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THE SIGNIFICANCE OF CARBONATE-CLASTIC TRANSITIONS IN THE CARBONIFEROUS OF WESTERN WYOMING

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A thesis submitted to

The Graduate School

of

Rutgers University

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

Written under the direction of

Dr. R.C. Murray

of the Department of Geology

and approved by

New Brunswick, New Jersey

May, 1972

ABSTRACT OF THE THESIS

The Significance of Carbonate-Clastic Transitions

in the Carboniferous of Western Wyoming

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A common occurrence throughout the geologic record is a stratigraphic sequence of carbonate rock overlain by detrital silicate rock with no conclusive stratigraphic or paleontologic evidence to indicate whether the contact is conformable or unconformable. The Carboniferous strata of western Wyoming offer the opportunity to examine this problem on two scales. The Lower Carboniferous section is a thick sequence of carbonate strata (Madison Group) overlain by detrital silicate rock (the lower part of the Amsden Formation). In the Upper Carboniferous (upper Amsden and Tensleep formations) carbonate-clastic transitions occur repeatedly on a scale of a few to several tens of feet apart.

Interpretation of the sedimentologic data concerning the nature of the carbonate-clastic transitions is facilitated by the use of a conceptual model of tidal flat-sabkha sedimentation. Carbonate sediment derived from the sea is deposited as far onshore as the tides will carry it. As tidal sedimentation builds up the depositional surface the various tide flat facies migrate seaward. Progradation of continental detritus across the abandoned supratidal flat marks the tran-

sition from coastal to continental sabkha. A long period of regressive sedimentation results in a conformable sequence of marine carbonate strata overlain by tide flat and sabkha carbonates and evaporites which are in turn overlain by detrital silicate sabkha and dune deposits. Repeated transgressions and regressions produce a sequence of repeatedly interbedded tide flat, sabkha and dune deposits.

The sedimentologic evidence indicates that the depositional history of the Lower Carboniferous strata in western Wyoming is one of generally regressive sedimentation. Shallow marine deposition of the Lodgepole Formation was followed by tide flat sedimentation of the Mission Canyon Formation. Regressive sedimentation of the Madison Group culminated with the creation of a land surface upon which sabkhas and dune fields developed. The basal strata of the Amsden Formation are the continental sabkha and dune deposits.

The depositional history of the Upper Carboniferous strata in western Wyoming is more complicated. During middle Amsden sedimentation an increased abundance of continental detritus shifted the carbonate-clastic boundary from the highest tide line into the shallow marine environments. Carbonate tide flat deposits at the base of the upper part of the Amsden Formation indicate the return of the carbonate-clastic boundary to the sabkha environment. The repeated interbedding of carbonate tidal flat and sabkha deposits with detrital sabkha and dune deposits throughout the upper Amsden and Tensleep Formations records the numerous minor transgressions and regressions in which the area was never far removed from the coastal-continental sabkha boundary.

ACKNOWLEDGMENTS

Field work during the summers of 1969 and 70 was supported by funds from the American Petroleum Institute through Project 101. While in the field, the author and his wife were the guests of the Department of Geology, The University of Michigan at the summer field camp in Hoback Canyon. The staff at Camp Davis, headed by Dr. C.I. Smith, were most cooperative and gracious hosts.

The author is indebted to the entire Department of Geology, Rutgers University for advice, criticism and encouragement throughout the preparation of the report. Dr. H.L. McKague, Mr. William Lodding, Mr. William Black (presently at the Department of Geology, University of North Carolina), Mr. Charles Bandoain and Mr. Allen Bliss were particularly helpful.

Dr. Harry Motto, Department of Soils and Crops, College of Agriculture and Environmental Science, Rutgers University was of invaluable assistance during the trace element analysis. He also performed the vanadium analysis on his department's atomic absorbtion unit. Dr. Richard Enright, Department of Earth Science, Bridgewater State College furnished the hollow cathode tube for the vanadium analysis. Dr. Richard Harvey, Biochemistry Department of the Medical School, Rutgers University permitted the use of his department's atomic absorbtion unit for the lithium analysis. Miss Linda Lewendon performed the analysis. Dr. M.L. Keith, Pennsylvania State University, Dr. Erling Dorf, Princeton University and Dr. S.K. Fox and Mr. William Lodding of Rutgers University contributed samples of known origin for the trace element analysis.

Mr. Steven Glanzrock prepared figure 1. Miss Jean Garofalo typed the manuscript.

The interest, guidance and patience of Dr. R.C. Murray, Department of Geology, Rutgers University is greatly appreciated.

INTRODUCTION

A stratigraphic sequence of carbonate rock overlain by detrital silicate rock is a common occurrence throughout the geologic record. Where paleontologic data is lacking or inconclusive the nature of the carbonate-clastic contact is a problem. There are at least two alternatives. The contact may be a major unconformity; in which case the detrital silicate rock is considerably younger than the carbonate rock and was deposited under entirely unrelated circumstances. Alternatively, the change in rock type may simply reflect a change in the environment of deposition. In the latter case sedimentologic conditions are related and the lithologic sequence will represent a logical sequence of sedimentologic facies.

The most extensively studied occurrence of carbonate-clastic transitions is that of the late Paleozoic cyclic strata in the Midland and Delaware basins of west Texas and southeastern New Mexico. There is extensive subsurface control in this area and the faunal data have proven to be conclusive. Numerous examples of conformable carbonate-clastic contacts have been documented. In these examples the clastic rock is the result of the progradation of continental detritus subsequent to the filling of the depositional basin by carbonate sediment.

The Carboniferous strata of western Wyoming offer the opportunity to examine carbonate-clastic transitions on two scales. The Lower Carboniferous section is a thick sequence of carbonate strata (Madison Group) overlain by detrital silicate rock (the lower part of the Amsden Formation). In the Upper Carboniferous (upper Amsden and Tensleep formations) carbonate-clastic transitions occur repeatedly on a scale of a few feet to several tens of feet apart. The sparse faunal data available are inadequate. Sedimentologic methods must be used to determine the nature of the carbonate-clastic transitions.

Stratigraphy

Madison Group -- Table I illustrates the Carboniferous stratigraphy of western Wyoming. The Madison Group is recognized throughout Wyoming, Montana and the Williston Basin (North Dakota, northern South Dakota and eastern Montana). The group is over 1900 feet thick in the Williston Basin and over 1700 feet thick in the central Montana trough. It is about 1200 feet thick along the Idaho-Wyoming state line and thins south and southeastward to its erosional limit in southeastern Wyoming. In southeastern Wyoming it rests unconformably upon Pre-Cambrian and Cambrian rock and is underlain by successively younger strata to the north and northwest until it is underlain by Devonian strata in central Montana and western Wyoming (Andrichuk, 1955).

<table>
<tr><th colspan="5">Table I
Carboniferous Stratigraphy, Western Wyoming</th></tr>
<tr><td colspan="3">Permian</td><td colspan="2">Phosphoria Formation</td></tr>
<tr><td rowspan="5">Upper Carboniferous</td><td rowspan="5">Pennsylvanian</td><td>Missouri</td><td colspan="2" rowspan="3">Tensleep Formation</td></tr>
<tr><td>Desmoines</td></tr>
<tr><td>Atoka</td></tr>
<tr><td>Morrow</td><td colspan="2" rowspan="2">? Amsden Formation</td></tr>
<tr><td>Springer</td></tr>
<tr><td rowspan="4">Lower Carboniferous</td><td rowspan="4">Mississippian</td><td>Chester</td><td colspan="2">? Darwin Member ?</td></tr>
<tr><td>Meramac</td><td>Mission Canyon Formation</td><td rowspan="3">Madison Group</td></tr>
<tr><td>Osage</td><td rowspan="2">? Lodgepole Formation</td></tr>
<tr><td>Kinderhook</td></tr>
<tr><td colspan="3">Devonian</td><td colspan="2">Darby Formation</td></tr>
</table>

Sando and Dutro (1960) mapped the basal 300 to 400 feet of the Madison Group in western Wyoming as the Lodgepole Formation (Collier and Cathcart, 1922) and the upper 800 to 900 feet as the Mission Canyon Formation (Collier and Cathcart, 1922). Strickland's (1956) sections in the area show the Lodgepole Formation as the basal 600 to 700 feet. He restricted the Mission Canyon Formation to the middle part of the group and called the upper 300 feet of section the Upper Madison. Strickland's Upper Madison is roughly equivalent to Wanless <u>et</u>. <u>al</u>.'s (1955) Brazer limestone and lower Amsden red shale sequence. This report will divide the Madison Group into the basal Lodgepole Formation as mapped by Strickland and the upper Mission Canyon Formation encompassing the remainder of the group. This usage is followed to facilitate the discussion of depositional environments. A revision of the stratigraphic nomenclature is not intended.

<u>Madison-Amsden Contact</u> -- Darton (1904) considered the Madison-Amsden contact to be disconformable when he defined the Amsden Formation from exposures in the Big Horn Mountains. He noted (Darton, 1906) the presence of Mississippian fossils in the lower beds of the formation and Pennsylvanian fossils in the upper beds. The Darwin Member of the Amsden Formation was named by Blackwelder (1918) who recognized only Pennsylvanian fossils above it and an unconformity at its base in the Gros Ventre Range. Branson (1937) proposed the name Sacajawea for Mississippian strata lying unconformably above

the Madison Group in the Wind River Range. Love (1939), working along the southern margin of the Absaroka Range, discarded the term Sacajawea as an unmappable unit and found the Madison-Amsden contact to be conformable. He reported Mississippian fossils about 36 feet above the Darwin Member and a Pennsylvanian fauna about 170 feet above the Darwin Member in Wiggins Fork Canyon. Thereafter, a debate followed concerning the age of the lower Amsden fauna, the stratigraphic position of the Darwin Member, and the age and stratigraphic position of the Sacajawea Formation (Branson, 1939; Baker, 1946; Scott and Wilson, 1953; Burk, 1954; Shaw and Bell, 1955; Wanless et. al., 1955; Strickland, 1956 and 1957; Sando and Dutro, 1960) which was reviewed by Sando (1967). The lower Amsden fauna has been designated Mississippian (late Chester) in age (megafaunal zone K, foraminiferal zones 16s, 17 and 18, Sando et. al., 1969). The upper Amsden fauna is early Pennsylvanian (megafaunal zone Post-K, foraminiferal zone Post-18, Sando et. al., 1969). Sando (1968) renamed the Sacajawea Formation, as redefined by Strickland (1957), the Bull Ridge Member of the Madison Limestone. At the type locality on Bull Lake Creek, where it represents the uppermost 75 feet of the Madison Group, the Bull Ridge Member contains a fauna dated as early Meramac (megafaunal zone D, foraminiferal zones 10 and 11, Sando et. al., 1969). Paleontologic data have established an early to middle Meramac unconformity in southeastern Idaho and northern Utah which is mapped as the contact between the Lodgepole Formation and the Little

Flat Formation (Brazer limestone). Middle and late Meramac fossils are missing from sections in Wyoming and Montana but the stratigraphic interval in which they would be expected is occupied by unfossiliferous strata (Sando et. al., 1969).

In southeastern Wyoming the upper beds of the Madison Group were truncated by erosion prior to deposition of the overlying Pennsylvanian strata (Andrichuk, 1955). Agatston (1954) describes channels cut into the upper Madison surface, which are filled with large angular blocks of limestone and chert (Madison) in a matrix of quartz sand from the overlying Amsden or equivalant formations, throughout much of northern and eastern Wyoming. The top of the Madison Group has been described as a paleokarst surface in many areas of Montana, northern Wyoming and the Wind River Range (Agatston, 1954; Andrichuk, 1955; Roberts, 1966; Sando, 1967). McCaleb and Wayhan (1969) demonstrate significant karst development on the upper Madison surface in the Elk Basin oil field (in the northern Big Horn Basin). They believe that solution brecciation within the Madison Group is related to and took place at the same time as the karst development. Other workers present evidence that solution brecciation within the Madison Group in Montana took place subsequent to the Larimide Orogeny (Severson, 1952 in Roberts, 1966). Surface exposures of solution breccias have been correlated with evaporite zones in the subsurface in many areas (Andrichuk, 1955; Roberts, 1966).

Amsden Formation -- In central and western Wyoming and southern Montana the Madison Group is overlain by the Amsden Formation. The Amsden Formation ranges in thickness from 200 to 500 feet (Wanless et. al., 1955). In western Wyoming the basal Darwin Member is an unfossiliferous orthoquartzite ranging from less than 60 to almost 100 feet in thickness. The middle part of the Amsden Formation is made up of a lower unfossiliferous shale interval and an upper interval of alternating shale and fossiliferous limestone. The upper part of the formation is composed of sandy dolomite, sandy dolomitic limestone and sandstone.

Tensleep Formation -- The Tensleep Formation is mappable throughout Wyoming and southern Montana (Quadrant Formation). Estimates of the thickness of the Tensleep Formation vary considerably due to the unconformity between it and the overlying Permian strata and to the various interpretations of the stratigraphic position of the Amsden-Tensleep contact (Darton, 1904; Branson, 1939; Walton, 1947; Agatston, 1954; Wanless et. al., 1955; Williams,1962; Wilson, 1962). In western Wyoming the Tensleep Formation consists of interbedded sandstone and dolomite.

Area of Study

This report is based primarily upon evidence obtained from exposures in southern Teton County, Wyoming. Sections were measured along the north wall of Hoback Canyon about 20 miles southeast of Jackson, Wyoming; on Open Door Mountain above the hot spring on Granite Creek at the southern margin of the Gros Ventre Range; on Glory Mountain the southernmost peak of the Teton Range; and along the Gros Ventre River and Flat Creek at the eastern edge of Jackson's Hole.

Table II
Location of Outcrops: Teton County, Wyoming

Glory Mountain	
Madison Group	
Amsden Formation	NW$\frac{1}{4}$ sec. 24, T. 41 N., R. 118 W.
Tensleep Formation	
Gros Ventre River	
Madison Group	SW$\frac{1}{4}$ sec. 1, T. 42 N., R. 115 W.
Darwin Member	NE$\frac{1}{4}$ sec. 1, T. 42 N., R. 115 W.
Tensleep Formation	NE$\frac{1}{4}$ sec. 1, T. 42 N., R. 115 W.
Flat Creek	
Tensleep Formation	NW$\frac{1}{4}$ sec. 6, T. 41 N., R. 114 W.
Hoback Canyon	
Madison Group	NW$\frac{1}{4}$ sec. 2, T. 38 N., R. 115 W.
Amsden Formation	NW$\frac{1}{4}$ sec. 2, T. 38 N., R. 115 W.
and	SW$\frac{1}{4}$ sec. 35, T. 39 N., R. 115 W.
Tensleep Formation	SW$\frac{1}{4}$ sec. 26, T. 39 N., R. 115 W.
Open Door Mountain	
Madison Group	
Amsden Formation	SW$\frac{1}{4}$ sec. 32, T. 40 N., R. 113 W.
Tensleep Formation	

SEDIMENTOLOGIC MODEL

The upper part of the Mission Canyon Formation and the lower part of the Amsden Formation are unfossiliferous in western Wyoming. There is no angular discordance of the strata above and below the contact. The absence of these definitive criteria necessitates the use of sedimentologic evidence to determine whether the carbonate-clastic contact represents a major unconformity or a change in depositional environment. A sedimentologic model which results in a conformable carbonate-clastic transition is proposed. The correspondence or discordance of the sedimentologic data with the proposed model will illustrate the nature of the Madison-Amsden contact in western Wyoming.

The model is similar to that developed for the cyclic deposits in the Midland and Delaware basins (Adams et. al., 1951; Van Siclen, 1958; Kendall, 1969; Silver and Todd, 1969; Tyrrell, 1969). Silver and Todd (1969, Figs. 4-7, p. 2227-2230) graphically illustrate the model for a typical Permian cycle. A cycle begins with the filling of the depositional basin by regressive tide flat sedimentation. Marine carbonate sediment is overlain by tide flat carbonates and evaporites which are in turn buried by the progradation of continental detritus across the abandoned supratidal flat.

The Madison Group is over 1000 feet thick in western

Wyoming. As Shinn et. al. (1969) point out, units of this thickness cannot accumulate through a single regression of the shoreline but must be the result of numerous trangressive-regressive cycles taking place over a long period of time in a gradually subsiding area. Subsidence may be tectonic or due to sediment compaction or both. Eustatic sea level fluctuations may or may not occur but relative changes in sea level due to changing rates of subsidence and/or sediment accumulation are probable. At any instant in time tide flats are being built in one part of the area and destroyed in another. The individual cycles are seldom identifiable in ancient rock because each new cycle redistributes much of the sediment of the previous cycle. The resultant sequence of strata will contain numerous minor disconformities. Superimposed on the minor transgressive-regressive cycles is a major regression of the shoreline and the strata preserved show a vertical change from predominantly marine to predominantly onshore deposition.

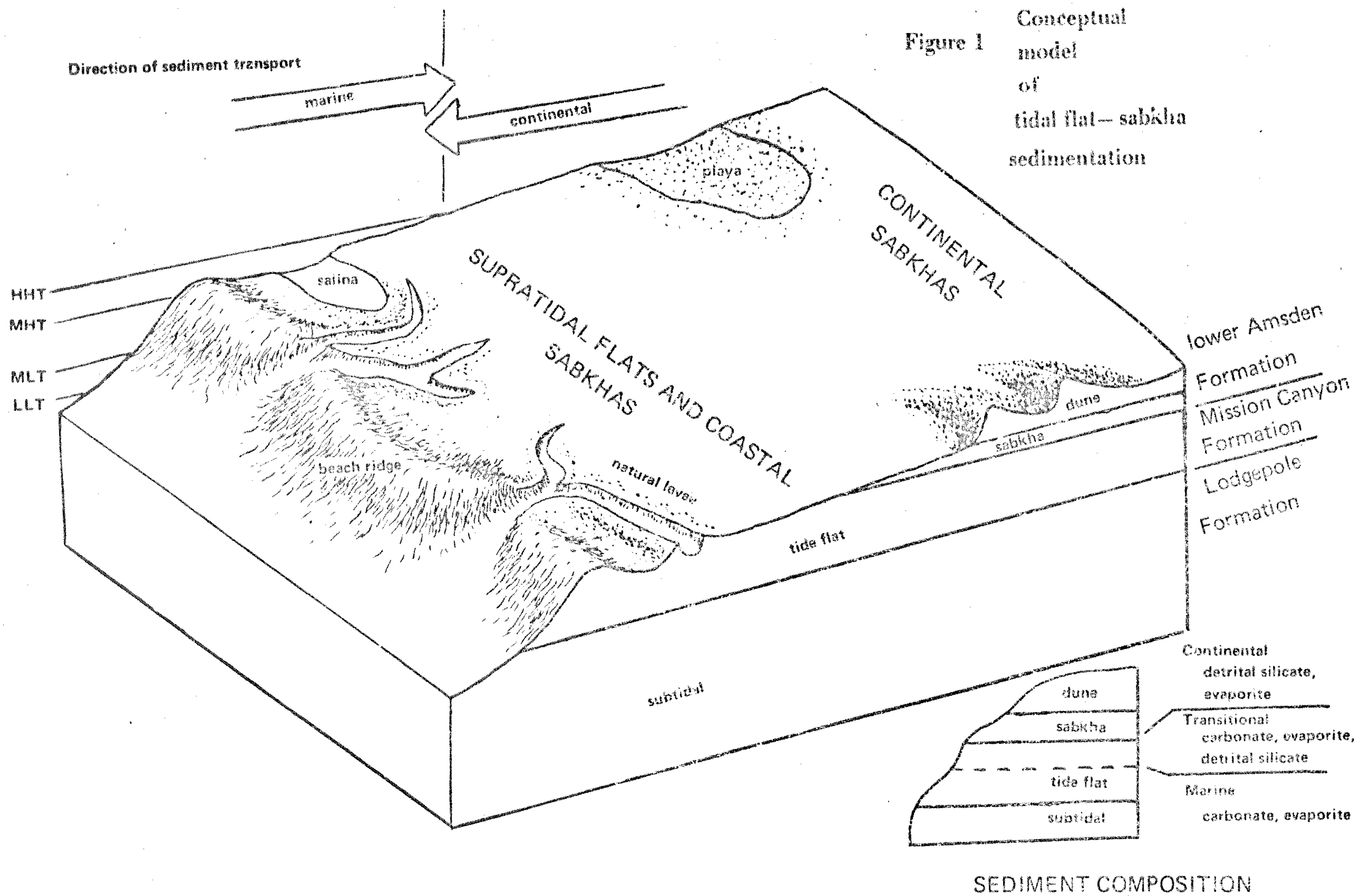
The shoreline in such an area is highly irregular. While tidal channels are continually migrating through the lower tide flats, the inter-channel tracts are isolated by natural levees and beach ridges. Shinn et. al. (1969) suggest that extensive channel systems are more likely to develop in a transgressive than a regressive sequence. However, the entire lithostratigraphic unit will be composed of all the minor transgressive and regressive phases. Hypersaline brines resulting from the evaporation of seawater will dolomitize the calcareous sediment in (Illing et. al., 1965; Shinn et. al., 1965; Kinsman, 1969) and below (Newell et. al., 1953; Adams and Rhodes, 1960; Deffeyes et. al., 1965) the exposed tidal flat sediment. Evaporites precipitated within this sediment are commonly leached out by subsequent tidal inundations (Shinn et. al., 1965) but they may leave vugs to indicate their presence. Where the evaporites are preserved they appear as nodules in ancient rock and if present in abundance are commonly described as having a chicken wire structure. Bedded evaporites result from evaporation of isolated bodies of water which occur as pans or salinas on the interchannel and higher supratidal flats (Kinsman, 1969; Murray, 1964; Phleger, 1969).

Local patches of the emergent tide flat might well be expected to remain exposed for longer periods of time than others during the early stages of progradation by continental detritus. Roehl (1967) called the abandoned supratidal flat the subaerial diagenetic terrane which he described as being characterized by desiccation or solution phenomena. Where solution processes dominate, a karst topography may develop. While karst development represents an unconformity in a strict definition of the word, the sequence of strata preserved after burial may not indicate a significant gap in the geologic record. Solution of carbonate minerals is a surface and vadose zone phenomenon. Evaporite minerals may be dissolved below the groundwater table by either marine or fresh water. Solution of evaporites may occur during or any time after the deposition of the overlying sediment but this would not indicate an unconformity due to a break in sedimentation. Whether surface karsting or subsurface solution occurs the resulting cavities will be filled with the overlying sediment. Either, or both processes may be operative and a distinction between the two may not be possible in ancient rock.

Where precipitation of evaporites and dolomitization continues the area is a coastal sabkha which may turn into a continental sabkha without a break in sedimentation. Sedimentation and erosion in the sabkhas are controlled by the level of the groundwater table. Sediment will be held on the sabkha surface as high above the groundwater table as there is sufficient capillary action to keep it wet. A lowering of the groundwater table will permit erosion by wind deflation. If the groundwater table is rising, eolian sediment will accumulate in the sabkha. Dunes will form wherever there is enough sediment available. The sabkha deposits exhibit nearly horizontal laminae with minor rippling in places. Large scale cross-bedding characterizes the dune fields and where the groundwater table is rising the toes of the dune cross-beds are preserved (Kinsman, 1969).

Figure 1 illustrates the sedimentologic model and its

Figure 1 Conceptual model of tidal flat— sabkha sedimentation



proposed application to the Lower Carboniferous strata in western Wyoming. The illustration draws no distinct boundary between areas of continental and marine sedimentation. This distinction can be made in recent sediment. Kinsman (1969) recognized coastal and continental sabkhas along the Trucial Coast of the Persian Gulf today. The coastal sabkhas are the end product of supratidal sedimentation; i.e., sediment and water are marine. There is a high percentage of continental detritus in the sediment of the continental sabkhas and the water is of continental origin. The coastal-continental sabkha boundary will shift landward and seaward with changing environmental conditions and some areas can only be described as transitional. With continued regression of the shoreline the continental sabkha will migrate across and bury the coastal sabkha. In ancient strata it is difficult to determine a distinct boundary between coastal and continental facies. The same problem arises where salinas and playas occur.

It must be noted that whether called continental or marine the environment of deposition was never far from the shoreline in either direction. The nearshore environments provide numerous opportunities for subaerial exposure and even erosion on a local scale. The resultant diastems are limited in areal extent and occur at different stratigraphic horizons in different localities. By their nature they cannot represent a significant gap in the geologic record. Actually, the record is more complete in that they are indicative of the environment of deposition.

The model illustrates one way in which carbonate and detrital silicate rocks are formed in related sedimentary environments. The sea is the source of carbonate sediment which is deposited as far onshore as the tides will carry it. As tidal sedimentation builds up the depositional surface the various tide flat facies migrate seaward. Progradation of continental detritus marks the transition from coastal to continental sabkha. The demonstration of this model's applicability to the Lower Carboniferous strata in western Wyoming requires evidence of an analagous sequence of events not separated by significant amounts of time.

LOWER CARBONIFEROUS

The key points in the evaluation of the proposed model are: 1) the regressive nature of the Madison Group, 2) deposition of the lower beds of the Amsden Formation in a sabkha-dune complex and 3) the interpretation of the Madison-Amsden contact.

Madison Group

Lodgepole Formation -- In western Wyoming the Lodgepole Formation is composed of limestone and dolomitic limestone. Nodular chert occurs throughout the formation. The basal strata are predominantly grainstone, packstone and wackestone (terminology of Dunham, 1962). Much of the middle and upper part of the formation is composed of grainstone or packstone interbedded with wackestone or mudstone. The grains are pelletoids and fossil debris -- primarily pelmetazoan -- which are often oolitically coated. Oolites are somewhat less common and usually found in cross-bedded strata. Bryozoans and whole brachiopods and rugose corals are abundant in many beds. Other beds contain tabulate coral -- syringoporids. Horizontal burrows are common in the lower part of the formation. Vertical burrows are found throughout the unit. Beds containing intraclasts are common in the upper part of the formation.

The presence of both horizontal and vertical burrows, oolites and oolitic coatings, and a diverse fauna is consid-

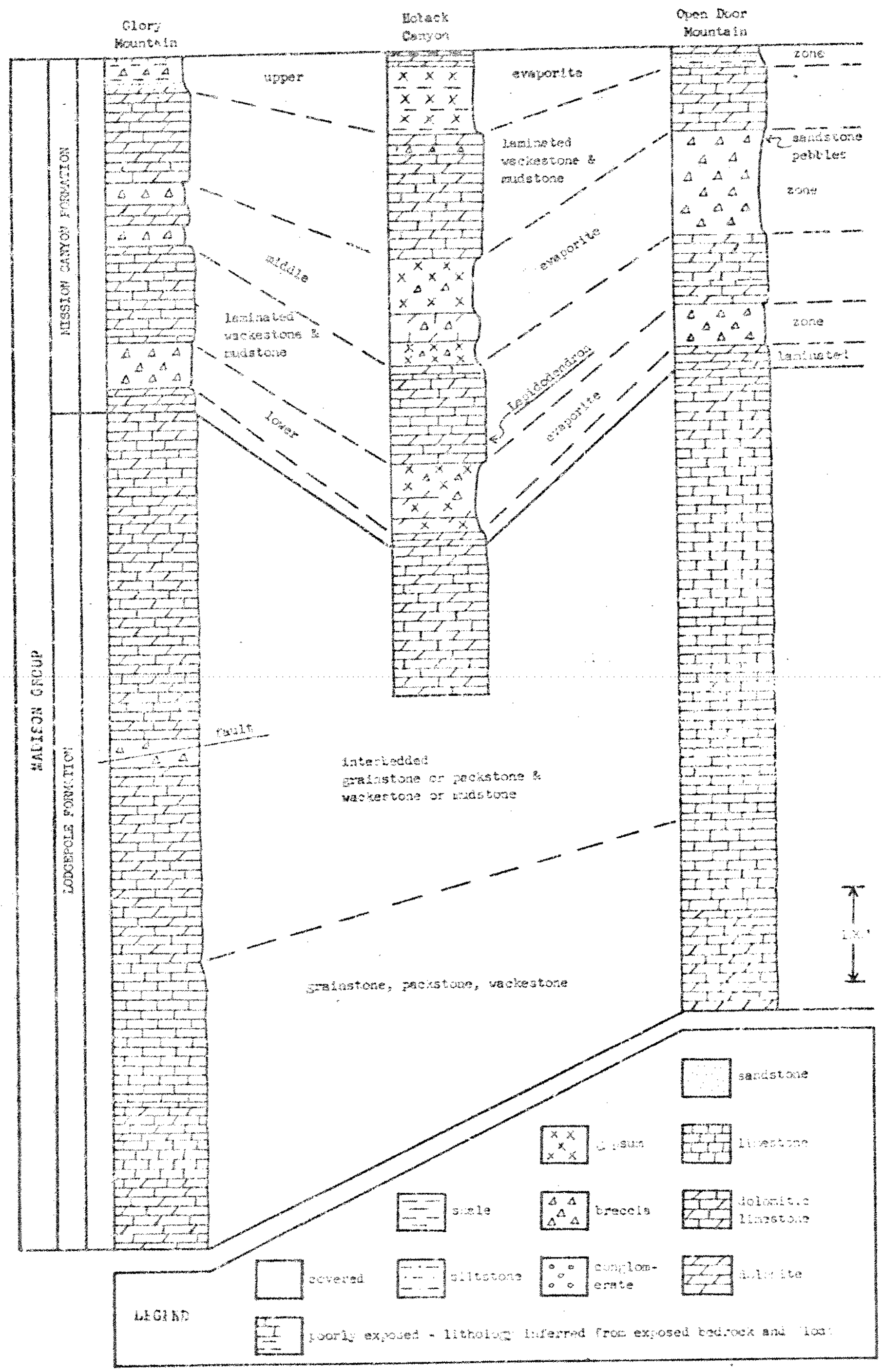


Figure 2. Measured sections: Madison Group

ered indicative of sedimentation in the shallow subtidal environments (Laporte, 1967, 1969, 1971). The formation contains grainstone, packstone, wackestone and mudstone. Kendall and Skipwith (1969) show how the distribution of mud and grains in the lagoons and shallow shelf off the Trucial Coast is related to bottom topography and water turbulence.

Mission Canyon Formation -- The Mission Canyon Formation in western Wyoming is predominantly dolomitic limestone and dolomite. There are three evaporite zones in the formation (Fig. 2). In Hoback Canyon the evaporite intervals are represented in outcrop by gypsum. At other localities solution breccias occupy those stratigraphic horizons. In the lower and middle evaporite zones the gypsum is interbedded with dolomite which is commonly vuggy. The gypsum beds are pure and massive indicating precipitation from a standing body of water. In the upper evaporite zone, which forms the uppermost strata of the formation, shale, siltstone, dolomite and sandstone are interbedded with the gypsum or solution breccias. The carbonate strata are predominantly wackestone or mudstone, most of which are laminated. There are wavy algal laminae, fine planar laminae, fine laminae with micro-cross-bedding and laminae containing torn up mud flakes from the underlying layer. Rounded and/or angular vugs are abundant at many horizons. Whole fossils are rare but a few whole corals and brachiopods were found associated with thin (1 to 3 or 4 cm.) layers of pelmetazoan, coral and brachiopod debris. The debris layers

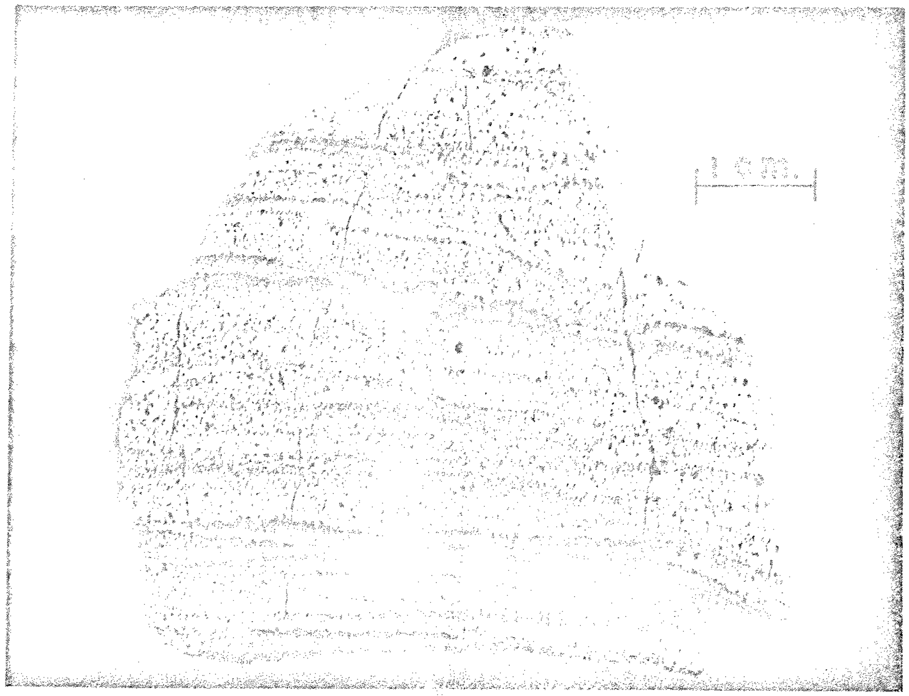


Figure 3. Etched slab, Mission Canyon Formation.

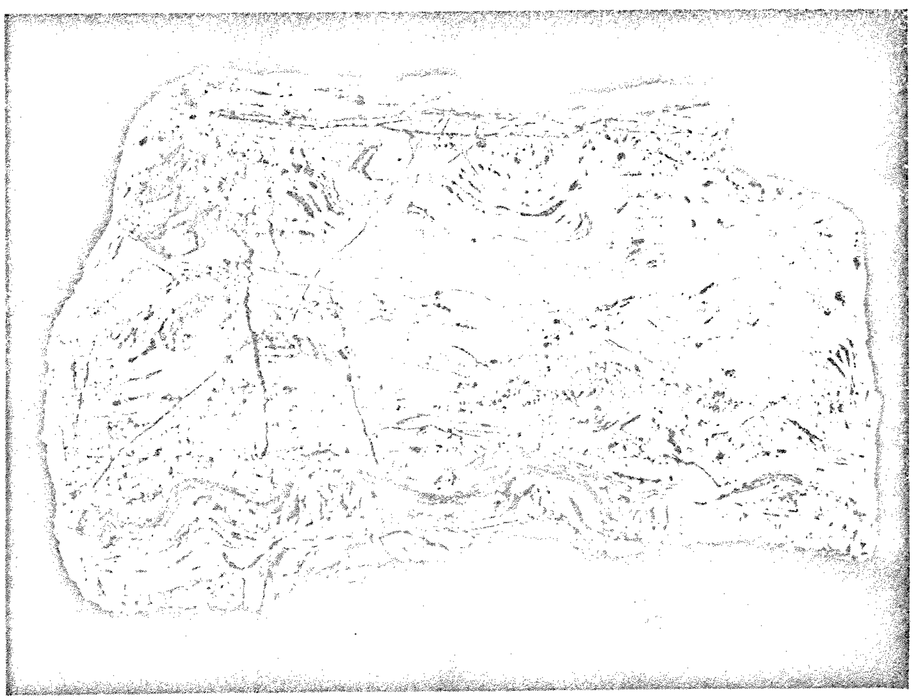


Figure 4. Etched slab, Mission Canyon Formation.

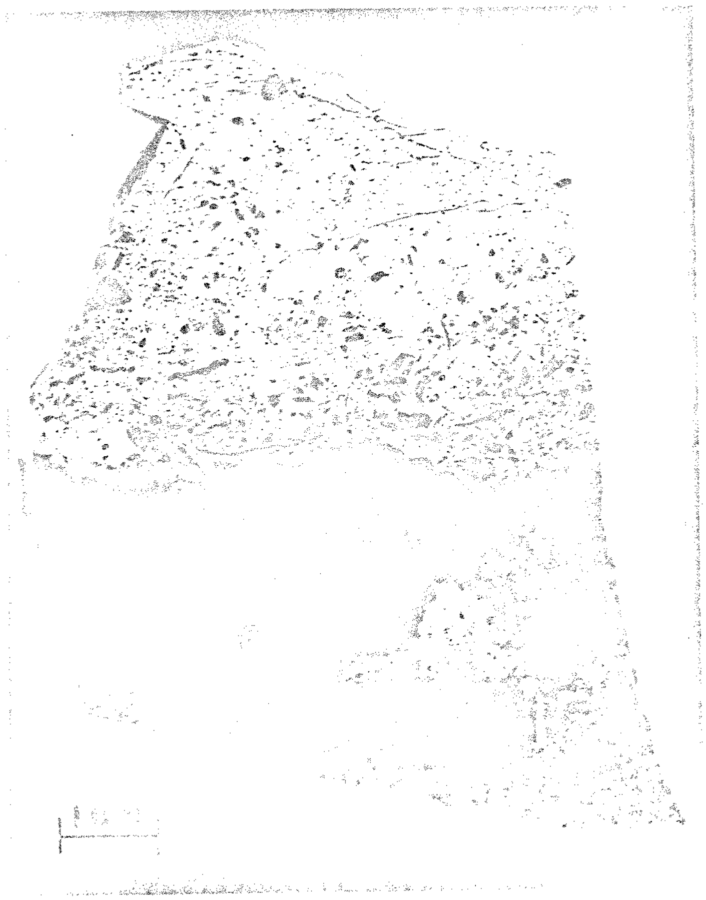


Figure 5. Etched slab, Mission Canyon Formation.

are common below the middle evaporite zone but rare above it. Fragments of *Lepidodendron* and other land plants were found between the lower and middle evaporite zones about 400 feet below the top of the formation in Hoback Canyon.

The association of algal and sheet laminae, mud cracks and redeposited mud flakes, sparse fauna, low percentage of grain supported rock, and evaporite pans or salinas is considered characteristic of tidal flat sedimentation (Laporte, 1967, 1969, 1971).

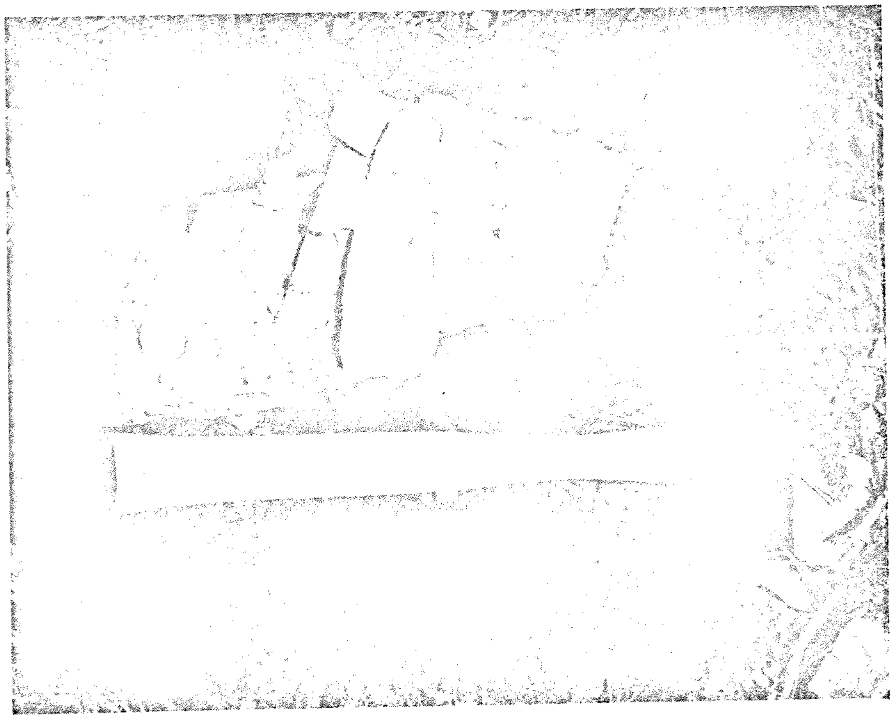


Figure 6. Mud cracks, Mission Canyon Formation. (Photo by R.C. Murray)

Regressive Sedimentation -- The Lodgepole Formation is predominantly of shallow marine origin. There are indications of an increasingly onshore aspect upward in the section. Horizontal burrows are limited to the lower part of the formation. The intraclasts in the upper beds of the unit may indicate periods of subaerial exposure or close proximity to exposed sediment. The Mission Canyon Formation resulted from tidal flat sedimentation. An upward increase in onshore character is also indicated by an upward decrease in recognizable marine fossil material. The upper evaporite zone contains both carbonate and detrital silicate interbeds. Since the zone is underlain by carbonate and overlain by detrital silicate sediment, deposition must have taken place in the transitional

Table III

Diagnostic assemblages of sedimentary features in the nearshore facies of the Carboniferous of western Wyoming

facies	sedimentary features	sediment type	strat. unit
dune	large scale cross-bedding	detrital silicate	the lower part of the Amsden Formation
continental sabkha	horizontal and nearly horizontal laminae some ripple marks locally	detrital silicate, evaporite	the lower part of the Amsden Formation
transitional -- as above	(as above)	detrital silicate, evaporite, carbonate	Mission Canyon Formation
tidal flat & coastal sabkha	as above & sheet laminae algal laminae mud cracks and mud flakes vertical burrows small scale cross-bedding fossil debris	evaporite, carbonate	Mission Canyon Formation
shallow subtidal	oölites and oölitic coatings horizontal & vertical burrows medium scale cross-bedding tabulate and rugose coral brachiopods bryozoans fossil debris	carbonate	Lodgepole Formation

zone. Significant to the evaluation of the model is the demonstration that deposition of the Madison Group began in the marine and culminated with the creation of a land surface.

Lower Amsden

Darwin Member -- The Darwin Member of the Amsden Formation is an unfossiliferous orthoquartzite. Sand size chert, orthoclase, microcline and plagioclase grains were identified but in aggregate compose less than 10% of a sample. Silt size opaque grains were identified as hematite. They are weathering to limonite and give the rock its color. The sub-angular to rounded quartz grains are well sorted and fine to medium sand sized -- except in the Open Door Mountain exposure. The Darwin Member on Open Door Mountain is cemented by calcite and composed almost entirely of thick (3-6 feet) sets of cross-beds. The basal 60 feet are medium to coarse grained and cross-bed dips often exceed 45 degrees. The upper 43 feet are fine to medium grained and cross-bed dips vary from 30 to 45 degrees. In Hoback Canyon the Darwin Member is cemented by silica. The basal bed (20 inches thick) exhibits irregular laminae. It is overlain by 2 feet of ripple marked siltstone. The remaining 54 feet are horizontally laminated sandstone. On Glory Mountain the basal sandstone bed (1 foot thick) is overlain by 3 feet of siltstone. Above this is a 57 foot section containing thick (3-8 feet) sets of cross-beds with dips up to 45 degrees. One cross bed set at about the middle of the unit is 14 feet thick. The

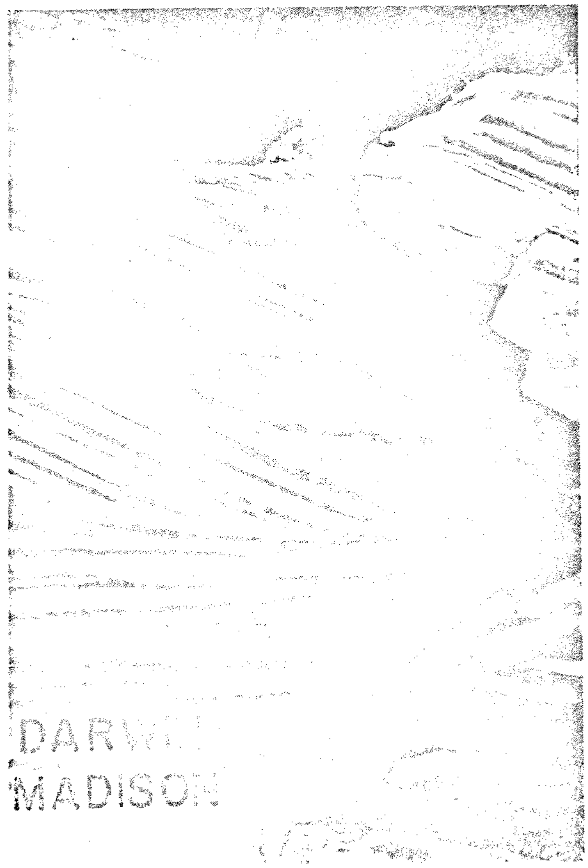


Figure 7. Darwin Member, Open Door Mountain.

cross-bedded strata are separated by 1 to 4 foot zones of thin horizontal beds. Within the latter zones there are cross-bedded units 8 to 12 inches thick. The member is cemented by calcite on Glory Mountain. Angular vugs in horizontally laminated beds near the top of the unit may be molds of evaporite crystals.

The complete absence of fossils indicates a non-marine origin for the Darwin Member. The association of high angle cross-bedding with horizontal laminae and some ripple marks suggests an analogy with the sabkhas and dune fields of the Trucial Coast. The good sorting and fine to medium sand size of the quartz grains is in agreement with Kinsman's (1969) description of sabkha and dune sediment. The toes of many of the cross-bed sets on Open Door Mountain have been preserved (Fig. 7). A sabkha-dune origin of the Darwin Member is consistant with the model.

Post-Darwin Transgression -- The strata above the Darwin Member on Glory Mountain indicate a sequence of events which would result from the submergence of a sabkha. Immediately overlying the Darwin Member are three beds (4 feet thick in aggregate) which show a gradual change from a calcareous sandstone at the base to a sandy dolomite in the upper part. This is overlain by a red calcareous siltstone (19 feet thick) which is horizontally laminated and vuggy. A rise in sea level (eustatic or relative) would bring about a rise in the groundwater table and thus a rise in the base level of wind deflation (Kinsman, 1969). Eolian silt would then accumulate in the sabkha. The siltstone is overlain by 12 feet of limestone the middle part of which contains irregular lenses and balls of red clay. The upper part of the limestone unit contains irregular stringers of coarse sand and/or pebble size gravel. This is overlain by a limestone pebble conglomerate. Many of the carbonate pebbles in the pebble conglomerate have been replaced by hematite. Hematite pisolites about 1 mm. in diameter are found at the top of the bed. Shale stringers

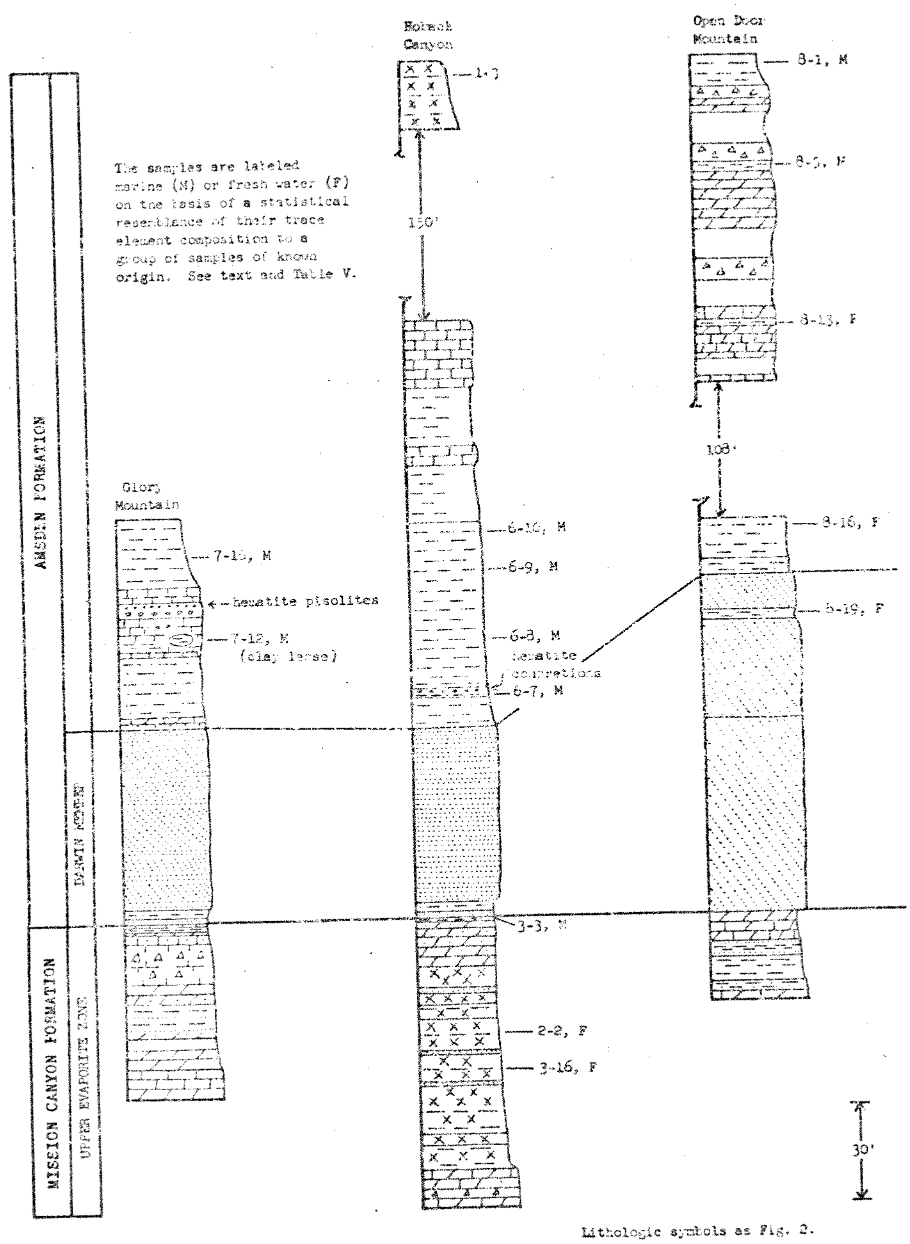


Figure 8. Measured sections: Darwin Member, and the location of shale samples used in the trace element analysis.

and pebble conglomerates are often found in the intertidal to supratidal environments (Braun and Friedman, 1969). Above the pebble conglomerate are 4 feet of limestone with thin argillaceous partings. The limestone has sand size fossil debris in the lower part, and larger fragments and whole brachiopods in the upper part.

The strata recording the marine transgression were not preserved in the Hoback Canyon section and that stratigraphic interval is not exposed on Open Door Mountain. In Hoback Canyon the Darwin Member is overlain by glauconitic siltstone and shale. On Open Door Mountain the Darwin Member is overlain by 5 feet of calcareous gray siltstone which is in turn overlain by 12 feet of calcareous red shale. Approximately 112 feet of strata above this are covered with the exception of a bed of limestone containing fossil debris exposed about 108 feet above the red shale.

Trace Element Analysis

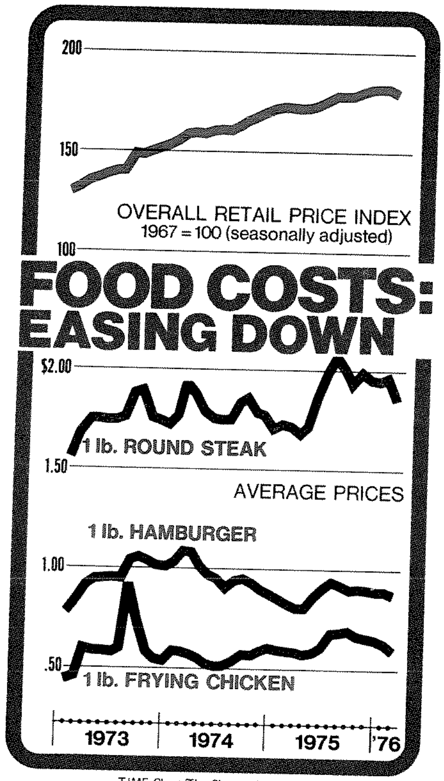
Kinsman's (1969) distinction between coastal and continental sabkhas is based upon the origin of the sediment and the water in each facies. While the water chemistry is modified by evaporation in the sabkhas and there may be mixing in the transition zone, it is of value to have an estimate of paleosalinity.

Interest in the use of trace elements as salinity indicators began with the work of Goldschmidt and Peters (1932) and Landergren (1945). Recent papers by Curtis (1964), Walker (1968), Cody (1971) and Couch (1971) review the development of the theory. At present, boron is thought to be the best indicator and more is known about the adsorption and fixation of boron with different clay minerals under varying environmental conditions. Considerable progress has been made toward developing a quantitative approach to the use of boron (Walker, 1969; Couch, 1971). However, at this point, a more empirical approach employing several elements and not relying upon assumptions about the geochemical processes involved is more likely to give reliable results where there are no other lines of evidence for comparison. Boron, vanadium, lithium, rubidium and gallium have been used sucessfully in this manner (Degens _et_. _al_., 1957; Keith and Degens, 1959; Potter _et_. _al_., 1963).

Twelve Amsden samples, three Madison samples (Fig. 8) and fourteen samples known to be marine or fresh water in origin (Table IV) were analyzed. The results are tabulated in tables V and VI. X-ray diffraction analysis of the -2μ size fraction of the Madison and Amsden samples revealed each to be predominantly illite. Quartz made up 10% to 25% of the clay fraction and minor amounts of feldspar, calcite and dolomite were detected in most samples. Aside from the sample containing glauconite (6-7, Hoback Canyon), no other clay mineral was detected in amounts exceeding 5% of the clay fraction.

ulatory outlook and the industry's depressed revenues are preventing the carriers from borrowing the money they need to buy newer, cheaper-to-run aircraft. United, unable to get financing, was forced to cancel an order for a fleet of new Boeing 727 jets. To keep its present equipment going, the line now faces higher maintenance costs and lower productivity, which cut into its revenues.

Beyond these woes, the airlines confront yet another gnawing worry. Says Citibank Vice President Frederick W. Bradley Jr.: "Over the next few years we do not see sufficient traffic growth to support anticipated further increases in fuel, wage costs and other costs. The long-term outlook at this point is bleak." In short, there is a growing question about whether the U.S. market is big enough to support all its major carriers. If it is not, the weaker lines may well have to be weeded out, through merger or failure, to allow the healthy, resourceful carriers to survive and prosper.



TIME Chart/The Chartmakers,Inc.

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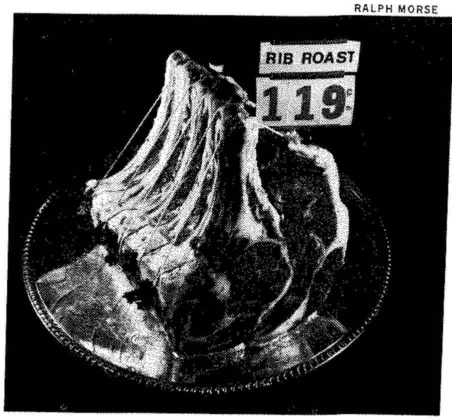
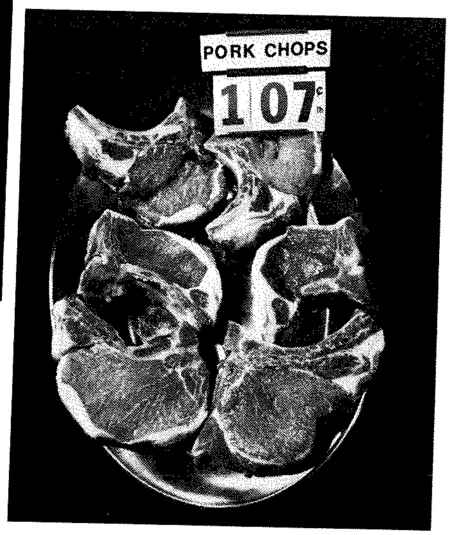




PRICES

Food Calms Down

No part of the inflationary wave that swept through the U.S. over the past three years hit consumers harder than spiraling prices at the supermarket. From 1972 to the end of last year, the cost of food jumped 42%, reflecting the price-boosting pressures of the big Soviet grain sales, drought, destructively heavy rains and lively speculation on commodity exchanges. Now the price wave seems to be subsiding. During the past six months, food prices rose by only 1.1%, and Agriculture Department economists forecast an increase of no more than 3% for the rest of 1976, compared with 8.5% last year.

Market-shelf prices actually fell from January to February; the decline was only 1.5%, but it was the biggest monthly slide in the grocery component of the consumer price index since the early 1950s. The sharpest drop occurred in the area where housewives had been hit hardest: the meat case. Beef prices plunged 6% as cattlemen, reacting to dwindling demand, trimmed the sizes of their herds and pumped beef onto the market. Beef prices may well rebound in coming weeks as supplies begin to tighten again: when store prices begin to edge up, hamburger will probably rise relatively more than prime steak, largely because it had showed the biggest decline. The expected run-up in beef prices should end this summer as larger supplies of cattle come to market.

Hog Crop. The dynamics of U.S. food production has not been so balanced in favor of the consumer since 1971. Dairy prices have gone up 6.5% in recent months, but a decline soon is almost assured because milk production is rising; butter and milk prices are beginning to slide at the wholesale level. Bountiful supplies are also depressing poultry prices. By late summer, say economists, the cost of pork should tumble as more of the big crop of hogs farrowed last winter comes to market. Canners' and distributors' stocks of most fruits and vegetables are large, and in some cases they are selling to retailers more cheaply than at any time since the fall of 1974.

No one seems to be suffering seriously from the calm in food costs. Farmers may be getting less for what they produced than in 1972 and 1973, but they are still doing well. Says Agriculture Department Economist Dawson Ahalt: "What they have lost in prices they are making up in volume." Moreover, profit margins for processors, wholesalers and retailers remain healthy.

What could upset the relatively pleasing picture? A weather disaster affecting this year's corn, wheat or soybean crops could do it, but the impact would not be noticeable on market shelves until 1977. Although many farmers from Iowa to Texas are worried about a drought, and there has been some damage to the winter wheat crop, grain prices have so far been only slightly affected. The outlook is for continued calm, with the main beneficiaries—in this election year—being the millions of middle- and lower-income families that spend more of their available cash on food than wealthier Americans.

VENEZUELA

Terror and Takeover

Just why they singled out William F. Niehous, general manager of Owens-Illinois' Venezuelan operation, is unclear. But on the evening of Feb. 27, seven armed guerrillas broke into the American glass-company executive's home in an affluent suburb of Caracas. While his wife and a maid watched helplessly, Niehous, 44, was injected with a soporific and carried into the night. At first it was expected that the ultra-leftist terrorists, like the majority of their counterparts in Uruguay and Argentina, would simply demand that a huge ransom be paid by the company's big (1975 sales: $2.2 billion) Ohio-based U.S. parent. Instead, the Niehous case brought a new dimension to the political kidnapings that have been plaguing businessmen, particularly in Latin America. Indeed, it led last week to a startlingly abrupt—and arbitrary—government takeover of Owens-Illinois' three glass-making factories in Venezuela.

The terrorists identified themselves as part of a little-known leftist movement named the Argimiro Gabaldon Revolutionary Command. Instead of asking for a cash ransom, they demanded that Owens-Illinois 1) pay each of its 1,600 Venezuelan employees $116 as compensation for its "exploitation"; 2) distribute 18,000 packages of food to needy families; and 3) buy space in Venezuelan and foreign newspapers for a lengthy manifesto, written by the extremists, denouncing the company and the Caracas government. Otherwise, they implied, Niehous would be killed.

In complying with the third point, the company ran into trouble. The dif-

Table IV
Samples Of Known Origin For Trace Element Analysis

Marine		
CB-15	Cannonball Formation - Tertiary North Dakota*
826	Alloway Clay - Tertiary Yorktown, New Jersey**
ME-31	Cody Shale - Cretaceous Yellowstone Park, Wyoming*
615	Merchantville Formation - Cretaceous Bordentown, New Jersey**
635	Merchantville Formation - Cretaceous Mansfield Square, New Jersey**
640	Merchantville Formation - Cretaceous Jamesburg, New Jersey**
56-309 ...	Lower Kittanning Member - Pennsylvanian Holden, Pennsylvania***
Fresh Water	
625	Pleistocene, Whippany, New Jersey**
658	Pleistocene, Moonachie, New Jersey**
847	Pleistocene, Sterling, New Jersey**
P-1	Paskapoo Formation - Tertiary Alberta, Canada****
L-1	Lance Formation - Cretaceous Rock Springs, Wyoming****
642	Brunswick Shale - Triassic Piscataway, New Jersey**
56-316 ...	Upper Freeport Member - Pennsylvanian Juneau, Pennsylvania***

Samples were contributed by:
* Dr. S.K. Fox, Rutgers University
** Mr. William Lodding, Rutgers University
*** Dr. M.L. Keith, Pennsylvania State University, see Degens et. al., 1957, pp. 2434, 2442, 2444.
**** Dr. Erling Dorf, Princeton University

Table V
Trace Element Data (ppm): Samples Of Known Origin

sample #	B	V	Li	Rb	Ga
Marine					
CB-15	106	415	50	165	21
826	140	205	67	148	21
ME-31	188	100	59	128	16
615	165	130	130	188	45
635	116	195	136	165	36
640	110	65	229	160	36
56-309	126	125	227	195	46
mean	135.9	176.4	128.3	164.1	31.6
Fresh Water					
625	94	65	54	90	26
658	64	70	25	91	13
847	112	450	53	191	36
P-1	47	260	112	84	10
L-1	72	130	58	185	6
642	90	325	56	79	10
56-316	100	75	76	211	28
mean	82.7	203.6	62.0	133.0	18.4

Table VI
Trace Element Data (ppm): Madison And Amsden Shales

sample #	B	V	Li	Rb	Ga	Y_5	classified M-marine F-fresh water
Madison Group, Hoback Canyon							
3-16	84	85	55	120	9	-0.39499	F
2-2	72	40	<10	118	8	-0.76329	F
3-3	185	155	18	185	20	0.45506	M
Darwin Member, Open Door Mountain							
8-19	64	125	<10	112	8	-0.97412	F
Amsden Formation							
Glory Mountain							
7-12	148	105	39	157	29	0.05525	M
7-16	161	>500	91	158	30	0.69251	M
Hoback Canyon							
6-7	358	45	<10	240	41	2.02224	M
6-8	415	35	225	<40	8	3.97717	M
6-9	338	200	191	<40	10	3.07262	M
6-10	330	285	234	<40	10	3.25043	M
1-3	125	460	33	181	20	0.07879	M
Open Door Mountain							
8-16	66	50	<10	81	10	-0.83377	F
8-13	<40	150	39	251	6	-0.89480	F
8-5	330	330	108	240	43	2.36408	M
8-1	190	80	68	250	10	0.78061	M

Analytical Procedure -- Since all samples analyzed were shale and since a discriminant function was applied to the data, the analysis was performed on whole rock rather than clay fraction samples. Potter et. al. (1963) found that while trace element abundances are higher in the clay fraction, the differences between the values for marine and fresh water sediment are greater in the whole rock sample.

Boron and gallium analyses were performed on a Jarral Ash 3.4 meter grating emission spectrograph. Synthetic standards were prepared after the procedure of Degens et. al. (1957). Samples and standards were mixed in 1:1 ratio with a graphite-BeO mixture so that each sample or standard contained 0.225% beryllium as internal standard. These were loaded into high purity carbon electrodes and preheated at 400 degrees centigrade for 12 hours. The samples were burned to completion in a CO_2 atmosphere in a 6 ampere direct current arc. Exposures were made on Kodak SA-1 plates. Analysis lines were Be 2348 Å, B 2497 Å and Ga 2874 Å.

Lithium and vanadium analyses were done by atomic absorption spectrophotometry (Li - Techtron model AA4, V - Perkin Elmer model 303). Standards were the U.S.G.S. AGV-1, BCR-1 and G-2. The samples and standards were digested in hydrofluoric and perchloric acids by the procedure of Pratt (1965).

Rubidium analyses were performed on a Phillips-Norelco

X-ray fluorescence spectrograph. Standards were the U.S.G.S. AGV-1, BCR-1 and G-2. 500 mg. of sample or standard were mixed with 120 mg. of an H_3BO_4-As_2O_5 mixture so that each sample or standard contained 500 ppm arsenic as internal standard. These were pressed into dry pellets with a boric acid backing. Tungsten radiation, a lithium fluoride analyzer and a scintillation counter were used. Rubidium $K\alpha$ radiation was measured at 26.51 degrees 2θ. Background was estimated by projecting a curve through counts taken at 21.6, 23.2, 24.5, 25.95 and 27.2 degrees 2θ. Arsenic $K\alpha$ radiation was counted at 34.0 degrees 2θ. Background was counted at 33.5 degrees 2θ.

Statistical Analysis -- The data from the samples of known origin were submitted to a discriminant function analysis for two groups (BMD04M, Dixon, 1968). The application of the discriminant function is described by Potter _et_. _al_. (1963). Both the raw data and logarithmically transformed data were analyzed. There was no significant difference in the results from the two sets of data, but the F ratios from the functions based on the raw data tended to be more significant than those from the logarithmically transformed data. The raw data calculations are reported here. The discriminant function based upon all five elements is

$$X_5 = 0.01075x_1 + 0.00064x_2 + 0.00487x_3 - 0.00012x_4 - 0.00841x_5$$

where x_1 = ppm B, x_2 = ppm V, x_3 = ppm Li, x_4 = ppm Rb and x_5 = ppm Ca. This function accurately discriminated all the known marine and fresh water samples. Its F ratio is F = 4.26808 which is significant at the 0.95 significance level ($F_{5,8}$= 3.6975, I_F = 0.05). The probability of misclassifing an unknown sample using this function is 1 - F(D/2) = 0.066. To classify an unknown sample the mean of X_5 is calculated for the known marine ($\bar{X}_{5m}$) and the known fresh water ($\bar{X}_{5f}$) groups and X_5 is calculated for the unknown sample (X_{5u}). The quantity Y (Y is used instead of V to avoid confusion with vanadium)

$$Y = X_{5u} - (\bar{X}_{5m} + \bar{X}_{5f})/2$$

determines whether X_{5u} is closer to $\bar{X}_{5m}$ or $\bar{X}_{5f}$. The unknown sample is classified marine if $Y > 0$ and fresh water if $Y \leq 0$.

Following the statistical procedures described by Rao (1952) and used by Potter <u>et. al</u> (1963) it was found that the most efficient discriminant function was one based on boron and lithium alone

$$X_2 = 0.00837x_1 + 0.00308x_3$$

Its F ratio is F = 12.49759 which is highly significant at the 0.95 level ($F_{2,11}$ = 3.9823, I_F = 0.05). The probability of error is 0.098. The elimination of vanadium, rubidium and gallium did not result in a significant loss in discrimination ($U_{3,21}$ = 0.0621, $F_{3,21}$ = 0.4347).

These two functions classified all samples identically except one. The shale (1-3) interbedded with gypsum near the top of the Amsden Formation in Hoback Canyon was classified marine by the function based upon five elements ($Y_5 = 0.07879$) and fresh water by the function based on boron and lithium alone ($Y_2 = -0.06022$). Since the shale was deposited in an evaporitic environment where water chemistry changes frequently and since Y is close to zero in both cases, this descrepancy is not disturbing.

Results -- As can be seen in Figure 8 the Amsden samples with a trace element composition more like that of fresh water shale are all from Open Door Mountain. This includes the shale bed in the Darwin Member which further supports the theory of a continental origin for the unit. Two of the samples from the upper Mission Canyon evaporite zone resembled fresh water shale but the third was more like the known marine group. This is consistent with the hypothesis of deposition of these beds in the transition zone. The samples from Hoback Canyon, Glory Mountain and the top of the Amsden Formation on Open Door Mountain have trace element compositions more like that of marine shale.

The discriminant function is a purely statistical analysis. The trace element composition of a sample is represented by a number. A sample is classified on the basis of whether that number is closer to the mean of the marine group or the mean of the fresh water group. The statistical data are consistant with the model. Perhaps more importantly, however, they point out that the shales above and below the Madison-Amsden contact can be divided into two groups on the basis of their trace element composition. The composition of one group being more like that of marine shale while the other group is more like fresh water shale. Both groups are found above and below the contact and, in the Amsden Formation, both are found at approximately the same stratigraphic horizon at different localities (Fig. 8). This illustrates another similarity between the upper Mission Canyon and lower Amsden formations. Both contain marine and non-marine strata. The environment of deposition could never have been far from the shoreline in order to allow for the oscillating conditions.

Madison-Amsden Contact

The carbonate strata of the Madison Group and the clastic beds in the lower part of the Amsden Formation were deposited in related sedimentary environments. The Mission Canyon and Darwin strata are concordant. The planar contact exhibits no evidence of having been subjected to erosion and no fragments of the rock below are found in the strata above (Fig. 7). The clastic beds in the upper Mission Canyon evaporite zone indicate a gradual transition from predominantly carbonate to predominantly clastic sedimentation in the sabkha complex.

While significant pre-Amsden karst development may have occurred in areas to the north and east, no sinkholes were found in the area of study. Breccias in the Mission Canyon Formation are solution-collapse breccias which resulted from the removal of evaporites. There is evidence that the solution activity occurred after the deposition and lithification of the Darwin Member. Sub-angular, pebble size fragments of sandstone were found in a breccia about 100 feet below the contact on Open Door Mountain (Fig. 9). Petrographic evidence indicates that the pebbles were transported to this site as lithified rock fragments. The stratigraphic position of the Darwin Member makes it the most likely source of the pebbles. There is no sandstone lower in the stratigraphic section above the Cambrian Flathead Formation. Any late Mississippian outcrop of Cambrian strata would have been a considerable distance away (Williams, 1962; Wilson, 1962) and one would expect that pebbles from the Flathead Formation would have been well rounded if they were transported into the area. If the pebbles are from higher in the section an even younger date of solution activity is indicated. In order to further substantiate the origin of the pebbles, point counts were made on thin sections of the pebbles and samples of the Darwin Member from Open Door Mountain. Since the pebbles and the Darwin Member are orthoquartzite, the counts were made on the basis of six types of quartz grains classified by mode of extinction and whether single or multicrystalline grains (Folk, 1964). The data were submitted to a multivariate analysis for two groups which yielded F ratios

Figure 9. Sandstone pebbles in solution breccia, Mission Canyon Formation, Open Door Mountain.

less than unity. This indicates that the variance between the pebbles and the Darwin samples is no more significant than that within each sample. However, there were not enough samples of the pebbles to make a statistically valid estimate of them as a population. Lacking any other reasonable candidate as a source of the pebbles, the assumption that they came from the Darwin Member seems valid.

The evidence for an unconformable contact in other areas is also consistant with the model. Erosion and truncation are to be expected toward the area of uplift; i.e., the Ancestral Rocky Mountains in southeastern Wyoming. Much of the terrain between the area of active erosion and the area of continuous sedimentation might well undergo significant karst development.

Discussion

The sedimentologic evidence indicates that the depositional history of the Lower Carboniferous strata in western Wyoming is analagous to the model. Shallow marine deposition of the Lodgepole Formation was followed by tide flat sedimentation of the Mission Canyon Formation. The basal strata of the Amsden Formation were deposited in a sabkha-dune complex. A number of points indicate that no significant amount of geologic time elapsed between deposition of the last bed of the Mission Canyon Formation and the first bed of the Amsden Formation.

1. The strata above and below the contact are concordant.
2. There is no evidence of physical erosion on the upper Madison surface.
3. The contact is not a paleokarst surface.
4. Solution brecciation in the Mission Canyon Formation occurred after the lithification of the Darwin Member.
5. The clay mineralogy of shale above and below the contact is similar.
6. The trace element composition of shale above and below the contact suggests that both units contain marine and non-marine strata.

7. The upper Mission Canyon evaporite zone was deposited in the zone of transition between marine (Madison) and continental (lower Amsden) facies.

These data demonstrate that the carbonate-clastic transition was the gradual result of seaward migration of the nearshore facies through regressive sedimentation. The transition began with the periodic introduction of terrestrial sediment to the area during the last Madison evaporite interval. The Madison-Amsden contact is the conformable result of the completion of the transition from coastal to continental sabkha.

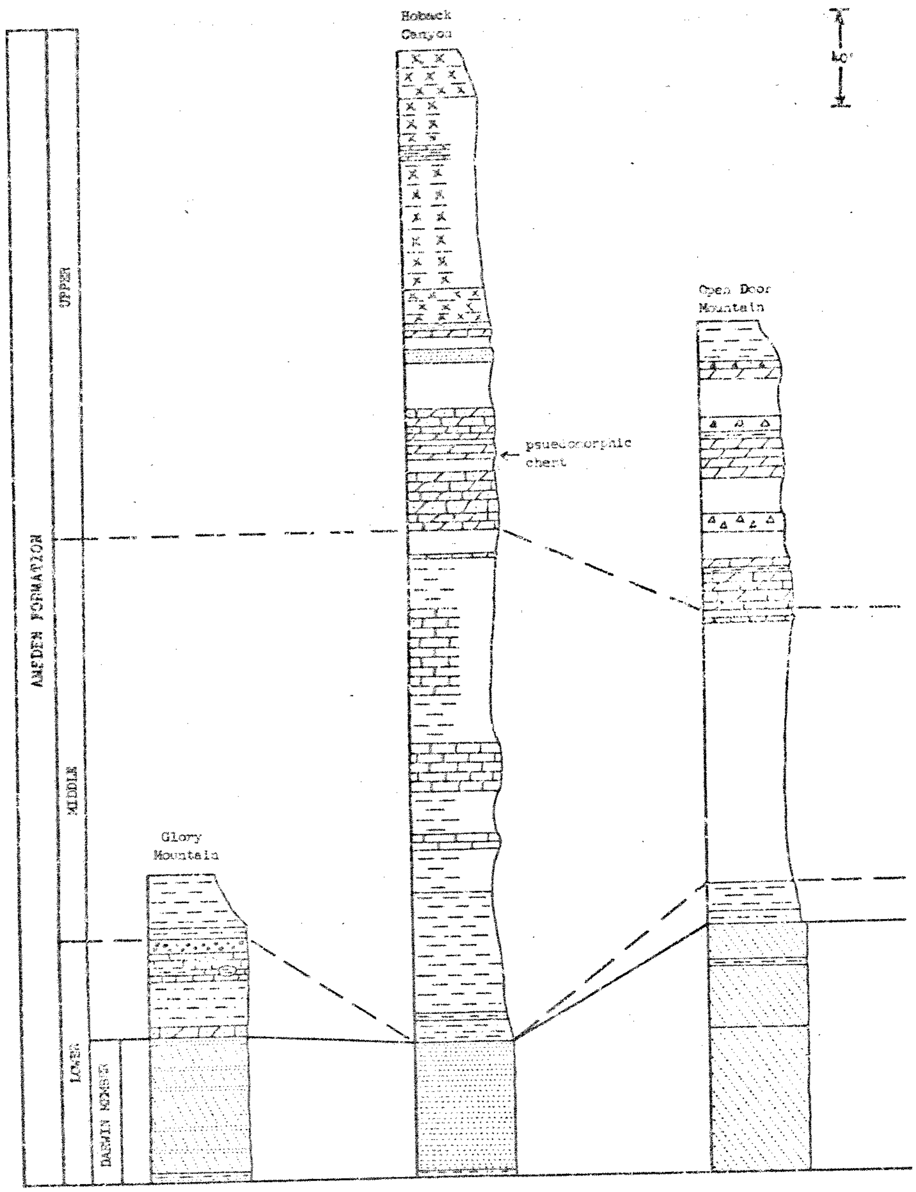
UPPER CARBONIFEROUS

The model of tide flat-sabkha sedimentation served successfully as a working hypothesis in approaching the problem of a thick sequence of carbonate strata overlain by detrital silicate rock. The Upper Carboniferous strata of western Wyoming offer the opportunity to demonstrate the model's utility in explaining carbonate-clastic transitions on a smaller scale. The lithologic sequence will be discussed before testing the applicability of the model.

Middle Amsden

The basal strata of the middle part of the Amsden Formation are marine -- fossiliferous limestone on Glory Mountain, glauconitic siltstone and shale in Hoback Canyon (Figs. 8 & 10). The interval is not exposed on Open Door Mountain and poorly exposed on Glory Mountain but the sequence appears to be the same as that in Hoback Canyon above the iron concretions.

In Hoback Canyon the Darwin Member is overlain by 9 feet of glauconitic siltstone which is overlain by 3 feet of silty glauconitic shale containing beds of iron concretions. Wanless et. al. (1955) described this exposure and Branson (1937, 1939) noted a similar occurrence near Greybull, Wyoming in the Big Horn Basin. The concretions are composed of hematite and range in size from 0.5 to over 3 cm. in diameter.



Lithologic symbols as Fig. 2.

Figure 10. Measured sections: Amsden Formation.

Some show concentric banding in which some of the bands have hydrated to limonite but most exhibit no internal structure. The matrix of the concretionary beds contains glauconite. A problem arises with the coexistence of the oxidized and reduced forms of iron. It is not likely, although not impossible, that both the hematite and glauconite are authigenetic. Whether the hematite is diagenetic or the product of ancient or recent weathering could not be determined.

There are over 50 feet of shale above the iron concretions. No glauconite was detected in these beds and they contain no invertebrate fossils. Wanless et. al. (1955) found traces of plant leaves and rootlets and beds they described as resembling the underclay of coal beds in this shale interval. The shale is poorly exposed and this author did not find these beds. Samples taken from the upper part of the shale sequence did contain numerous bits and flakes of carbon ranging in size up to 2 mm. The trace element data indicate that this shale is marine -- or at least the water in which the shale was deposited was more like marine than fresh water. Unfortunately, trace element data are of little use in distinguishing brackish water deposition of shale (Degens et. al., 1957). The absence of invertebrate fossils suggests that the environment was not normal marine or lagoonal. The plant remains may indicate deltaic or swamp environments.

Wanless et. al., (1970) included the Amsden Formation in their list of possible ancient deltaic deposits. They note that in the late Paleozoic deltas of the central and eastern United States the delta-front (includes delta-front and pro-delta of Fisk et. al., 1954) deposits composed of gray shale, often with ironstone concretions, usually grade upward into sandy shale and are succeeded by conformable sheet sands or unconformable lenticular sandstones. If the middle Amsden shale in western Wyoming is of delta-front origin, there should be correlative delta topset and fluvial strata near-by. A review of the literature on the late Mississippian and early Pennsylvanian strata in surrounding areas did not reveal any of the equivalent formations to be of obvious deltaic or fluvial origin (Agatston, 1954; Williams, 1962; Wilson, 1962).

Rather than being succeeded by sandstone, the shale is overlain by 150 feet of similar shale alternating with lime-stone containing marine fossils. This sequence of alternat-ing shale and limestone is interpreted as resulting from the development of salt or brackish water swamp or marsh environ-ments. After the sabkha complex was submerged, marine shale was deposited. Glauconite formed in the sediment. Continued deposition of shale brought the level of sedimentation up to about sea level in a tract along the shoreline. This tract of marsh and/or swamp lands trapped terrestrial detritus and permitted the deposition of limestone in the adjacent marine. The situation was not unlike that in the south of Florida to-day where continental detritus is trapped in the Everglades and limestone is forming in Florida Bay. Through time, lateral shifting of these facies created a vertical sequence of alternating shale and fossiliferous limestone.

Upper Amsden

The basal 50 feet of the upper part of the Amsden Formation in Hoback Canyon are predominantly dolomite, sandy dolomite and sandy dolomitic limestone. The dolomite beds are sucrosic and either structureless or horizontally laminated. The dolomitic limestone has either horizontal or high angle cross-laminae. The laminae are layers of large dolomite rhombs alternating with layers of smaller rhombs in a limestone matrix. Quartz grains are found throughout. There are sandstone beds in the upper part of the interval which are either horizontally laminated or have very low angle cross-laminae. Many of the carbonate beds are vuggy; some vugs being angular and some rounded or oval shaped. Two specimens of chert pseudomorphic after selenite were collected from a bed of sucrosic dolomite (Fig. 11). On Open Door Mountain there are shales interbedded with the sandy carbonates. Samples from three of the shale beds were included in the trace element analysis. The lower was classified fresh water and the upper two were classified marine (Fig. 8).

In the Hoback Canyon exposure the uppermost 115 feet of the Amsden Formation are interbedded gypsum and shale. There are solution breccias in this interval on Open Door Mountain

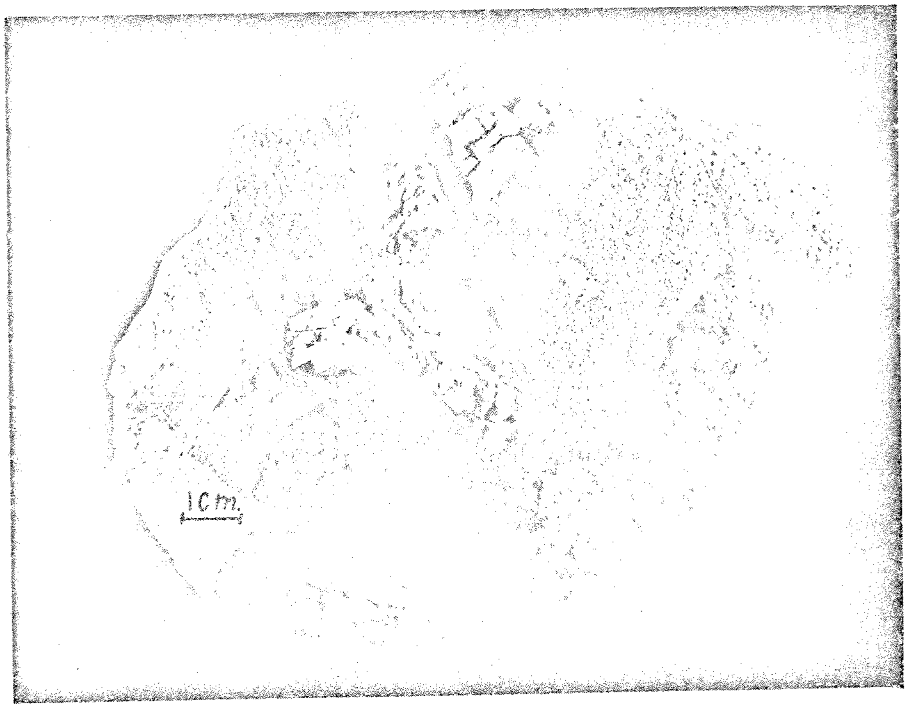


Figure 11. Chert pseudomorphic after selenite, upper Amsden Formation, Hoback Canyon.

indicating that evaporites may also have been deposited there.

The association of horizontal and high angle cross-laminae, abundant quartz grains, dolomitization of the limestone and precipitation of evaporites indicates a return to tide flat and sabkha-dune sedimentation. The repeated occurrence of sandstone or shale throughout the section suggests the area remained in or near the transition zone. Bedded gypsum in Hoback Canyon demonstrates the presence of salinas or playas in at least one locality.

Tensleep Formation

In western Wyoming the Tensleep Formation is composed of

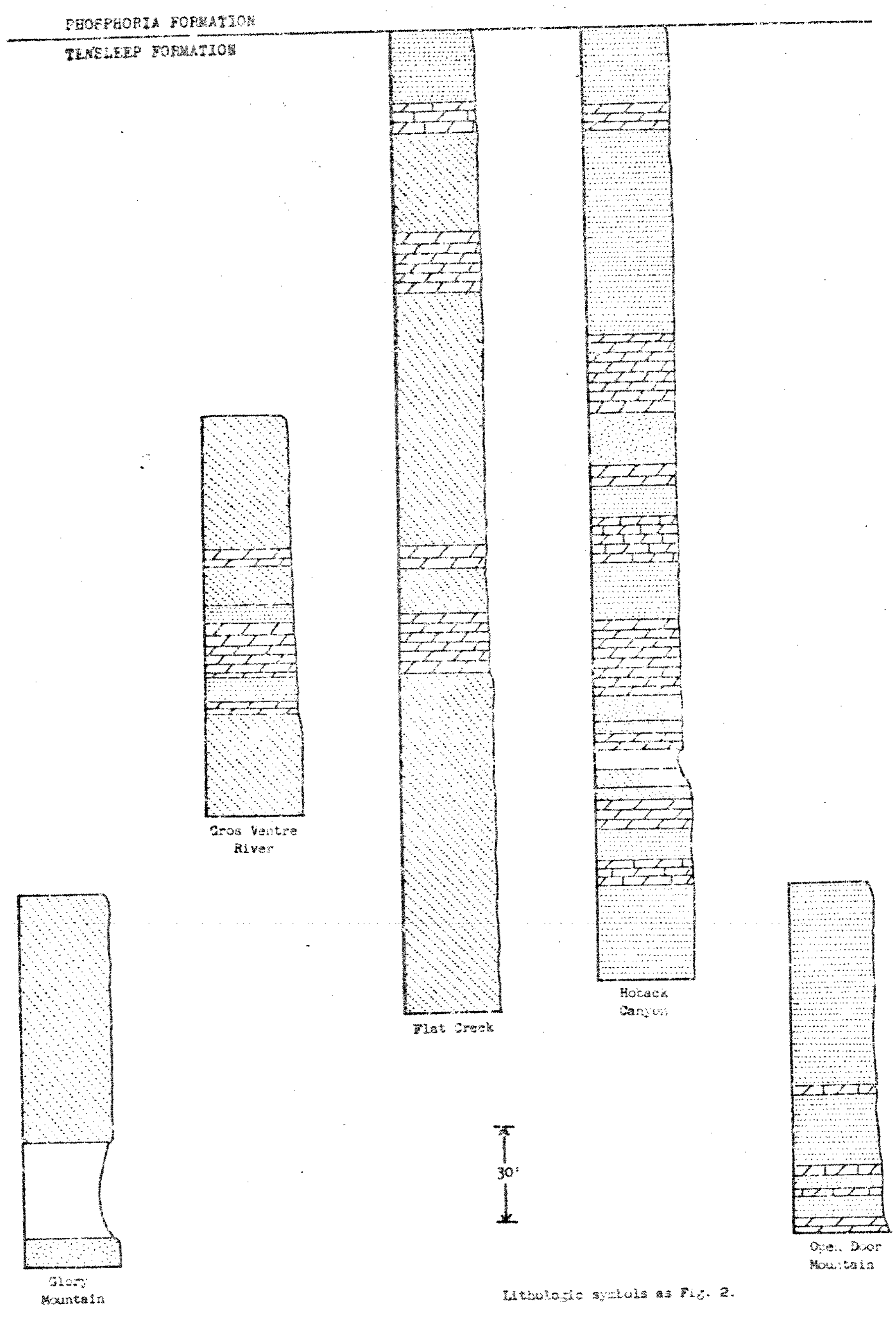


Figure 12. Measured sections: Tensleep Formation

interbedded orthoquartzite and dolomite or dolomitic limestone either of which may be cemented by calcite or silica. More often than not the dolomite-sandstone contacts show evidence of minor erosion or dissolution. Most of the dolomite and much of the sandstone is horizontally laminated. The sandstones, particularly the thicker units, are more commonly cross-bedded -- generally dipping from 30 to 45 degrees. The sands are well sorted. Grains are normally sub-rounded to rounded and fine to medium sand sized. There are no fossils or fossil debris in the sandstone. Much of the dolomite in the lower part of the formation contains fine grained fossil debris. Varying amounts of quartz grains are found in the dolomite. Evaporites are present (Agatston, 1954; Wilson, 1962) and reptile tracks (Branson, 1939; Love, 1939) have been found in the Tensleep Formation in other areas.

Individual beds cannot be correlated from one outcrop to another and the number of dolomite-sandstone transitions varies from one locality to another (Fig. 12). The Tensleep Formation is interpreted to be the result of sedimentation in the nearshore environments. Numerous changes in facies between coastal sabkha or supratidal flat (laminated dolomite), continental sabkha (laminated sandstone) and dune field (cross-bedded sandstone) occurred at different times in different localities throughout the depositional history of the formation. This also explains the local variations in the nature and stratigraphic position of the Amsden-Tensleep contact.

Discussion

Application of the model to smaller scale carbonate-clastic transitions requires looking at the model on a smaller scale. The point of reference is the zone of transition from predominantly carbonate to predominantly detrital sedimentation. When lateral migration of the depositional environments occurs but the area remains in or near the transition zone the result is a sequence of interbedded tidal flat, sabkha and dune sediment. Deposition of the upper Amsden and Tensleep strata took place in and near the transition zone. Interbedded sandstone and dolomite record the oscillation of the carbonate-clastic boundary through time. In this case, as in the problem of the Madison-Amsden contact, the carbonate-clastic boundary occurred at about the reach of the highest tides. During middle Amsden sedimentation there was considerably more detrital sediment available and clastic sedimentation extended into the marine environments.

SUMMARY AND CONCLUSIONS

Interpretation of the sedimentologic data concerning the nature of carbonate-clastic transitions in the Carboniferous of western Wyoming was facilitated by the use of a conceptual model of tide flat-sabkha sedimentation. The model provides for a conformable sequence of marine carbonate strata overlain by tidal flat and sabkha carbonates and evaporites which are in turn overlain by detrital sabkha and dune deposits.

Correspondence of the lower Carboniferous lithologic sequence with that proposed by the model indicates that the contact between the carbonate strata of the Madison Group and the clastic strata of the Amsden Formation is conformable. The Lodgepole Formation is predominantly of shallow marine origin. The Mission Canyon Formation is the result of tide flat sedimentation. Regressive sedimentation of the Madison Group culminated with the creation of a land surface upon which sabkhas and dune fields developed. The lower beds of the Amsden Formation are the continental sabkha and dune deposits.

A late Mississippian trangression submerged the sabkha-dune complex. During late Mississippian and early Pennsylvanian time an increased abundance of continental detritus shifted the boundary between carbonate and clastic sedimentation from the high tide line to below the low tide line.

The middle part of the Amsden Formation is the result of clastic sedimentation in coastal swamp and/or marsh lands and carbonate sedimentation in the adjacent marine.

The upper part of the Amsden Formation and the Tensleep Formation contain carbonate tide flat and sabkha deposits and clastic sabkha and dune deposits often separated by minor disconformities. These strata resulted from numerous minor transgressions and regressions in which the area was never far removed from the coastal-continental sabkha boundary.

The sedimentologic model may serve well as a working hypothesis in the approach to similar problems in other areas. Since sediment type and sedimentary structure are the primary lines of evidence and conclusive faunal data are not required, a preliminary evaluation can easily be made in the field.

REFERENCES CITED

Adams, J.E., H.N. Frenzel, M.L. Rhodes and D.P. Johnson, 1951, Starved Pennsylvanian Midland basin: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 2600-2607.

______ and M.L. Rhodes, 1960, Dolomitization by seepage refluxion: Am. Assoc. Petroleum Geologists Bull., v. 44, p. 1912-1920.

Agatston, R.S., 1954, Pennsylvanian and lower Permian of northern and eastern Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 508-583.

Andrichuk, J.M., 1955, Mississippian Madison Group stratigraphy and sedimentation in Wyoming and southern Montana: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 2170-2210.

Baker, C.L., 1946, Geology of the northwestern Wind River Mountains, Wyoming: Geol. Soc. America Bull., v. 57, p. 565-596.

Blackwelder, E., 1918, New geological formations in western Wyoming: Washington Acad. Sci. Jour., v. 8, p. 417-426.

Branson, C.C., 1937, Stratigraphy and fauna of the Sacajawea Formation, Mississippian of Wyoming: Jour. Paleontology, v. 11, p. 650-660.

______, 1939, Pennsylvanian formations of central Wyoming: Geol. Soc. America Bull., v. 50, p. 1199-1226.

Braun, M., and G.M. Friedman, 1969, Carbonate lithofacies and environments of the Tribes Hill Formation (Lower Ordovician) of the Mohawk Valley, New York: Jour. Sedimentary Petrology, v. 39, p. 113-135.

Burk, C.A., 1954, Faunas and age of the Amsden Formation in Wyoming: Jour. Paleontology, v. 28, p. 1-16.

Cody, R.D., 1971, Adsorption and the reliability of trace elements as environment indicators for shales: Jour. Sedimentary Petrology, v. 41, p. 461-471.

Collier, A.J., and S.H. Cathcart, 1922, Possibility of finding oil in laccolithic domes south of the Little Rocky Mountains, Montana: U.S. Geol. Survey Bull. 736F, p. 171-178.

Couch, E.L., 1971, Calculation of paleosalinities from boron and clay mineral data: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 1829-1837.

Curtis, C.D., 1964, Studies on the use of boron as a paleoenvironmental indicator: Geochim. et Cosmochim. Acta, v. 28, p. 1125-1137.

Darton, N.H., 1904, Comparison of the stratigraphy of the Black Hills, Bighorn Mountains, and Rocky Mountain front range: Geol. Soc. America Bull., v. 15, p. 379-448.

______, 1906, Geology of the Bighorn Mountains: U.S. Geol. Survey Prof. Paper 51.

Deffeyes, K.S., F.J. Lucia and P.K. Weyl, 1965, Dolomitization of recent and Plio-Pleistocene sediments by marine evaporite waters on Bonaire, Netherlands Antilles, p. 71-88 in Pray, L.C. and R.C. Murray, eds., Dolomitization and limestone diagenesis: Soc. Econ. Paleontologists Mineralogists Spec. Pub. 13, 180 p.

Degens, E.T., E.G. Williams and M.L. Keith, 1957, Environmental studies of Carboniferous sediments. Part I: Geochemical criteria for differentiating marine from freshwater shales: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 2427-2455.

Dixon, W.J., ed., 1968, BMD, Biomedical Computer Programs: Univ. Calif. Pub. in Automatic Computation, no. 2, p. 185-195.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, p. 108-121 in Ham, W.E., ed., Classification of carbonate rocks: Am. Assoc. Petroleum Geologists Mem. 1, 279 p.

Fisk, H.N., E. McFarlan, C.R. Kolb and L.J. Wilbert, 1954, Sedimentary framework of the modern Mississippi delta: Jour. Sed. Petrology, v. 24, p. 76-99.

Folk, R.L. 1964, Petrology of sedimentary rocks: Hemphill's Austin, Texas, 154 p.

Goldschmidt, V.M., and C. Peters, 1932, Zur Geochemie des Bors. Teil I u II: Akad. Wiss. Gottigen, Nachr., Mat.-Phys. Kl., p. 402-407 & 528-554.

Illing, L.V., A.J. Wells and J.C.M. Taylor, 1965, Penecontemporary dolomite in the Persian Gulf, p. 89-111 in Pray, L.C. and R.C. Murray eds., Dolomitization and limestone diagenesis: Soc. Econ. Paleontologists Mineralogists Spec. Pub. 13, 180 p.

Keith, M.L., and E.T. Degens, 1959, Geochemical indicators of marine and fresh water sediments, p. 38-61 in Abelson, P.H., ed., Researches in geochemistry: J. Wiley and Sons, New York, N.Y., 511 p.

Kendall, C.G. St. C., 1969, An environmental reinterpretation of the Permian evaporite/carbonate shelf sediments of the Guadalupe Mountains: Geol. Soc. America Bull., v. 80, p. 2503-2526.

_____ and Sir P.A. d'E. Skipwith, 1969, Holocene shallow water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 841-869.

Kinsman, D.J.J., 1969, Modes of formation, sedimentary associations, and diagnostic features of shallow-water and supratidal evaporites: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 830-840.

Landergren, S., 1945, Contributions to the geochemistry of boron. II. The distribution of boron, in Some Swedish sediments, rocks, and iron ores; the boron cycle in the upper lithosphere: Arkiv. Kemi, Mineralogi och Geologi, Bd. 19, Heft 5, Ano. 26, 31 p.

Laporte, L.F., 1967, Carbonate deposition near mean sea-level and resultant facies mosaic, Manlius Formation (Lower Devonian) of New York State: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 73-101.

_____, 1969, Recognition of a transgressive carbonate sequence within an epeiric sea: Heldeberg Group (Lower Devonian) of New York State, p. 98-119 in Friedman, G.M. ed., Depositional environments in carbonate rocks: Soc. Econ. Paleontologists Mineralogists Spec. Pub. 14, 209 p.

_____, 1971, Paleozoic carbonate facies of the central Appalachian shelf: Jour. Sedimentary Petrology, v. 41, p. 724-740.

Love, J.D., 1939, Geology along the southern margin of the Absaroka Range, Wyoming: Geol. Soc. America Spec. Paper 20.

McCaleb, J.A., and D.A. Wayhan, 1969, Geologic reservoir analysis, Mississippian Madison Formation, Elk Basin Field, Wyoming-Montana: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 2094-2113.

Murray, R.C., 1964, Origin and diagenesis of gypsum and anhydrite: Jour. Sedimentary Petrology, v. 30, p. 512-523.

Newell, N.D., J.K. Rigby, A.G. Fisher, A.J. Whiteman, J.E. Hickox and J.S. Bradley, 1953, The Permian reef complex of the Guadalupe Mountains region, Texas and New Mexico: W.F. Freeman, San Francisco, Calif., 236 p.

Phleger, F.B., 1969, A modern evaporite deposit in Mexico: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 824-829.

Potter, P.E., N.F. Shimp and J. Witters, 1963, Trace elements in marine and fresh water argillaceous sediments: Geochim. et. Cosmochim. Acta, v. 27, p. 669-694.

Pratt, P.F., 1965, Digestion with hydrofluoric and perchloric acids for total potassium and sodium, p. 1019-1021 in Black, C.A., ed., Methods of soil analysis, part 2: Am. Soc. Agronomy, Madison, Wisconsin.

Rao, C.R., 1952, Advanced statistical methods in biometric research: John Wiley, New York, N.Y., p. 252-257.

Roberts, A.E., 1966, Stratigraphy of Madison Group near Livingston, Montana and discussion of karst and solution-breccia features: U.S. Geol. Survey Prof. Paper 526-B.

Roehl, P.O., 1967, Stony Mountain (Ordovician) and Interlake (Silurian) facies analogs of recent low-energy marine and subaerial carbonates, Bahamas: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 1979-2032.

Sando, W.J., 1967, Madison Limestone (Mississippian), Wind River, Washakie and Owl Creek Mountains, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 529-557.

_____, 1968, A new member of the Madison Limestone (Mississippian) in Wyoming: Geol. Soc. America Bull., v. 79, p. 1855-1858.

_____, and J.T. Dutro, Jr., 1960, Stratigraphy and coral zonation of the Madison Group and Brazer Dolomite in northeastern Utah, western Wyoming, and southwestern Montana, p. 117-126 in Guidebook, Fifteenth Ann. Field Conf.: Wyoming Geol. Assoc., 285 p.

_____, B.L. Mamet and J.T. Dutro, Jr., 1969, Carboniferous magafaunal and microfaunal zonation in the Northern Cordillera of the United States: U.S. Geol. Survey Prof. Paper 613-E.

Scott, H.W., and P.C. Wilson, 1953, Revision and extension of the Sacajawea Formation in Wyoming and Montana (abst.): Geol. Soc. America Bull., v. 64, p. 1554.

Severson, J.L., 1952, A comparison of the Madison Group (Mississippian) with its subsurface equivalents in central Montana: unpub. Ph.D. thesis, Univ. Wisconsin.

Shaw, A.B., and W.G. Bell, 1955, Age of Amsden Formation, Cherry Creek, Wind River Mountains, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 333-337.

Shinn, E.A., R.N. Ginsburg and R.M. Lloyd, 1965, Recent supratidal dolomite from Andros Island, Bahamas, p. 112-123 in Pray, L.C., and R.C. Murray, eds., Dolomitization and limestone diagenesis: Soc. Econ. Paleontologists Mineralogists Spec. Pub. 13, 180 p.

_____, R.M. Lloyd and R.N. Ginsburg, 1969, Anatomy of a modern carbonate tidal-flat, Andros Island, Bahamas: Jour. Sedimentary Petrology, v. 39, p. 1202-1228.

Silver, B.A., and R.G. Todd, 1969, Permian cyclic strata, northern Midland and Delaware basins, west Texas and southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 2223-2251.

Strickland, J.W., 1956, Mississippian stratigraphy, western Wyoming, p. 51-57 in Guidebook, Eleventh Ann. Field Conf.: Wyoming Geol. Assoc., 256 p.

_____, 1957, Summary of Mississippian and Devonian stratigraphy, Wind River Basin, Wyoming, p. 20-27 in Guidebook, Twelfth Ann. Field Conf.: Wyoming Geol. Assoc., 226 p.

Tyrrell, W.W., Jr., 1969, Criteria usefull in interpreting environments of unlike but time equivalent carbonate units (Tansill-Capitan-Lamar), Capitan reef complex, west Texas and New Mexico, p. 80-97 in Friedman, G.M., ed., Depositional environments in carbonate rocks: Soc. Econ. Paleontologists Mineralogists Spec. Pub. 14, 209 p.

Van Siclen, D.C., 1958, Depositional topography - examples and theory: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 1897-1913.

Walker, C.T., 1968, Evaluation of boron as a paleosalinity indicator and its application to offshore prospects: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 751-766.

Walton, P.T., 1947, Oregon basin oil and gas field, Park County, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 1431-1453.

Wanless, H.R., J.R. Baroffio, J.C. Gamble, J.C. Horne, D.R. Orlopp, A. Rocha-Campos, J.E. Souter, P.C. Trescott, R.C. Vail and C.R. Wright, 1970, Late Paleozoic deltas in the central and eastern United States, p. 215-245 in Morgan, J.P., ed., Deltaic sedimentation, modern and ancient: Soc. Econ. Paleontologists Mineralogists Spec. Pub. 15, 312 p.

_____, R.L. Belknap and H.L. Foster, 1955, Paleozoic and Mesozoic rocks of Gros Ventre, Teton, Hoback and Snake River ranges, Wyoming: Geol. Soc. America Mem. 63.

Williams, J.S., 1962, Pennsylvanian System in central and northern Rocky Mountains, p. 159-187 in Branson, C.C., ed., Pennsylvanian System in the United States: Am. Assoc. Petroleum Geologists.

Wilson, P.C., 1962, Pennsylvanian stratigraphy of Powder River Basin and adjoining areas, p. 117-158 in Branson, C.C., ed., Pennsylvanian System in the United States: Am. Assoc. Petroleum Geologists.

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