance basin. In the Williston basin the top of the Pine Salt generally lies 4,000-7,500 feet below the surface (Sandberg, 1962 pp. 77-79). In the Alliance basin the top of equivalent rocks is generally between 3,000 and 6,000 feet deep.

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