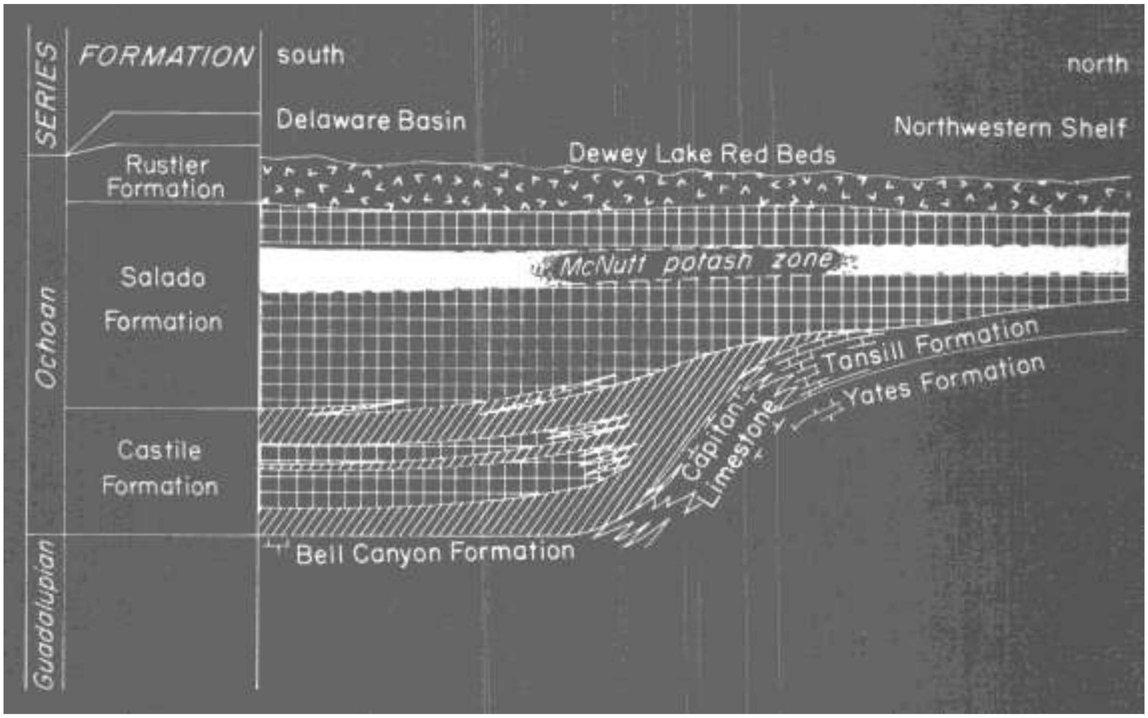
Circular 159 1978



Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas

compiled by George S. Austin

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Circular 159

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas

compiled by George S. Austin
in cooperation with 26 other coauthors

A symposium on Ochoan rocks of southeast
New Mexico and west Texas, held May 4, 1977,
in Carlsbad, New Mexico

SOCORRO 1978

NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY
Kenneth W. Ford, *President*

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES
Frank E. Kottlowski, *Director*
George S. Austin, *Deputy Director*

BOARD OF REGENTS
Ex Officio
Jerry Apodaca, *Governor of New Mexico*
Leonard DeLayo, *Superintendent of Public Instruction*

Appointed
William G. Abbott, 1961-1979, *Hobbs*
Judy Floyd, 1977-1981, *Las Cruces*
Owen Lopez, Secretary-Treasurer, 1977-1983, *Santa Fe*
Dave Rice, President, 1972-1977, *Carlsbad*
Steve Torres, 1967-1979, *Socorro*

BUREAU STAFF
Full Time

William E. Arnold, *Scientific Illustrator*
Robert A. Bieberman, *Senior Petrol. Geologist*
Lynn A. Brandvold, *Chemist*
Corale Brierley, *Chemical Microbiologist*
Brenda R. Broadwell, *Assist. Lab. Geoscientist*
Charles E. Chapin, *Senior Geologist*
Jeanette Chavez, *Admin. Secretary I*
Richard R. Chavez, *Laboratory Technician IV*
Ruben A. Crespin, *Laboratory Technician II*
Lois M. Devlin, *Director, Bus.–Pub. Office*
Jim P. Dodson, *Laboratory Technician I*
Robert W. Eveleth, *Mining Engineer*
Rousseau H. Flower, *Sr. Emeritus Paleontologist*
Roy W. Foster, *Senior Petrol. Geologist*
Stephen J. Frost, *Coal Geologist*
John W. Hawley, *Environmental Geologist*
Stephen C. Hook, *Paleontologist*
Bradley B. House, *Draftsperson*
Robert W. Kelley, *Editor & Geologist*
Stephanie Landregan, *Draftsperson*
Gary L. Massingill, *Coal Geologist*
Terrence McMahon, *Geophys. Field Engineer*
Norma J. Meeks, *Staff Secretary*
Candace H. Merillat, *Associate Editor*
Arleen Montoya, *Librarian*
Robert M. North, *Mineralogist*
Glenn R. Osburn, *Volcanologist*
Karen D. Patterson, *Staff Secretary*
Neila M. Pearson, *Assistant Editor*
Joan C. Pendleton, *Assistant Editor*
Judy Peralta, *Executive Secretary*
Barbara R. Popp, *Lab. Biotechnologist*
Robert Quick, *Driller's Helper*
Marshall A. Reiter, *Geophysicist*
Jacques R. Renault, *Geologist*
James M. Robertson, *Mining Geologist*
Barbara Robinson, *Geologist*
W. Terry Siemers, *Indust. Minerals Geologist*
Jackie H. Smith, *Laboratory Technician IV*
Chantravadee Songkran, *Staff Secretary*
William J. Stone, *Hydrogeologist*
David E. Tabet, *Geologist*
Samuel Thompson III, *Petroleum Geologist*
Robert H. Weber, *Senior Geologist*
William T. Willis, *Driller*
Michael W. Woolridge, *Scientific Illustrator*

Part Time

Christina L. Balk, *Geologist*
Nancy H. Mizell, *Geologist*
Howard B. Nickelson, *Coal Geologist*
Jack B. Pearce, *Director, Information Services*
Allan R. Sanford, *Geophysicist*
Thomas E. Zimmerman, *Chief Security Officer*

Graduate Students

Scott K. Anderholm
Sam Bowring
Gerry W. Clarkson
Steven D. Craigg
Martin A. Donze
K. Babette Faris
Susan C. Kent
Matt LaRoche
David M. Petty
Susan Roth
Charles R. Shearer

Plus about 25 undergraduate assistants

First printing, 1978

Example of suggested reference style

Cheeseman, R. J., 1978, Geology and oil-potash resources of Delaware Basin, Eddy and Lea Counties, New Mexico, *in* Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas: New Mexico Bureau of Mines and Mineral Resources, Circ. 159, p. 7-14, 2 tables, 7 figs.

Circular 159 abstract

On May 4, 1977, in Carlsbad, New Mexico, the Symposium on the Ochoan Rocks of Southeastern New Mexico and West Texas was held. This volume contains 13 expanded papers from the symposium, along with 1 expanded abstract and 5 abstracts of papers that were also given at the symposium but not presented for publication.

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63-1-4
Printed by University of New Mexico Printing Plant, October, 1978

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801 Price $6.50

Preface

Rocks of Upper Permian age in southeastern New Mexico and west Texas have produced an abundance of hydrocarbons, potash, and sulfur. Although much geologic literature is available on the region in general and on petroleum geology in particular, relatively little has been published recently on the nonmetallic ores, and there seems to be a paucity of information on southwestern New Mexico. In addition the relationships of the petroleum industry to the potash industry and of mining engineers to geologists have not been adequately examined. With these points in mind, the New Mexico Bureau of Mines and Mineral Resources decided in 1975 that a conference held in Carlsbad to address these problems would be particularly appropriate.

Two other interested groups, the New Mexico Geological Society and the Permian Basin Section of the Society of Economic Paleontologists and Mineralogists, were subsequently invited to co-sponsor the meeting. In a division of responsibilities, the NMGS decided to oversee the symposium on Ochoan rocks, which was to be held on the first day of the meeting, and a series of premeeting trips to all 7 operating potash mines and to Carlsbad Caverns. The symposium on the Upper Guadalupian rocks on the second day of the meeting and a postmeeting 2-day field trip to the Upper Guadalupian shelf and shelf facies of the Permian reef complex in the nearby Guadalupe Mountains were handled by the PBS-SEPM. The PBS-SEPM also published a volume for the conference containing all of the papers given at the Upper Guadalupian symposium, plus the road logs for the post-meeting field trip. And now the New Mexico Bureau of Mines and Mineral Resources is publishing the collection of the papers given at the Ochoan symposium.

The conference was held on May 3-7, 1977, in Carlsbad and was attended by about 150 geologists and engineers; most were from the southwestern United States, but one participant came all the way from France. Circular 159 represents the final link of the entire project. It is the end result of the tremendous amount of work by all of the participants, the chairpersons and workers on the many committees, the authors of the papers, and the editors and secretaries; even the general chairman did some work.

Circular 159, the "Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas," contains 13 expanded papers from the 18 oral presentations given at the Ochoan symposium, plus an expanded abstract of one of the papers from the Upper Guadalupian symposium. These papers contain much of the latest information of the area and include several papers from the mining industry that—I think—significantly increase its value. Abstracts of the papers given at the Ochoan symposium but not presented for publication are included at the back.

Although I and the editing staff of the Bureau have done some editing, the honor and responsibilities of each paper belong to each author. We tried, of course, to set a deadline of one month after the meeting when all papers should have been in, but I am sure that many will understand why such a "reasonable" deadline had to be adjusted in light of other commitments.

I would like to thank Frank Kottlowski, Director of the Bureau, the Executive Committee of the New Mexico Geological Society, and the Permian Basin Section of SEPM for approving the idea of the conference. The greatest measure of the credit for the present volume goes to the authors whom I gratefully acknowledge, but putting it all together into a useful, well organized, and attractive publication required the skill of a capable editor like Candace Merillat.

George S. Austin
Deputy Director, New Mexico Bureau
of Mines and Mineral Resources
General Chairman of symposium

Socorro
February 20, 1978

Contents

GEOLOGY AND OIL/POTASH RESOURCES OF DELAWARE BASIN, EDDY AND LEA COUNTIES *by Raymond J. Cheeseman*

Abstract **7**
Introduction **7**
Location and extent **7**
Geologic history of deposition **7**
Stratigraphy of Permian potash-bearing rocks **10**
Origin of Salado Formation **11**
Potash production history **12**
Hydrocarbon production history **12**
Regulation history **12**
References **14**

SALINITY CYCLES: EVIDENCE FOR SUBAQUEOUS DEPOSITION OF CASTILE FORMATION AND LOWER PART OF SALADO FORMATION, DELAWARE BASIN, TEXAS AND NEW MEXICO *by Walter E. Dean and Roger Y. Anderson*

Abstract **15**
Introduction **15**
Castile-lower Salado salinity cycles **15**
  Description of salinity cycles **15**
  Geochemical changes within salinity cycles **17**
  Factors affecting precipitation of $CaSO_4$ and $CaCO_3$ **18**
Depth of water in the Delaware Basin **18**
  Initial depth **18**
  Changes in water depth **18**
Summary **19**
References **20**

CLAY-MINERAL ASSEMBLAGES FROM DRILL CORE OF OCHOAN EVAPORITES, EDDY COUNTY *by Marc W. Bodine, Jr.*

Abstract **21**
Introduction **21**
  Clay minerals in marine-evaporite rocks **21**
ERDA-9 drill core **22**
Sample preparation and analysis **22**
  Diffraction analysis **23**
  Fluorescence analysis **23**
Clay mineralogy **23**
Chemical analyses of EDTA-leach residues **27**
Discussion **27**
  Chemical composition and clay mineralogy **27**
  Residue variation with stratigraphy and host lithology **28**
    Salzton and associated salt lithology residues **28**
    (?) Talc-saponite association with polyhalite beds **28**
    Chemico-mineralogic discontinuity in lower Salado Formation **28**
Genesis **29**
References **30**

GEOCHEMISTRY OF DELAWARE BASIN GROUND WATERS *by Steven J. Lambert*

Abstract **33**
Introduction **33**
Data **33**
Solutes **33**
Thermodynamics **36**
Stable isotopes **36**
Summary **37**
References **37**

IGNEOUS ROCKS IN NORTHERN DELAWARE BASIN, NEW MEXICO AND TEXAS *by J. P. Calzia and W. L. Hiss*

Abstract **39**
Introduction **39**
Previous work **39**
Geologic setting and occurrence of igneous rocks **39**
Petrography and chemical analyses **42**
Age **43**
Landsat analysis **44**
Discussion **45**
References **45**

DEVELOPMENT OF DISSOLUTION BRECCIAS, NORTHERN DELAWARE BASIN, NEW MEXICO AND TEXAS *by Roger Y. Anderson, Kenneth K. Kietzke, and Doris J. Rhodes*

Abstract **47**
Introduction **47**
Breccia beds **47**
  Dissolution breccias **47**
  Collapse breccias **48**
Correlation of dissolution horizons **48**
Development of dissolution **48**
  Big Sinks dissolution depression **49**
  Controls on dissolution **49**
  Development of breccias **49**
Conclusions **52**
References **52**

TRANSITIONAL NATURE AND SIGNIFICANCE OF THE CASTILE-BELL CANYON CONTACT *by John M. Cys*

Abstract **53**
Introduction **53**
Union No. 4 University "37" well core **53**
Seven Heart Gap **54**
Other areas **54**
Significance **55**
Conclusions **56**
References **56**

STRATIGRAPHY AND MINERAL RESOURCES OF GUADALUPIAN AND OCHOAN ROCKS IN THE TEXAS PANHANDLE AND WESTERN OKLAHOMA *by Kenneth S. Johnson*

Abstract **57**
Introduction **57**
Stratigraphy **58**
  Early Guadalupian **58**
  Late Guadalupian **59**
  Ochoan **60**
Mineral resources **60**
References **62**

CONVENTIONAL POTASH MINING *by Clark H. McNaughton*

Abstract **63**
Introduction **63**
IMC operations **63**
Carlsbad district **64**

CATIONIC FLOTATION OF SYLVITE *by M. P. Scroggin*

Abstract **65**
Introduction **65**
Process **65**
References **67**

LEACH/CRYSTALLIZATION—PROCESS FOR POTASH PRODUCTION *by Walter S. Case, Jr.*
  Abstract **69**
  Introduction **69**
  Process **69**
  Mill operations **69**
  References **70**

SULFUR DEPOSITS IN OCHOAN ROCKS OF SOUTHEAST NEW MEXICO AND WEST TEXAS *by A. Richard Smith*
  Abstract **71**
  Introduction **71**
  Stratigraphy **71**
  Structure **73**
  Sulfur deposits **73**
    Castile Formation **73**
    Salado Formation **74**
    Deposition and localization **75**
  Sulfur exploration and development **76**
  References **77**

SALT ANTICLINES IN CASTILE-SALADO EVAPORITE SEQUENCE, NORTHERN DELAWARE BASIN *by Roger Y. Anderson and Dennis W. Powers*
  Abstract **79**
  Introduction **79**
  ERDA No. 6 anticline **79**
    Brief description of core **79**
    Identity of stratigraphic units **80**
    Interpretation of structure **80**
  Other salt anticlines **81**
    Distribution of salt anticlines **81**
    Poker Lake anticline **81**
  Age and origin of anticlinal structures **81**
    Age **81**
    Origin **82**
  Conclusions **83**
  References **83**

LATE GUADALUPIAN CORRELATIONS, PERMIAN REEF COMPLEX, WEST TEXAS AND NEW MEXICO *by Willis W. Tyrrell, Jr., Donald H. Lokke, George A. Sanderson, and George J. Verville*
  Abstract **85**
  References **85**

SOLUTION OF PERMIAN OCHOAN EVAPORITES, NORTHERN DELAWARE BASIN *by J. W. Mercer and W. L. Hiss*
  Abstract **87**

LOG EVALUATION OF NONMETALLIC MINERAL DEPOSITS *by M. P. Tixier and R. P. Alger*
  Abstract **87**

CONTINUOUS MINING: THE PROBLEM AND THE ANSWER *by C. C. Wynne*
  Abstract **88**

UNDERGROUND ORE-HAULAGE METHODS IN NEW MEXICO POTASH MILLING *by W. N. Ellett*
  Abstract **88**

SOLUTION FEATURES IN DELAWARE BASIN EVAPORITES *by A. J. Bodenlos*
  Abstract **88**

TABLES

Cheeseman

1—Evaporite minerals of potash ore deposits, Salado Formation **12**
2—Six ore zones, Salado Formation **12**

Bodine

1—Distribution of clay minerals in samples from ERDA-9 **24**
2—Atom proportions of EDTA-leach residues of samples **28**
3—Chemical analyses and atom proportions of EDTA-leach residues of samples **28**
4—Mineral distribution and atom ratios in EDTA-leach residues of samples **29**

Lambert

1—Inventory of Delaware Basin ground waters sampled **34**
2—Geochemical analyses of Delaware Basin ground waters **34**
3—Duval mine vent hole water no. 16 **35**
4—Todd Federal 26-4 water no. 9 **35**
5—ERDA 6 water no. 14 **35**

Calzia & Hiss

1—Location and description of igneous rocks, northern Delaware Basin **41**
2—Modal analyses of igneous rocks, southeastern New Mexico **43**
3—Chemical analyses and normative minerals of basaltic dikes east of Pecos River **44**
4—K-Ar and He-method age dates of igneous rocks, southeastern New Mexico **44**

Smith

1—Sulfur exploration wells, Delaware Basin **76**

FIGURES

Cheeseman

1—Generalized potash enclave map, Carlsbad potash district **8**
2—Conceptual diagrams showing depositional history of Delaware Basin **9**
3—Generalized stratigraphic column, Permian and younger strata **10**
4—a) Bromine profile for rock salt, Angora-Lena Basin, Russia; b) bromine profile for halite, Salado Formation **11**
5—Oil-potash plat, northeastern part of potash area **13**
6—Oil-potash plat of successful gas wells **13**
7—Oil-potash plat of proposed oil-and-gas locations **14**

Dean & Anderson

1—Correlation between Union-University "37" No. 4 well and calcite-anhydrite couplet thickness of UNM—Phillips No. 1 core **16**
2—Diagram of complete salinity cycle, Castile and Salado Formation **16**
3—Photographs of nodular anhydrite, UNM-Phillips No. 1 core **17**

(continued)

4—Data plotted vs. time for interval 24-26 thousand years above base of Anhydrite I **17**
5—Plot of anhydrite thickness vs. time, UNM-Phillips No. 1 core **19**
6—Plot of amplitude of varve-thickness changes vs. time for UNM-Phillips No. 1 core **19**

Bodine

1—Schematic log of ERDA-9 core **23**
2—X-ray diffraction traces of EDTA-leach residue (JL-CS-3) **25**
3—X-ray diffraction traces of EDTA-leach residues (MB-CS-10 and JL-CS-9) **25**
4—X-ray diffraction traces of EDTA-leach residues (MB-CS-13 and MB-CS-27) **26**
5—X-ray diffraction traces of EDTA-leach residues of samples in table 3 **26**
6—X-ray diffraction traces of EDTA-leach residues (MB-CS-15 and MB-CS-42) **27**
7—X-ray diffraction traces of bulk EDTA-leach residues **29**

Lambert

1—Map of New Mexico portion of Delaware Basin **32**
2—Predominance area diagram, oxygen partial pressure vs. pH, for System S-O-H **36**
3—Stable-isotope compositions, dD vs. d^{18}O, for Delaware Basin ground waters **36**

Calzia & Hiss

1—Generalized geologic map showing igneous rocks in northern Delaware Basin **40**
2—Diagrammatic cross section of zone of basaltic rocks **42**
3—Diagrammatic sketch of east wall of Kerr-McGee potash mine **43**

Anderson, Kietzke, & Rhodes

1—Index map of northern Delaware Basin **46**
2—Dissolution breccia overlain by collapse breccia, UNM-Phillips No. 1 core **47**
3—Laminae correlation A at base of Halite III **48**
4—Laminae correlation B from anhydrite bed within Halite III **49**
5—Diagram of locations of laminae correlations A and B and correlation of breccia beds **50**
6—Correlation diagram of dissolution horizons of salt within Big Sinks **51**
7—Relationship between structure, top of Rustler Formation, and removal of salt, lower part of Salado Formation **52**

Cys

1—Location index map **53**
2—Mechanical log of Union No. 4 University "37" well, showing Castile-Bell Canyon contact **54**
3—Diagram of basal 70 ft of Union No. 4 University "37" well **54**
4—Photograph of contact interval, Union No. 4 University "37" well core **54**
5—Topographic map of Castile-Bell Canyon contact, Seven Heart Gap **55**
6—Contact locality, Seven Heart Gap **55**
7—Castile-Bell Canyon contact, Seven Heart Gap **55**
8—Possible flow-roll and pillow structures, Bell Canyon Formation, Seven Heart Gap **55**

Johnson

1—Map of major tectonic features, Texas Panhandle and western Oklahoma **57**
2—Map of outcrops of Guadalupian and Ochoan strata **58**
3—Chart of Late Permian stratigraphic nomenclature **58**
4—Map of Early Guadalupian paleogeography and schematic cross section **59**
5—Map of Late Guadalupian paleogeography and schematic cross section **59**
6—Map of Ochoan paleogeography and schematic cross section **60**
7—Map of distribution of salt and potash resources **60**
8—Map of distribution of gypsum and celestite resources **61**
9—Map of distribution of copper-bearing and uranium-bearing strata **61**

McNaughton

1—No. 1 headframe at IMC potash mine **63**
2—Two-boom Joy Jumbo Drill putting holes into mined seam **63**
3—Joy undercutter **64**
4—AN/FO blown into drill holes **64**
5—Jeffrey ram car loaded by Joy gathering-arm loader **64**
6—Ore hauled to Jeffrey ratio feeder **64**
7—Thirty-by-fifty-foot pillars left for support **64**

Scroggin

1—Portion of desliming section, Duval plant **66**
2—Flotation cells, Duval plant **66**
3—Centrifuge deck where sylvite is separated from brine **67**

Smith

1—Delaware Basin, showing sulfur occurrence area **71**
2—Larger scale map of sulfur area **72**
3—North-south cross section, Phillips Ranch deposit **73**
4—Isopachous map of secondary, sulfur-bearing limestone, Phillips Ranch deposit **74**
5—Structure contour map, base of Castile Formation, Phillips Ranch deposit **74**
6—Generalized sulfur mineralization map, Rustler Springs deposit **75**

Anderson & Powers

1—Index map of distribution of halite beds I and II **78**
2—Section of relevant beds from ERDA No. 6 **79**
3—Slabbed and polished section from upper anhydrite **80**
4—Diagrammatic cross section of structure at ERDA No. 6 **81**
5—Structure contour map, top, Halite II **81**
6—Detached maps of Poker Lake anticline **82**

Tyrell, Lokke, Sanderson, & Verville

1—Stratigraphic section showing relationships of Amoco core holes to nearby well control **84**

GEOLOGY AND OIL/POTASH RESOURCES OF DELAWARE BASIN, EDDY AND LEA COUNTIES, NEW MEXICO

by Raymond J. Cheeseman, *U.S. Geological Survey, Box 25046, Mail Stop 609, Denver, Colorado 80225*

Abstract

The Carlsbad Potash Leasing Area, some 20 mi (32.2 km) east of Carlsbad in southeastern New Mexico, comprises approximately 425 sq mi (1,105 sq km) of east-central Eddy County and adjoining Lea County. This Potash Area is one of the world's major potassium deposits and dominates the domestic mining and processing of potassic ores. Twelve ore zones occur at stratigraphic intervals in the mineralized middle part of the Upper Permian Salado Formation. The oil and gas potential of the Carlsbad Potash Area is great; major fields within the Potash Area are the James Ranch, South Salt Lake, Lynch, Dos Hermanos, Teas-Lynch, and Cabin Lake. By the mid-1920's, this area was already producing oil and gas—mostly shallow wells in the Permian Yates. In recent years, hydrocarbon production (mostly gas) from Pennsylvanian rocks has been increasingly important. All of the productive horizons are older than (and therefore deeper than) the potash-bearing Salado Formation. The U.S. Geological Survey denies approval of most applications for permits to drill oil and gas tests from surface locations within the measured ore, or enclave, of the Carlsbad Potash Area. There are two exceptions to this ban: 1) Drilling will be permitted in potash-barren areas within the potash enclave when the Area Mining Supervisor determines that such operations will not interfere with existing or planned mine workings in the vicinity. 2) Drilling will be permitted from a "drilling island" that will be established by the Area Mining Supervisor, when, in the opinion of the Area Oil and Gas Supervisor, the target formations beneath a remote interior lease cannot be reached by a well directionally drilled from a surface location outside the potash enclave.

Introduction

This paper summarizes the geology of the Delaware Basin from Ordovician through Permian time, emphasizing the depositional history of potash-bearing and hydrocarbon reservoir rocks, in addition to describing how the dual development of these resources is being accomplished.

ACKNOWLEDGMENTS—This work was carried out during my employment as a U.S. Geological Survey geologist in the office of the Area Geologist, Southern Rocky Mountain Area, Roswell, New Mexico. I wish to thank Mr. Marvin Millgate, of the U.S. Geological Survey, for extensive discussions and review.

Location and extent

The Carlsbad Potash Leasing Area is 20 mi (32.2 km) east of Carlsbad in east-central Eddy and west-central Lea Counties, southeastern New Mexico. The generalized potash enclave map (fig. 1) shows the areal extent of Federal lands in the KPLA (Known Potash Leasing Area) and the leasing-grade composite ore zone boundary. Measured ore areas, indicated areas, and barren or unevaluated areas exist within the 425 sq mi (1,105 sq km) KPLA, which includes one of the world's major potassium ore deposits currently being mined. The area within the KPLA must be leased by competitive bidding; outside the KPLA, potash lands can be acquired by prospecting permit.

Geologic history of deposition

Prior to Pennsylvanian time, the present Delaware Basin area was part of a broad depression called the Tobosa Basin (Adams, 1965). During pre-Ordovician time the area was emergent, and no deposition took place. Transgression of a sea began in Ordovician time, resulting in the accumulation of the thick carbonate shelf deposits of the Ellenburger Group (fig. 2-1). As the Tobosa Basin subsided in Middle and Late Ordovician time, carbonates and clastics of the Simpson Group of subsurface usage and the Montoya Dolomite were deposited (fig. 2-1).

During Silurian and Devonian time (fig. 2-2), more shelf carbonates were deposited, and dense limestone, chert, and black shale were deposited in deep waters. In Late Devonian time the area was uplifted, eroded, and invaded by the transgressing sea. The Mississippian was again a time of deposition of shelf carbonate rocks and basinal shale.

In Early Pennsylvanian time (fig. 2-3) the Tobosa Basin was divided into the Midland Basin on the east and the Delaware Basin on the west by the emergence of the Central Basin Platform. Lower Pennsylvanian rocks, or rocks of Morrowan age, in the Delaware Basin consist dominantly of sandstone and shale. Deposition of these clastic rocks was followed by an accumulation of the limestone and shale of Atokan and Strawn ages and then by the formation of the northeast-trending reefs in late Strawn time along the northwest margin of the basin. In Late Pennsylvanian time predominantly shale and limestone deposits of the Canyon and Cisco Groups were formed.

Renewed tectonic activity during the Early Permian (fig. 2-4) resulted in rapid sinking of the Delaware Basin and the growth of many local structural features. Thick deposits of Wolfcampian or Early Permian age, consisting mostly of clastic sedimentary rocks, were deposited in the southern part of the basin, while shelf limestone and reef deposits formed in the northern part. Following Wolfcampian deposition, subsidence resumed, resulting in deposition of thick Leonardian Bone Spring Limestone in the northern part of the basin. Within the basin, thick clastics of the Lower Permian Brushy Canyon and Cherry Canyon Formations were overlain by clastic and carbonate rocks of the Upper Permian Bell Canyon Formation, which accumulated basinward from the encircling Capitan Limestone reef (fig. 2-5). Growth of this reef may have barred the interior basin from further influx of clastic material, resulting in accumulation of a thick Upper Permian evaporite sequence represented by the Castile, Salado, and Rustler Formations. The Castile Formation is composed of anhydrite and halite with subordinate limestone and, according to Evans (1977), is a good example of a thick evaporite sequence formed in deep water. The Rustler and Salado Formations are found shoreward of the reef. The Salado Formation contains more clastic sedimentary rocks than the Castile, which is almost a pure, chemical precipitate.

Evans (1977) explained how the Delaware Basin changed in Late Permian time: "Deep-water deposition which produced the Castile Formation changed to shallow-water and supra-tidal sedimentation after the original basin filled and the Salado Formation therefore is markedly different in sedimentologic features from the Castile, even though the two deposits are stratigraphically adjacent and superficially

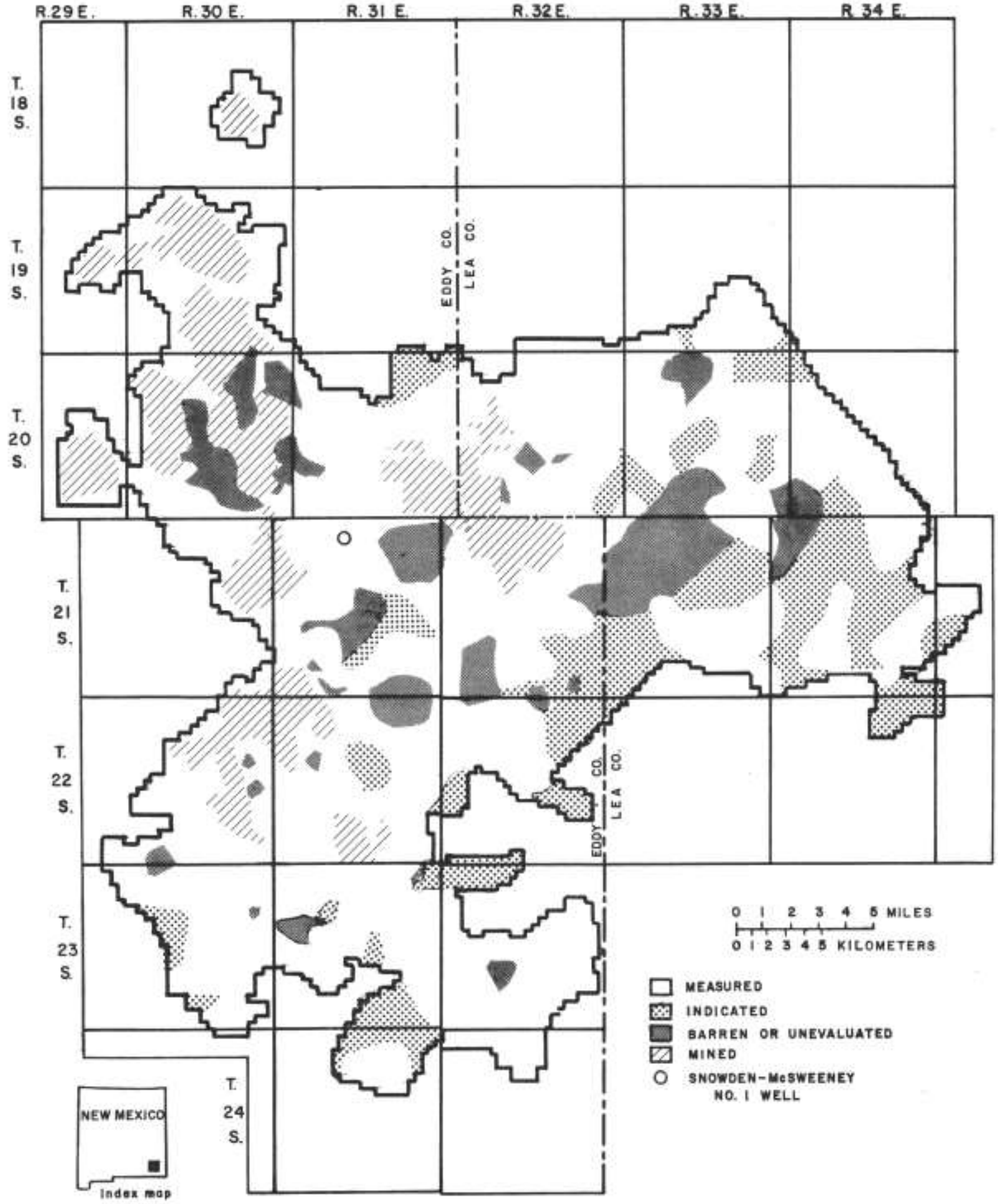
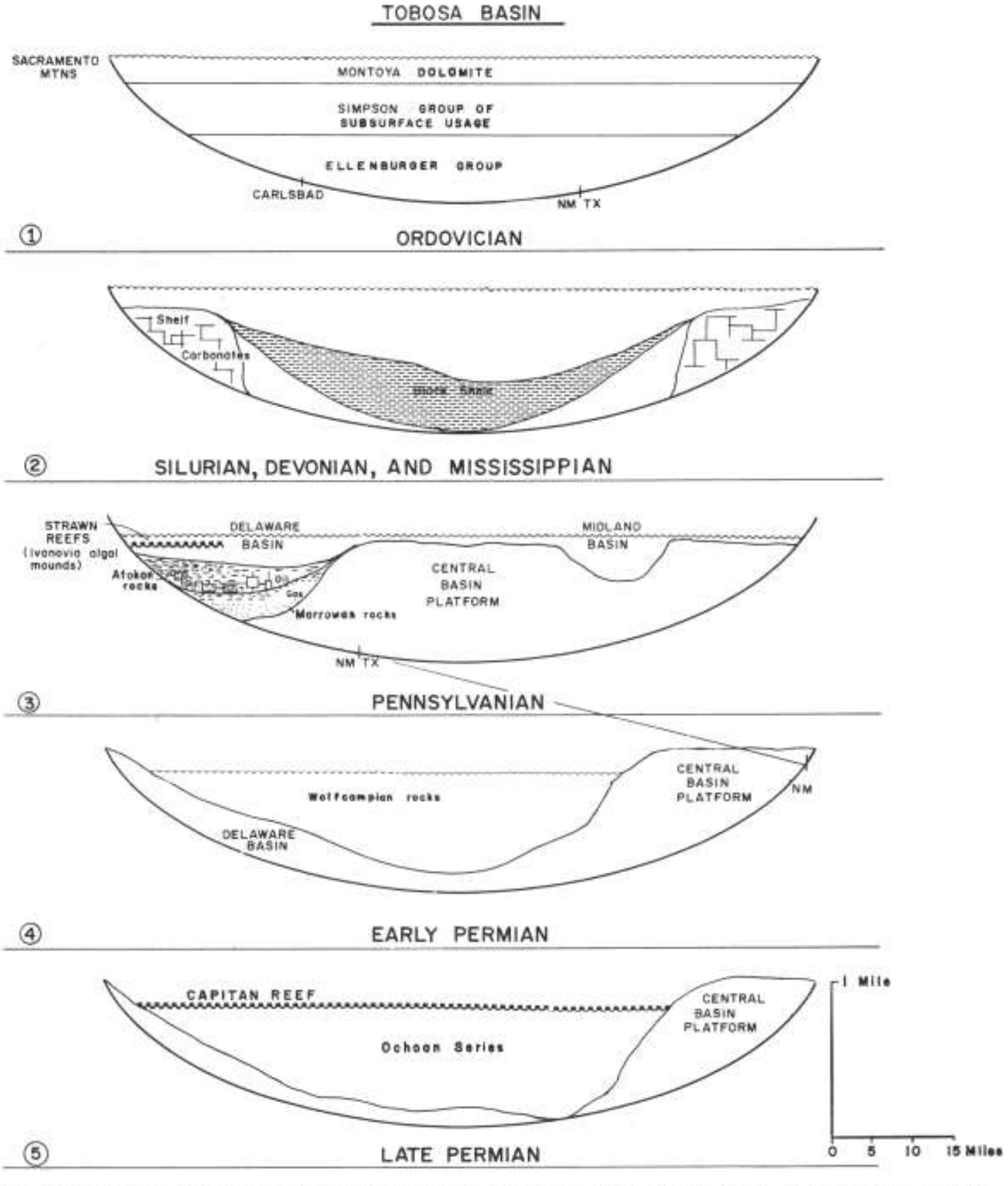


FIGURE 1—Generalized potash enclave map of the Carlsbad potash district, New Mexico. The extent of the KPLA (Known Potash Leasing Area), indicated by the heavy outer line, is determined by the leasing-grade composite ore-zone boundary.



① ORDOVICIAN

② SILURIAN, DEVONIAN, AND MISSISSIPPIAN

③ PENNSYLVANIAN

④ EARLY PERMIAN

⑤ LATE PERMIAN

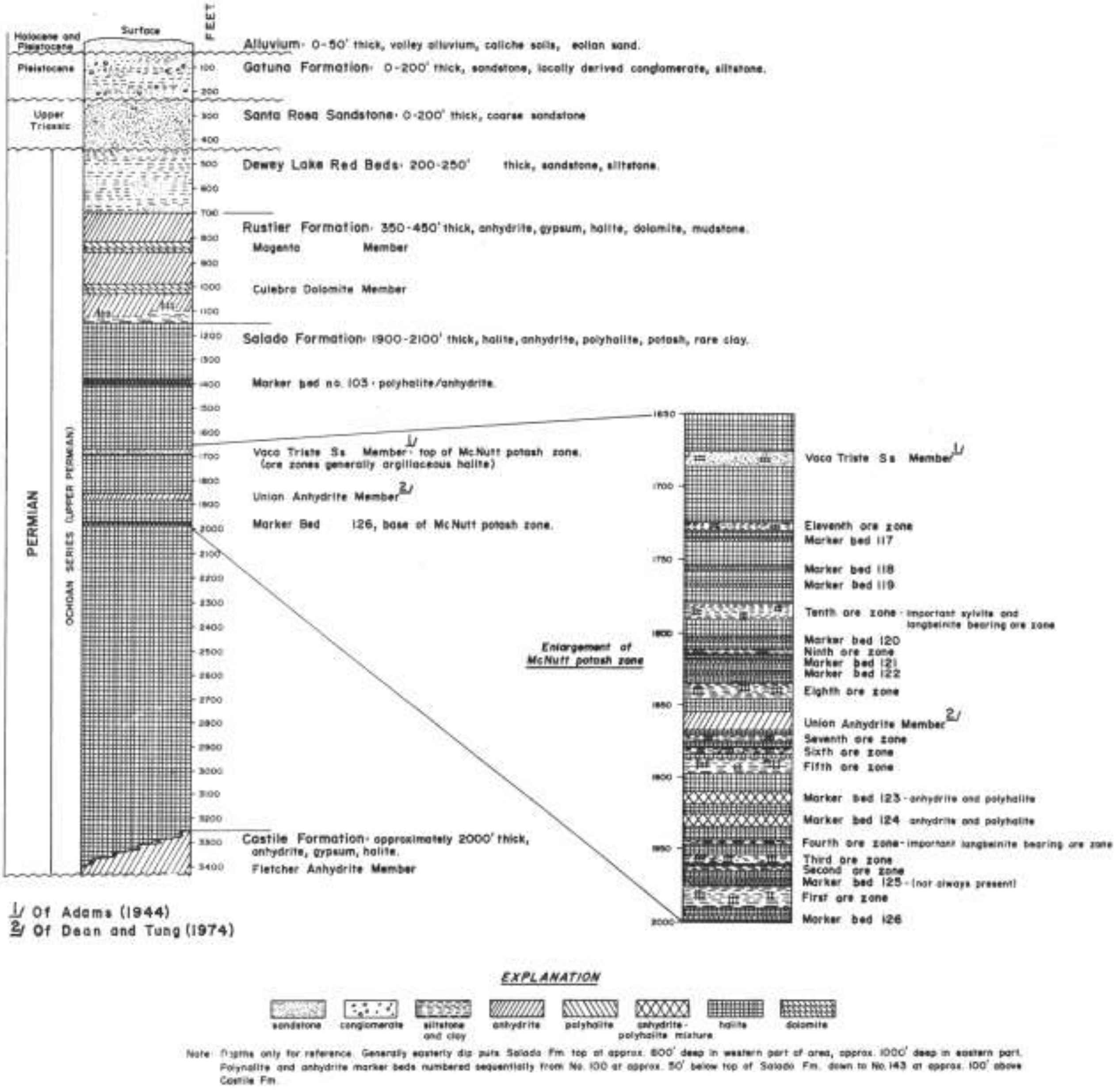
FIGURE 2—Conceptual diagrams showing depositional history of the Delaware Basin, Lea and Eddy Counties, New Mexico.

similar." At the end of Permian time the sea retreated, initiating the deposition of the Upper Permian Dewey Lake Red Beds.

Stratigraphy of Permian potash-bearing rocks

Fig. 3, a generalized stratigraphic column, depicts Upper Permian and younger strata in southeastern New Mexico. The Ochoan Series contains three salt-bearing formations, with the Castile Formation at the base, then the potash-bearing Salado Formation, and, finally, the Rustler Formation. The Castile Formation is confined to the Delaware Basin, but the two younger salt-bearing formations, the Salado and the Rustler, extend northward and eastward over the Northwestern Shelf area, the Central Basin Platform, and the Midland Basin. The Salado Formation is composed of halite and argillaceous halite with lesser amounts of anhydrite and polyhalite, and rare amounts of potassium salts in a central part of the formation, locally known as the McNutt potash zone.

A systematic study of the Carlsbad potash area by Jones (1954) indicates that ore zones occur at several stratigraphic intervals in the approximately 700-ft (213-m)-thick mineralized portion of the Salado Formation (Late Permian). The 12 ore zones have been numbered from deepest to shallowest in ascending order, the first ore zone being at the greatest depth. This numbering system is in general usage throughout the potash area and is also used in this report. The enlargement of the McNutt potash zone (fig. 3) shows 11 of the 12 zones. Important stratigraphic tops and marker beds often listed on core-hole recapitulations and gamma-ray logs are "top of salt"—at 1,150 ft (351 m) on fig. 3, "marker bed 117," "eleventh ore zone," "marker bed 119," "tenth ore zone," "marker bed 124," and "fourth ore zone." Some



1/ Of Adams (1944)
2/ Of Dean and Tung (1974)

Note: Depths only for reference. Generally easterly dip puts Salado Fm. top at approx. 800' deep in western part of area, approx. 1000' deep in eastern part. Polyhalite and anhydrite marker beds numbered sequentially from No. 100 at approx. 50' below top of Salado Fm. down to No. 143 at approx. 100' above Castile Fm.

FIGURE 3—GENERALIZED STRATIGRAPHIC COLUMN OF PERMIAN AND YOUNGER STRATA, EDDY COUNTY, NEW MEXICO (adapted from Jones and others, 1960).

marker beds, which are conspicuous log markers, help to locate nearby ore zones; for example, 119 and 124 help to locate the "tenth ore zone" and "fourth ore zone," respectively.

In the Salado Formation, clastic material is minor—generally less than 4 percent. The Vaca Triste Sandstone Member of Adams (1944) is a 10-ft (3.0-m) layer of reddish, fine-grained halitic sandstone about 475 ft (145 m) below the top of the formation. The thin La Huerta Siltstone Member occurs approximately 30 ft (9.1 m) above the base of the Salado. These units are the only named clastic members of the Salado. Table 1 shows the evaporite minerals (mostly sodium and potassium chlorides and sulfates) that are present in the Salado Formation. Sylvite and langbeinite are the important potash ore minerals. A typical breakdown of a mixed ore would include 60 percent halite, 30 percent sylvite, 5 percent langbeinite, and 2 percent each of polyhalite and insolubles.

Origin of Salado Formation

Adams (1969) stated that potash ore zones are high in clay material, regardless of the presence of potash minerals. Figs. 4a and b demonstrate one of Adams' conclusions about the origin of the Salado Formation; that is, that the uniformly low bromine content of halite in the formation reflects a second cycle origin of most of the salt. The bromine content of a primary salt basin, the Angara-Lena Basin in Russia, is approximately seven times that of the Salado Formation (figs. 4a, b). The repetitive sequence of halite, argillaceous halite,

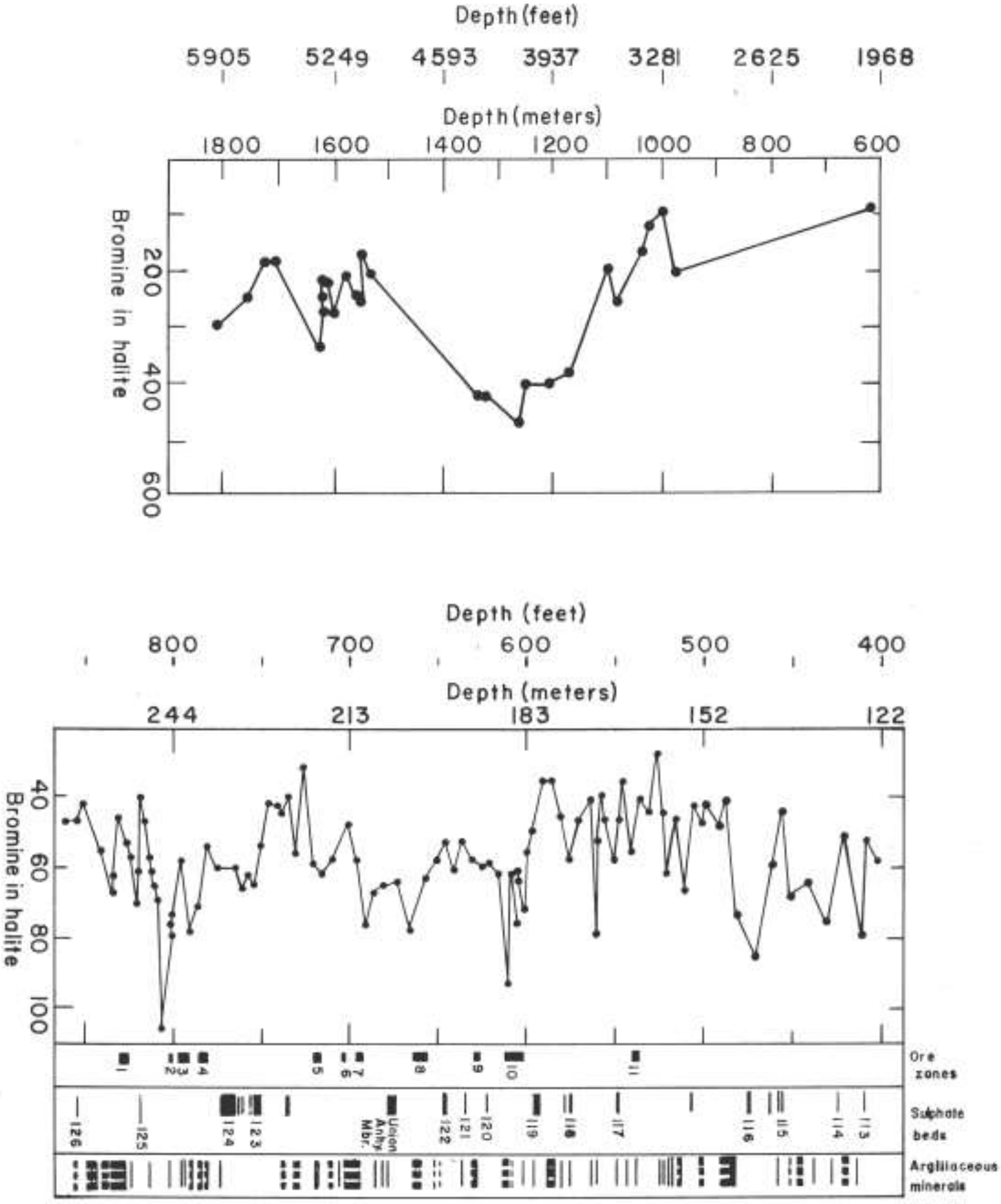


FIGURE 4—a) Bromine profile for rock salt of the Angara-Lena Basin, Russia (Adams, 1969); b) bromine profile for halite in the Salado Formation (core test 115 by International Minerals and Chemicals Corporation).

sylvinite, and sulfate beds indicates that the basin received repeated influxes of solution. These influxes are recorded in the bromine decrease.

TABLE 1—EVAPORITE MINERALS OF THE POTASH ORE DEPOSITS OF THE SALADO FORMATION, NEW MEXICO (from Jones, 1975).

	Formula	Weight % K_2O
Ore minerals		
Sylvite	KCl	63.17
Langbeinite	$K_2Mg_2(SO_4)_3$	22.69
Gangue minerals		
Leonite	$K_2Mg(SO_4)_2 \cdot 4H_2O$	25.68
Kainite	$KMgClSO_4 \cdot 3H_2O$	18.91
Carnallite	$KMgCl_3 \cdot 6H_2O$	16.95
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	15.62
Kieserite	$MgSO_4 \cdot H_2O$	—
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	—
Halite	$NaCl$	—
Anhydrite	$CaSO_4$	—

Potash production history

The Carlsbad Potash Area dominates the domestic mining and processing of potassic ores, and until fairly recently when the Canadian potash mines in Saskatchewan opened, it also dominated the world market. The aggregate output from the mines from 1931 through 1974 amounted to about 400 million tons (363 million tonnes) of potassium ore from which potassium salts worth more than $2.2 billion were extracted. At the time the Carlsbad KPLA was defined by the U.S. Geological Survey in the mid-1960's, sylvite ore accounted for most of the production; mining companies still mine more sylvite ore, but langbeinite ore has become increasingly important.

Six ore zones have been mined to date in the Salado Formation. A brief description of these zones and the general location of some of them are shown on table 2. The third ore zone, the most recent addition to this group, has been in production since mid-1976; the fourth ore zone probably represents the future of New Mexico's langbeinite potash reserves, and the tenth ore zone represents the remaining major sylvite reserves.

Hydrocarbon production history

Over the years, an oil-potash competition has developed in the Carlsbad area. The dual operation started in 1925 when the Snowden-McSweeney No. 1 well in sec. 4, T. 21 S., R. 31 E. (fig. 1), northeast of the city of Carlsbad, penetrated potash—a find of national importance because of U.S. dependence on Germany for potash. Just before World War I, the German potash supply was cut off, and potash prices rose to $500/ton on the international market. By the mid-1920's, the Carlsbad area was producing oil and gas, mostly from shallow (780-3,500 ft; 238-1,067 m) wells in the Yates and the Queen Formations of the Artesia Group and from wells in Brushy Canyon, Cherry Canyon, and Bell Canyon Formations of the Delaware Mountain Group (4,700-5,200 ft; 1,422-1,585 m), all of Permian age. In recent years, hydrocarbon production, mostly gas, from rocks of Pennsylvanian age has become increasingly important. All of the productive formations are older and thus are beneath the potash-bearing Salado Formation.

TABLE 2—SIX ORE ZONES THAT HAVE BEEN MINED IN THE SALADO FORMATION, CARLSBAD POTASH DISTRICT, NEW MEXICO.

Ore zone	Description
1st	Principal source of potash in district, now in decline
3rd	Recent mining in northwest part of district
4th	Rich langbeinite reserves particularly in the southern part of district
5th	Langbeinite zone, occasionally sylvite-bearing, found locally in central part of district
7th	Sylvite zone important mainly in central part of district
10th	After the 1st, the most consistent ore zone in grade, thickness, and extent

Major rock units of the Pennsylvanian System in the potash area are those of Morrowan and Atokan age, and the Strawn, Canyon, and Cisco Groups. The geology of these units has been extensively described by Meyer (1966). In the central part of the potash area Morrowan rocks range in thickness from 500 ft (152 m) in the north to 1,000 ft (305 m) in the south. They are composed of interbedded sandstone and shale with occasional limestone beds. Thin porous sandstone beds scattered erratically throughout the Morrowan rocks are gas productive on structural highs. These thin sandstone beds are often not connected and are frequently absent in offset wells. The oil-and-gas potential of the Carlsbad potash area is great; major fields within the potash area include the James Ranch, South Salt Lake, Lynch, Dos Hermanos, Teas-Lynch, and Cabin Lake. There are also several small, unnamed fields within the potash area.

Regulation history

In 1934, the Federal government (by Executive Order 6797) withdrew 2,560 acres from oil and gas leasing; other withdrawals followed in 1939 (Secretarial) and 1949 (Executive). In May 1951 the State of New Mexico offered 5 tracts of land for oil-and-gas lease sale in the area. In October 1951, the Secretary of the Interior revoked the Secretarial Order of 1939. The new Federal Order in 1951 established a potash area of approximately 300,000 acres (121,410 hectares), which was subsequently increased by Secretarial Orders of May 11, 1965, and November 5, 1975. Oil and gas leases in the Secretary's Potash Area are subject to special stipulations, the most recent of which are paraphrased below:

a) No wells will be drilled for oil or gas except upon approval of the Area Oil and Gas Supervisor of the Geological Survey. Drilling will be permitted only after it is satisfactorily established that such drilling will not interfere with the mining and recovery of potash deposits, or that the interest of the United States would best be subserved thereby.

b) No wells will be drilled for oil or gas at a location that, in the opinion of the Area Oil and Gas Supervisor of the Geological Survey, would result in undue waste of potash deposits or constitute a hazard to or unduly interfere with mining operations being conducted for the extraction of potash deposits.

c) When it is determined by the Area Oil and Gas Supervisor of the Geological Survey that unitization is necessary for orderly oil-and-gas development and proper protection of potash deposits, no well shall be drilled for oil or gas except pursuant to a unit plan approved by the Area Oil and Gas Supervisor.

d) The drilling or the abandonment of any well on said lease shall be done in accordance with applicable oil-and-gas operating regulations, including such requirements as the Area Oil and Gas Supervisor of the Geological Survey may prescribe as necessary to prevent the infiltration of oil, gas, or water into formations containing potash deposits or into mines or workings being utilized in the extraction of such deposits.

In any action taken under items a, b, c, or d above, the Area Oil and Gas Supervisor shall take into consideration the recommendations of the Area Mining Supervisor of the Geological Survey and the applicable conservation rules and regulations of the NMOCC (New Mexico Oil Conservation Commission).

The Federal potash lessees have the right to protest to the NMOCC the drilling of a proposed oil and gas test on Federal lands provided that the location of said well is within the State of New Mexico's "Oil-Potash Area" as that area is delineated by NMOCC Order 111, as amended. However, the Department of the Interior will exercise its prerogative to make the final decision of whether to approve the drilling of any proposed well on a Federal oil-and-gas lease within the Order 1 1 1 potash area.

All new or renewed potash prospecting permits and leases are subject to a requirement that no mining or exploratory operations will be conducted that, in the opinion of the Area Mining Supervisor, would constitute a hazard to oil or gas production. This requirement must either be included in the lease or permit or be imposed by the Supervisor. U.S. Geological Survey leasing standards are as follows: 4 ft (1.2 m) of 10-percent K_2O as sylvite and 4 ft (1.2 m) of 4-percent K_2O as langbeinite or equivalent combination of the 2 minerals.

It is the policy of the U.S. Geological Survey to deny approval of most new applications for permits to drill oil-and-gas tests from surface locations within the Secretary's KPLA when the location is within a delineated potash enclave (Aguilar and others, 1976). There are two exceptions to this ban: 1) Drilling will be permitted in potash-barren areas within the potash enclave when the Area Mining Supervisor determines that such operations will not interfere with existing or planned mine workings in the vicinity, and 2) drilling will be permitted from a drilling island that will be established by the Area Mining Supervisor when, in the opinion of the Area Oil and Gas Supervisor, the target formations beneath a remote interior lease cannot be reached by a well directionally drilled from a surface location outside the potash enclave. While no such drilling islands have yet been established, dual objectives have been accomplished by authorizing oil-and-gas operations in barren and indicated ore areas. The following specific instances (not actual docketed legal cases) demonstrate the decision process regarding which resources will be developed.

Example 1—Well No. 9, NE 1/4 SE 1/4 sec. 20, T. 20 S., R. 34 E. (dry hole, fig. 5), is a type of drilling island situation. A proposed well was to be drilled to a depth of 3,700 ft (1,128 m) to test the Yates and Seven Rivers Formations (Upper Permian) in an area already developed for oil production. A waiver was executed by the potash lessee and the oil and gas operator, who had done extensive coring in this area, and the well was drilled.

Example 2—The proposed well location was in the potash enclave, and recent core tests by the mining company proved the presence of ore in the tenth ore zone underlying the proposed location (fig. 5). The mining company exhibited to the NMOCC a copy of the mine map, showing that they were mining the tenth ore zone at a point about 2 mi (3.2 km) southwest of the proposed location and intended to extend their mining operation into the southeast corner of sec. 24 within the next 5 years. The NMOCC requested a U.S. Geological Survey opinion and was advised that the Geological Survey would have no alternative other than to deny the location in view of the validity of the core-hole information and existing and future mining plans. It was therefore agreed that this oil-and-gas test would not be drilled.

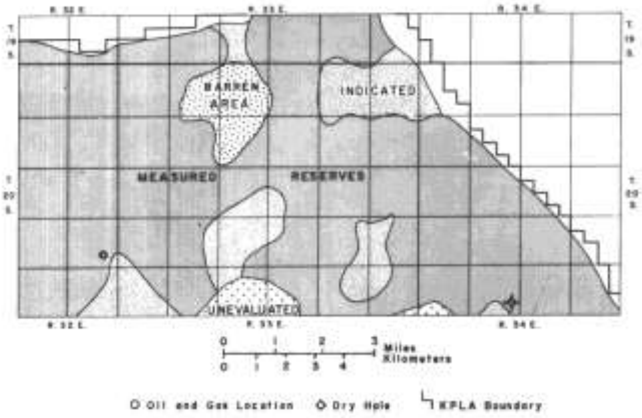


FIGURE 5—OIL-POTASH PLAT OF NORTHEASTERN PART OF THE POTASH AREA, SHOWING THE LOCATION OF 2 WELLS DISCUSSED IN TEXT.

Example 3—An oil and gas operator completed a well in the potash enclave and then asked for approval for a second location, in the barren area (fig. 6). The potash company drilled three core holes around the second location to identify possible potash deposits; the area proved to be barren or poorly mineralized and the oil-and-gas test was allowed to proceed.

Example 4—An application for a permit to drill was filed by an oil and gas operator at a location in sec. 7, T. 23 S., R. 31 E., and was protested by the potash lessee. An arbitration meeting was held pursuant to NMOCC Order No. R-111-A. This joint meeting by the NMOCC and the U.S. Geological Survey effected the establishment of a compromise location (No 1, fig. 7) on the edge of the potash enclave and outside the subsidence distance of a core hole with very strong mineralization in sec. 7. The potash lessee agreed to drill a core test to evaluate the ore on the compromise location. The final decision was to deny the oil and gas location after ore was found in this new core hole.

Another problem is shown in the instance of a proposed well in sec. 31 (No. 2, fig. 7). The site is not underlain by ore-grade potash; however, ERDA (Energy Research and Development Administration) requested that this area be withdrawn because very little of their proposed WIPP (Waste Isolation Pilot Plant) site is potash barren (Cheeseman and Lorenz, 1977). As of August 1977, no decision had yet been reached on this well.

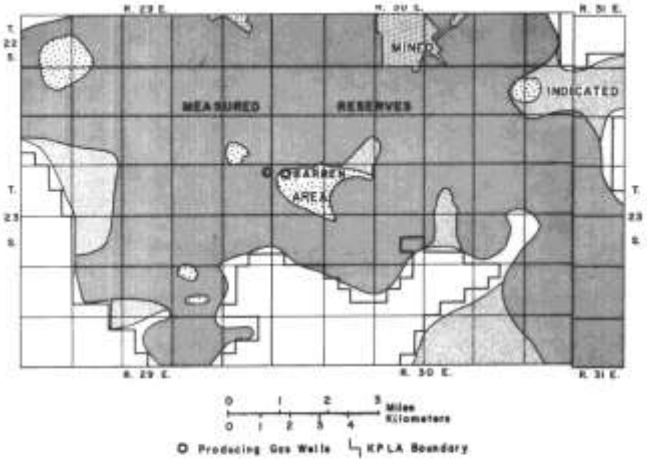


FIGURE 6—OIL-POTASH PLAT SHOWING LOCATION OF SUCCESSFUL GAS WELLS.

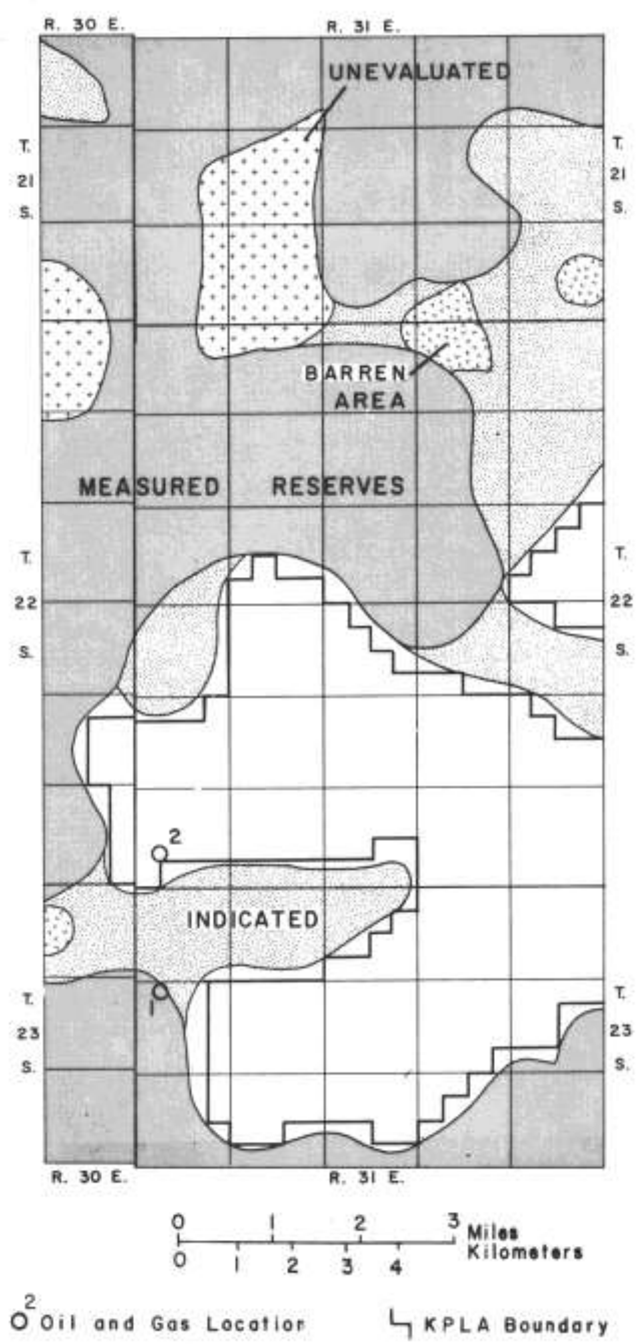


FIGURE 7—Oil-potash plat showing 2 proposed oil-and-ga locations.

References

Adams, J. E., 1944, Upper Permian Ochoa series of Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists, Bull., v. 28, no. 11, p. 1596-1625

, 1965, Stratigraphic-tectonic development of Delaware Basin: American Association of Petroleum Geologists, Bull., v. 49, no. 11, p. 2140-2148

Adams, S. S., 1969, Bromine in the Salado Formation, Carlsbad potash district, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bull. 93, 122 p.

Aguilar, P. C., Cheeseman, R. J., and Sandell, E. T., 1976, Preliminary map showing distribution of potash resources, Carlsbad mining district, Eddy and Lea Counties, New Mexico: U.S. Geological Survey, Open-file Rept. 76-554

Cheeseman, R. J., and Lorenz, J. C., 1977, Potash ore reserves in the proposed Waste Isolation Pilot Plant area, Eddy County, southeastern New Mexico: U.S. Geological Survey, open-file rept. 78-828

Dean, W. E., and Tung, A. L., 1974, Trace and minor elements in anhydrite and halite, Supai Formation (Permian), east-central Arizona, *in* 4th Symposium on Salt: Northern Ohio Geological Society, Inc., v. 1, no. 4, p. 287-301

Evans, R., 1977, Environments of evaporitic sedimentation—shallows, sabkhas, shelves, and sumps [abs.]: American Association of Petroleum Geologists, Bull., v. 61, no. 2, p. 295

Jones, C. L., 1954, The occurrence and distribution of potassium minerals in southeastern New Mexico: New Mexico Geological Society, Guidebook 5th field conference, p. 107-112

, 1975, Potash resources in part of Los Medanos area of Eddy and Lea Counties, New Mexico: U.S. Geological Survey, Open-file Rept. 75-407, 37 p.

Jones, C. L., Bowles, C. G., and Disbrow, A. E., 1960, Generalized columnar section and radioactivity log, Carlsbad potash district: U.S. Geological Survey, Open-file Rept.

Meyer, R. F., 1966, Geology of Pennsylvanian and Wolfcampian rocks in southeast New Mexico: New Mexico Bureau of Mines and Mineral Resources, Mem. 17, 123 p.

SALINITY CYCLES: EVIDENCE FOR SUBAQUEOUS DEPOSITION OF CASTILE FORMATION AND LOWER PART OF SALADO FORMATION, DELAWARE BASIN, TEXAS AND NEW MEXICO

by Walter E. Dean, *U.S. Geological Survey, Box 25046, Denver Federal Center, Denver, Colorado 80225*
and
Roger Y. Anderson, *Department of Geology, University of New Mexico, Albuquerque, New Mexico 87106*

Abstract

Varve laminations characterize the entire Castile Formation and the lower part of the overlying Salado Formation, and provide time calibration for evaluating rates and magnitudes of chemical changes within the Delaware Basin during early Ochoan time. Salinity cycles having periods of 1,000 to 3,000 years are conspicuous, persistent features of the Castile and lower part of the Salado; they are synchronous over most of the basin. A complete salinity cycle is manifested by an upward increase in thickness of anhydrite laminae, development of nodular anhydrite within anhydrite laminae near the end of a cycle, and final deposition of a bed of halite. Most cycles are not complete; not every bed of nodular anhydrite is overlain by a bed of halite. However, nodular anhydrite is best developed in complete cycles in which the original laminated anhydrite lying immediately below a bed of halite has been almost completely recrystallized. Although salinity cycles are more pronounced in the upper part of the evaporite sequence (upper part of the Castile and lower part of the Salado), they are present throughout, beginning with the first bed of nodular anhydrite, which was deposited about 1,000 years after the first anhydrite deposition. By the end of Guadalupian time, the Delaware Basin was a deep, starved basin, which then was rapidly filled with evaporites of the Castile and Salado Formations during early Ochoan time. The rate of filling was relatively constant at 1.9 mm per year for calcite-laminated anhydrite. Salinity cycles have greater amplitudes in the upper part of the varved evaporite sequence than in the lower part of the Castile Formation. This is evidenced by increased intercalation of anhydrite and halite as more salinity cycles went to completion and by a more variable range of anhydrite varve thickness within salinity cycles. The increase in amplitude with time indicates an aqueous control of the salinity cycles with attendant subaqueous deposition of evaporites and suggests a progressive shallowing of the basin.

Introduction

In recent years the widespread and often uncritical acceptance and application of the supratidal (or sabkha) model of evaporite deposition and diagenesis has tended to overemphasize evidence supporting the subaerial origin of evaporites. This paper demonstrates that the Upper Permian (Ochoan) Castile Formation of the Delaware Basin provides an outstanding example of subaqueous evaporite deposition for which there is no modern analogue.

Certainly the most distinctive feature of the Castile is the rhythmic alternation of calcite and anhydrite laminae forming the banded anhydrite that is so typical of the Castile. In several earlier papers we placed most of our emphasis on sedimentary structures, particularly the laminae, to demonstrate the subaqueous nature of the Castile (Anderson and Kirkland, 1966; Anderson and others, 1972; Dean and Anderson, 1974; Dean and others, 1975). In this paper we discuss salinity cycles within the Castile Formation and the lower part of the Salado Formation that we feel could only have formed by basin-wide changes in water chemistry within a standing body of water. The laminae are still an important aspect of this study because changes in salinity are manifested in the character of the laminae, and the laminae provide the time calibration for determining rates of change and for detailed correlation of the cycles.

ACKNOWLEDGMENTS—Much of this research was supported by the National Science Foundation and the National Aeronautics and Space Administration. We are indebted to W. T. Holser, University of Oregon, and Chevron Research Company for contributing slabs from the Union Oil Company-University "37" core. Douglas W. Kirkland, Omer B. Raup, and Robert J. Hite reviewed the initial draft of this paper.

Castile-lower Salado salinity cycles

Description of salinity cycles

Anderson and others (1972) presented a time series for the Castile Formation and the lower part of the Salado Formation based on measurements of thicknesses of individual calcite-anhydrite varve couplets. They demonstrated that the varve couplets in the Castile and lower Salado are repeated with remarkable regularity, with over 250,000 couplets within about 440 m of stratigraphic section (fig. 1). Dean and others (1975) pointed out that it is the remarkable vertical repetition and lateral continuity of laminae in the Castile that serve to distinguish basinal (subaqueous) laminations from less regular and discontinuous algal-laminated sediments of tide flat environments.

Apart from the obvious laminations, the most conspicuous and persistent features of the Castile and lower Salado are lithologic cycles with periods on the order of 1,000 to 3,000 years. These cycles are interpreted as representing changes in salinity within the basin. A complete salinity cycle is illustrated diagrammatically in fig. 2. A complete cycle begins with thin calcite-anhydrite varve couplets in which calcite may be the dominant component. The anhydrite member of the varve couplets increases in thickness upward within the cycle, forming the calcite-banded anhydrite typical of most of the Castile Formation and the lower part of the Salado Formation. Near the end of a cycle, nodular anhydrite has developed by recrystallization within thicker anhydrite laminae. A complete cycle ends with a bed of halite, usually containing laminae of anhydrite, immediately overlying nodular anhydrite.

Most cycles are incomplete because not every bed of nodular anhydrite is overlain by halite. However, nodular anhydrite is best developed in complete cycles, so that the original laminated anhydrite lying immediately below a bed of halite is almost completely recrystallized into nodular anhydrite (fig. 3, E-I). Nodular anhydrite most commonly occurs in the form of occasional widening of anhydrite laminae (fig. 3, A and B). However, in those complete cycles where

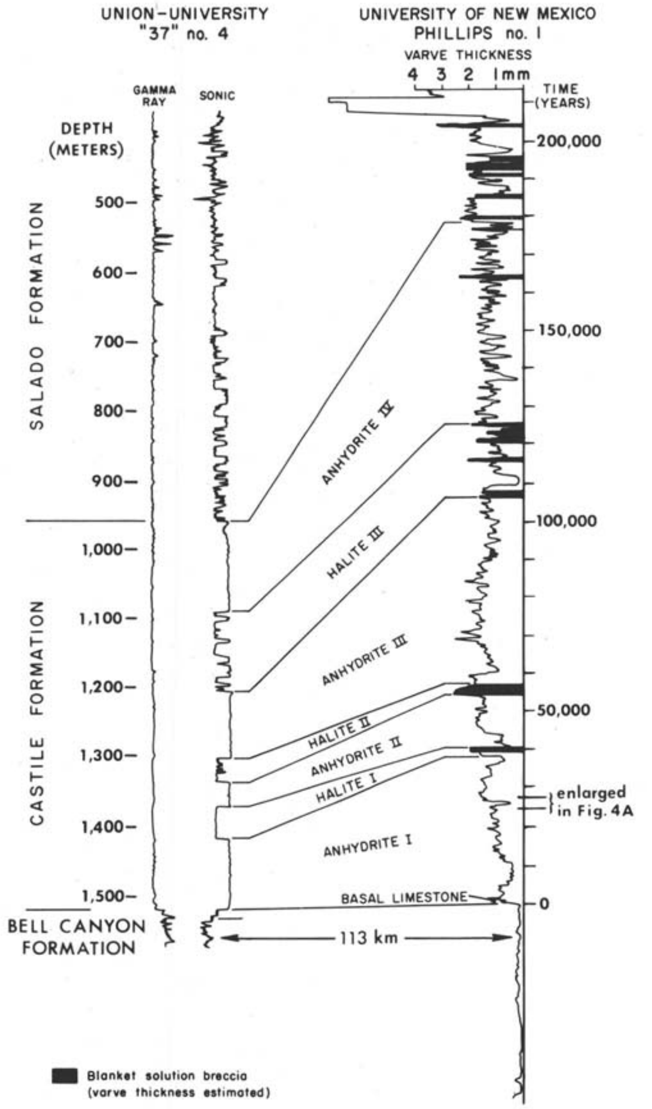


FIGURE 1—Correlation between gamma ray and sonic logs of the Union-University "37" No. 4 well and smoothed calcite-anhydrite couplet thickness in the University of New Mexico-Phillips No. 1 core of the Castile and lower Salado Formations. Couplet thicknesses are estimated for halite units. T = 0 on the time scale refers to the beginning of evaporite deposition, which is the Anhydrite I unit of the Castile Formation (modified from Anderson and others, 1972).

laminated anhydrite has been almost completely recrystallized to nodular anhydrite, the result is a fabric similar to "chicken-wire anhydrite," which is commonly used as the main criterion for inferring a sabkha origin (Dean and others, 1975). Nodular anhydrite in the Castile and lower Salado formed by postdepositional recrystallization of calcium sulfate within preexisting laminae, and it is not related to subaerial exposure (Dean and others, 1975).

The dominant lithologic changes within salinity cycles are changes in relative proportions of calcite and anhydrite. At the base of a cycle, calcite may form as much as 80 percent of the rock so that the lithology is actually a laminated limestone (bottom photograph in fig. 2), although this is rare. In the typical calcite-banded anhydrite in the middle of a cycle—the material that makes up most of the Castile (fig. 2)—calcite constitutes about 10 to 15 percent of the rock, with anhydrite comprising the remaining 85 to 90 percent. In the thicker anhydrite-calcite couplets at the top of a cycle, anhydrite may

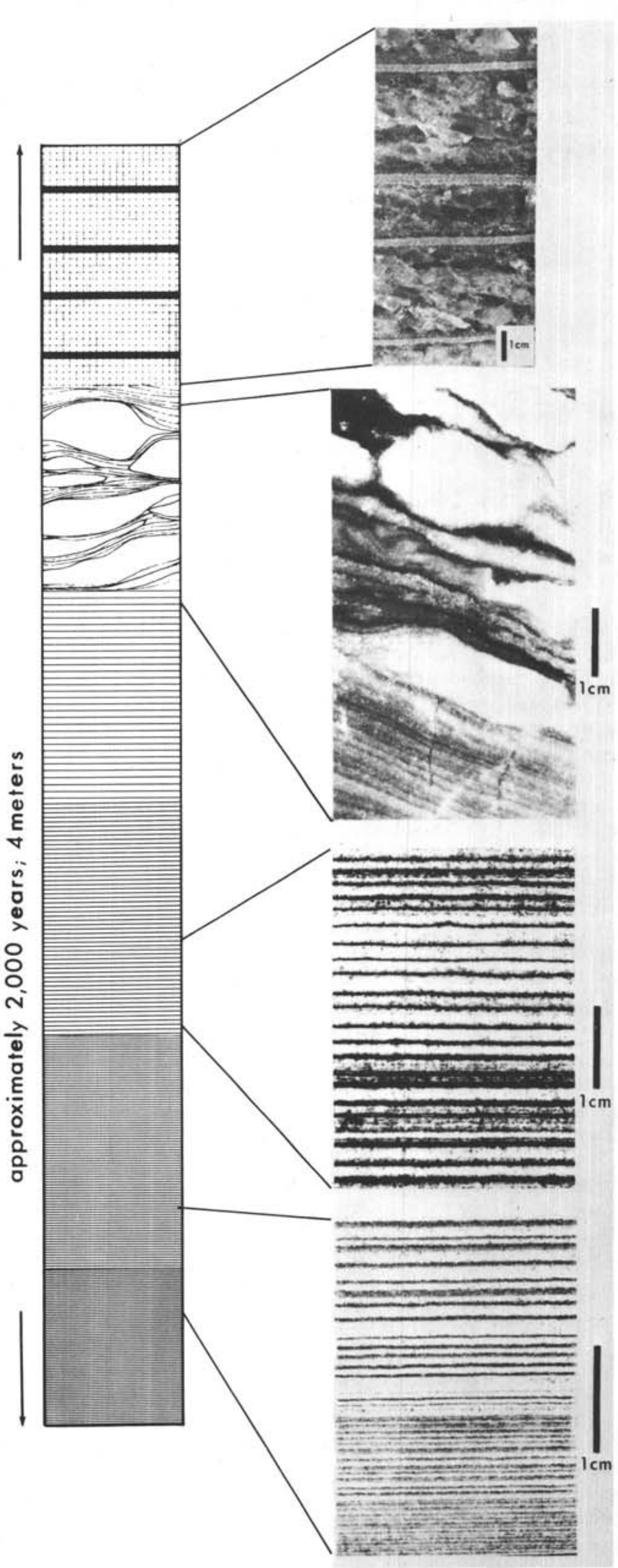


FIGURE 2—Diagrammatic illustration of a complete salinity cycle in the Castile Formation and lower part of the Salado Formation.

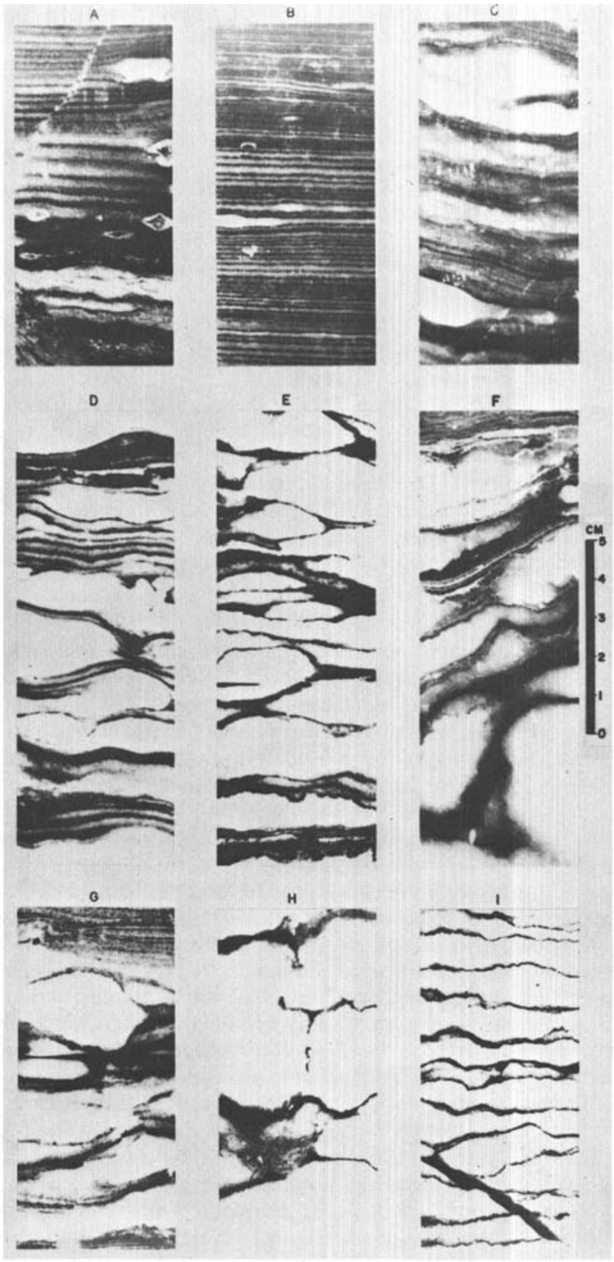


FIGURE 3—PHOTOGRAPHS OF NODULAR ANHYDRITE IN THE UNIVERSITY OF NEW MEXICO-PHILLIPS NO. 1 CORE OF THE CASTILE FORMATION. Photographs are not in any particular stratigraphic order but are arranged in approximate order of increasing degree of nodular development

make up more than 95 percent of the rock. Because thicknesses of calcite laminae tend to be much more constant than thicknesses of anhydrite laminae, changes in relative proportions of calcite and anhydrite are largely due to changes in rate of sulfate precipitation (Anderson and others, 1972; Dean and Anderson, 1974).

Geochemical changes within salinity cycles

Changes in salinity and the kinetics of precipitation of calcium sulfate are also manifested in changes in several geochemical parameters. For example, with increased rate of precipitation of calcium sulfate, there was less time for incorporation of trace and minor elements, even though these elements were probably more concentrated in the water during times of greater sulfate precipitation.

Fig. 4 shows plots of laminae thickness and several geochemical parameters for a part of a salinity cycle in which precipitation of calcium sulfate was markedly reduced, resulting in very thin calcite-anhydrite varve couplets. The location of this cycle within the Anhydrite I unit of the Castile is shown in fig. 1, and laminae from a portion of this cycle are illustrated in the bottom photograph of fig. 2. The time scale in fig. 4 is given with reference to the position of the cycle within the Castile and lower Salado varved evaporite sequence, and begins at 24,790 varve couplets above the base of Anhydrite I.

Within the portion of the salinity cycle illustrated in fig. 4 where the laminae are thinnest, the percent of calcium sulfate decreases considerably (fig. 4B) and the percent of calcium carbonate increases considerably (fig. 4C). Within the same time period of reduced calcium sulfate deposition, the concentrations of Sr and other minor elements (Mg, Na, K, Fe, and Mn) in the anhydrite increase by as much as an order of magnitude. In fig. 4D and in this discussion, Sr is used as an example, but the conclusions apply to other minor elements. Assuming that periods of reduced rate of precipitation of calcium sulfate represent periods of reduced salinity within

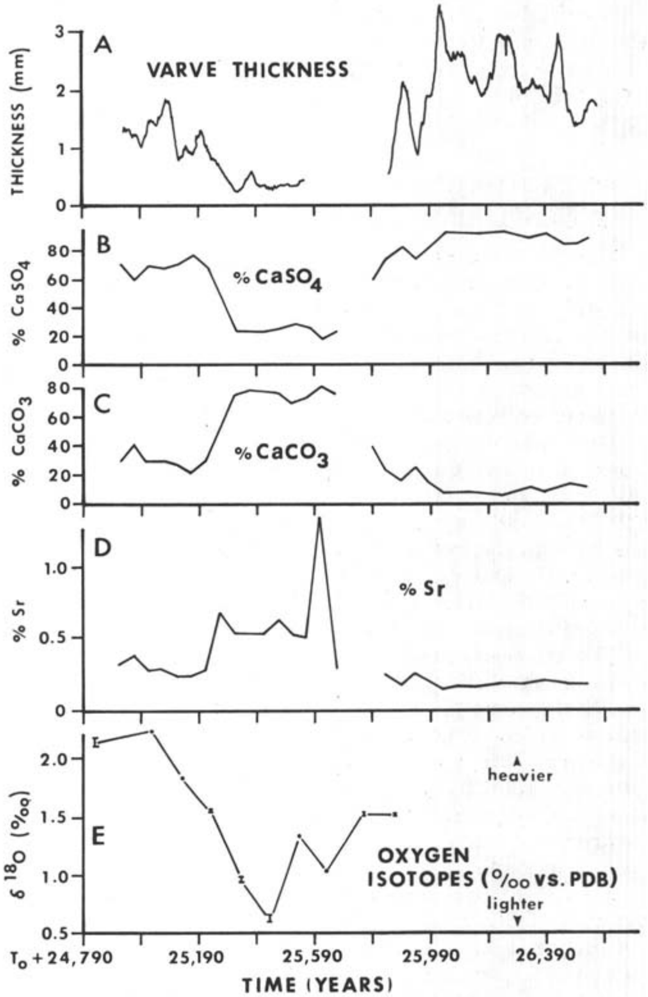


FIGURE 4—PLOTS OF **A)** SMOOTHED CARBONATE-SULFATE THICKNESS, **B)** PERCENT $CaSO_4$, **C)** PERCENT $CaCO_3$, **D)** PERCENT SR, AND **E)** $\delta^{18}O$ FOR THE TIME INTERVAL 24,788 TO 26,638 YEARS ABOVE THE BASE OF ANHYDRITE I OF THE CASTILE FORMATION. Values of $\delta^{18}O$ are relative to the University of Chicago PDB standard. Bars on oxygen isotope plot **(E)** represent results of duplicate analyses.

the basin, we would expect concentrations of minor elements, such as Sr, in the water also to be lower than they are in periods of increased salinity and increased rate of precipitation of calcium sulfate. Consequently, concentrations of minor elements incorporated in calcium sulfate should also be lower during periods of lower salinity assuming equilibrium incorporation by either the homogeneous or logarithmic distribution laws. To explain the observed inverse relationship between salinity and minor-element concentration in anhydrite, Dean and Anderson (1974) concluded that minor element incorporation in anhydrite is not an equilibrium process but is more closely related to the rate of precipitation. During periods of rapid precipitation of calcium sulfate, there was not enough time for the precipitating calcium sulfate to equilibrate with the water, resulting in lower concentrations of Sr and other minor elements. During periods of slower precipitation of calcium sulfate, equilibrium incorporation of minor elements was more nearly attained, resulting in higher concentrations of minor elements.

The ratio of oxygen isotopes in the carbonate also changes considerably with inferred changes in salinity. The oxygen isotopic composition of carbonate in the same salinity cycle discussed above is shown in fig. 4E. Notice that the oxygen in the carbonate is isotopically much lighter (lower value of $6^{18}0$) at the time of inferred lower salinity (thinner laminae) than during periods of inferred higher salinity (thicker laminae). This supports the interpretation that a change to higher relative content of $CaCO_3$ at the beginning of a cycle is the result of a decrease in salinity of the water, which would also be isotopically lighter, owing to Rayleigh distillation (Lloyd, 1966).

Factors affecting precipitation of $CaSO_4$ and $CaCO_3$

The above observations suggest that the rate of precipitation of calcium sulfate, and therefore the thickness of anhydrite laminae, is mainly controlled by changes in water salinity on a basin-wide scale. Dean and Anderson (1974) have shown that the rates of precipitation of calcium sulfate and calcium carbonate are generally not correlated and may even be negatively correlated.

The general descriptions of calcite-anhydrite laminae couplets in the Castile by Udden (1924), Adams (1944), Anderson and Kirkland (1966), and Anderson and others (1972) have all emphasized an intimate association of organic matter with the calcite. Adams (1944, 1967) concluded that the organic matter represented phytoplankton debris brought into the basin by spring floods. However, the basin-wide correlation of organic laminae in the Bell Canyon Formation, as well as the evaporites of the Castile and Salado Formations, suggests that the organic matter may be related to periodic (probably annual) increases in phytoplankton productivity on a basin-wide scale (Anderson and others, 1972). Evaporite environments are known to have extremely high levels of primary productivity. Phleger (1969) and Carpelan (1957) have demonstrated that precipitation of $CaCO_3$ in evaporite environments they studied was related to increases in pH caused by removal of CO, by high rates of algal photosynthesis. In all probability, phytoplankton productivity and removal of CO, by algal photosynthesis exerted some control on precipitation of $CaCO_3$ in the Castile and lower Salado evaporite sequence. In addition, precipitation of $CaCO_3$ may be affected by changes in temperature, by changes in total ionic strength of the solution, and by changes in the CaCO3 ion-activity product by precipitation of CaSO4. The controls on precipitation of $CaCO_3$ are complex, and this may explain the lack of correlation between the rates of precipitation of $CaCO_3$ and CaSO4.

Depth of water in the Delaware Basin

Initial depth

By the end of Guadalupian time, the Delaware Basin was a deep, starved basin, which was then rapidly, continuously, and completely filled with evaporites during Ochoan time (Adams, 1944 and 1965; Adams and Frenzel, 1950; Kelley, 1972). Estimates of water depth in the Delaware Basin at the beginning of Ochoan time range from several hundred meters (King, 1934) to more than 700 m (Adams, 1936). Most estimates are on the order of 600 m and are based on the present difference in elevation between the reef crest and the top of the Lamar Limestone Member of the Bell Canyon Formation of latest Guadalupian age.

Based on the sedimentological evidence within the Castile and lower Salado varved evaporite sequence, about all one can conclude is that the water was deep enough to preserve delicate details of individual laminae over most of the basin. In addition, water levels in the basin may have fluctuated during individual salinity cycles in response to evaporitive drawdown (Maiklem, 1971).

Changes in water depth

Two rather remarkable features of the entire Castile and lower Salado time series compiled by Anderson and others (1972) provide the best indication that the basin was relatively deep at the onset of evaporite deposition and underwent progressive shallowing. These are the amplitude changes in the 1,000- to 3,000-year salinity cycles and the constant rate of sediment accumulation.

Fig. 5 is a plot of cumulative thickness of anhydrite vs. time for the Castile and lower Salado in the UNM Phillips No. 1 core. Halite is not present in this core, and the halite units of the Castile and lower Salado are represented by beds of halite—correlative anhydrite breccia and interbeds of calcite-laminated anhydrite (Anderson and others, 1972). Fig. 5 shows that the rate of deposition of calcite-laminated anhydrite in the basin was remarkably constant at approximately 1.8 to 1.9 mm per year (the dashed line represents a constant accumulation rate of 1.9 mm per year, provided for reference). There are very slight long-term changes in accumulation rate, and even greater short-term changes within the 1,000- to 3,000-year salinity cycles, but the net effect (fig. 5) is one of constant rate of accumulation. We cannot envision any evaporite depositional model, other than constant accumulation from a standing body of water, that would produce an accumulation rate this constant. If one were to assume a model of shallow depth and continuous subsidence, it seems most unlikely that subsidence would occur at such a constant rate, and be so finely tuned to the rate of deposition that several hundred meters of uninterrupted basin-wide lamination would be preserved.

The net effect of continuous filling of the basin was that those factors affecting salinity (climate, rate of inflow, etc.) were operating on a progressively shallower basin. A possible manifestation of basin shallowing is the fact that salinity cycles in the upper part of the varved evaporite sequence (upper Castile and lower Salado) have greater amplitudes than those in the lower part of the Castile.

Increased amplitudes of salinity cycles are shown in fig. 1 by increased amplitudes of varve thickness in the graph on the right side of the illustration. For example, compare the relative variation in varve thickness in Anhydrite I with those in Anhydrite IV. Periods of the cycles remain about the same (1,000 to 3,000 years) but amplitudes visibly change. Fig. 6 shows that the increase in amplitude of salinity cycles with time, as recorded by increased amplitude of varve thickness with time, is approximately linear. At the base of the varved evaporite sequence, indicated by T = 0 in figs. 1, 5, and 6, the

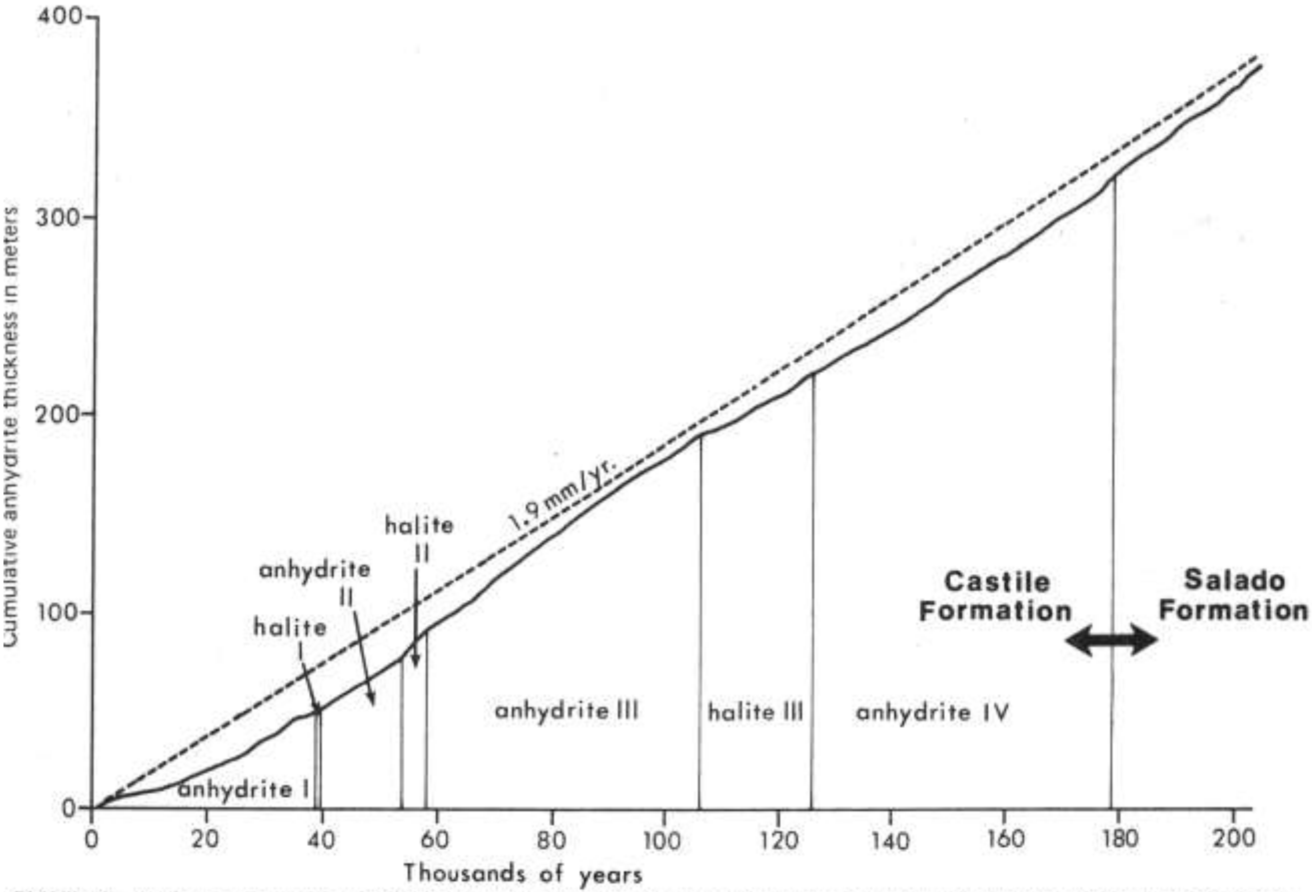


FIGURE 5—Plot of cumulative thickness of anhydrite vs. time for anhydrite in the University of New Mexico-Phillips No. 1 core of the Castile Formation and lower part of the Salado Formation. The dashed line represents a constant accumulation rate of 1.9 mm per year, provided for reference.

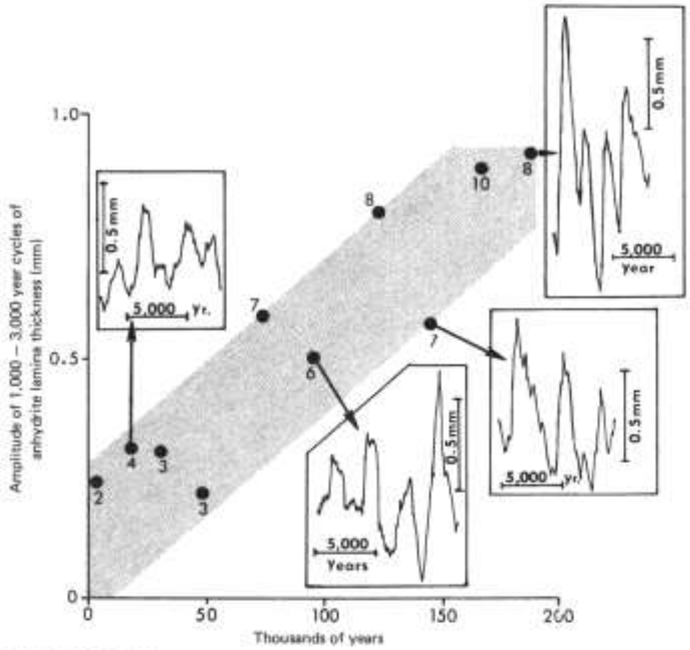


FIGURE 6—Plot of amplitude of variations in anhydrite-lamina thickness within 1,000- to 3,000-year salinity cycles vs. time for the University of New Mexico-Phillips No. 1 core of the Castile Formation and lower part of the Salado Formation. Four plots of smoothed (500-year moving average) anhydrite thickness are provided to illustrate the increasing amplitude of varve-thickness changes (increasing amplitude of salinity cycles) with increasing time (increasing shallowing of the basin). Numbers adjacent to data points are the number of cycles averaged to obtain the data point.

amplitudes of varve thickness are about 0.2 mm. The amplitudes increase linearly to almost 1.0 mm in the upper Castile and lower Salado.

Greater changes in lamina thickness as the basin became progressively shallower implies that there were greater changes in salinity within the 1,000- to 3,000-year period of individual salinity cycles. Also, with shallowing, more salinity cycles were completed, as evidenced by the increased interbedding of halite and anhydrite that characterizes the Salado Formation (fig. 1).

The relatively constant periods of salinity cycles in the Castile and lower Salado suggest that the timing of salinity changes in the basin was controlled by some factor or combination of factors external to the basin, probably climatically related variables. The amplitudes of the cycles were largely controlled by internal factors, particularly the depth of water. The alternative is to assume that the progressive increase in amplitude of the 1,000- to 3,000-year salinity cycles is the result of progressive changes in external factors (for example, climate) that maintained a fixed period. Internal control by basin geometry is the simpler explanation. The fact that gradual and progressive shallowing of the basin affected salinity of the water so directly indicates that the deposition of the evaporites of the Castile and lower Salado does not fit the classic model of deep-water evaporite deposition in which only the salinity of the surface water controls precipitation.

Summary

Precise correlation provided by lateral persistence of individual varve laminations shows that lithologic and geochemical changes within individual salinity cycles in the Castile Formation and lower part of the Salado Formation occur rapidly and synchronously over most of the Delaware Basin. This suggests that salinity changes within the basin during deposition of the evaporites occurred rapidly over most of the basin. Water depth may have varied during individual salinity cycles, but the sediment-water interface was always below wave base. Over a period of about 200,000 years, the basin filled at a very constant rate of about 1.9 mm per year. This implies that by the end of lower Salado deposition, the average water depth in the basin was considerably less than at the beginning of Castile deposition.

We conclude that rapid, synchronous changes in salinity within the relatively constant period of several thousand years represented by the salinity cycles, which resulted in widespread lithologic and geochemical changes that can be correlated down to the finest lamination, could only occur by basin-wide changes in water chemistry within a standing body of water. In addition, this is the only depositional model for evaporites that could produce such a constant sediment accumulation rate over 200,000 years.

References

Adams, J. E., 1936, Oil pool of open reservoir type: American Association of Petroleum Geologists, Bull., v. 20, p. 780-796

, 1944, Upper Permian Ochoa Series of Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists, Bull., v. 28, p. 1592-1625

, 1965, Stratigraphic-tectonic development of Delaware Basin: American Association of Petroleum Geologists, Bull., v. 49, p. 2140-2148

______________, 1967, Semi-cyclicity in the Castile Evaporite, *in* Cyclic sedimentation in the Permian Basin, J. G. Elam and S. Chuber, eds.: West Texas Geological Society, Symposium, p. 197-203

Adams, J. E., and Frenzel, H. N., 1950, Capitan barrier reef, Texas and New Mexico: Journal of Geology, v. 58, p. 289-312

Anderson, R. Y., Dean, W. E., Jr., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved evaporite sequence, west Texas and New Mexico: Geological Society of America, Bull., v. 83, p. 59-86

Anderson, R. Y., and Kirkland, D. W., 1966, Intrabasin varve correlation: Geological Society of America, Bull., v. 77, p. 241-256

Carpelan, L. H., 1957, Hydrobiology of the Alviso salt ponds: Ecology, v. 38, p. 375-390

Dean, W. E., and Anderson, R. Y., 1974, Trace and minor element variations in the Permian Castile Formation, Delaware Basin, Texas and New Mexico, revealed by varve calibration: Fourth International Symposium on Salt, Northern Ohio Geological Society, v. 1, p. 275-285

Dean, W. E., Davies, G. R., and Anderson, R. Y., 1975, Sedimentological significance of nodular and laminated anhydrite: Geology, v. 3, p. 367-372

Kelley, V. C., 1972, Geometry and correlation along Permian Capitan escarpment, New Mexico and Texas: American Association of Petroleum Geologists, Bull., v. 56, p. 2192-2211

King, P. B., 1934, Permian stratigraphy of trans-Pecos Texas: Geological Society of America, Bull., v. 45, p. 697-798

Lloyd, R. M., 1966, Oxygen isotope enrichment of sea water by evaporation: Geochimica et Cosmochimica Acta, v. 30, p. 801-814

Maiklem, W. R., 1971, Evaporitive drawdown-a mechanism for water-level lowering and diagenesis in the Elk Point Basin: Bull. Canadian Petroleum Geology, v. 19, p. 467-503

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

Udden, J. A.,.1924, Laminated anhydrite in Texas: Geological Society of America, Bull., v. 35, p. 347-354

CLAY-MINERAL ASSEMBLAGES FROM DRILL CORE OF OCHOAN EVAPORITES, EDDY COUNTY, NEW MEXICO

by Marc W. Bodine, Jr., *Department of Geoscience, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801*

Abstract

The ERDA-9 drill hole, Eddy County, New Mexico, was cored for 1,987 ft, from 230 ft below the top of the Salado Formation through the upper 41 ft of the Castile Formation. Clay minerals in 47 insoluble residues include corrensite, random to partially ordered clinochlore-saponite mixed-layer clays, illite, clinochlore, saponite, a tentatively identified talc-saponite mixed-layer clay, serpentine, and talc. Serpentine is restricted to the Castile and lowermost Salado Formations; (?)talc-saponite is confined to some polyhalite beds in and overlying the McNutt potash zone. The salztons (thin argillaceous seams) consist of corrensite, illite, and clinochlore, while the adjacent evaporite strata often contain abundant random mixed-layer clinochlore-saponite, mixed-layer (?)talc-saponite, or saponite. Chemical compositions of the residues have high Mg-Al atom ratios reflecting abundance of the trioctahedral clays. Mineralogy and chemistry of the assemblages strongly indicate that severe alteration and Mg-enrichment of normal clay detritus occurred in the evaporite environment through brine-sediment interaction. It is further suggested that the relatively immature clays—saponite, mixed-layer (?)talc-saponite, and randomly interstratified clinochlore-saponite—formed later through recrystallization of preexisting trioctahedral clays in response to transient pore fluids; the salztons, impermeable to such fluids, developed a more mature clay assemblage in a static pore fluid environment. The serpentine-saponite residues with their high Mg-Al and Si-Al atom ratios in Castile and lowermost Salado evaporites are indicative of a silica-rich detrital source; the more aluminous clay assemblages with decreased Mg-Al and Si-Al atom ratios in the overlying evaporite strata suggest a substantially more argillaceous detrital source.

Introduction

Clay assemblages in core samples from the Salado Formation and the uppermost anhydrites of the Castile Formation from the ERDA-9 drill hole in Eddy County, New Mexico, are highly distinctive. They have unusually extreme Al-Ca-poor and Mg-rich compositions and consist of a variety of abundant trioctahedral clays with subordinate amounts of illite. Although far different from most sedimentary clay assemblages, they do show a marked similarity to clays in marine evaporite rocks from other localities. Their pronounced dissimilarity with clays in normal fluvial or marine sediments strongly suggests that detrital accumulations in the marine hypersaline environment must have been subjected to severe alteration and magnesium enrichment as a result of brine-sediment interaction. It is equally likely that alteration, through reaction with subsequent transient pore fluids, continued long after deposition and burial.

This project is one part of a recently initiated geochemical and mineralogical investigation of silicate assemblages in the Ochoan evaporites of southeastern New Mexico. The project is not completed, and the conclusions presented in this report are tentative and susceptible to later modification as additional data become available.

ACKNOWLEDGMENTS—Support for this study has come from Sandia Laboratories (Contract No. 05-3718); their assistance, particularly that of Dennis Powers, in providing the suitable core samples, core photographs, and well logs, as well as financial support, is gratefully acknowledged. I also wish to thank my graduate assistant, John Laskin, who enthusiastically provided much of the analytical data in this report. John MacMillan (a co-investigator on a related project) and Joseph Taggart offered valuable advice and criticism during the course of the study; Patricia Valentine and William Arnold helpfully provided the necessary secretarial and drafting services. George Austin offered many helpful suggestions and kindly reviewed the manuscript.

Clay minerals in marine evaporite rocks

Earlier investigations of clay assemblages in Ochoan rocks from the Permian Basin are not comprehensive; they consist of brief remarks, or, alternatively, of longer reports restricted to a relatively narrow topic. Thus, Bailey (1949) briefly reported the occurrence of talc associated with potash ores; subsequently, Adams (1969), equally briefly, assigned talc's occurrence solely to the K-rich horizons. There are also the detailed and significant studies of the regularly interstratified 1:1 chlorite-vermiculite/smectite mixed-layer clay in Ochoan strata by Grim and others (1961) and Fournier (1961), but, at the same time, these investigations were concerned exclusively with the diffraction and related properties of a single mineral species rather than with the character of the total clay assemblage, its petrographic setting, genesis, and occurrence throughout the evaporite section.

The clay assemblages in marine evaporite rocks at other localities have been investigated at, among others, several German Zechstein localities (for example, Braitsch, 1958; Füchtbauer and Goldschmidt, 1959; Dreizler, 1962; Pundeer, 1969), the Austrian Haselgebirge (Bodine, 1971a), the German Keuper (Lippmann and Savascin, 1969; Echle, 1961), the Oligocene of Alsace (Sittler, 1962), the Silurian of Michigan (Lounsbury, 1963), and the Silurian of western New York (Bodine and Standaert, 1977).

The important clay mineral constituents in marine evaporite rocks and their intercalated salztons form three major groups: illites and related dioctahedral illite-smectite mixed-layer clays; the trioctahedral aluminous clays with their several mixed-layer varients; and the magnesium silicates. In this report I have appropriated the German term "salzton" to specify a discrete clay or clay-quartz lithology intercalated with the evaporite strata; the terms "shale" and "mudstone" are neither appropriate nor necessarily accurate, and American usage of the term "salt clay" (the literal translation of "salzton") often refers to clay particles included in evaporite salts as well as to interbedded clay-rich lithologies.

Illite and chlorite dominate the clay assemblage in most Paleozoic marine evaporite rocks (Droste, 1963; Millot, 1970). Although other clays (for example, talc and corrensite) do occur in older salts, they are generally restricted to specific evaporite lithologies and are only rarely abundant (Füchtbauer and Goldschmidt, 1959; Bodine and Standaert, 1977). In younger evaporites illite, or, in some cases, an illite- smectite mixed-layer clay, remains abundant; chlorite abundance, on the other hand, decreases markedly and is replaced by mixed-layer clays or smectites (Droste, 1963; Millot, 1970).

Illite and chlorite are also common clays in many sedimentary rocks and occur in a broad range of depositional environments, yet the two minerals appear to have distinctive compositions when found in marine evaporite rocks. Microprobe analysis of the illite and chlorite from the Retsof salt (Silurian) of western New York (Bodine and Standaert, 1977), for example, yields compositions for these clays that reflect their hypersaline origin. The illite has a substantially higher tetrahedral Al content and interlayer cation site occupancy than do illites observed in normal sediments, for example, those compiled by Weaver and Pollard (1973); the stoichiometry of the hypersaline illites lies much closer to a true muscovite than does that of average shale illite. The Retsof chlorite is exceedingly rich in Mg, that is, $Mg/(Mg + Fe) > 0.9$, and approaches the end member clinochlore composition as contrasted with the more ferruginous and aluminous varieties encountered in most sedimentary clay assemblages.

The most abundant and thoroughly studied of the trioctahedral mixed-layer clay minerals that occur in evaporite rocks is corrensite, the 1:1 regularly interstratified chlorite-expandable clay mixed-layer species (Lippmann, 1954). This clay mineral is locally extremely abundant, for example, in some anhydrites of the German Zechstein (Füchtbauer and Goldschmidt, 1959; Dreizler, 1962), the German Keuper (Lippmann, 1954; Lippmann and Savascin, 1969), as well as the Ochoan evaporites of New Mexico (Grim and others, 1961; Fournier, 1961). The structure of corrensite has not yet been unequivocally resolved; Grim and others (1961) and Fournier (1961) propose a 1:1 regularly interstratified chlorite-vermiculite mixed-layering, whereas Lippmann (1954; 1959) believes the clay is a 1:1 regularly interstratified chlorite-smectite (saponite). Whether both varieties do in fact exist or determinative difficulties have precluded satisfactory identification is unclear. These regularly interstratified chlorite-expandable clay species are also occasionally observed in normal marine or only slightly hypersaline environments (for example, Earley and others, 1956; Bradley and Weaver, 1956).

Randomly interstratified chlorite-expandable clay as well as relatively pure smectite have been identified in hypersaline clay assemblages from several localities; in many cases, however, these minerals have neither been adequately defined nor have their compositions been supported by chemical analysis. Their occurrence does appear to be most common in younger evaporite strata (Droste, 1963; Millot, 1970).

Talc is by far the most abundant of the magnesium silicates occurring in evaporite clay assemblages. In the German Zechstein, for example, talc is common—even dominant—in some anhydrites and rock salts, but it is absent or very rare in the salzton, carbonate, and bitter salt facies (Füchtbauer and Goldschmidt, 1959). In the New York Silurian, talc is similarly abundant in rock salt but absent in salzton and dolomite (Bodine and Standaert, 1977). Talc in evaporites ranges in age from the Cambrian (Kosolov and others, 1969) through the Silurian (Bodine and Standaert, 1977), Permian (Füchtbauer and Goldschmidt, 1959; Dreizler, 1962; Adams, 1969), and the Permo-Triassic (Bodine, 1971a), to the recent (Bodine, 1971b). The mineral invariably occurs as a well crystallized phase yielding very sharp diffraction maxima and is relatively course-grained; that is, talc is generally absent from <0.5 fractions.

Serpentine in marine evaporites was tentatively identified in the German Zechstein (Füchtbauer and Goldschmidt, 1956) and more recently confirmed from the Silurian of New York (Bodine and Standaert, 1977). The diffraction maxima of serpentine are often masked by the even-ordered 00Q chlorite reflections that preclude its routine identification; serpentine may well be a common constituent in some evaporite residues.

The chemical compositions of these assemblages are as distinctive as their mineralogy. The silicate fractions of evaporite rocks and their associated salztons are substantially enriched in MgO and occasionally K_2O when compared with normal marine or fluvial clay assemblages; the evaporite residues are also then substantially depleted in A120$_3$, CaO, and, in some cases, Na_2O (Braitsch, 1971; Niemann, 1960).

The combined mineralogic and chemical distinctiveness of these assemblages has led many to the general conclusion that the clays cannot be considered as solely detrital accumulates; rather, they formed authigenically through alteration of detrital clays and precipitation of magnesium silicates in response to the primary evaporite brine environment and underwent further recrystallization after burial.

ERDA-9 drill core

The core sampled in this study is from the ERDA-9 hole on the James Ranch in Eddy County near the southeastern periphery of the Carlsbad potash enclave in sec. 20, T. 22 S., R. 31 E.; the hole was drilled for Sandia Laboratories by the Sonora Drilling Co. in the spring of 1976 as a part of the WIPP project evaluating potential radioactive waste disposal sites. The hole is collared at an elevation of 3,414 ft, and drilling proceeded to a depth of 2,889 ft; the hole was cored from a depth of 1,090 ft (230 ft below the Rustler-Salado contact) to a depth of 2,877 ft (41 ft below the base of the Salado Formation, in the Castile Formation). Forty-seven samples from the core were selected for clay analysis; their stratigraphic positions and lithology are given in fig. 1.

Sample preparation and analysis

A 25-500-g split of each sample selected for analysis was crushed and ground to <200 mesh; the amount prepared was based on a visual estimate of the quantity of included silicate material. A fraction of the powder was retained as the whole-rock sample; the remainder was leached in water to dissolve water-soluble salts, then repeatedly centrifuged, decanted, and washed with distilled water. The residue was dried with a split retained as the water-leach residue. The remainder of the water-leach residue was refluxed for 4 hours in boiling 0.2M Na_4 EDTA solution to dissolve the "acid-soluble" minerals, for example, Ca-Mg carbonates, anhydrite, and polyhalite, following Bodine and Fernalld's procedure (1973). This residue was again repeatedly centrifuged, decanted, and washed; it then dried as the EDTA-leach residue. This final fraction consisted chiefly of the included silicates along with any resistant oxides and sulfides that occurred in the sample.

A split of the EDTA-leach fraction was then sized into the >2µm and <2µm effective spherical diameter by resuspending the powder in distilled water, thoroughly disaggregating with an ultrasonic probe, and fractionating using timed sedimentation of the suspended particles. Several of the <2µm fractions were further fractionated into various submicron fractions, using timed centrifugation of the disaggregated suspension.

Where a sufficient quantity of the EDTA-leach fractions was available, a split was pressed into a pellet or "briquette" appropriate for quantitative x-ray fluorescence analysis as well as whole-residue x-ray diffraction analysis. In those cases where insufficient EDTA-leach powder was available for briquetting, a paste or smear mount was prepared on a glass slide; this limited the analysis to x-ray diffraction.

The splits of the <2µm fraction(s) were resuspended, disaggregated, and sedimented by air-drying several drops of the suspension on three or more glass slide mounts; these constituted the oriented clay mounts and were investigated by x-ray diffraction after appropriate treatment to form an untreated air-dried mount, an ethylene glycol saturated sample, and 375° and 550°C heated samples.

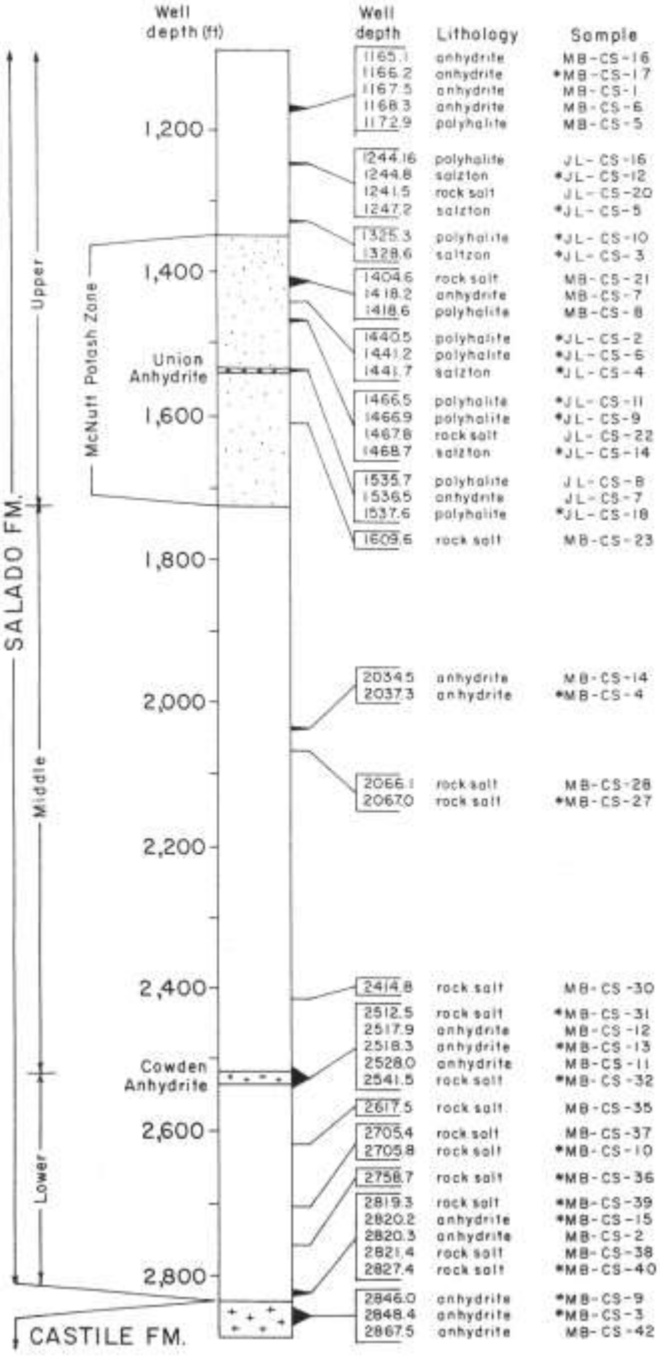


FIGURE 1—SCHEMATIC LOG OF ERDA-9 CORE WITH CLAY-SAMPLE LOCATIONS, THEIR HOST LITHOLOGIES, AND SAMPLE NUMBERS; * signifies bulk EDTA-leach residue was chemically analyzed. Lithologic summary of the section: *uppermost Castile Formation*—banded and massive anhydrite; *lower Salado Formation*—rock salt with thin interbeds of anhydrite, unit capped by Cowden Anhydrite; *middle Salado*—rock salt with somewhat thicker interbeds of anhydrite, polyhalite interbeds become common in upper half; *McNutt potash zone*—rock salt with interbeds of anhydrite, polyhalite, soluble potash salt assemblages (ore zones), and thin salztons; overlying barren *upper Salado Formation*—rock salt with interbeds of anhydrite, polyhalite, and thin salztons.

Diffraction analysis

A conventional Norelco diffractometer with a curved crystal monochromator and conventional signal detector and electronics was used throughout this study. A scanning speed of 2°26 per minute and a chart speed of 1 inch per minute provided consistently suitable traces using a slit train of 1 °-4 °-1°.

Fluorescence analysis

Quantitative analytical data for SiO_2, TiO_2, $A1_2O_3$, total Fe as FeO, MgO, CaO, Na_2O, and K_2O by x-ray fluorescence were obtained with a Norelco Universal Vacuum X-ray Spectograph, type 19010016 and Tennelec electronics with teletype printout; a Model 706 Kicksort channel pulse height analyzer aided in identifying appropriate energies for each element.

Counts for each element were recorded for 2 repetitions of each peak, and the associated background was measured. A drift pellet with each batch was similarly counted; the counting statistics achieved a 1 o standard deviation. After averaging the recorded counts minus background to obtain net counts for each sample, the sample net counts were divided by the net counts from the drift pellet with each batch; this yielded net counts per drift and became the counting value that was correlated with concentration.

Similar procedures were followed for the analyzed materials used as standards; these consisted of U.S. Geological Survey standards and several of our own clay samples analyzed by both the New Mexico Bureau of Mines and Mineral Resources and by Herron Testing Laboratories, Cleveland, Ohio.

The data presented in this report have not yet been fitted to experimentally determined regression curves; straight-line unit slope regressions have been used, and, because of matrix effects, these data must be considered as semiquantitative.

Clay mineralogy

The clay minerals in these samples include illite, clinochlore, a continuum from very regular to completely random interstratification of clinochlore-saponite in mixed-layer clays, a second mixed-layer clay tentatively identified as an interstratified talc-saponite, saponite, talc, and serpentine. Other minerals occurring in the EDTA-leach residue include quartz, alkali feldspars, hematite, and occasional pyrite. The distribution of the clays in the core samples is summarized in table 1.

ILLITE—Illite occurs pervasively through the core except in 6 of the 8 samples from the uppermost Castile Formation and lowermost Salado Formation and in 3 other samples scattered through the section (table 1). Although only rarely dominant, illite's abundance is commonly substantial.

The illite is characteristically well crystallized, yielding very sharp diffraction maxima whose basal (00Q) reflections follow the expected muscovite periodicity and relative intensities; that is, the 002 reflection at 5A is moderately strops when compared with the stronger 001 (10A) and 003 (3.3A) reflections (fig. 2). The basal maxima show no shift after glycol-saturation and remain unaffected by heating. The 060 reflection at 1.50-1.51A conforms to its dioctahedral structure.

CLINOCHLORE—Chlorite occurs in 37 of the samples (table 1); it was not detected in 5 (4 anhydrites and 1 rock salt) of the 6 deepest samples and in 5 other samples scattered throughout the section (1 from the Cowden Anhydrite, 1 from polyhalite in the McNutt potash zone, and 2 anhydrites and 1 polyhalite from the Upper Salado Formation). Only 12 of the chlorite-bearing samples contain more

TABLE 1—DISTRIBUTION OF CLAY MINERALS IN 47 SAMPLES FROM THE ERDA-9 DRILL CORE, THROUGH THE SALADO AND UPPERMOST CASTILE FORMATIONS, IN EDDY COUNTY, NEW MEXICO. Symbols: N—number of samples; Il—illite; Cl—clinochlore; Co—corrensite; Cl-S—randomly interstratified clinochlore-saponite; S—saponite; Ta-S—interstratified talc-saponite (identification tentative); Ta—talc; Se—serpentine.

	N	Il	Cl	Co	Cl-S	S	Ta-S	Ta	Se
Upper Salado	11	10	8	5	5	—	1	—	—
salzton	3	3	3	3	—	—	—	—	—
anhydrite	4	4	3	1	3	—	—	—	—
rock salt	1	1	1	—	1	—	—	—	—
polyhalite	3	2	1	1	1	—	1	—	—
McNutt potash zone	14	13	13	5	6	1	4	1	—
salzton	2	2	2	2	—	—	—	—	—
anhydrite	2	1	1	—	1	—	1	—	—
rock salt	3	3	3	2	1	—	—	1	—
polyhalite	7	7	7	1	4	1	3	—	—
Middle Salado	6	6	6	2	3	1	—	—	—
anhydrite	2	2	2	1	1	—	—	—	—
rock salt	4	4	4	1	2	1	—	—	—
Lower Salado	13	9	9	5	6	2	—	1	2
anhydrite	5	3	3	1	3	1	—	—	—
rock salt	8	6	6	4	3	1	—	1	2
Upper Castile	3	—	1	—	—	3	—	—	3
anhydrite	3	—	1	—	—	3	—	—	3
Lithologic totals	47	38	37	17	20	7	5	2	5
salzton	5	5	5	5	—	—	—	—	—
anhydrite	16	10	10	3	8	4	1	—	3
rock salt	16	14	14	7	7	2	—	2	2
polyhalite	10	9	8	2	5	1	4	—	—

than minor quantities of the mineral, and in these its abundance is never dominant; 5 of the 12 samples containing substantial amounts of chlorite are the 5 salzton samples.

The chlorite is identified as a clinochlore based on its diffraction properties (fig. 2). The 14A sequence of basal spacings yield a c-dimension of 14.23 ± 0.03A, which suggests 1.0 ± 0.2 Al atoms per 4 tetrahedral sites (Brindley, 1961). The moderately high relative intensities of the 001 (when not obscured by the 14A reflection of an expandable clay) and 003 reflections, when compared to the stronger 002 and 004 reflections, indicate a high Mg content in the octahedral sites (Grim, 1968). And finally, with $d_{060} = 1.537 \pm 0.002$ and generating $b_0 = 9.22$A, it would appear that 0.1-0.4 Fe^{+2} occurs in each set of 6 octahedral sites (Shirozu, 1958; Englehardt, 1942; and MacMurchy, 1934).

CORRENSITE—The 1:1 regularly interstratified mixed-layer expandable clay that has been identified as a 1:1 chlorite-vermiculite by Grim and others (1961) and Fournier (1961) is abundant in numerous samples throughout the core; it is unequivocally identified (the presence of a strong 001 superlattice reflection at 26-30A) in 17 samples (table 1) and may well be present in association with its more randomly interstratified analog in up to 10-12 additional samples. Corrensite is particularly abundant and well crystallized in each of the 5 salzton samples and is also relatively common in many rock salts throughout the section; it is observed much less frequently in anhydrites and polyhalites and is not detected in any of the 3 samples from the Castile Formation or the 4 lowermost samples from the Salado Formation.

The 001 superlattice peak is well developed (fig. 2) and varies between 26.5-30A in air-dried samples; this peak expands to 31-32A after glycol saturation. Higher order 002 reflections generate a near-rational succession of spacings indicative of a 1:1 regularity; the odd 00ℓ spacings, for example, $d_{003} = 9.7$A (air-dried) and 11.3A (glycol-saturated), are prominent.

Air-dried residues commonly exhibit either one of two sets of basal spacing dimensions, a 29-14-9.7A 002 succession or a 27-13.5-8.8A 002 succession; each set then expands to 32-15.5-10.3A with glycol saturation. I suggest this is persuasive evidence of a clinochlore-saponite interstratification in the corrensite as determined by Lippmann (1954; 1959) and Brindley (1961), rather than the chlorite-vermiculite interstratification suggested for these clays by Grim and others (1961) and Fournier (1961). The two alternative successions of spacings in air-dried samples reflect either the presence of a saponite with interlayer Na, which generates a 12.6A contribution to the 001 superlattice spacing, or with interlayer Mg, supplying a 14A contribution in the corrensite; each variety of saponite then expands to 17A with glycol saturation to generate the 31-32A superlattice.

RANDOMLY INTERSTRATIFIED CLINOCHLORE-SAPONITE—Interstratified clinochlore-saponite, with substantially less than perfect ordering, to completely randomly interstratified varieties occur in 20 samples from the core (table 1). This phase is not present in the salztons but does occur in the other lithologies; it is particularly abundant in anhydrites from the Salado Formation (8 out of 13).

There exists a continuum from the well-ordered 1:1 corrensite with a strong superlattice reflection at ti30A through mixed-layer varieties; this causes a poorly developed shoulder or a nearly imperceptible bulge in the ~30A region to varieties showing no odd 002 reflections corresponding to the superlattice dimension. In this report I have arbitrarily restricted designation as corrensite to those clays that exhibit several maxima for the odd 002 superlattice spacings, and, in particular, show a well-defined reflection in the 26-30A region. The remaining varieties, whether or not they show incipient features of nonrandom interstratification, will be referred to as randomly interstratified chloritesaponite.

The range of ordering in such clays from that in a partially ordered structure to that in the completely randomly interstratified variety is shown in fig. 3. Sample No. 1 (JL-CS-10) does contain weak odd 002 spacings with a 001 reflection existing only as a shelf or shoulder above

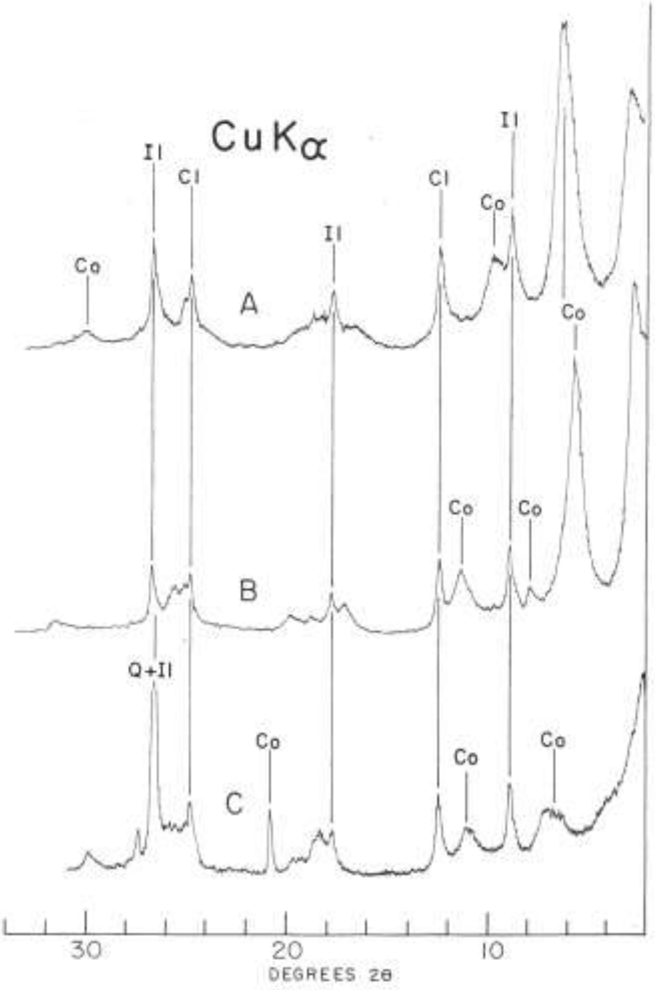


FIGURE 2—X-RAY DIFFRACTION TRACES OF EDTA-LEACH RESIDUE FROM JL-CS-3, A SALZTON FROM THE BARREN UPPER SALADO, containing the characteristic salzton clay assemblage of corrensite-illite-clinochlore: A. <2μm air-dried; B. <2μm glycol-saturated; C. bulk residue heated to 500°C. Mineral symbols: Co—corrensite; Il—illite; Cl—clinochlore; Q—quartz.

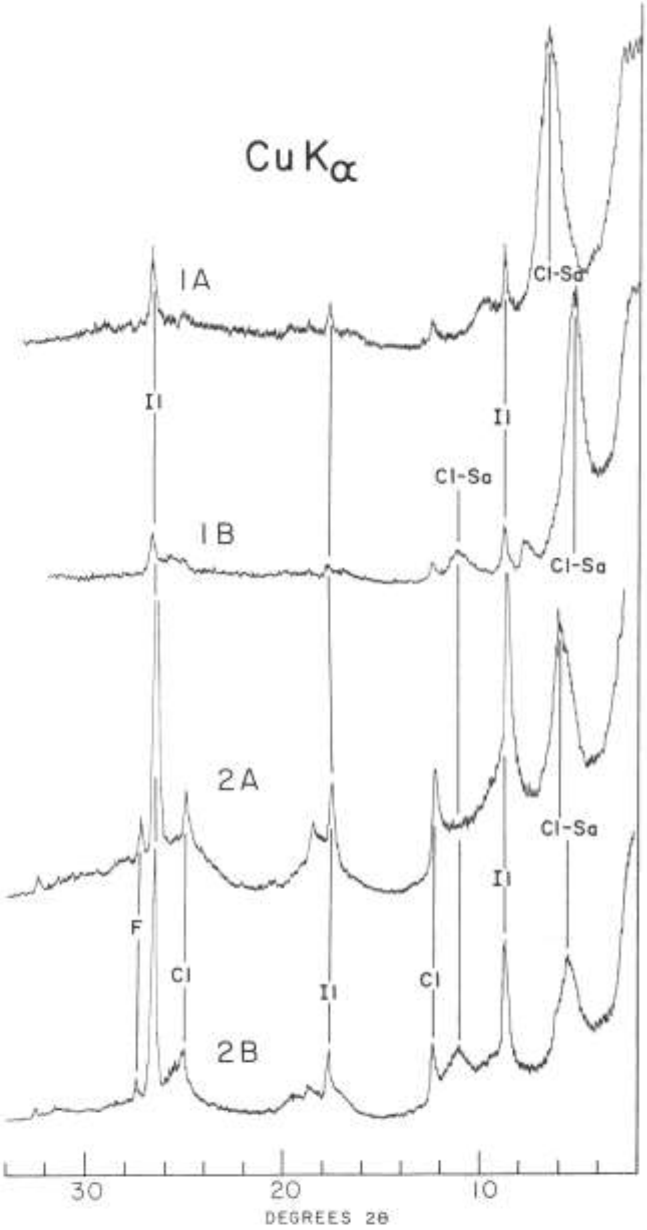


FIGURE 3—X-RAY DIFFRACTION TRACES OF <2μm FRACTIONS FROM 2 EDTA-LEACH RESIDUES. Mineral symbols: Cl-sa—randomly and partially ordered clinochlore-saponite; Il—illite; Cl—clinochlore; F—alkali feldspar(s). 1) MB-CS-10, polyhalite from the barren upper Salado Formation, containing a partially ordered clinochlore-(Na)saponite mixed-layer clay; subdued odd 00ℓ reflections; clinochlore and illite also present: A. air-dried; B. glycol-saturated. 2) JS-CS-9, polyhalite from the McNutt potash zone, containing randomly interstratified clinochlore-(Na)saponite mixed-layer clay; no odd 00ℓ reflections; minor illite and clinochlore also present: A. air-dried; B. glycol-saturated.

background; this clay is partially ordered. On the othe hand, Sample No. 2 (JL-CS-9) contains only the even 00ℓ reflections with no 26-30A bulge or shoulder; it is essentially totally randomly interstratified. Each of the three samples show expansion to essentially a $_0$15.5A spacing for the 002 reflection, that is, d002 = 1/2 (14A [clinochlore 001] + 17A [glycol-saturated saponite 001]), with glycol saturation. In several cases, particularly in those varieties showing features of only incipient ordering or no ordering, the 002 reflection is alternatively >15.5A or <15.5A after glycol saturation; this reflects an excess number of saponite layers or an excess number of clinochlore layers respectively in the mixed-layer clay; this phenomenon is not observed in corrensite.

SAPONITE—Although abundant as a constituent in the clinochlore-saponite mixed-layer clays, the mineral occurs relatively infrequently in its pure form. The 7 samples that contain saponite as a discrete mineral include the 3 anhydrite samples from the Castile Formation, a rock salt and an anhydrite from the lower Salado, a middle Salado rock salt, and a McNutt potash zone polyhalite.

Diffraction data for saponite in 2 of the EDTA-leach residues are given in table 3 and fig. 4. The overwhelmingly strong 001 reflection has a spacing of either 12.6A or 14.4A, either Na-saponite or Mg-saponite respectively, both of which expand to 17A after glycol saturation. The trioctahedral nature of this smectite is confirmed by d060 = 1.52A.

(?)TALC-SAPONITE MIXED-LAYER CLAY—An unusual clay that appears to be confined to some polyhalites and occasional anhydrites in the McNutt potash zone and overlying strata (table 1) has thus far eluded conclusive identification. I am tentatively identifying the mineral as a partially ordered talc-saponite mixed-layer clay—a mineral not previously reported from evaporites.

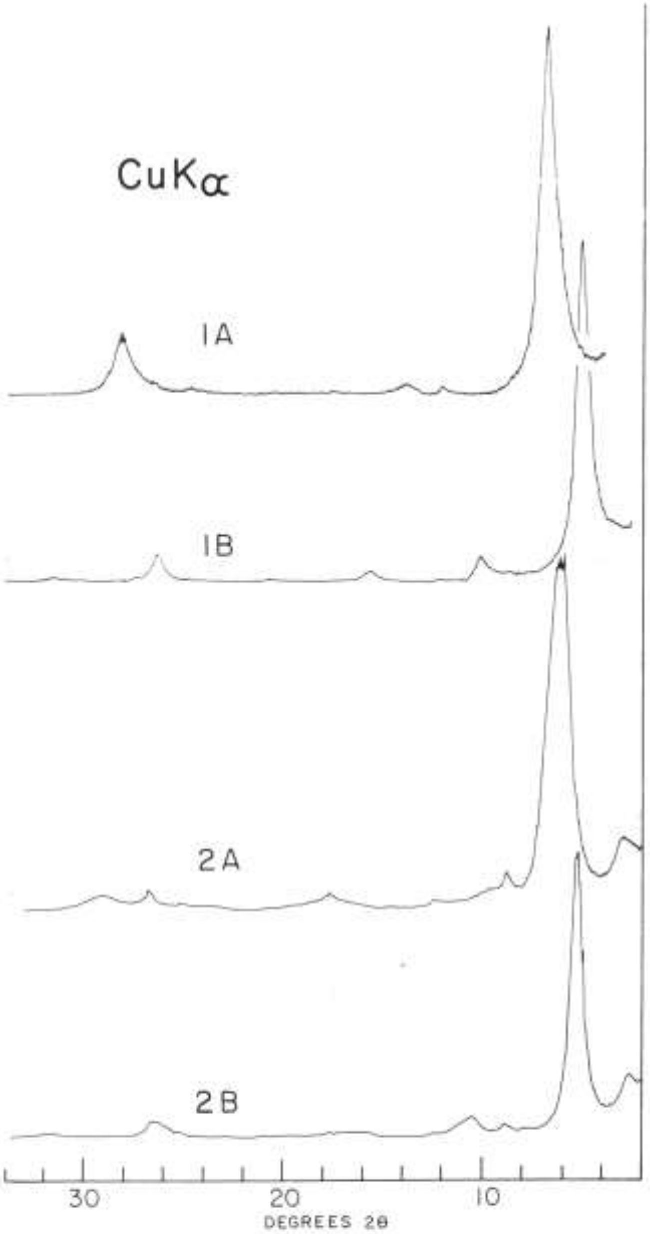


FIGURE 4—X-RAY DIFFRACTION TRACES FROM TWO SAPONITE-BEARING <2μm FRACTIONS OF EDTA-LEACH RESIDUES. 1) MB-CS-13, anhydrite from the Cowden Anhydrite, containing Na-saponite with minor clinochlore: A. air-dried; B. glycol-saturated. 2) MB-CS-27, rock salt from the middle Salado Formation, containing Mg-saponite with minor illite, clinochlore, and mixed-layer clinochlore-saponite: A. air-dried; B. glycol-saturated.

The diffraction trace from an. air-dried mount (fig. 5) shows a strong reflection at 10.2A with 2 other somewhat broadened subsidiary maxima at 4.53 and 3.14A. This sequence of reflections neither forms a rational periodicity nor do they satisfactorily conform to data from a known mineral. The data most closely resemble those from a talcsaponite described by Guenot (1970) and compiled in Thorez (1975) but are not identical.

With glycol saturation the 10.2X reflections become an assymetrical doublet with a strong reflection at 9.3A and a subsidiary but pronounced shoulder at 12.6A. The 4.53A peak expands to 4.62A and broadens substantially, suggesting a possible second reflection at 4.93A; the 3.14 peak expands to form a maximum at 3.21A and a probable shoulder at 3.13A (fig. 5).

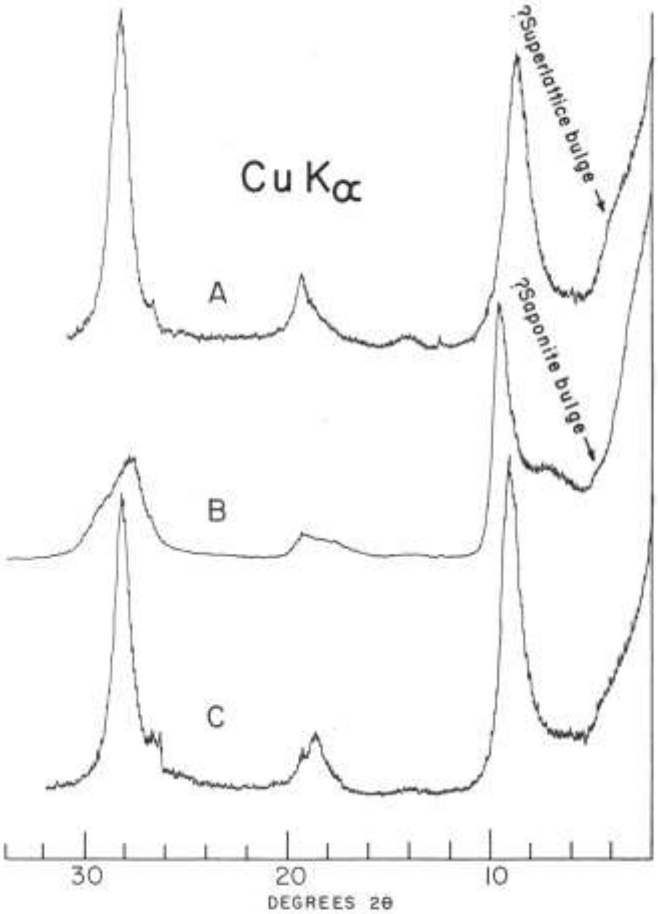


FIGURE 5—X-RAY DIFFRACTION TRACES FROM THE <2μm FRACTION OF THE EDTA-LEACH RESIDUE, in polyhalite from the upper Salado Formation, containing the tentatively identified mixed-layer talc-saponite clay: A. air-dried; B. glycol-saturated; C. heated at 500°C.

Two minor features on these traces (fig. 5) appear helpful in the mineral's identification. The air-dried mount yields a very weak bulge on the low-angle background curve at 21.6A; this expands to an equally poorly defined bulge at 26.5A with glycol saturation. Also present on the trace of the glycol-saturated mount is a slight incipient bulge at 17A denoted by an abrupt but slight change in slope of the low-angle background curve.

The presence of the talc basal reflections (albeit with atypical relative intensity values) at 9.3, 4.62, and 3.13A after glycol saturation suggests talc may constitute one of the mixed-layer. species (fig. 5). The apparent superlattice spacing at 21.6A with a nonrational 002 spacing at 10.2X for the air-dried mount suggests partial regular 1:1 interstratification of a 9.3A phase and a 12.3A phase with an excess of the 9.3A phase. The hint of a.17A reflection after glycol saturation, along with a 27.5A superlattice basal reflection, suggests the presence of a 17A phase, coupled with a 9.3A-12.6A doublet; this latter reflection becomes the expanded nonrational 002 spacing when the number of talc layers exceeds the number of expanded smectite layers. The expandable clay constituting the mixed-layer phase has a 12.3A basal spacing that expands to 17A upon glycol saturation—very close to the behavior of a Na-smectite.

As discussed later, the chemistry of the EDTA-leach residue, whose dominant mineral is 10.2A clay, precludes the clay having dioctahedral smectite layers; thus, it is tentatively identified as a talc-saponite mixed-layer clay with some degree of regular 1:1 interstratification.

TALC—Talc is a relatively rare silicate mineral in this suite of samples; it is observed in one rock salt from the McNutt potash ore zone and in one rock salt from near the base of the Salado Formation. At the same time, talc has been recognized as a common, even abundant, clay constituent in many of the potash ores from the McNutt potash zone (Adams, 1969; Bodine and Loehr, 1978); samples of the potash ores from this core were not available to me when this study was initiated.

Talc is readily identified on the basis of its 9.4A periodicity of basal spacings that do not shift with glycol saturation (fig. 6). The talc was distinguished from. its di-octahedral analog pyrophyllite by its d_{060} = 1.52A. The basal reflections are always very sharp, indicating talc's well-crystallized character. As has been observed in other evaporite localities, the talc is comparatively coarse grained; in these residues talc is effectively removed from the <0.5μm size fraction.

SERPENTINE—Well-crystallized serpentine occurs in the 5 deepest samples from the core, 3 of which are Castile anhydrites, and 2 are lowermost Salado rock salts (table 1).

X-ray diffraction data (fig. 6) permit a reasonably definitive serpentine identification: a relatively large c-dimension based on the very strong and sharp reflections at 7.3 and 3.66A, plus a weaker but sharp reflection at 2.43A (001, 003, and 002 respectively); the complete absence of the. intervening "003" and "005" reflections, were this a 14A three-layer clay; and a 060 spacing of 1.534A. These features preclude identification as a chlorite or kaolinite.

Chemical analyses of EDTA-leach residues

Chemical analyses of the EDTA-leach residue from 24 samples, specified in fig. 1, were obtained by x-ray fluorescence; at this time the results are semiquantitative since the fluorescence counting data (net counts per drift) have not yet been fitted to experimentally determined regression curves for each element but only to unit-slope linear regressions.

The analytical data for the residues have been summarized in table 2 after recasting the data to atom proportions with unit aluminum; averages are presented for both the major stratigraphic intervals and for the host lithologies. In the latter grouping, the data for residues from anhydrites have been divided into those anhydrites occurring at depths of less than 2,800 ft in the drill hole and those at depths exceeding 2,800 ft, since the residues from these 2 anhydrite populations show markedly different chemical and mineralogic compositions.

In addition, in order to provide chemical data to support mineral identifications, the analytical data from 4 individual residues in which a single clay dominates the assemblage are given in table 3. Chemical analysis of the <2μm fraction of the EDTA-leach residues are currently in progress; these substantially more useful data for clay-mineral determinations will be presented in a subsequent report.

Discussion

Chemical composition and clay mineralogy

Clay assemblages in the EDTA-leach residues are dominated by the trioctahedral clays: clinochlore, saponite, serpentine, talc, and their various mixed-layer combinations, along with subsidiary amounts of dioctahedral mica clay (illite), alkali feldspar, and quartz. The abundance of the trioctahedral clays is certainly compatible with the chemistry of the residues (table 2); there is simply insufficient aluminum in these residues to accommodate all the magnesium unless the clays are overwhelmingly trioctahedral.

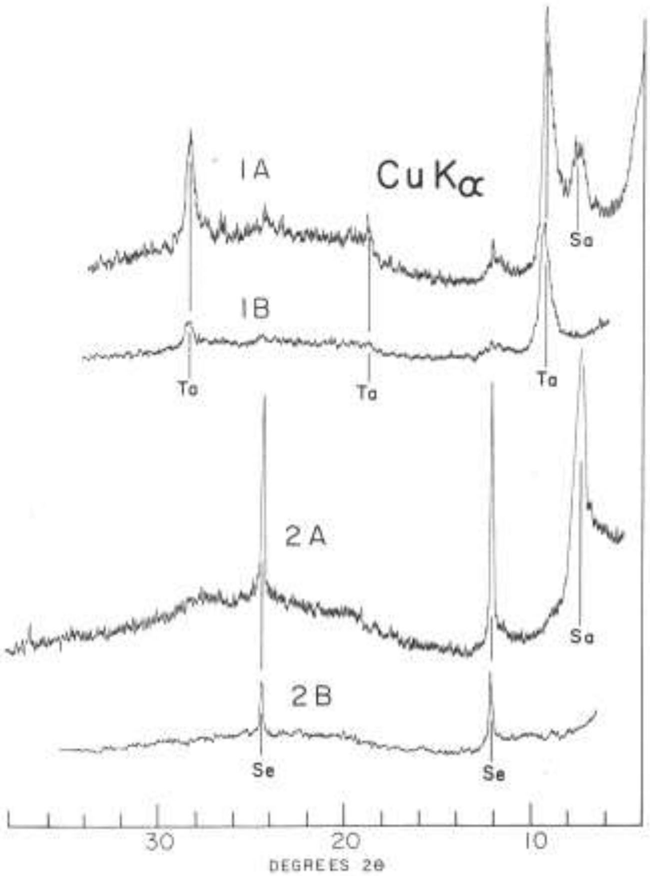


FIGURE 6—X-RAY DIFFRACTION TRACES OF <2μm FRACTIONS FROM TWO EDTA-LEACH RESIDUES, containing magnesium silicate minerals. Mineral symbols: Ta—talc; Se—serpentine; Sa—saponite. 1) MB-CS-15, anhydrite from the lower Salado Formation, containing talc and Na-saponite with minor clinochlore: A. air-dried; B. glycol-saturated. 2) MB-CS-42, anhydrite from the upper Castile Formation, containing serpentine with Na-saponite: A. air-dried; B. glycol-saturated.

The chemical analyses and their recast atom proportions of bulk residues from 4 samples in table 3, coupled with their diffraction data in fig. 7, allow qualitative interpretation of mineral compositions.

No. 1 (MB-CS-40) contains serpentine with some saponite and minor illite (fig. 7); the atom proportions (table 3) show a very high Mg-Al ratio that would exceed 12 after deleting the aluminum required to form illite from the potassium. This, coupled with a Si-Mg atom ratio less than unity can only support a saponite-serpentine assemblage. No. 2 (MB-CS-13) in table 3 contains abundant saponite with minor quantities of illite, clinochlore, and quartz (fig. 7); after deleting the aluminum required to form illite and an estimated quantity of clinochlore the remaining aluminum yields a Mg-Al atom ratio of 6-12 (table 3), which is compatible with a saponite stoichiometry.

No. 3 (MB-CS-17) consists of corrensite with quartz, illite, clinochlore, and some alkali feldspar (fig. 7); after deleting some aluminum by estimating quantities of illite, clinochlore, and feldspar, sufficient aluminum remains to construct clinochlore-saponite, but there is insufficient aluminum to generate an interstratified clinochlore-dioctahedral smectite. Finally, No. 4 in table 3 (JL-CS-10) contains abundant mixed-layer (?)talc-saponite with minor

TABLE 2—ATOM PROPORTIONS (Al = 1.00) OF THE EDTA-LEACH RESIDUES OF 24 CORE SAMPLES FROM ERDA-9 DRILL CORE, averaged by stratigraphic interval and lithology. CaO also determined; in all cases Ca/Al (atom proportion) ≪0.01. N—number of samples. Lithology of samples analyzed: 1. salzton; 2. anhydrite above 2,800-ft depth; 3. anhydrite below 2,800-ft depth; 4. rock salt; 5. polyhalite.

	Stratigraphic interval				
	Upper Barren Salado	McNutt potash zone	Middle Salado	Lower Salado	Upper Castile
N	5	7	3	7	2
Si	3.5	5.4	3.5	5.9	11.5
Ti	.04	.07	.04	.04	.04
Al	1.0	1.0	1.0	1.0	1.0
Fe	.12	1.09	.23	.20	.45
Mg	2.2	3.50	1.61	4.3	13.5
Na	.12	.34	.28	.40	1.13
K	.17	.41	.22	.20	.66

	Lithology				
	1	2	3	4	5
N	5	3	3	7	6
Si	2.7	2.8	11.0	4.1	6.3
Ti	.05	.04	.03	.04	.08
Al	1.0	1.0	1.0	1.0	1.0
Fe	.16	.17	.35	.22	1.2
Mg	1.8	2.7	13.0	2.4	4.1
Na	.13	.30	1.0	.31	.37
K	.25	.22	.50	.19	.38

quantities of clinochlore and quartz (fig. 7); the Mg-Al atom ratio is high and precludes the abundance of a mixed-layer clay containing either mica clay, dioctahedral smectite, or even clinochlore but the chemistry is compatible with a talc-saponite mixed-layer clay.

Residue variation with stratigraphy and host lithology

The variations of mineralogy and chemical composition of the EDTA-leach residues in terms of stratigraphic position and host lithology (tables 1 and 2, fig. 1) yield the following three relationships.

TABLE 3—CHEMICAL ANALYSES AND ATOM PROPORTIONS (Al = 1.00) OF 4 BULK EDTA-LEACH RESIDUES OF SAMPLES FROM THE ERDA-9 CORE. Total iron shown as FeO. Samples: 1. MB-CS-40; 2. MB-CS-13; 3. MB-CS-17; 4. JL-CS-10.

	Weight percent			
	1	2	3	4
SiO_2	33.	54.	59.	59.
TiO_2	0.3	0.4	0.8	0.2
Al_2O_3	5.0	7.0	12.	12.
FeO	1.4	2.1	1.2	1.3
MgO	29.	22.	20.	32.
CaO	1.0	0.04	0.01	0.002
Na_2O	0.9	2.7	1.2	1.0
K_2O	0.9	2.5	1.8	0.30
	Atom proportions			
Si	5.6	6.2	4.2	4.3
Ti	0.04	0.03	0.04	0.01
Al	1.0	1.0	1.0	1.0
Fe	0.20	0.20	0.07	0.08
Mg	7.3	3.8	2.1	3.5
Na	0.30	0.60	0.16	0.14
K	0.19	0.37	0.16	0.03

SALZTON AND ASSOCIATED SALT LITHOLOGY RESIDUES

The 5 salzton samples, which occur within the McNutt potash zone and the immediately overlying evaporite strata, consistently yield a corrensite-illite-clinochlore-alkali feldspar assemblage with or without quartz; the other mixed-layer clay varieties, as well as saponite, talc, and serpentine are not known to occur in the salztons. The average chemical composition of the EDTA-leach residues from the salztons yields moderately low Mg-Al and alkali-Al atom ratios of ~1.8 and ~0.^{4}, respectively, but yields a relatively high K-Na atom ratio of ~2.0.

Associated evaporite salt lithologies close to or adjacent to the salztons yield EDTA-leach residues with highly variable mineralogy and chemistry. The rock salts and anhydrites often contain randomly interstratified clinochlore-saponite rather than corrensite; and feldspar, illite, and clinochlore appear to be less abundant. Talc occurs in some rock salts and in many water-soluble potash ores (Adams, 1969; Bodine and Loehr, 1978); the mixed-layer (?)talc-saponite clay is abundant in some polyhalites. Atom ratios for these residues averaged by lithologic type yield similar variation: Mg/Al = ~2.2-4.1; alkali/Al = ~0.5-1; K/Na = 0.5-1.4.

(?)TALC-SAPONITE ASSOCIATION WITH POLYHALITE BEDS

Four of the five occurrences of the tentatively identified talc-saponite mixed-layer clay are from EDTA-leach residues of polyhalite beds in or immediately overlying the McNutt potash zone; the remaining (?)talc-saponite clay occurrence is from an anhydrite bed in the McNutt potash zone immediately underlying a polyhalite bed containing (?)talc-saponite.

CHEMICO-MINERALOGIC DISCONTINUITY IN LOWER SALADO FORMATION

An abrupt change in the mineralogy and chemical composition of the EDTA-leach residues occurs about 15 ft above the base of the Salado Formation at a drilling depth

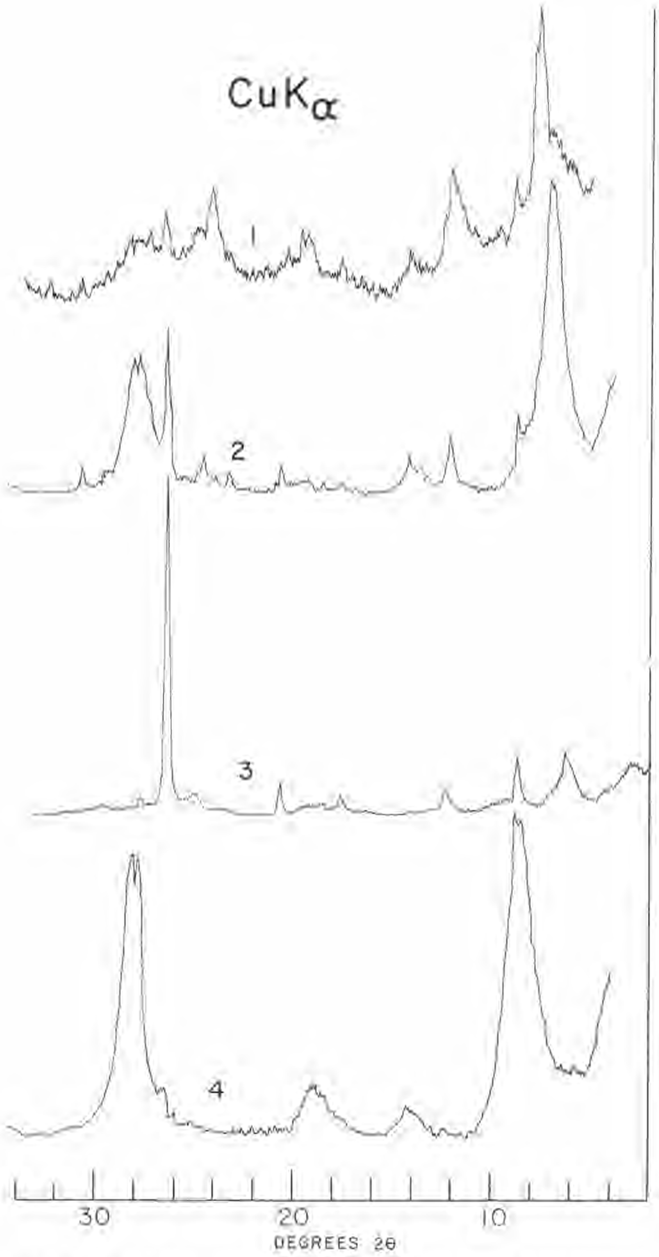


FIGURE 7—X-RAY DIFFRACTION TRACES OF BULK EDTA-LEACH RESIDUES FROM BRIQUETTE MOUNTS OF CHEMICALLY ANALYZED RESIDUES (table 3): 1. MB-CS-40; 2. MB-CS-13; 3. MB-CS-17; 4. JL-CS-10.

TABLE 4—MINERAL DISTRIBUTION AND ATOM RATIOS IN EDTA-LEACH RESIDUES FROM ERDA-9: A) the lower Salado Formation from 2,512.5-2,819.3 ft (Cowden Anhydrite to 16 ft above the base of the Salado Formation); B) the lowermost lower Salado and uppermost upper Castile Formations from 2,820.2-2,876.5 ft (15 ft above the base of the Salado Formation to 25 ft below the top of the Castile Formation). "Random" cl-sap refers to randomly interstratified or slightly ordered clinochlore-saponite mixed-layer clay.

Mineral distribution			Atom ratios		
	A	B		A	B
Samples	11	7	Samples	6	4
Quartz	10	3			
Feldspar	8	1	Mg/Al	2.1	12.
Illite	10	1	Si/Al	4.3	9.9
Clinochlore	10	2	Si/Mg	2.1	0.8
Corrensite	5	—	(Na + K)/Al	0.5	1.3
"Random" cl-sap	3	1	K/Na	0.6	0.5
Saponite	3	4			
Talc	—	1			
Serpentine	—	5			

of 2,810 ft in the ERDA-9 hole. The contrasting mineralogic and chemical features above and below this discontinuity are presented in table 4.

Above the discontinuity through the Cowden Anhydrite, the prevailing mineralogy in the residues of intercalated rock salts and anhydrites consists of either a dominant mixed-layer clinochlore-saponite variety or saponite alone, with lesser quantities of quartz, feldspar, illite, and clinochlore. Below the discontinuity through 15 ft of the lowermost Salado Formation and the uppermost 30 ft of the Castile Formation, the dominant mineralogy in the residues from anhydrites and rock salts is a saponite-serpentine association, with other silicates rarely present and never abundant.

The chemical data for the contrasting residues are compatible with their respective mineralogies; the residues below the discontinuity show far greater aluminum and silica deficiency than those above (table 4).

Genesis

The EDTA-leach residues throughout the section contain mineral assemblages and possess chemical compositions that are far different from those encountered in fluvial and normal marine sediments, for example, shale and sediment compositions summarized by Garrels and Mackenzie (1971). The striking abundance of Mg-rich trioctahedral clays and the extraordinarily high Mg-Al ratio in the Ochoan residues are the most pronounced anomalies; these are the same distinctive anomalies observed in silicate residues from marine evaporite rocks at other localities. This has led to the interpretation that these assemblages formed from detrital accumulates in which the normal clay detritus, characteristically illite-kaolinite-dioctahedral smectite assemblages, reacted extensively with marine evaporite brines and recrystallized into the trioctahedral clay-rich assemblages by incorporating magnesium from the brines. Thermochemical evidence—for example, Helgeson and others (1969), Bricker and others (1973), and Tardy and Garrels (1974)—supports the appropriateness of these reactions occurring in marine evaporite brines.

At the same time there are several features in the Ochoan residues that are distinctly different from those in clay assemblages observed at other Paleozoic marine evaporite localities. The Ochoan clays are considerably less mature. Instead of consisting essentially of clinochlore-illite or clinochlore-illite-corrensite assemblages with or without talc, which are pervasive throughout the European Permian and the eastern North American Upper Silurian evaporites (Braitsch, 1971; Droste, 1963; Bodine and Standaert, 1977), the Ochoan assemblages from New Mexico contain relatively minor clinochlore and illite, and only sporadic occurrences of abundant corrensite.

On the other hand, the Ochoan residues commonly do contain very abundant randomly interstratified clinochlore-saponite mixed-layer clay, saponite, or the (?)talc-saponite mixed-layer clay. This suggests that the Ochoan silicate fractions in the evaporite lithologies have undergone extensive postdepositional reaction and recrystallization over a long continuum of time—through the Mesozoic and possibly well into or through the Cenozoic—which is responsible for generating these relatively immature clays. Such phenomena may well have accompanied the widespread postdepositional salt-pore fluid reactions and recrystallization features that are apparent throughout the section. Examples include abundant replacement of anhydrite by polyhalite, replacement of primary bitter salt assemblages by the present Mg-deficient potash ore assemblages, abnormally low and highly variable levels of bromide substitution for chloride in the halites (Adams, 1969; Holser, 1966; Schaller and Henderson, 1932), as well as the wide-ranging K-Ar ages (18 ± 8-245 ± 10 m.y.), measured in 5 water-soluble potash salt samples (Schilling, 1973).

The Ochoan salztons, however, invariably consist of a more mature clay assemblage (corrensite-illite-clinochlore); the adjacent salt beds commonly contain assemblages with the less mature clays.

If the salztons behaved as reasonably impermeable units after burial and remained isolated from later transient pore fluids, a mature clay assemblage might evolve through a very long time span in a static pore fluid environment. This interpretation precludes the possibility that all or most of the salzton beds formed after burial through selective leaching of salt beds and resultant concentration of their insoluble constituents as thin argillaceous remnants; were such a process responsible for their formation, it would be expected that their mineralogy and chemistry would more closely resemble that in the highly variable and commonly immature clay assemblages observed in the neighboring salts.

Finally, the pronounced chemico-mineralogic discontinuity in the EDTA-leach residues above the base of the lower Salado is tentatively interpreted as representing a major change in the character of detrital influx into the basin. If the $Si0_2$ and $A1,0_3$ components in the detritus can be assumed to have been reasonably immobile following deposition and early burial, the Si-Al ratio values for the residues (table 4) become relict features of the original detritus. This indicates that below the discontinuity, the detritus that entered the basin, whether fluvial or air-borne as suggested by Adams (1969), consisted chiefly of free silica with relatively small proportions of the aluminous clays (an Si-Al atom ratio of 9.9), whereas later detritus entering the basin above the discontinuity contained a considerably higher proportion of aluminous clay material (an Si-Al ratio of 4.3).

References

Adams, S. S., 1969, Bromine in the Salado Formation, Carlsbad potash district: New Mexico Bureau of Mines and Mineral Resources, Bull. 93, 122 p.

Bailey, R. K., 1949, Talc in the salines of the potash field near Carlsbad, Eddy County, New Mexico: American Mineralogist, v. 34, p. 757-759

Bodine, M. W., Jr., 1971a, Alteration of basic volcanic rocks by marine hypersaline brines, Hallstatt, Upper Austria (abs.): Geological Society of America, Abstracts; v. 3, p. 509

, 1971b, Recent sediments in a hypersaline brine lake, St. Marteen, Lesser Antilles (abs.): American Geophysics Union, Trans., v. 52, p. 854

Bodine, M. W., Jr., and Fernalld, T. H., 1973, EDTA dissolution of gypsum, anhydrite, and Ca-Mg carbonates: Journal of Sedimentary Petrology, v. 43, p. 1152-1156

Bodine, M. W., Jr., and Loehr, C. A., 1978, Selected investigations of igneous dikes intruding Ochoan sediments in the Carlsbad region: Open-file Rept., Geoscience Dept., New Mexico Institute of Mining and Technology

Bodine, M. W., Jr., and Standaert, R. R., 1977, Chlorite and illite compositions from Upper Silurian rock salts, Retsof, New York: Clays and Clay Minerals, v. 25, p. 57-71

Bradley, W. F., and Weaver, C. E., 1956, A regularly interstratified chlorite-vermiculite clay mineral: American Mineralogist, v. 47, p. 497-504

Braitsch, 0., 1958, Ober den Mineralbestand der wasserunloslichen Ructände von Salzen der Stassfurtserie im südlichen Leinetal: Freiberger Forschungshefte, A123, p. 160-163

, 1971, Salt deposits: their origin and composition: Berlin, Springer-Verlag, 297 p.

Bricker, 0. P., Nesbitt, H. W., Gunter, W. D., 1973, The stability of talc: American Mineralogist, v. 58, p. 64-72

Brindley, G. W., 1961, Chlorite minerals, *in* The x-ray identification and crystal structures of clay minerals, 6. Brown, ed.: London Mineralogy Society, London, p. 242-296

Dreizler, I., 1962, Mineralogische Untersuchungen zweier Gipsvokkommen aus der Umgebung von Gottingen: Beiträge zur Mineralogie und Petrographie, v. 8, p. 323-338

Droste, J. B., 1963, Clay mineral composition of evaporite sequences, *in* Symposium on Salt: Northern Ohio Geological Society, p. 47-54

Earley, J. W., Brindley, G. W., McVeagh, W. V., Van den Heuvel, R. C., 1956, A regularly interstratified montmorillonite-chlorite: American Mineralogist, v. 41, p. 258-267

Echle, W., 1961, Mineralogische Untersuchungen an Sedimenten des Steinmergelskeupers und der Roten Wand aus der Umgebung von Gottingen: Beiträge zur Mineralogie und Petrographie, v. 8, p. 28-59

Englehardt, W. von, 1942, Structures of thuringite, bravalite, and chamosite: Zeitschrift für Kristallographie, v. 104, p. 142-159

Fournier, R. 0., 1961, Regular interlayered chlorite-vermiculite in evaporite of the Salado Formation, New Mexico: U.S. Geological Survey, Prof. Paper 424-D, p. 323-327

Füchtbauer, H., and Goldschmidt, H., 1956, Ein Zechsteinanhydrit-Profil mit Einlagerungen von Montmorillonit und einer abweichenden Serpentinvarietät: Heidelberger Beiträge zur Mineralogie und Petrographie, v. 5, p. 187-203

, 1959, Die Tonminerale der Zechsteinformation: Beiträge zur Mineralogie und Petrographie, v. 6, p. 320-345

Garrels, R. M., and Mackenzie, F. T., 1971, The evolution of sedimentary rocks: New York, W. W. Norton, 397 p.

Grim, R. E., 1968, Clay mineralogy: New York, McGraw-Hill Book Company, 596 p.

Grim, R. E., Droste, J. B., and Bradley, W. F., 1961, A mixed-layer clay mineral associated with an evaporite: Clays and Clay Minerals, Proc., National Conference of Clays and Clay Minerals, v. 8, p. 228-236

Guenot, B., 1970, Etude d'un mineral argileux du type interstatifie talc-saponite trouve dans le Precambrien du Congo Kinshasa: Bull. Groupe Franc. Argiles, v. 22, p. 97-104

Helgeson, H. C., Brown, T. H., and Leeper, R. H., 1969, Handbook of theoretical activity diagrams depicting chemical equilibria in geologic systems involving an aqueous phase at one atm and 0-300 °C: San Francisco, Freeman, Cooper

Holser, W. T., 1966, Bromide geochemistry of salt rocks, *in* Second Symposium on Salt: Northern Ohio Geological Society, v. 1, p. 248-275

Kosolov, A. S., Pustyk'nikov, A. M., Moshkina, I. A., and Mel'nikova, Z. M., 1969, Talc in Cambrian salts of the Kontaseyevka Depression: Dokl. Akademiya Nauk SSR, v. 185, p. 127-129

Lippmann, F., 1954, Ober einen Keuperton von Zaiserweiker bei Maulbronn: Heidelberge Beiträge zur Mineralogie und Petrographie, v. 4, p. 130-134

, 1959, Corrensit, *in* Hintze-Chudoba, Handbook der Mineralogie Erg.: v. 2, p. 668-691

Lippmann, F., and Savascin, M. Y., 1969, Mineralogische Untersuchungen an Losungsrückstände eines wurtembergischen Keupergipsvorkommen: Tschermaks Mineralogische und Petrographische Mitteilungen, v. 13, p. 165-190

Lounsbury, R. W., 1963, Clay mineralogy of the Salina Formation, Detroit, Michigan, *in* Symposium on Salt: Northern Ohio Geological Society, p. 56-63

MacMurchy, R. C., 1934, The crystal structure of the chlorite minerals: Zeitschrift fur Kristallographie, v. 88, p. 421-432

Millot, G., 1970, Geology of clays: New York, Springer-Verlag, 429 p.

Niemann, H., 1960, Untersuchungen am Grauen Salzton der Grube "Konigshall-Hindenburg," Reyerhausen b. Gottingen: Beiträge zur Mineralogie und Petrographie, v. 7, p. 137-165

Pundeer, G. S., 1969, Mineralogy, genesis, and diagenesis of a brecciated shaley clay from the Zechstein evaporite series of Germany: Contr. Mineralogy and Petrology, v. 23, p. 65-85

Schaller, W. T., and Henderson, E. P., 1932, Mineralogy of drill cores from the potash field of New Mexico and Texas: U.S. Geological Survey, Bull. 883, 124 p.

Schilling, J. H., ed., 1973, K-Ar dates on Permian potash minerals from southeastern New Mexico: lsochron/West, no. 6, p. 37

Shirozu, H., 1958, X-ray powder patterns and cell dimensions of some chlorites in Japan: Mineralogy Journal of Japan, v. 2, p. 209-223

Sittler, C., 1962, Relations sedimentologiques entre divers bassins oligocenes de l'Est de la France: I Coll. Intern. Strat. Paleogene, Bordeaux

Tardy, Y., and Garrels, R. M., 1974, A method of estimating the Gibbs energies of formation of layer silicates: Geochimica et Cosmochimica Acta, v. 38, p. 1101-1116

Thorez, J., 1975, Phyllosilicates and clay minerals: G. LeLotte, Dison, Belgium, 579 p.

Weaver, C. E., and Pollard, L. D., 1973, The chemistry of clay minerals: Amsterdam, Elsevier Scientific Publishing Company, 213 p.

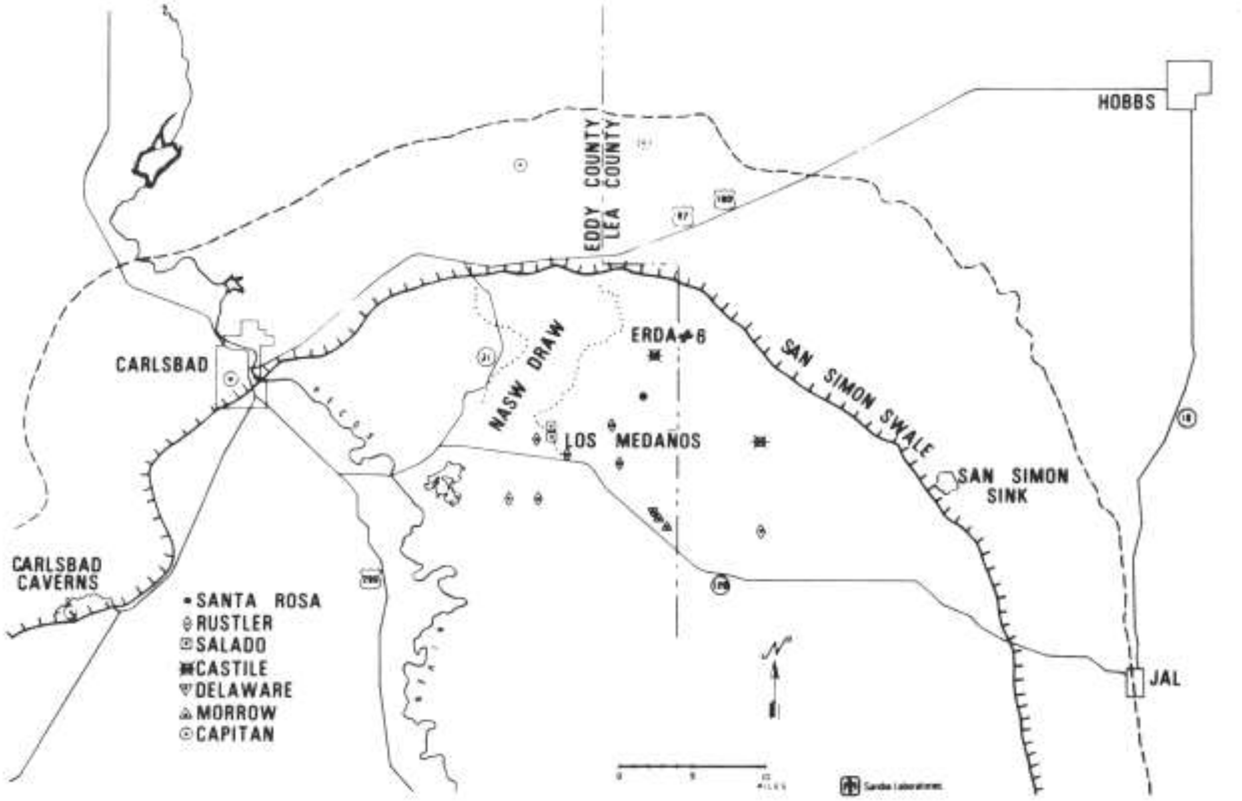


FIGURE 1—MAP OF THE NEW MEXICO PORTION OF THE DELAWARE BASIN, SHOWING LOCATIONS OF WATER SAMPLING POINTS IN THIS STUDY. The solid hachured line is the basinward margin of the Capitan Reef; the dashed line is the shelfward edge.

GEOCHEMISTRY OF DELAWARE BASIN GROUND WATERS

by Steven J. Lambert, *Nuclear Waste Technology, Division 1141, Sandia Laboratories, Albuquerque, New Mexico 87115*

Abstract

Subsurface samples of water from various rock types in the Delaware Basin of southeastern New Mexico and west Texas have been analyzed for their solute contents and $^{18}0/^{16}0$ and D/H ratios. Saturated brines (TDS> 300,000 mg/1) were found in one well in the Bell Canyon Formation, two wells in the Castile Formation and in potash mine seeps in the Salado Formation. According to Cl/Br ratios, all the water samples have derived their dominant solute (NaCl) from nearby rocks. Potash mine seeps and saline Capitan water samples contained solutes corresponding to common primary evaporite mineral assemblages, indicative of simple uptake of dissolved solids. Brines from the Bell Canyon and Morrow contained less magnesium but more calcium than primary evaporite assemblages and have participated in ion exchange reactions. Stable isotope measurements indicated that sampled waters from the Santa Rosa, Rustler, and Capitan Formations were meteoric, while samples from the Salado, Bell Canyon, and Morrow Formations, along with one from the Castile Formation (ERDA No. 6 drill hole), have undergone episodes of low-temperature isotopic exchange with oxygen- and hydrogen-bearing minerals. Isotopically, the Carlsbad Caverns hydrologic system is unique to the Guadalupe Mountains, unrelated to the Delaware Basin as a whole. The ERDA No. 6 occurrence of saturated brine and H_2S-rich gas in the Castile Formation represents a biogenically-produced sulfide-sulfate disequilibrium. The brine's Na_2SO_4 content may have arisen by rock/fluid ion exchange involving a replacement of magnesium by sodium in the solution. None of the saline ground waters were found to be original evaporite mother-liquors or products of partial evaporation.

Introduction

Geochemical studies of waters found in Permian and younger rocks of the Delaware Basin of southeast New Mexico and west Texas have assumed a new importance in recent years. This renaissance began in 1975 when Sandia Laboratories, in cooperation with ERDA (U.S. Energy Research and Development Administration), undertook studies of the suitability of Delaware Basin evaporite deposits for the long-term storage of radioactive wastes generated by the national nuclear defense program.

In particular, three aspects of fluid geochemistry have bearing on an understanding of the geology of the area: 1) *rock history—the* relationships between dissolution features and nearby fluids that may have dissolved evaporites; 2) *fluid history—evidence* of rock/fluid interactions preserved in fluid chemistry, indicating the complexities of fluid movement; and 3) *fluid origins—the* ultimate sources of fluids that have participated or have potential for participating in dissolution of evaporites.

Many of the waters considered here were bailed from preexisting wells with the assistance of the U.S. Geological Survey between December 1975 and June 1976. In addition, boreholes for subsurface exploration of the Los Medanos site (the ERDA study area) tapped some fluid-producing zones. These holes include ERDA No. 6, which at a depth of 2,711 ft produced H_2S-rich gas associated with saturated brine from the Castile Formation. In this hole, stratigraphic marker beds were found several hundred feet above their expected positions. Nine holes penetrating the Rustler Formation have facilitated hydrological testing and sampling of Rustler waters. Finally, samples of waters were collected from Carlsbad Caverns pools. Table 1 is an inventory of water samples, together with their locations of collection. New Mexico locations are given in fig. 1, which shows the distribution with respect to the Capitan Limestone.

Three geochemical approaches will be followed in this paper. Each approach will consider a few examples of various "types" of water: 1) *solute chemistry—dissolved* solids content, 2) *thermodynamics—equilibria* and non-equilibria of a fluid-gas system, and 3) *stable-isotope ratios—variations* in deuterium/hydrogen and $^{18}0/^{16}0$.

ACKNOWLEDGMENTS—My thanks go to Dennis Powers and George Griswold for their contributions to the early part of the project. Robert Statler, William Vollendorf, Jerry Mercer (U.S.G.S.), and Brennon Orr (U.S.G.S.) were instrumental in sample collection from wells, and I am indebted to Gary Ahlstrand and Patricia Fry of Carlsbad Caverns National Park for the assistance in obtaining cave waters. All stable isotope analyses were performed by the laboratory staff of James O'Neil (U.S.G.S.). Robert Dosch provided some solute analyses. I am grateful to Leslie Hill, George Barr, Charles Jones, and James Krumhansl for critical comments and stimulating discussions. This work was supported by the U.S. Energy Research and Development Administration through Sandia Laboratories.

Data

Analytical results for the 29 sampled waters are given in table 2. Solute analyses are expressed in mg/1, performed according to the American Public Health Association (1971) methods, with modifications by Collins (1975). Analyses by Martin Water Laboratories have a precision of about ± 5-10 percent; others ± 3 percent (table 1).

Stable isotope analyses were made according to Epstein and Mayeda (1953) and Bigeleisen and others (1952), and they are reported in "6" notation as deviations of the D/H or $^{18}0/^{16}0$ ratio from the corresponding ratio of SMOW (Standard Mean Ocean Water) (Craig, 1961b, Epstein and Mayeda, 1953), in parts per thousand (Woo, "per mille"). For *example*

$$\delta D = \frac{(D/H)\,\text{sample} - (D/H)\,\text{SMOW}}{(D/H)\,\text{SMOW}} \times 1000$$

The precision of $\delta^{18}O$ values is better than $\pm 0.1\ ^{o}/oo$ and that of δD is better than $\pm 1\ ^{o}/oo$.

Solutes

In this discussion "fresh water" is taken to contain less than 3,000 mg/1 TDS (total dissolved solids) and is potable at least to local cattle. "Brackish water" refers to TDS contents between 3,000 and 30,000 mg/l. Brines are waters containing more than 30,000 mg/1 TDS. According to these definitions, numbers 1 and probably 18 and 26 through 29 (table 1), found in the Capitan and Santa Rosa Formations, were fresh. Numbers 2, 6, 11, 17, 22, 24, and probably 19 through 21 are brackish. These included most Rustler water samples, one Capitan, and one Castile. The fresh and brackish waters contained the solutes expected to be found

TABLE 1—INVENTORY OF FLUIDS SAMPLED FOR GEOCHEMICAL STUDIES OF DELAWARE BASIN GROUND WATERS.

Sample No.	Sample Name	Formation Sampled	Location	Solutes	Stable Isotopes	Solute *Analyst
1	Carlsbad City #7	Capitan	T22S-R26E-S1	X	X	M
2	Duval Mine/Collector Ring	Rustler	T22S-R30E-S33	X	X	M
3	Duval Mine/Seep-BT26	Salado	T22S-R30E-S33	X	X	S
4	Duval Mine/Seep-BT48	Salado	T22S-R30E-S33	X	X	M
5	Duval Mine/Seep-BT58	Salado	T22S-R30E-S33	X		M
6	James Ranch	Rustler	T23S-R31E-S5	X	X	M
7	Fairview	Rustler	T23S-R32E-S36	X	X	M
8	Todd State 36-1	Morrow	T23S-R31E-S36	X	X	M
9	Todd Federal 26-4	Bell Canyon	T23S-R31E-S26	X	X	M
10	Todd Federal 26-1	Morrow	T23S-R31E-S26	X	X	M
11	Shell No. 28	Capitan	PSL Blk 74-S34 (Texas)	X	X	M
12	Middleton	Capitan	T19S-R32E-S21	X	X	M
13	Hackberry	Capitan	T19S-R31E-S31	X	X	M
14	ERDA #6	Castile	T21S-R31E-S35	X	X	S
15	Shell Bootleg	Castile	T22S-R32E-S36	X		Sh
16	Duval Mine/Vent Hole	Salado	T22S-R30E-S33	X		M
17	UNM Pokorny	Castile	PSL Blk 61-S3 (Texas)	X	X	M
18	Smith Livingston Ridge	Santa Rosa	T22S-R31E-S15		X	
19	Indian	Rustler	T23S-R30E-S21		X	
20	Mobley	Rustler	T23S-R30E-S19		X	
21	Mobley #3	Rustler	T23S-R30E-S2		X	
22	H1-Magenta	Rustler	T22S-R31E-S29	X	X	U
23	H1-Culebra	Rustler	T22S-R31E-S29	X	X	U
24	H3-Magenta	Rustler	T22S-R31E-S29	X	X	U
25	H3-Culebra	Rustler	T22S-R31E-S29	X	X	U
26	Green Lake	Capitan	Carlsbad Caverns		X	
27	Mirror Lake	Capitan	Carlsbad Caverns		X	
28	Longfellow's Bathtub	Capitan	Carlsbad Caverns		X	
29	Celery Stalk Pool	Capitan	Carlsbad Caverns		X	

* Analysts:
M-Martin Water Laboratories
S-Sandia
Sh-Shell
U-U.S.Geological Survey

TABLE 2—GEOCHEMICAL ANALYSES OF DELAWARE BASIN GROUND WATERS (solutes in mg/l).

No.	pH	$\delta^{18}O$ $^0/_{oo}$	δD $^0/_{oo}$	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Cl^{-}	Br^{-}	$SO_4^{=}$	HCO_3^{-}	TDS	Other Information
1	7.2	- 7.9	-54	74	29	8	1	10	0	72	285	474	NO_3:5
2	7.4	- 6.4	-48	1100	280	3600	405	6400	0	2500	122	14380	Sr:30
3	5.5	+ 3.0	-10	640	55400	27500	30000	236500	305	3650	1090	355085	BO_3:660
4	5.4	+ 2.6	-12	500	62600	44400	30250	251500	530	3300	1170	395000	BO_3:840
5	5.5			520	62000	46300	30250	250000	582	3100	1170	395000	BO_3:990
6	7.6	- 5.0	-40	590	175	68	5	400	0	1570	190	3240	NO_3:225
7	7.6	- 7.1	-53	590	200	120	3	142	0	2140	130	3350	
8	6.4	+ 2.7	-15	1600	240	11300	500	20600	23	300	380	35600	Sr:240
9	7.1	+ 2.2	-13	27600	6075	76700	1700	185000	410	210	215	295400	Sr:1750
10	6.6	+ 9.2	-18	4880	920	28700	200	55400	90	30	300	92400	Sr:1750
11	7.1	- 7.7	-56	940	280	2280	57	3900	0	2400	550	11300	
12	7.4	- 7.5	-55	1100	570	10600	330	17050		3720	300	33800	Sr:64
13	6.0	- 6.5	-46	2200	1680	68700	2950	110800		5150	132	192000	Sr:140,Fe:312
14	7.3	+10.3	0	130	350	112000	5100	186100	240	16000	1310	321000	BO_3:650,Li:160
15	7.7			550	1860	124500		185000		16800	1480	330700	
16	5.8			1260	38500	49000	52500	241500	385	3600	700	388650	BO_3:1160
17	1.6	- 6.0	-50	190	100	200	18	2700	0	570	0	3800	
18		- 7.2	-52										
19		- 6.3	-46										
20		- 6.9	-44										
21		- 5.9	-44										
22	7.4	- 6.8	-48	890	270	5700	70	8000		3900	92	18922	
23	7.6	- 7.0	-50	780	280	9400	190	12000		7400	105	30155	
24	7.4	- 7.3	-53	760	190	4200	100	5800		2600	1150	14800	
25	7.4	- 7.0	-53	1500	720	19000	450	33000		5200	88	60000	
26		- 3.6	-24										
27		- 4.3	-28										
28		- 4.2	-29										
29		- 3.0	-20										

in carbonate and anhydritic or gypsiferous aquifers. All the other samples were brines, and included the Salado, Morrow, Delaware (Bell Canyon) samples, two Castile, one Capitan, and even two from the Rustler Formation; these Rustler samples came from the Culebra Dolomite Member, adjacent to halite-bearing parts of the Rustler Formation.

Brines are treated in the most detail here, because their presence has implications regarding either their representation of original evaporite mother-liquors or their solutes having been derived through rock-water interaction. Their geochemical complexity cannot be understood from solute chemistry alone, and a brine's occurrence in a particular rock unit does not necessarily imply that the brine has interacted with its host rock.

The chloride/bromide ratios of all the brines (where obtainable) were between 430 and 900, compared to 292 for modern sea water (Collins, 1975). If the Permian Basin water had a Cl/Br ratio similar to that of sea water, as suggested by Holser (1963) for fluid inclusions in Kansas salt, then these Delaware Basin brines do not contain "original" Permian water as a major component. Because halite crystallizing from sea water selectively excludes bromine from the NaCl lattice, halite has a Cl/Br ratio greater than 300 (Adams, 1969), as would brine resulting from the dissolution of halite. Hence, the NaCI in these brines has been dissolved from rocks, but not necessarily the rocks in which the brines were found.

Rather than discuss abundances of individual ions in brine solutions, it is more instructive to consider solute ions combined as solids that might be expected to precipitate from solution upon complete evaporation. Following the crystallization sequences compiled by Braitsch (1971), some similarities were observed between the resulting normative mineral assemblages, but there were also some significant differences. Results from the analysis of water samples 16, 9, and 14 (Salado, Bell Canyon, and Castile Formations, respectively) are presented as examples.

Water from the Duval Mine Vent Hole is similar to the other potash mine seeps (samples 3, 4, and 5), all of which are saturated. Table 3 shows the relative proportions of minerals expected to precipitate from this solution. This assemblage is similar to that expected to precipitate from sea water, even though the relative proportions are different; note the overwhelming preponderance of carnallite. In view of the incongruent dissolution of polyhalite, resulting in a calcium-poor solution, this brine is what one would expect for water that has dissolved a potash-rich unit. Note the presence of normative borax, an evaporite mineral not commonly reported in the Carlsbad potash district (Jones, 1975).

Water samples from the more saline portions of the Capitan aquifer (samples 11, 12, and 13) contain the normative assemblage dolomite-anhydrite-kainite/carnallite-halite ± sylvite, in various proportions, and the samples are also indicative of solutes obtained by dissolution of adjacent evaporites.

Water sample 9, from the Bell Canyon Formation, is examined in table 4. The solution was calcium-rich, as indicated by the less common minerals tachyhydrite and antarcticite. These two minerals are not known to precipitate from sea water, and, together with a magnesium deficiency, distinguish this sample from a simple solution of primary evaporites. Graf and others (1966) have given attention to the origin of calcium chloride waters and emphasized shale ultrafiltration as an explanation. Other possibilities include diagenetic reactions in which magnesium in solution displaces calcium in carbonates to form dolomite (found in the Bell Canyon) or magnesite (found in the Salado). Alternatively, magnesium-rich sheet silicates might have been formed through replacement of cations such as Na and Ca by Mg (Grim, 1968) in the original clay minerals. Magnesium-rich sheet silicates are present in the Ochoan evaporites overlying the Bell Canyon (Bodine, this volume). Since brine number 9 is a saturated solution, and calcite—not dolomite—is the prevalent carbonate mineral of the Bell Canyon, neither dolomitization nor shale ultrafiltration (which tends also to produce a low-calcium water, not yet found here) appears to be a satisfactory model for the in situ evolution of Bell Canyon brine. The sulfate deficiency could have arisen from biogenic degradation of sulfate. However, the most likely explanation for the in situ calcium-enrichment is ion exchange. This brine probably did not originate in the Bell Canyon, but its solutes probably came from nearby evaporites.

TABLE 4—TODD FEDERAL 26-4 WATER NO. 9.

One liter of solution might be expressed as the following amounts of common evaporite minerals:

0.10	moles	(52 gm)	$CaMg_2Cl_6 \cdot 12H_2O$	Tachyhydrite
0.04	moles	(4 gm)	$KMgCl_3 \cdot 6H_2O$	Carnallite
0.59	moles	(129 gm)	$CaCl_2 \cdot 6H_2O$	Antarcticite
3.34	moles	(195 gm)	NaCl	Halite

Samples 8 and 10 have a much lower TDS content than does 9 but otherwise yield most of the same minerals. The high strontium content of all three could be taken to indicate that these samples have indeed participated in the recrystallization of carbonates but probably not within the Delaware Mountain Group of sandstones, which includes the Bell Canyon. According to the Sr/Ca studies of Ox-burgh and others (1959), this solution would have been in equilibrium with a calcite containing about 4,000 ppm Sr, a value too high for most natural calcites and dolomites. The Sr in solution could easily have come from the diagenetic alteration of aragonite outside the Bell Canyon.

On July 30, 1975, borehole ERDA No. 6 produced saturated brine (table 1, number 14) and H_2S-rich gas (0.16 cu ft STP [standard temperature and pressure] per gallon) from a fractured, gray, laminated Castile anhydrite unit 2,711 ft below the surface. Similar phenomena in the Castile have been reported by oil companies, but the companies have reported an order of magnitude more gas. The analysis of one other such brine (Shell Bootleg, table 1, number 15) is given in table 2, and it is quite similar to the analysis of the ERDA No. 6 brine. The solutes are resolved in table 5, and,

TABLE 3—DUVAL MINE VENT HOLE WATER NO. 16.

One liter of solution might be expressed as the following amounts of common evaporite minerals:

0.006	moles	(1 gm)	$CaMg(CO_3)_2$	Dolomite
0.026	moles	(4 gm)	$CaSO_4$	Anhydrite
0.012	moles	(3 gm)	$KMgClSO_4 \cdot 2\frac{3}{4}H_2O$	Kainite
1.343	moles	(370 gm)	$KMgCl_3 \cdot 6H_2O$	Carnallite
0.224	moles	(46 gm)	$MgCl_2 \cdot 6H_2O$	Bischofite
0.005	moles	(2 gm)	$Na_2B_4O_7 \cdot 10H_2O$	Borax
2.121	moles	(121 gm)	NaCl	Halite

TABLE 5—ERDA 6 WATER NO. 14.

One liter of solution might be expressed as the following amounts of common evaporite minerals:

0.003	moles	(1 gm)	$CaMg(CO_3)_2$	Dolomite
0.009	moles	(1 gm)	$MgCO_3$	Magnesite
0.011	moles	(3 gm)	$KMgClSO_4 \cdot 2\frac{3}{4}H_2O$	Kainite
0.130	moles	(9 gm)	KCl	Sylvite
0.155	moles	(22 gm)	Na_2SO_4	Thenardite
0.048	moles	(14 gm)	LiCl	?
4.521	moles	(265 gm)	NaCl	Halite

aside from thenardite and LiCl (resulting from an almost economic concentration of lithium), are similar to the case of the dissolved potash deposit. Na_2SO4 has been previously reported in subsurface brines (Reeves, 1963), and thenardite is known to precipitate from local surface lakes. Lithium is a common component of evaporites formed near igneous rocks, but the nearest igneous rock is several kilometers away (Calzia and Hiss, this volume). The brine is sodium-rich and magnesium-poor. In terms of ion exchange, a loss of evaporite-derived magnesium into silicates, thereby giving up sodium, appears to be the mechanism here, although this need not have taken place in the Castile. Similar processes may account both for magnesium depletion in the solution and the formation of magnesium silicates in the evaporite sequence.

Thermodynamics

The ERDA No. 6 gas and brine are the only fluids which lend themselves to multiphase thermodynamic considerations. The gas amounted to 1.22 liters (STP) per liter of liquid, and consisted of 55 percent CO2, 28 percent H_2S, 15 percent CH_4, 1.5 percent N2 and 0.5 percent C_2H_6, as determined with a mass spectrometer. The H_2S is not saturated in the solution, even in the light of the salting-out effect of high TDS content (Randall and Failey, 1927), and amounts only to 0.02 molal. In order to examine the role of sulfur in this system (the only multivalent element common to both liquid and gas phases), a predominance area diagram (Garrels and Christ, 1965) was constructed for the system S-O-H with the variables pH and oxygen partial pressure, and with total sulfur equal to 0.36 molal (approximating the sulfate and H_2S in solution). The resulting diagram is fig. 2, for the field temperature of 25°C. The field-measured pH is 6.3, and samples of the brine containing dissolved H_2S were observed to precipitate elemental sulfur when standing at atmospheric conditions. The diagram shows that at pH 6.3, the sulfur field occurs between the sulfate and H_2S fields. Thus, the diagram correctly predicts the oxidation of H_2S to sulfur, and the sulfate and H_2S cannot be in thermodynamic equilibrium with one another at pH <7. Unfortunately, the oxidation potential was not measured, and the precise position of the ERDA No. 6 system on the diagram is not known.

The most probable origin of the H_2S is biogenic reduction of sulfate, an ion abundant in the surrounding rocks as anhydrite as well as in solution. Kuznetsov and others (1963) have indicated that bacteria such as *Desulfovibrio aestuarii* can exist in saturated NaCl solutions, although their activity is inhibited by bivalent cations, which are not prevalent in the ERDA No. 6 brine.

Stable isotopes

Analysis of water samples for their $^{18}O/^{16}O$ and D/H ratios has been found to be a useful method of identifying the source of water molecules, and, to some degree, identifying the types of interactions the water has undergone in the presence of other phases.

Fig. 3 is a δD vs. $\delta^{18}O$ plot for Delaware Basin ground waters. Most of the earth's meteoric waters have isotopic compositions that fall between the lines described by the equations:

$$\delta D = 8\delta^{18}O + 5$$ (Epstein and others, 1965; 1970)

and

$$\delta D = 8\delta^{18}O + 10$$ (Craig, 1961a).

These lines are included in fig. 3, and the area between them is labeled "Meteoric field."

Most of the points in fig. 3 lie in or near the meteoric field. Except for Carlsbad Caverns, a $\delta^{18}O$ value of -7 ‰ and a δD value of -50 ‰ appears to be a good approximation to local meteoric water in the Delaware

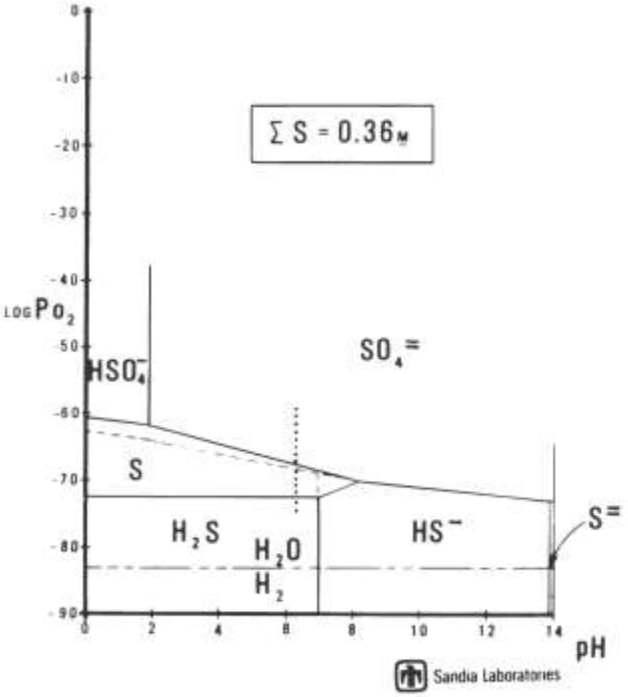


FIGURE 2—PREDOMINANCE AREA DIAGRAM, oxygen partial pressure vs. pH, for the System S-O-H at 25°C, 1 atmosphere and total sulfur concentration of 0.36m. Dashed lines are metastable extensions of boundaries; dotted line represents the field-measured pH of ERDA No. 6, 6.3.

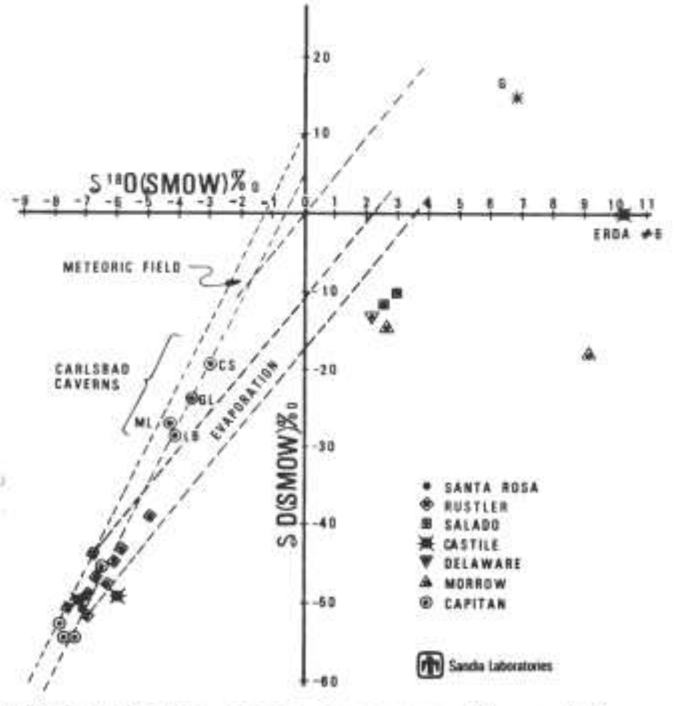


FIGURE 3—STABLE ISOTOPE COMPOSITIONS, δD VS. $\delta^{18}O$, FOR DELAWARE BASIN GROUND WATERS. Relationships are shown for meteoric waters, evaporating meteoric and sea waters. Hypothetical evaporite mother-liquor for gypsum (G) is shown for the case in which ERDA No. 6 is taken to be the water of crystallization for that gypsum.

Basin. The Caverns are part of a hydrologic system independent of the rest of the Capitan. Their enrichment in D and ^{18}O reflects the water's origin from air-mass conditions different from those which produce other Delaware Basin rains.

Bracketing the cluster of meteoric points are two dashed lines; the intervening field is labeled "evaporation." This field is the trajectory of isotopic compositions that the meteoric waters would follow during evaporation. The trajectory slope is 5, according to Craig and others (1963). The few points that lie in or near the evaporation field (4 points in the Rustler and 1 in the Castile) may indeed have suffered partial evaporation prior to infiltration but definitely originated as meteoric waters.

The dashed line through the origin, also of slope 5, is the trajectory of isotopic compositions of evaporating sea water. This line is also valid for the evaporation of warm-climate coastal meteoric waters (δ^{18}O $\sim -2\,^{0}/oo$, δD $\sim -10\,^{0}/oo$), as indicated by the intersection of this line with the meteoric field. Such waters were postulated by Holser (1963; 1966) to have been potential contributors to the Delaware Basin. The figure shows that the waters of positive δ^{18}O values are not the products of partial evaporation, either of Delaware Basin water or of modern meteoric water. This conclusion is the same as that drawn from the Cl/Br ratios.

The environments in which the Salado, Morrow, and Delaware (Bell Canyon) water samples were found involved a rock/water ratio that was very large, as deduced from the low productivity of these reservoirs. Consequently, any interaction involving isotopic exchange between these waters and host rocks would tend to alter the isotopic composition of the waters toward δD and δ^{18}O values consistent with equilibrium isotopic fractionation between water and minerals in the rock. The oxygen and hydrogen in clay minerals are known to be readily exchangeable with water (O'Neil and Kharaka, 1976). The Delaware, Morrow, and Salado waters have isotopic compositions that are suggestive of at least partial isotopic exchange between local meteoric waters and clay minerals in the sediments, in which the mineral/water ratio was very large (Savin and Epstein, 1969) for at least several thousand years. Other mineral sources of exchangeable oxygen and hydrogen are fluid inclusions and the water of crystallization of many evaporite minerals. The stable isotopes of the fluid inclusions have not been studied yet. The potash seep waters may have interacted with hydrous minerals. However, gypsum-water is the only such mineral-water system for which the ^{18}O/^{16}O and D/H fractionation factors are known.

None of the samples have resulted directly from the dehydration of gypsum to form anhydrite. If ERDA No. 6 were such a sample, the point marked "G" in fig. 3 would be the isotopic composition of the water from which that gypsum precipitated (using the gypsum-water fractionation factors of Fontes and Gonfiantini, 1967). "G" is not consistent with evaporating Delaware Basin water, whose anticipated δD – δ^{18}O trajectory was discussed above. The isotopic composition of ERDA No. 6 brine is consistent with an approach to isotopic equilibrium between water and clay minerals, not necessarily in the Castile. The isotopic exchange of this brine, together with its history of cation exchange, has resulted in a brine with a history similar to that of oil-field brines of Alberta and the Gulf Coast (Clayton and others, 1966).

Summary

Many types of rock/fluid interactions are evident in the geochemistry of ground waters found in Delaware Basin rocks. It is not possible to completely characterize these interactions from solutes or stable isotopes alone, nor through a study of water samples alone, without a similar study of rock. In addition to fresh and brackish waters, which have acquired solutes from their host rocks, the brines have here illustrated three examples of various types of rock/fluid interactions:

1) Dissolution of evaporites (saline Capitan waters)
2) Dissolution of evaporites with isotopic exchange between fluid and rock (Salado potash seeps)
3) Dissolution of evaporites, isotopic exchange, and cationic exchange (Delaware, Morrow, and ERDA No. 6 waters)

The latter two types indicate more profound interactions than the first, since these involve changes in the water molecules themselves.

No original Permian water could be identified. If much of the evaporite section has been recrystallized, as Holser (1963) suggests, not even the fluid inclusions are expected to preserve such water.

References

Adams, S. S., 1969, Bromine in the Salado Formation, Carlsbad potash district, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bull. 93, p. 1-122

American Public Health Association, 1971, Standard methods for the examination of water and wastewater (13th ed.): American Public Health Association and American Water Works Association, Water Pollution Control Fed., Washington, D.C.

Bigeleisen, J., Perlman, M. L., and Prosser, H. C., 1952, Conversion of hydrogenic materials to hydrogen for isotopic analysis: Analytical Chemistry, v. 24, p. 1356-1357

Braitsch, O., 1971, Salt deposits—their origin and composition, translation by P. J. Burek and A. E. M. Nairn: Heidelberg, Springer-Verlag, p. 1-297

Clayton, R. N., Friedman, I., Graf, D. L., Mayeda, T. K., Meents, W. F., and Shimp, N. F., 1966, The origin of saline formation waters, I. Isotopic composition: Journal of Geophysical Research, v. 71, p. 3869-3882

Collins, A. G., 1975, Geochemistry of oilfield waters: Amsterdam, Elsevier Scientific Publishing Company, p. 1-496

Craig, H., 1961a, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703

———, 1961b, Standard for reporting concentrations of deuterium and oxygen-18 in natural waters: Science, v. 133, p. 1833-1834

Craig, H., Gordon, L. I., and Horibe, Y., 1963, Isotopic exchange effects in the evaporation of water, I. Low-temperature experimental results: Journal of Geophysical Research, v. 68, p. 5079-5087

Epstein, S., and Mayeda, T., 1953, Variation of ^{18}O content of waters from natural sources: Geochimica et Cosmochimica Acta, v. 4, p. 213-224

Epstein, S., Sharp, R. P., and Gow, A. J., 1965, Six-year record of oxygen and hydrogen isotope variations in South Pole firn: Journal of Geophysical Research, v. 70, p. 1809-1814

———, 1970, Antarctic ice sheet: stable isotope analyses of Byrd station cores and interhemispheric climatic implications: Science, v. 168, p. 1570-1572

Fontes, J., and Gonfiantini, R., 1967, Fractionment isotopique de l'hydrogene dans l'eau de cristallisation du gypse: C. R. Acad. So. Paris, Ser. D., v. 265, p. 4-6

Garrels, R. M., and Christ, C. L., 1965, Solutions, minerals, and equilibria: New York, Harper and Row, p. 1-450

Graf, D. L., Meents, W. F., Friedman, I., and Shimp, N. F., 1966, The origin of saline formation waters, III. Calcium chloride waters: Illinois State Geological Survey, Circ. 397, p. 1-60

Grim, R. E., 1968, Clay mineralogy (2nd ed.): New York, McGraw-Hill Book Company, p. 1-596

Holser, W. T., 1963, Chemistry of brine inclusions in Permian salt from Hutchison, Kansas, *in* Symposium on salt, J. L. Rau, ed.: Northern Ohio Geological Society, p. 86-103

———, 1966, Bromide geochemistry of salt rocks, *in* Second symposium on salt, J. L. Rau, ed.: Northern Ohio Geological Society, p. 248-275

Jones, C. L., 1975, Potash resources in part of Los Medaños area of Eddy and Lea Counties, New Mexico: U.S. Geological Survey, Open-file Rept. 75-407, p. l-37

Kuznetsov, S. I., Ivanov, M. V., and Lyalikova, N. N., 1963, Introduction to geological microbiology (transl. P. T. Broneer): New York, McGraw-Hill Book Company, p. 1-245

O'Neil, J. R., and Kharaka, Y. K., 1976, Hydrogen and oxygen isotope exchange reactions between clay minerals and water: Geochimica et Cosmochimica Acta, v. 40, p. 241-246

Oxburgh, V. M., Segnit, R. E., and Holland, H. D., 1959, Coprecipitation of strontium with calcium carbonate from aqueous solutions (abs.): Geological Society of America, Bull., v. 70, p. 1653

Randall, M., and Failey, C. F., 1927, The activity coefficient of gases in aqueous salt solutions: Chemical Reviews, v. 4, p. 271-284

Reeves, C. C., Jr., 1963, Subterranean natural brines produce sodium sulphate in west Texas: Ground Water, v. l, p. 35-36

Savin, S. M., and Epstein, S., 1970, The oxygen and hydrogen isotope geochemistry of clay minerals: Geochimica et Cosmochimica Acta, v. 34, p. 25-42

IGNEOUS ROCKS IN NORTHERN DELAWARE BASIN, NEW MEXICO AND TEXAS

by J. P. Calzia and W. L. Hiss, *U.S. Geological Survey, Menlo Park, California 94025*

Abstract

Tertiary igneous dikes and sills are found in three areas within the northern Delaware Basin of New Mexico and Texas. Early Oligocene (32.2 to 33.9 m.y.) basalt dikes reported in the subsurface east of the Pecos River align with outcrops of en echelon basaltic andesite dikes in the Yeso Hills 50 km to the southwest. Although the basaltic andesite dikes are emplaced in older stratigraphic units than the basalt dikes, similarity in composition and age suggests that a system of igneous dikes may be projected 160 km northeastward across the northern Delaware Basin. Aeromagnetic data and computer enhancement of Landsat images are used to locate igneous dikes between the Yeso Hills and the Pecos River. Tertiary(?) diorite, syenodiorite, and monzonite sills located southeast of the Yeso Hills and in the Delaware Mountains are coarser grained and are emplaced in older stratigraphic units than are the dikes. The sills in the Delaware Mountains become more silicic to the southwest.

Introduction

Igneous rocks were first reported in the northern Delaware Basin by N. H. Darton in 1928 (Pratt, 1954). Darton described a lamprophyre dike of basaltic habit that intrudes gypsum deposits of Permian (Ochoan) age in the Yeso Hills, New Mexico (fig. 1). Since then igneous dikes or sills have been reported in potash mines and test wells (table 1) in three areas in the northern Delaware Basin: east of the Pecos River and in the Yeso Hills and Delaware Mountains.

Jones (1973) and Hiss (1975) have projected a series of Tertiary lamprophyre dikes 160 km northeastward from the Yeso Hills to an area 24 km southwest of Lovington, New Mexico (fig. 1). This projection is based on the similar composition, age, and alignment of dikes in the Yeso Hills with dikes reported in the subsurface east of the Pecos River; however, igneous rocks have not been reported between these two areas. This present report locates and describes igneous rocks in test wells or potash mines in the northern Delaware Basin. The petrography of dikes east of the Pecos River is compared to the petrography of dikes in the Yeso Hills. Chemical analyses and potassium-argon age dates of dikes east of the Pecos River also are described. Dikes between the Pecos River and the Yeso Hills are located by computer enhancement of Landsat images and aeromagnetic data.

ACKNOWLEDGMENTS—George Austin, New Mexico Bureau of Mines and Mineral Resources (Socorro, New Mexico), Frank Condon, Noranda Corp. (Sarasota, Florida), and W. E. Pratt (Tucson, Arizona) provided samples of igneous rocks from mines and test wells within the northern Delaware Basin. Computer-compatible tapes of Landsat images of the northern Delaware Basin were provided by George Griswold and D. W. Powers of Sandia Laboratories (Albuquerque, New Mexico). Computer facilities to analyze these tapes were provided by R. J. P. Lyon of Stanford University (Palo Alto, California).

Previous work

Igneous rocks in the Yeso Hills were first described in detail by Pratt (1954). He reported three east-northeast-trending en echelon dikes that are as much as 6 m wide and 805 m long. Pratt classified the northernmost dike an alkali to soda trachyte that becomes porphyritic toward its east end. Hayes and Gale (1957) noted that the location of the dikes is controlled by joints in the country rock. Kelley (1971), however, reports that they are emplaced along faults. Hayes and Gale (1957) and Hayes (1964) conclude that these dikes probably are Tertiary in age.

Pratt (1954) reports angular fragments of dark igneous rocks mixed with unconsolidated sandstone and limestone fragments of Cretaceous age 4.8 km northeast of the Yeso Hills. Pratt described the porphyritic igneous rock fragments as olivine and biotite trachyandesite. Lang (1947) concluded that the igneous and sedimentary rock fragments collected as fill within a solution channel and have been preserved as the enclosing rocks were removed by erosion.

King (1948) described an early Tertiary igneous plug of probable trachyte composition in the Delaware Mountains of Texas. Pratt (1954) examined this and other nearby outcrops of similar character and concluded that the rocks described by King are actually silicified sandstone that overlie igneous dikes or plugs.

Jones and Madsen (1959) described a northeasterly trending system of thin, steeply dipping dikes of basalt and porphyritic alkalic rock east of the Pecos River. The alkalic dike exhibits flow structure and has a chilled border. This dike is reported to change abruptly upward and laterally to a vein of polyhalite. Jones and Madsen suggest that the basalt and alkalic dikes are genetically related.

Jones (1973) described near-vertical, northeast-trending dikes of middle Tertiary age at two localities, approximately 16 km apart, east of Carlsbad, New Mexico. At both localities the dikes are strikingly similar in appearance, composition, and structure. Jones described these rocks as porphyritic lamprophyre with chilled borders and poorly developed flow structure.

Geologic setting and occurrence of igneous rocks

The northern boundary of the Delaware Basin (fig. 1) is outlined by the Capitan aquifer (Hiss, 1976). The geology of this area has been studied extensively as a result of exploration for oil, gas, and potash resources. King (1948), Hayes (1964), and Kelley (1971) have described the complex structural and stratigraphic history of this area.

A linear zone of basaltic dikes approximately 2 km wide and 68 km long is interpreted from potash-mine and test-well data east of the Pecos River. This zone trends N. 45-48° E and aligns with outcrops of igneous dikes in the Yeso Hills. Where observed in potash mines, the dikes are parallel, nearly vertical, and 0.1-4.2 m wide. The top of the dikes, as defined by the first intercept in test wells, is variable. The dikes die out within Permian (Ochoan) deposits and are not exposed at the ground surface. Elliot (1976) reports that this zone consists of a swarm of en echelon dikes that rise generally vertically from basement rocks and pinch out in an upward direction (fig. 2). Small sills probably are common. Basement rocks in this area consist of middle Precambrian granite and granodiorite of the Texas craton (Flawn, 1956). Granitic rocks described in Big Eddy no. 44 (table 1, no. 6) may be part of this basement complex.

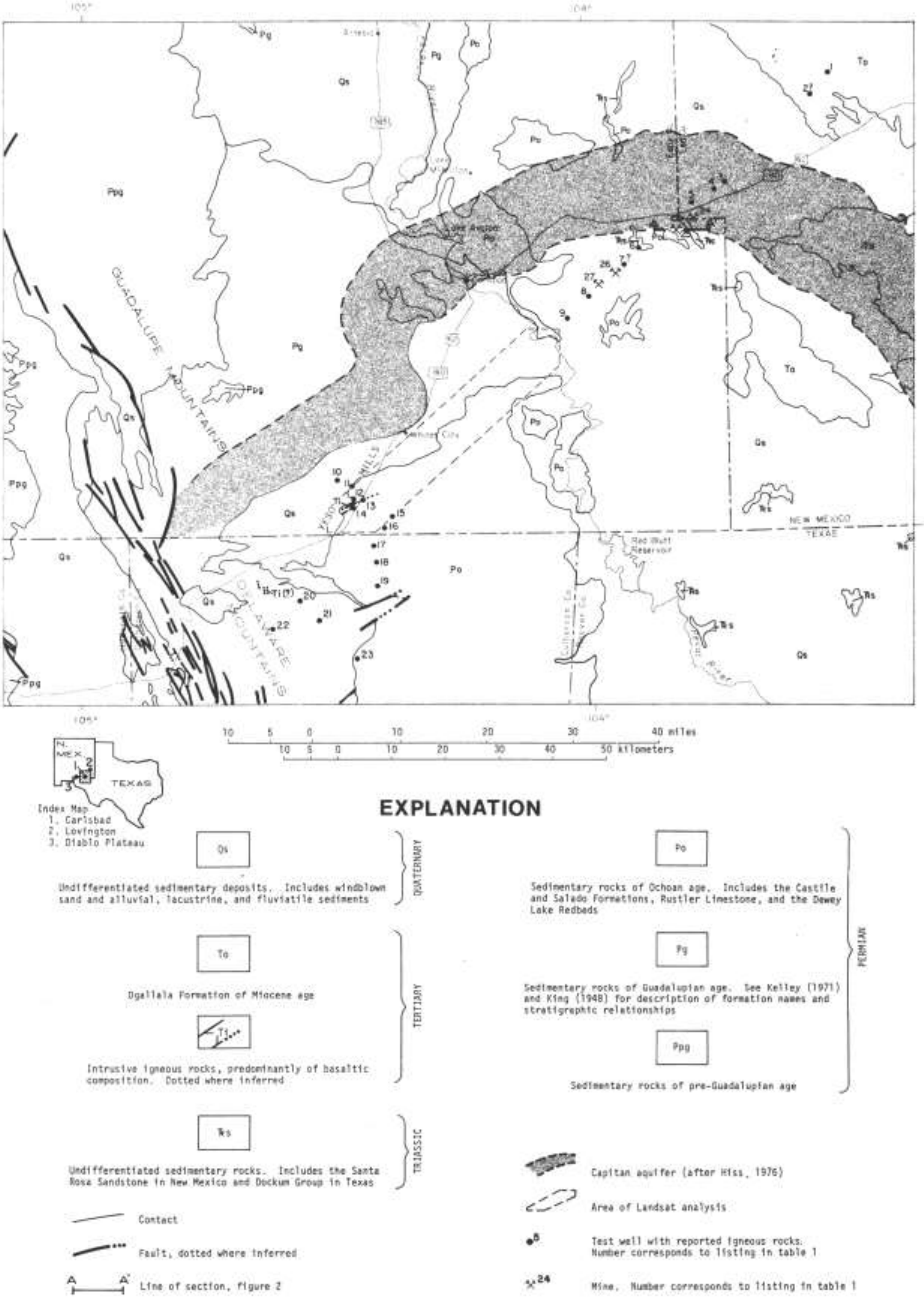


FIGURE 1—GENERALIZED GEOLOGIC MAP SHOWING REPORTED OCCURRENCE OF IGNEOUS ROCKS IN THE NORTHERN DELAWARE BASIN, NEW MEXICO AND TEXAS. Geology modified from Dane and Bachman (1965) and Barnes (1968, 1976).

[New Mexico Bureau Mines & Mineral Resources, Circular 159, 1978]

TABLE 1—LOCATION AND DESCRIPTION OF IGNEOUS ROCKS, NORTHERN DELAWARE BASIN, NEW MEXICO AND TEXAS.

Map no. (from fig. 1)	Location[2]	Name Elevation (ft)[3]	Igneous rock intercepts (depth in ft)[3]	Original description of igneous rock	Age of country rock (series and formation name, if known)	Reference
			Test wells			
1.	12/18S/32E 1980 FSL, 2302 FEL	Humble State BO #3 3995	8170-8430	Basalt fragments	Permian (Leonardian)	Garner Wilde (1976, personal commun.)
2.?[1]	22/18S/34E 2310 FSL, 1980 FEL	Forest Oil Co. Continental State #1 4009	7210-8640	----	----	Elliot (1976) No igneous rocks, G.P. Walker (1977, written commun.)
3.	12/20S/32E NW¼	IMC ConcDale #95	2239	----	----	Elliott (1976)
4.	14/20S/32E 2905 FSL, 368 FWL	Noranda HB #10 3520	1700-1804	Black basalt	Permian (Ochoan Salado Formation)	Frank Condon (1977, personal commun.)
5.	21/21S/32E 1980 FS & EL	Texas Moore #1 3508	2115-2160	Basalt	Permian (Ochoan)	Flawn (1956, p. 64)
6.	16/21S/30E 1980 FSL, 660 FWL	Perry R. Bass Big Eddy #44 3324 KB	11,230-11,270 12,470-12,550 12,700-12,900 13,170-13,330	Granite-diorite do do Not described	Permian (Wolfcampian) Pennsylvanian (Morrowan) do do	W.J. Parsons (1977, written commun.)
7.?[1]	30/21S/30E 660 FSL, 3300 FEL	Stanolind Duncan #1 3320	470-2710 (8 intercepts)	----	----	Elliot (1976) No igneous rocks, G.P. Walker (1977, written commun.)
8.	9/22S/29E 660 FSL, 660 FEL	H & W Drilling Co. Danford #1 3247	2208-2230	Basalt sill	Permian (Ochoan Castile Formation)	P.T. Hayes (1976, written ommun.)
9.	25/22S/28E 1980 FS & EL	Perry R. Bass Big Eddy #43 3168	940-1150 1990-2080	Black, basic igneous material	Permian (Ochoan Salado or Castile Formations)	W.J. Parsons (1977, written commun.)
10.	28/25S/24E 660 FS & EL	CITCO Government #1M 3766	7498-7521	Diorite (includes green hornblende, brown biotite, abundant pyrite)	Mississippian (lower Chesterian or upper Meramecian)	G.P. Walker (1977, written commun.)
11.	34/25S/24E 2310 FS & EL	Black River Corp. Cities Fed. #2 3705	7242-7245 7248-7266 7271-7280	Sills (probably basaltic rock as suggested by wireline correlation)	do	Do.
12.	11/26S/24E 1980 FNL, 2080 FEL	J.M. Huber #1 Superior USA 3752	7492-7495 7535-7540 7554-7556 7591-7600	Very fine grained to coarse-grained diorite sills	do	Do.
13.	12/26S/24E 1980 FNL, 660 FEL	Superior Oil Corp. #1 Government "134" 3866	7780-7804	Sill (probably basaltic rock as suggested by wireline correlation)	do	Do.
14.	14/26S/24E 1980 FNL, 2043 FEL	J.M. Huber #1 Western USA 3827	8021-8023 8027-8032 8048-8072	Fine- to medium-grained diorite sills	do	Do.
15.	22/26S/25E 1630 FN & WL	Hydrocarbon Exploration Inc. Marathon Fed. #1 3635	10,162-10,182	Sill	do	Do.
16.	28/26S/25E 2080 FNL, 1980 FWL	Coquina Oil Corp. Black River Fed. #1 3704	9889-9910	Diorite sill, trace of biotite	do	Do.
17.	6/Blk 61/T1S 1980 FSL, 660 FEL	Natural Gas Exploration Corp. Pokorny #1 3875 (approx.)	9600-9625 9631-9650	Sill of granular, pyritic igneous rock	Pennsylvanian (lower Morrowan sandstone, shale, and limestone)	Do.
			10,358-10,375	Sill of igneous rock with glauconite and pyrite	Mississippian (lower Chesterian or upper Meramecian)	Do.
18.	18/Blk 61/T1S 660 FSL, 1980 FEL	Continental Oil Corp. Pokorny #1 3800 (approx.)	9790-9807 9810-9815 9819-9831	Sills of andesite with trace of glass	Pennsylvanian (Morrowan shale)	Do.
19.	31/Blk 61/T1S 660 FSL, 1980 FEL	Texaco Culberson Fee #1M 3600 (approx.)	9896-9900 10,076-10,081 10,105-10,113 10,160-10,389	Andesite Fine-grained diorite do Fine- to medium-grained diorite, biotite increases near base	Mississippian or Pennsylvanian (Chesterian or lower Morrowan shale)	Do.
20.	46/Blk 63/T1S 660 FNL, 1980 FEL	Socony Mobil State Cowden B#1 4006 DF	7330-7350 7400-7432 7640-7665	Sills of quartz diorite	Mississippian (Chesterian shale)	H.J. Homquest (1977, personal commun.)
				Sills at 7330-7336 and 7418-7430 classified as trachyte	Mississippian or Pennsylvanian (upper Chesterian or lower Morrowan shale)	G. P. Walker (1977, written commun.)

TABLE 1, cont.

Map no. (from fig. 1)	Location[2]	Name Elevation (ft)[3]	Igneous rock intercepts (depth in ft)[3]	Original description of igneous rock	Age of country rock (series and formation name, if known)	Reference
			Test wells			
21.	12/Blk 63/T2S 1980 FSL, 660 FEL	Magnolia Mobil Homer Cowden #1 3917	8738-8770 8810-9122	Sill	Mississippian or Pennsylvanian (upper Chesterian or lower Morrown shale)	G.P. Walker (1977, written commun.)
				Sill between 8760-8770 classified as biotite syenodiorite	Pennsylvanian	Flawn (1956, p. 148)
				Sill at 8730-9140 classified leuco syenodiorite		Pratt (1954, p. 147)
22.	18/Blk 63/T2S 1980 FN & EL	Socony Mobil State Barret #1 4269 DF	7335-7355	Monzonite sill	Mississippian (Chesterian shale)	H.J. Homquest (1977, personal commun.)
				Sill at 7349-7353 classified syenodiorite or diorite	Mississippian or Pennsylvanian (upper Chesterian or lower Morrowan shale)	G.P. Walker (1977, written commun.)
23.	33/Blk 62/T2S 1980 FS & EL	TXL Culberson Fee #1B-T 4000 (approx.)	10,145-10,150	Not described	do	Do.
			Mines			
24.	31/20S/32E	Kerr-McGee 3560 (approx.)	1530	Two basalt dikes; N44-46°E, nearly vertical	Permian (Ochoan Salado Formation)	This report
25.	6/21S/31E	Kerr-McGee 3601 (approx.)	1400	Trachyte dike, 8 ft wide, nearly vertical	do	Wm. Henderson (1977, personal commun.)
26.	36/21S/29E	IMC 3320 (approx.)	790	Basalt or lamprophyre dike, 1 ft wide	do	Hiss (1975)
27.	2/22S/29E	IMC 3335 (approx.)	875 (Polyhalite at 738 ft)	Dikes of basalt and alkalic intrusive rocks 0.3 ft. wide that grade upward and laterally to polyhalite	Permian (Ochoan Castile and Salado Formations)	Jones and Madsen (1959)

[1] Question mark indicates conflicting reports regarding the occurrence of igneous rock at that location.

[2] Test wells located in New Mexico (map nos. 1 through 16) are listed as section/township/range with reference to New Mexico Principal Meridian and Base Line. The remaining test wells are listed as section/block/township with reference to Texas and Pacific Railroad Survey in Culberson County, Tex. All mines are in New Mexico. Abbreviations: FN(or S, E, or W)L = distance, in feet, from north (or south, east, or west) line of the section; KB = kelly bushing; DF = derrick floor.

[3] 1 ft = 0.3 m.

Test wells adjacent to outcrops of igneous dikes in the Yeso Hills do not penetrate igneous rocks at depths less than 2,284 m. This suggests that these dikes are narrow and may be structurally similar to dikes east of the Pecos River, as shown in fig. 2.

A north-northeast-trending zone of diorite or andesite sills is located 8 km southeast of the Yeso Hills. Other sills of diorite, syenodiorite, and monzonite occur in a broad area on the eastern slope of the Delaware Mountains. The sills are coarser grained and are emplaced in older stratigraphic units than are the dikes east of the Pecos River. The sills in the Delaware Mountains generally become more silicic to the southwest.

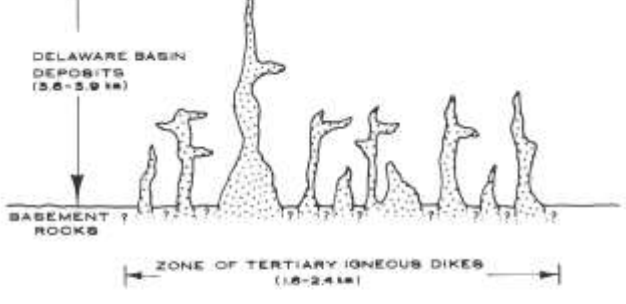


FIGURE 2—DIAGRAMMATIC CROSS SECTION, BASED ON AEROMAGNETIC DATA, OF A ZONE OF BASALTIC DIKES, SOUTHEASTERN NEW MEXICO (modified from Elliot, 1976).

Elliot (1976) reports that dikes in the Yeso Hills and east of the Pecos River generally have similar magnetic properties and may be genetically related. Pratt (1954) suggests that a syenodiorite sill cut in Homer Cowden no. 1 (fig. 1, no. 21) and near-surface igneous intrusions in the Delaware Mountains are presumably Tertiary in age and may be comagmatic. These similarities suggest that all igneous dikes, sills, or plugs in the northern Delaware Basin may have been emplaced during a single magmatic episode. Chemical and isotopic data are needed to test these hypotheses.

Petrography and chemical analyses

Samples of igneous dikes for petrographic study were collected from a potash mine east of the Pecos River (fig. 3) and from outcrops in the Yeso Hills. Modal analyses of these samples are listed in table 2.

Two parallel dikes are exposed in the potash mine. The larger dike strikes N. 44-46° E. and is approximately 5 m wide. The smaller dike, 9.5 m south of the larger dike, is 0.3-0.4 m wide. Both dikes are badly fractured and altered, especially near contacts with the country rock.

The dike rocks are very fine grained and vesicular in hand sample. Many vesicles are lined or filled with anhydrite or chalcedony. Minor amounts (less than 5 percent) of halite, gypsum, and pyrite have been identified in hand samples. The dike rocks are holocrystalline and are nearly equigranular in thin section. Grain size varies from 0.1 mm near contacts with the country rock to 0.5 mm near the center of the dikes. The primary minerals generally are anhedral to subhedral. Planar flow is expressed by lath-shaped plagioclase crystals of labradorite composition.

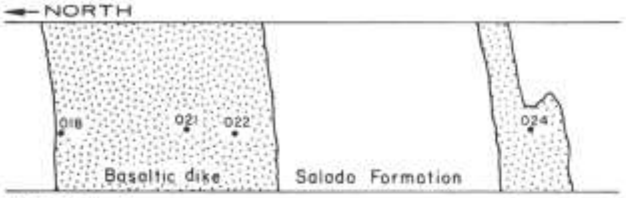


FIGURE 3—DIAGRAMMATIC SKETCH OF EAST WALL OF KERR-MCGEE POTASH MINE (fig. 1, no. 24) showing collection localities of rock samples.

Albite twinning and continuously zoned plagioclase crystals with more calcic cores are common. Most of the plagioclase crystals are altered to sericite, especially along cleavage or fracture planes. Zeolites also may be present. This identification, however, is based on optical properties and was not confirmed by x-ray diffraction.

Ferromagnesium minerals are slightly more common near the margins of the dikes than near the center. Biotite is pleochroic from yellowish brown to brown or slightly greenish brown. Pyroxene is rare. Other ferromagnesium minerals are partially resorbed with reaction rims of biotite, magnetite, and fibrous chlorite. Accessory minerals include apatite and magnetite. Some ilmenite may be present, but polished sections were not made to distinguish between the opaque oxides. Apatite occurs as slender crystals in plagioclase. Magnetite occurs as interstitial euhedral cubes and as fracture fillings in plagioclase and the ferromagnesium crystals.

Chemical analyses and normative minerals of samples from the potash mine are listed in table 3. These rocks are undersaturated with respect to silica and are peraluminous. They are low in MgO and CaO, but rich in P_2O_5, K_2O, and H_2O+ (combined water) when compared to basaltic rocks described by Nockolds (1954).

Excessive P_2O_5 corresponds to the abundance of apatite (table 2). The deficiency of CaO and MgO but excessive H_2O+ and the alteration mineral assemblage suggest hydrothermal reactions between the basaltic magma and the potash-rich country rock. The absence of modal orthoclase suggests post-magmatic incorporation of K_2O. Extensive alteration and evidence of chemical exchange between the magma and the country rock preclude a chemical or normative mineral classification of these igneous rocks.

A core of an igneous dike cut in a potash test well also was examined in thin section (table 2, no. 032). This rock is holocrystalline and very fine grained. The plagioclase crystals at this locality are more sodic than plagioclase in samples from the potash mine. Anhedral biotite crystals are pleochroic from yellow brown to olive brown or brown. Ferromagnesium minerals are partially resorbed and altered to chlorite. Pyroxene crystals are rare. Magnetite occurs as cubic crystals and as fracture fillings in plagioclase.

The samples of dike rocks from east of the Pecos River are classified as biotite basalt or basaltic andesite on the basis of their plagioclase composition and abundance of biotite. Although Jones (1973) described lamprophyre dikes in this area, these samples do not have lamprophyric texture and are chemically distinct from the varieties of lamprophyre described by Metais and Chayes (1963).

The location of igneous dikes in the Yeso Hills is indicated by linear zones of brown soil that trend N. 54-56° E. Two samples were collected from a gray, aphanitic dike near the center of sec. 11, T. 26 S., R. 43 E. The dike is massive but badly fractured in outcrop. The country rock is sheared and altered along the dike's eastern contact. The dike is holocrystalline and porphyritic in thin section. Subhedral plagioclase phenocrysts, 3 to 6 mm long near the center of the dike, contain a ring of optically discontinuous, very fine grained inclusions of plagioclase and ferromagnesium minerals. The fine-grained groundmass (0.05 to 0.4 mm) consists of: lath-shaped plagioclase of andesine to labradorite composition; rare subhedral orthoclase that is perthitic; anhedral biotite that is pleochroic from reddish brown to very dark red brown; partially resorbed ferromagnesium minerals that have altered to fibrous yellowish-brown chlorite; minor apatite; and abundant magnetite. Plagioclase crystals usually are altered to sericite and zeolites and often are coated by iron-oxide stain. Cleavage from a single crystal suggests that some of the unidentified ferromagnesium minerals are pyroxene. Abundant vesicles often are filled with chalcedony or lined with anhydrite, calcite, or chlorite. These rock samples are classified as basaltic andesite on the basis of their plagioclase composition and on the presence of orthoclase.

Age

Urry (1936) and Jones (1976, written communication) report Oligocene helium-method and potassium-argon age dates, respectively, from igneous dikes east of the Pecos River. Kaneoka (1972), however, concludes that rocks with greater than 1 percent H_2O+ may have lost radiogenic argon by hydration during weathering or alteration. This loss results in age dates that are younger than age dates from unaltered rocks. A sample (fig. 3, no. 022) was collected from an igneous dike east of the Pecos River to test the effect of alteration on the potassium-argon age date reported by Jones. This sample was prepared by crushing to

TABLE 2—MODAL ANALYSES (VOLUME PERCENT) OF IGNEOUS ROCKS, SOUTHEASTERN NEW MEXICO.

	East of Pecos River				Yeso Hills	
Sample no.	018	021	024	032	031	030
Location (map no., fig. 1)	24	24	24	4	West Contact	Center
Primary Minerals						
Plagioclase	45.7 (An_{40+})	49.2 (An_{54-60})	13.7	45.0 (An_{43-46})	8.4	48.4 (An_{47-50})
Biotite	14.2	13.3	3.0	11.5	Tr	5.7
Ferromagnesium minerals	16.0	15.6	11.6	17.2	8.4	30.3
Magnetite (± ilmenite)	14.7	11.6	9.0	12.7	11.0	10.6
Apatite	2.9	3.6	1.3	3.8	----	3.3
Groundmass	----	----	61.4^1	----	63.4^2	----
Secondary Minerals						
Carbonates	2.6	2.2	----	2.0	2.3	Tr
Zeolites (?)	1.7	3.4	Tr	3.1	1.7	1.7
Chalcedony	1.2	Tr	----	4.7	Tr	----
Anhydrite	1.0	1.1	Tr	Tr	4.8	----
Total points counted	1517	1081	901	817	1077	1000

Tr = Trace (< 1.0%)

[1] Includes plagioclase + biotite + magnetite

[2] Includes plagioclase + orthoclase + ferromagnesium minerals + magnetite

TABLE 3—CHEMICAL ANALYSES AND NORMATIVE MINERALS (WEIGHT PERCENT) OF BASALTIC DIKES EAST OF THE PECOS RIVER, SOUTHEASTERN NEW MEXICO.

Sample no.	018	021	024
SiO_2	44.90	46.00	46.10
Al_2O_3	14.20	13.20	14.50
Fe_2O_3	2.80	3.60	3.10
FeO	7.30	7.30	7.50
MgO	6.00	6.00	5.10
CaO	3.90	3.40	2.40
Na_2O	3.80	2.00	2.50
K_2O	4.80	6.30	8.00
H_2O+	2.87	2.74	3.14
H_2O-	1.22	1.83	0.92
TiO_2	2.40	2.80	2.30
P_2O_5	1.20	1.30	1.20
MnO	0.14	0.19	0.12
CO_2	0.20	0.10	0.10
SO_3	1.25	0.42	0.27
Cl	1.15	0.38	1.10
F	0.16	0.16	0.17
S	0.55	0.30	0.20
Total	98.84	98.02	98.72
Normative Minerals			
C	2.45	1.51	2.62
OR	29.06	38.70	48.34
AB	15.84	11.81	11.50
AN	10.10	7.71	3.04
HL	1.94	0.63	1.85
TH	2.27	0.78	0.49
HY-EN	14.93	13.93	2.44
HY-FS	6.25	5.17	1.39
FO	0.27	1.12	7.40
FA	0.12	0.46	4.64
MT	4.16	5.43	4.60
IL	4.67	5.53	4.47
AP	2.91	3.20	2.91
FR	0.11	0.09	0.13
PR	1.05	0.58	0.38
CC	0.46	0.24	0.23
D.I.	44.90	55.51	59.84

D.I. = Differentiation Index (Thorton and Tuttle, 1960)
Chemical analyses by E.V. Post, Skyline Labs, Inc., Denver, Colo. Water analyses by Marcelyn Cremer, U.S. Geol. Survey, Menlo Park, Calif.

0.50-0.25 mm and boiling in distilled water to remove soluble potassium salts. The calculated age dates and potassium-argon analyses are listed in table 4.

Since the rate of argon diffusion varies during alteration, it is not likely that analysis of two altered samples would produce: 1) closely similar percentages of radiogenic argon, and 2) calculated age dates that agree within the range of standard deviation. These data suggest that radiogenic argon was not lost during alteration and that igneous dikes east of the Pecos River are early Oligocene (32.2 to 33.9 m.y.) in age.

Landsat analysis

Although Jones (1973) and Hiss (1975) have projected an igneous dike system across the northern Delaware Basin, igneous rocks have not been reported between the Yeso Hills and the Pecos River. Two linear magnetic highs are shown on a regional aeromagnetic map (U.S. Geological Survey, 1973) of this area: one trends N. 40° E. from the Yeso Hills to White City; the other trends N. 70° E. from east of White City to the Pecos River. A similar linear magnetic feature east of the Pecos River has been geologically interpreted as a dike of Tertiary age (Elliot, 1976).

Jones and Madsen (1959) and Jones (1973) report that the basaltic dikes east of the Pecos River have altered and recrystallized the country rock adjacent to intrusive contacts. Pratt (1954) interprets linear ridges of silicified sandstone deeply stained with iron as evidence of underlying intrusive dikes or plugs. If alteration, recrystallization, silification, or iron-oxide staining results in subtle color changes at the ground surface, then igneous dikes may be located in the subsurface by computer enhancement of digital brightness data from Landsat images.

A Landsat image of the Carlsbad area was analyzed using the GRIMAGE computer program. GRIMAGE is designed to control the generation of enhanced, three-color composites of Landsat images from computer-compatible tapes by means of the Grinnell television imaging system. GRIMAGE permits the extraction of raw or ratioed data from four Landsat bands (4, 5, 6, or 7) to enhance or optimize any feature within the image displayed on the television monitor. Normal color selection for Landsat bands are: red for band 6 or 7, green for band 5, and blue for band 4. Color selection for ratioed images is arbitrary and subjective. Multicolored images are obtained by superposition of up to three individual bands or ratios.

A single dark linear feature was located in the Yeso Hills (fig. 1) by superimposing bands 4, 5, and 7. This linear feature trends N. 60° E. and is inferred to be a zone of igneous dikes because it passes exactly through outcrops of igneous rocks described by Pratt (1954). This zone is approximately 0.1 km wide and 7.5 km long. It is abruptly terminated by a northwest-trending linear feature east of Highway 62-180 and is overlain by Quaternary alluvial deposits to the southwest. No other linear features that could be related to igneous activity were found in this area.

Aeromagnetic surveys, Landsat data, and the alignment of basalt dikes east of the Pecos River with basaltic andesite dikes in the Yeso Hills suggest the presence of igneous rocks in the subsurface between these two areas. Test-well data to prove their existence currently are not available or are unknown to the authors. We would appreciate knowledge of this data when or if it becomes available.

TABLE 4—POTASSIUM-ARGON- AND HELIUM-METHOD AGE DATES OF IGNEOUS DIKES, SOUTHEASTERN NEW MEXICO.

Sample no.	Rock type	Location (map no., fig. 1)	K_2O (percent)	moles $^{40}Ar_{rad.}/g$ ($\times 10^{-10}$)	$^{40}Ar_{rad.}$ (percent)	Age ± 2σ (m.y.)	Reference
022 WR[1]	Biotite basalt	24	3.97	2.79	67	32.2 ± 1.0	This report
3-1-71 WR[2]	Lamprophyre	24	3.96	2.76	65	33.9 ± 0.8	Jones (1976, written commun.)
			Helium method				
	Basalt	5				30 ± 1.5	Urry (1936)

WR = whole rock.

[1] Potassium analysis by Z. H. Tilling; argon analysis and age calculation by Janet Morton and M. L. Silberman.
Constants: $\lambda_e + \lambda_{e'} = 0.581 \times 10^{-10}/yr$; $\lambda_\beta = 4.963 \times 10^{-10}/yr$; $^{40}K/K = 1.167 \times 10^{-4}$.

[2] Analysts: R.R. Marvin, H.H. Mehnert, and Violet Merritt.
Constants: $\lambda_e = 0.585 \times 10^{-10}/yr$; $\lambda_\beta = 4.72 \times 10^{-10}/yr$; $^{40}K/K = 1.19 \times 10^{-4}$.

Discussion

The texture and composition of early Oligocene (32.2 to 33.9 m.y.) basalt dikes, reported in test wells and potash mines east of the Pecos River, are similar to outcrops of Tertiary basaltic andesite dikes in the Yeso Hills. The andesite dikes and the diorite, syenodiorite, and monzonite sills, reported in a north-northeast-trending belt southeast of the Yeso Hills and in the Delaware Mountains, are emplaced in older stratigraphic units than are the basalt dikes east of Pecos River. Although the sills become more silicic to the southwest, Pratt (1954) believes they may be co-magmatic and Tertiary in age.

Barker and others (1977) have described syenite, trachyte, and phonolite laccoliths, sills, and plugs of early Oligocene age (34 to 36 m.y.) in the Diablo Plateau. This area is 50 km west of the Yeso Hills (fig. 1) at the northern end of the Trans-Pecos magmatic province (Barker, 1977). A comparison of the magmatic relationships and tectonic implications of Tertiary igneous rocks in the northern Delaware Basin to igneous rocks in the Diablo Plateau merits attention.

References

Barker, D. S., 1977, Northern Trans-Pecos magmatic province: Introduction and comparison with the Kenya Rift: Geological Society of America, Bull., v. 88, p. 1421-1427

Barker, D. S., Long, L. E., Hoops, G. K., and Hodges, F. N., 1977, Petrology and Rb-Sr isotope geochemistry of intrusions in the Diablo Plateau, northern Trans-Pecos magmatic province, Texas and New Mexico: Geological Society of America, Bull., v. 88, p. 1437-1446

Barnes, V. E., 1968, Geologic atlas of Texas, Van Horn-El Paso sheet: University of Texas Bureau of Economic Geology, scale 1:250,000

, 1976, Geologic atlas of Texas, Pecos sheet: University of Texas Bureau of Economic Geology, scale 1:250,000

Dane, C. H., and Bachman, G. 0., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000

Elliot, C. L., 1976, A preliminary geophysical study of a trachyte dike in close proximity to the proposed Los Medaños nuclear waste disposal site, Eddy and Lea Counties, New Mexico: Albuquerque, Sandia Laboratories, Open-file Rept., 19 p.

Flawn, P. T., 1956, Basement rocks of Texas and southeast New Mexico: University of Texas Bureau of Economic Geology, Bull. 5605, 261 p.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey, Prof. Paper 446, 69 p.

Hayes, P. T., and Gale, B. T., 1957, Geology of the Carlsbad Caverns East quadrangle, New Mexico: U.S. Geological Survey, Geol. Quad. Map GQ-98, scale 1:62,500

Hiss, W. L., 1975, Stratigraphy and ground-water hydrology of the Capitan aquifer, southeastern New Mexico and western Texas: University of Colorado, Boulder, Ph.D. thesis, 396 p.

, 1976, Structure of the Permian Guadalupian Capitan aquifer, southeast New Mexico and west Texas: New Mexico Bureau of Mines and Mineral Resources, Resource Map 6

Jones, C. L., 1973, Salt deposits of Los Medaños area, Eddy and Lea Counties, New Mexico: U.S. Geological Survey, Open-file Rept., 67 p.

Jones, C. L., and Madsen, B. M., 1959, Observations on igneous intrusions in Late Permian evaporites, southeastern New Mexico: Geological Society of America, Bull., v. 70, p. 1625-1626

Kaneoka, Ichiro, 1972, The effect of hydration on the K/Ar ages of volcanic rocks: Earth and Planetary Science Letters, v. 14, p. 216-220

Kelley, V. C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Mem. 24, 75 p.

King, P. B., 1948, Geology of the southern Guadalupe Mountains, Texas: U.S. Geological Survey, Prof. Paper 215, 183 p.

Lang, W. B., 1947, Occurrence of Comanche rocks in Black River valley, New Mexico: American Association of Petroleum Geologists, Bull., v. 31, p. 1472-1478

Metais, D., and Chayes, Felix, 1963, Varieties of lamprophyre: Carnegie Institute, Washington Year Book 62, p. 156-157

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geological Society of America, Bull., v. 65, p. 1007-1032

Pratt, W. E., 1954, Evidences of igneous activity in the northwestern part of the Delaware Basin: New Mexico Geological Society, Guidebook 5th field conference, p. 143-147

Thorton, C. P., and Tuttle, 0. F., 1960, Chemistry of igneous rocks: I. Differentiation index: American Journal of Science, v. 258, p. 664-684

Urry, W. D., 1936, Post-Keweenawan time scale, *in* Report of the committee on the measurement of geologic time: National Research Council, Appendix K, p. 35-40

U.S. Geological Survey, 1973, Aeromagnetic map of the Carlsbad area, New Mexico and Texas: U.S. Geological Survey, Geophys. Inv. Map GP-861, scale 1:250,000

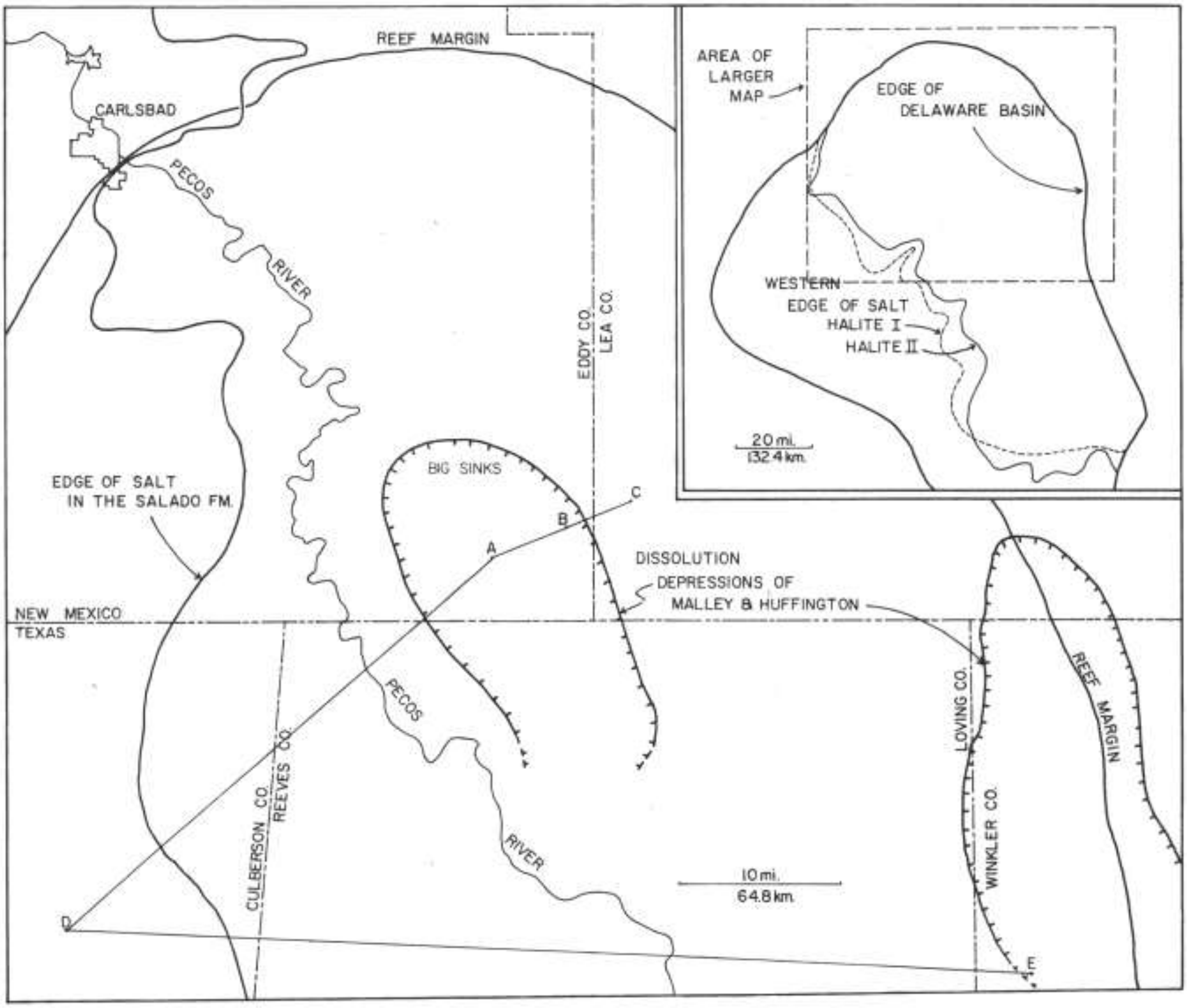


FIGURE 1—INDEX MAP OF NORTHERN DELAWARE BASIN SHOWING LOCATION OF BOREHOLES AND DISSOLUTION DEPRESSIONS.

[New Mexico Bureau Mines & Mineral Resources, Circular 159, 1978)

DEVELOPMENT OF DISSOLUTION BRECCIAS, NORTHERN DELAWARE BASIN, NEW MEXICO AND TEXAS

by Roger Y. Anderson, Kenneth K. Kietzke, and Doris J. Rhodes
Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131

Abstract

Beds of dissolution breccia are persistent in the Castile-Salado evaporites in the western part of the Delaware Basin. Dissolution breccia consists of subangular to somewhat rounded and elongate fragments of individual laminae of calcite-laminated anhydrite set in an anhydrite matrix. Collapse breccias consisting of angular fragments of laminated anhydrite with little or no matrix often overlie dissolution breccias or may occur separately within the anhydrite some distance above dissolution horizons. Correlation of individual calcite-laminated anhydrite laminae associated with dissolution breccias with the same laminae associated with halite beds shows that dissolution breccias are equivalent to halite beds. Even the thinnest halite beds in the eastern part of the basin once extended west of their present distribution, probably to near the western margin of the basin. The tracing of identified dissolution horizons to large areas of deep dissolution west of existing halite beds shows that it is removal of salt from the lower part of the Salado and upper part of the Castile Formations that has caused collapse of the depressions.

Introduction

A core of laminated anhydrite of the Castile and Salado Formations collected from Culberson County, Texas, in an area that had been subjected to complete dissolution of salt, contained a number of layers of anhydrite breccia (fig. 1, location D). Correlation of individual laminations in the anhydrite over distances up to 70 mi (113 km) (Anderson and Kirkland, 1966; Kirkland and Anderson, 1970) makes it possible to also correlate the breccia beds with particular salt horizons and to demonstate that the breccia was formed as a result of dissolution of salt. This approach has resulted in a more accurate appraisal of the original distribution of halite beds in the Delaware Basin (Anderson and others, 1972).

In these earlier works, the dissolution breccias were shown to relate to areas of dissolution, and the dissolution horizons were identified only in a general way. In this report we relate the dissolution breccias to specific salt beds in the upper part of the Castile and lower part of the Salado Formations, trace certain dissolution horizons to specific features of dissolution within the basin, and suggest some concepts concerning origin of the dissolution breccias and their relationship to collapse breccias.

ACKNOWLEDGMENTS—The earlier work on the Castile Formation was supported by several grants from the National Science Foundation, Washington, D.C. Some of the logs used in the present investigation were provided by Sandia Laboratories, Albuquerque, New Mexico. Douglas W. Kirkland, Mobil Research and Development Corporation, reviewed the manuscript and provided several suggestions.

Breccia beds

Dissolution breccias

Dissolution breccias are characterized by an impure anhydrite matrix that suspends subangular to rectangular elongate fragments of laminated anhydrite (fig. 2). In some samples fragments are quite small (less than 0.5 cm), rounded, and suspended in random orientations within a matrix that comprises more than half the volume of material. In other samples the fragments are large (greater than 2 cm), with a more or less parallel orientation to the stratification of the overlying and underlying units and associated with a relatively small amount of matrix.

The thicknesses of the beds of dissolution breccia range from a few centimeters to several meters and are approximately proportional to the thicknesses of correlative salt beds. The textures and proportions of matrix to fragments appear to be related to the thicknesses of the salt laminae separating the individual or sets of anhydrite laminae in the

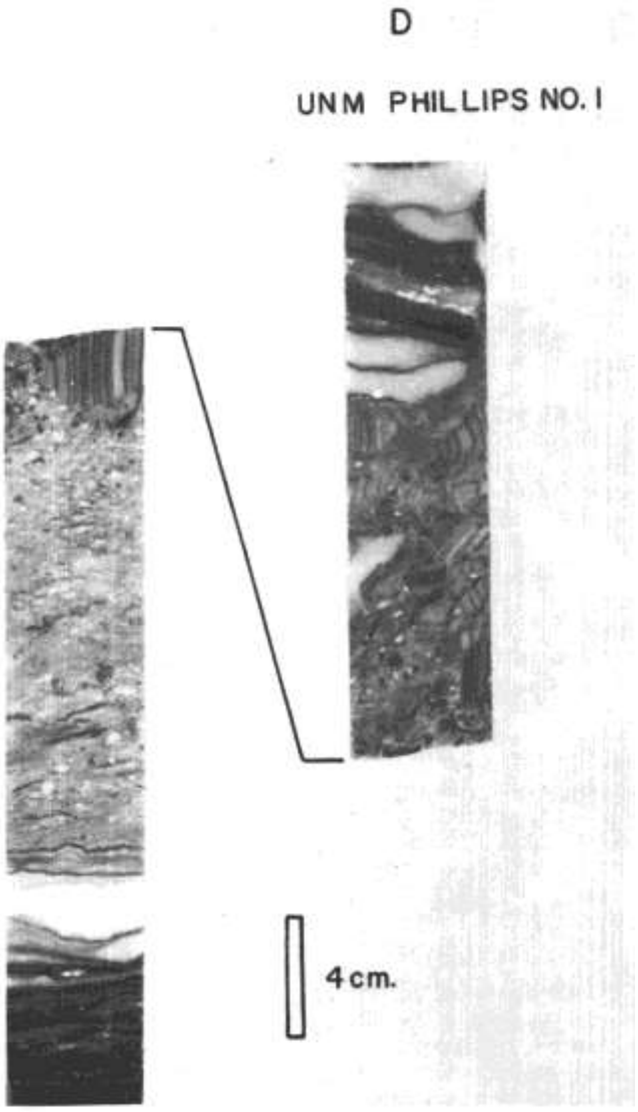


FIGURE 2—DISSOLUTION BRECCIA OVERLAIN BY COLLAPSE BRECCIA IN UNM-PHILLIPS NO. 1 CORE (LOCATION D). Third breccia bed above the base of Halite III, fig. 5.

[New Mexico Bureau Mines & Mineral Resources, Circular 159, 1978]

original salt bed. Hence, the matrix is probably the finely disseminated anhydrite, calcite, and organic matter contained within the original halite laminae, often along microlaminations within halite laminae. As salt is dissolved, the matrix encloses the elongate fragments of larger anhydrite laminae to produce a dense unit of dissolution breccia.

Because we are able to trace the breccia beds to salt layers, we can show that there is an approximate relationship between the thickness of the salt bed and the thickness of the correlative breccia bed. However, because the thickness of the original salt beds at the breccia bed locality (fig. 1, location D) is not known, the exact ratio cannot be determined. The examples available show that one foot (0.3 m) of dissolution breccia is equivalent to between 20 and 30 ft (6 and 9 m) of halite.

Collapse breccias

Many, but not all, beds of dissolution breccia are overlain by a collapse breccia of angular fragments of laminated anhydrite (fig. 2). The angular fragments are fitted together in a tight interlocking pattern with little or no fine-grained anhydrite matrix. The fragments range in size from a few millimeters to blocks of more than 30 cm, with a definite tendency for fragments of similar size to be found together.

An examination of the breccia fragments and their association with the intervening undisturbed layers of laminated anhydrite reveals some information about the probable nature of the collapse process. Beds of collapse breccia, for example, have developed several meters above underlying layers of dissolution breccia. In certain parts of the UNM-Phillips No. 1 core the overlying column of laminated anhydrite fractured. This fracture created a void some distance above a chamber formed by dissolution of salt; and the void, thus created, in turn collapsed to produce a breccia. Hence, removal of a salt layer at depth resulted in a diminishing chain reaction above in which breccia layers form at apparently random positions in overlying anhydrite beds. An almost identical occurrence in connection with collapse associated with salt solution mining has been reported by Dowhan (1976) in which an overlying column of dolomite and sandstone was brecciated at random positions by removal of salt and collapse at depth. Intraformational breccia in the Michigan Basin has also been described by Landes (1959) and appears to be of similar origin.

There is some evidence for lateral movement of breccia blocks and fragments. Large (up to 30 cm) blocks of laminated anhydrite in vertical orientation occur between separated horizontal laminae of anhydrite, indicating that the disturbed block has moved laterally into the void space. Some moderately dipping (30-40°) fractures in the horizontally laminated anhydrite are filled with angular breccia fragments of uniform size, suggesting that the breccia was actually a slurry injected between walls of the separated fracture. Hence, the brecciation process may not have been entirely dry, and fluids may have played a role in the movement of breccia blocks and fragments.

Correlation of dissolution horizons

The feasibility of correlating individual calcite-anhydrite laminae over long distances in the Delaware Basin was demonstrated by Anderson and Kirkland (1966). This same technique can be used to demonstrate that a particular salt bed correlates with a particular layer of dissolution breccia. A comparison of the anhydrite laminae a few centimeters below the lowermost halite bed in the Halite III unit of the Castile Formation (from a Winkler County, Texas, core; fig. 1, locality E) with the equivalent laminae associated with dissolution breccia (from a Culberson County, Texas, core; fig. 1, locality D), shows positively that the overlying halite and dissolution breccia are equivalent (fig. 3, correlation A). The equivalency of halite and dissolution breccia is also verified by correlating individual anhydrite laminae within a 2-ft-thick (0.6 m) anhydrite bed within a halite bed in the lower part of Halite III (fig. 4, laminae correlation B). These two localities are separated by 70 mi (113 km) and are on nearly opposite sides of the Delaware Basin. The visual quality of the correlation is not as good as correlations over shorter distances, but the individual laminae indicated in the illustrations are unquestionably equivalent. Correlation is further verified by the thickness and spacing of other beds of halite and dissolution breccia within the Halite III Member of the Castile Formation as depicted in cores and acoustical logs (fig. 5).

Development of dissolution

The laminae and log correlations described above demonstrate that even the thinnest salt beds deposited in the eastern part of the Delaware Basin once extended far to the west and probably extended over most of the basin. This means that it is relatively safe to assume that the departures from full stratigraphic section observed in acoustical logs are the result of removal of original salt beds, rather than the result of facies changes within the basin. This conclusion makes possible an assessment of the development of salt dissolution for certain areas of the basin. It also makes it possible to trace dissolution horizons to specific dissolution features in the basin and to clarify their relationship to salt removal.

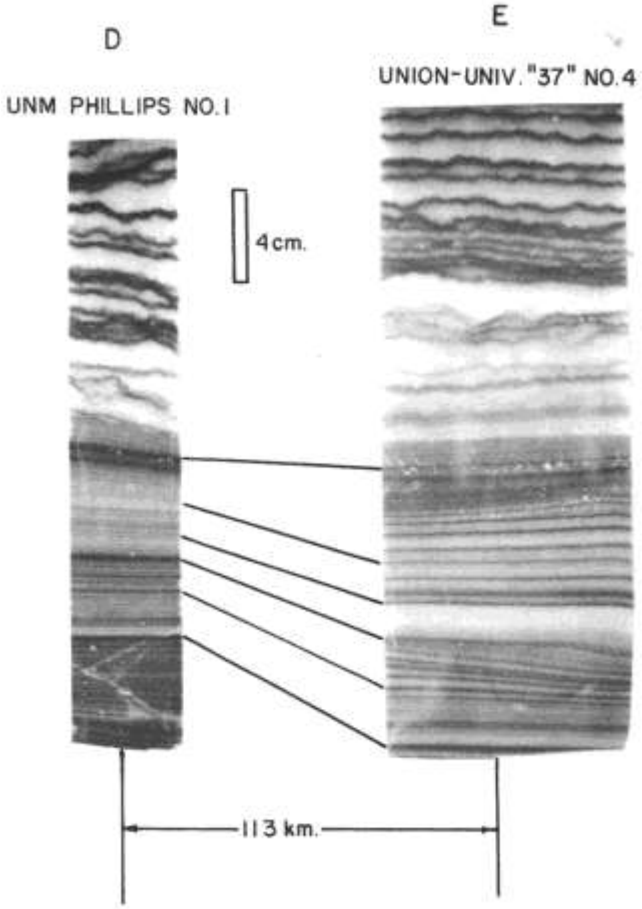


FIGURE 3—Laminae correlation A at the base of Halite III (fig. 5).

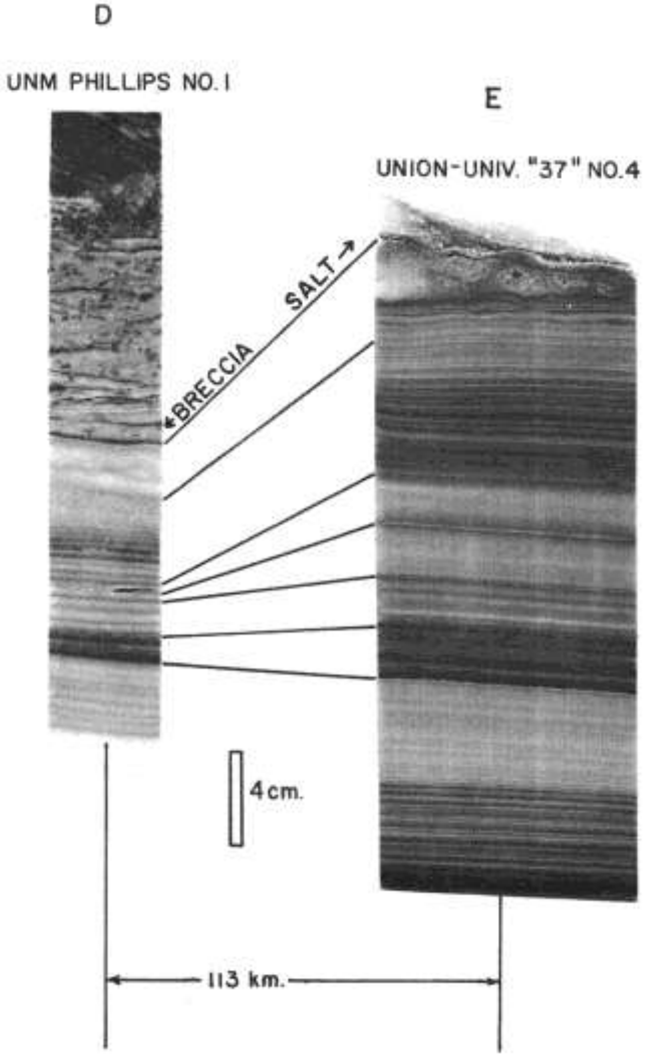


FIGURE 4—Laminae correlation B from thin anhydrite bed within lower halite bed of Halite III (fig. 5). Note that salt and breccia beds are correlative and that salt precipitation occurred at approximately the same time at both localities.

Big Sinks dissolution depression

Malley and Huffington (1953) mapped a number of large-scale dissolution depressions in the Delaware Basin that are filled with thick sequences of Cenozoic fill. Most of these depressions lie above the inner edge of the reef along the eastern margin of the basin (fig. 1). Several of these features, however, occur along the western margin of salt, and one extends from Texas into New Mexico in the vicinity of Big Sinks (fig. 1). An acoustical log across the sharp eastern margin of this depression reveals that salt in the lower part of the Salado and upper part of the Castile Formations has been dissolved to produce the depression (fig. 6). This interpretation is confirmed by comparing structure contours on the top of the overlying Rustler Formation with isopach contours of the salt lying between the Cowden Anhydrite Member and the 136 marker bed of the Salado Formation (lower Salado). Within a distance of a few miles, the 300-ft (91.5 m) salt section has been dissolved and is matched by an equivalent depression in the structure contours of the Rustler Formation (fig. 7). The dissolution depression has developed under an undisturbed layer of salt in the upper and middle Salado Formation and is about 20 mi (32 km) from the western edge of overlying salt. Salt dissolution in this particular depression has been extensive; the dissolution has even extended below the Salado into the lower part of the Castile Formation.

Controls on dissolution

The degree to which the overlying evaporites have been undermined by dissolution suggests certain hydrologic controls on the dissolution process. The large dissolution depressions along the eastern margin of the basin were formed by contact with undersaturated waters moving through the reef system (Hiss, 1975). A similar situation may have prevailed along the western margin of the basin in earlier stages of stripping and dissolution so that the salt horizons adjacent to the reef mass (upper Castile and lowest part of Salado) were preferentially dissolved. However, such a system of contact with reef waters could probably not maintain dissolution for distances in excess of 50 mi (80.5 km) from the reef (site of the Big Sinks depression). Present surface drainage on the top of the salt along the western margin generally follows the north-south flow of the Pecos drainage. A similar direction of flow in the subsurface, perhaps along predisposed horizons within the evaporite body and approximately along the axis of the Balmorhea-Pecos-Loving trough of Hiss (1975), would be needed to remove the volume of salt now occupied by the depressions.

Development of breccias

As the subsurface dissolution advanced eastward within the evaporites, it left behind a relatively undisturbed, albeit fractured, sequence of laminated anhydrite with various amounts of collapse breccia above dissolution horizons and within the overlying anhydrite beds. The presence of deep and extensive solution features such as the Big Sinks dissolution depression suggests that the eastward advance of the dissolution front in the subsurface was not always a gradual and uniform process. An advancing front of salt dissolution will develop caverns and tunnels at the leading edge and outliers of salt at the trailing edge. In the Delaware Basin, gradual dissolution along a leading edge apparently caused little disturbance to the overlying sequence in most of the basin, other than a minor wave of brecciation translated upward into the overlying anhydrite beds. The collapse of a pre-front cavern, however, can be expected to be a rather sudden event. Such a collapsing cavern could be expected to develop a brecciated chimney (pipe) above the cavern, and, if the height and size of the cavern were sufficient, this type of brecciation would be translated to the surface to produce a sink. Collapse breccias similar to those observed in breccia pipes have been observed forming in collapsing salt cavities produced by solution mining (Jaron, 1970). The development of such collapse structures, or clusters of collapse structures, may have been precursors to the development of large dissolution depressions such as the Big Sinks depression.

Breccia pipes and masses are a fairly common feature in evaporites. Landes (1959) described a trans-formational breccia on Mackinac Island within the Michigan Basin and attributed it to salt dissolution at depth. Similar structures were reported in Permian rocks of Oklahoma (Myers, 1962). Breccia pipes and collapse structures were described in the Delaware Basin by Vine (1960, 1976), and breccia is associated with some limestone buttes (Castile Formation) described by Kirkland and Evans (1976) on the Gypsum Plain of the Delaware Basin west of the present dissolution margin. The breccia pipes and smaller collapse structures of the Delaware Basin may have facilitated the advance of a dissolution front, thereby accelerating salt removal and collapse at depth.

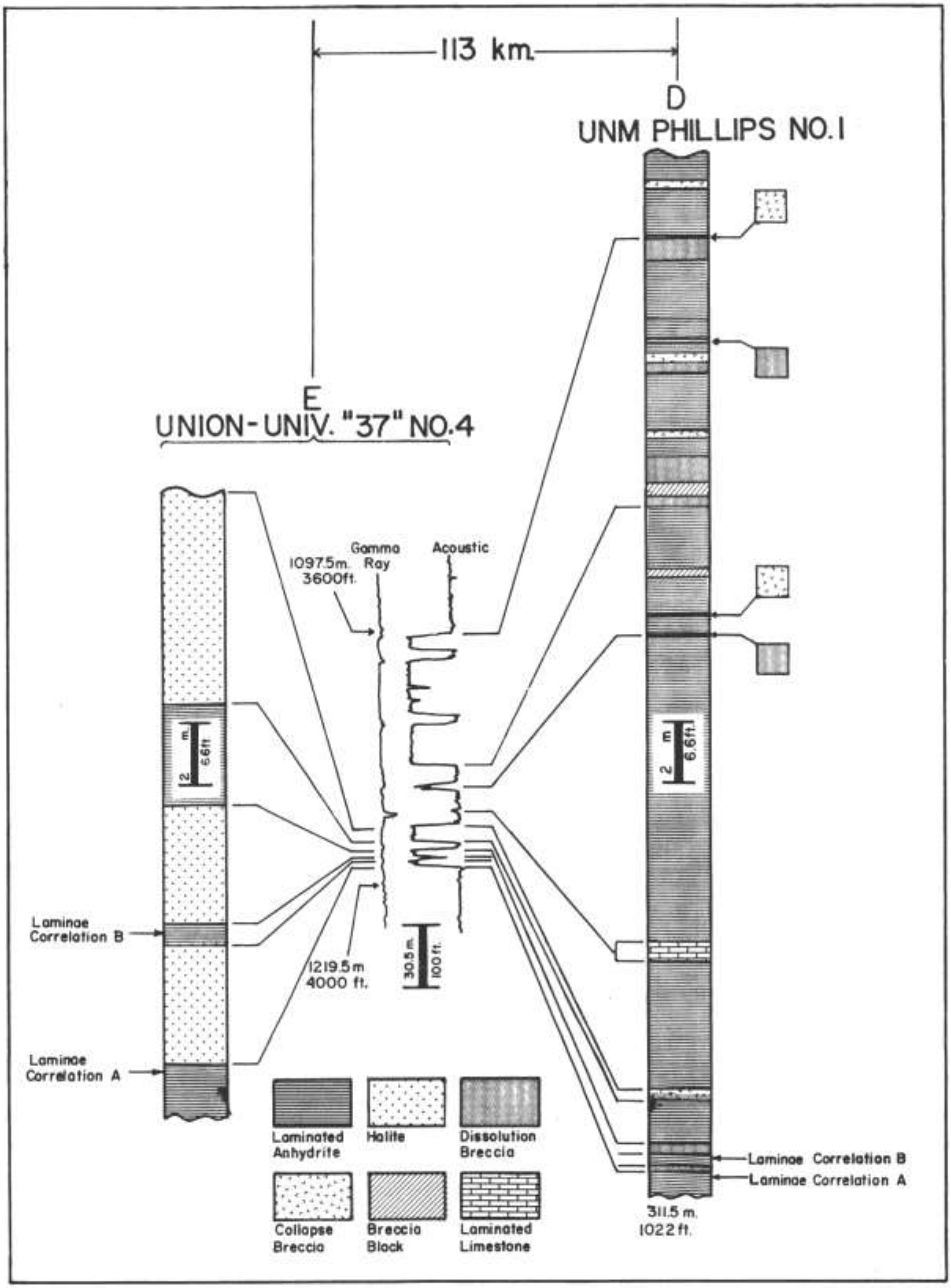


FIGURE 5—Correlation diagram showing stratigraphic locations of laminae correlations A and B and correlation of breccia beds in Halite III member between UNM-Phillips No. 1 core and acoustical log and core from Union-Univ. "37" No. 4. Note that collapse breccia may occur without an immediately underlying dissolution breccia.

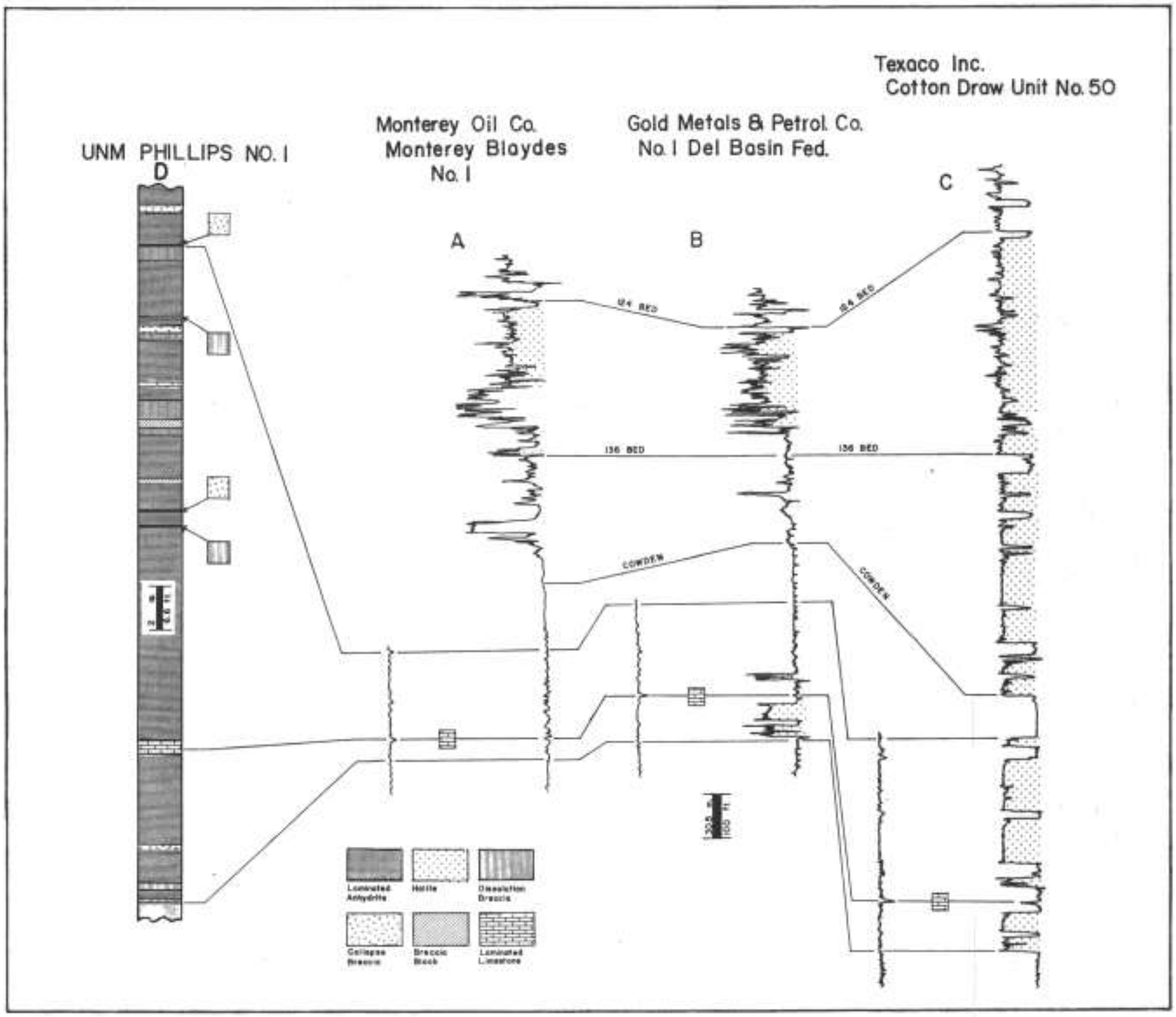


FIGURE 6—CORRELATION DIAGRAM SHOWING DISSOLUTION HORIZONS OF SALT WITHIN BIG SINKS DISSOLUTION DEPRESSION. Locality C is complete salt section. Note that horizon of most active or most complete dissolution is near the Cowden Anhydrite Member (fig. 1). Log on right at each locality is acoustic log; log on left is gamma ray log.

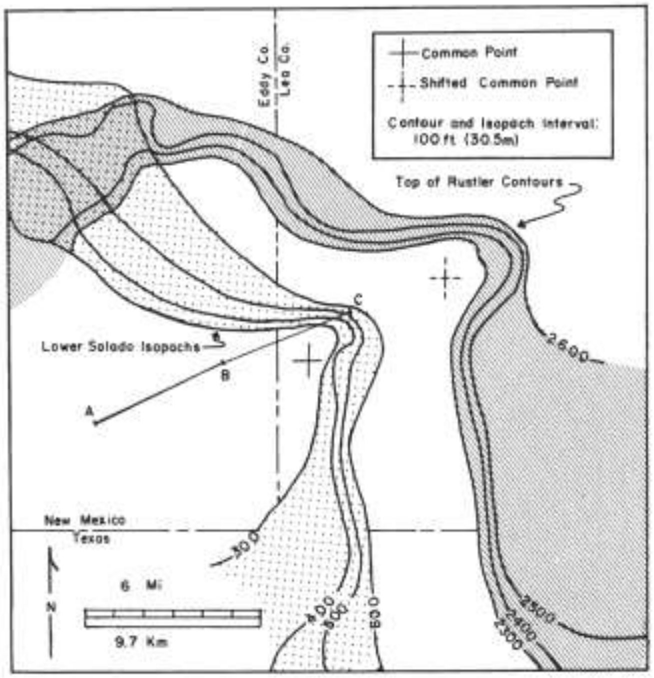


FIGURE 7—RELATIONSHIP BETWEEN STRUCTURE ON TOP OF RUSTLER FORMATION AND REMOVAL OF SALT FROM THE LOWER PART OF THE SALADO FORMATION. Note that removal of 300 ft (91 m) of Lower Salado salt has resulted in approximately the same amount of depression of Rustler contours. Common point of Rustler isopach contours must be shifted southwest to same location as common point of Salado contours for original placement. Isopach interval is between the Cowden Anhydrite Member and 136 marker bed; locations shown in fig. 1.

Conclusions

1) Every salt bed recognized on acoustical logs in the eastern side of the Delaware Basin has an equivalent bed of dissolution breccia in the western side of the basin, indicating that all of the western salt-bed margins are dissolutional rather than depositional.

2) The dissolution of salt beds proceeded downdip from the western edge of the basin with the preferred dissolution horizons occurring between the Halite HI salt of the Castile Formation and the 136 marker bed of the Salado Formation.

3) Downdip dissolution within the body of evaporites has undercut the overlying salt beds for distances in excess of 20 mi (32.4 km), and more extensive dissolution at these same horizons in localized areas resulted in large scale collapse and dissolution features such as the Big Sinks depression.

References

Anderson, R. Y., Dean, W. E., Jr., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved evaporite sequence, west Texas, and New Mexico: Geological Society of America, Bull., v. 83, p. 59-86

Anderson, R. Y., and Kirkland, D. W., 1966, Intrabasin varve correlation: Geological Society of America, Bull., v. 77, p. 241-255

Dowhan, D. J., 1976, Test drilling to investigate subsidence in bedded salt: Wyandotte, Michigan, Wyandotte Corp., unpub. rept., 13 p.

Hiss, W. L., 1975, Stratigraphy and ground water hydrology of the Capitan aquifer, southeastern New Mexico and western Texas: Ph.D. thesis, University of Colorado, 396 p.

Jaron, M. G., 1970, Investigation of solution collapse breccia in mature salt cavities: Third Symposium on Salt, Northern Ohio Geological Society, p. 422-428

Kirkland, D. W., and Anderson, R. Y., 1970, Microfolding in the Castile and Todilto evaporites, Texas and New Mexico: Geological Society of America, Bull., v. 81, p. 3259-3282

Kirkland, D. W., and Evans, R., 1976, Origin of limestone buttes, Gypsum Plain, Culberson County, Texas: American Association of Petroleum Geologists, Bull., v. 60, p. 2005-2018

Landes, K. K., 1959, The Mackinac breccia, *in* Geology of Mackinac Island and Lower and Middle Devonian south of the Straits of Mackinac, F. D. Shelden, ed.: Michigan Basin Geological Society, Guidebook, p. 19-24

Malley, V. C., and Huffington, R. M., 1953, Cenozoic fill and evaporite solution in the Delaware basin, Texas and New Mexico: Geological Society of America, Bull., v. 64, p. 539-545

Myers, A. J., 1962, A fossil sinkhole: Oklahoma Geology Notes, Oklahoma Geological Survey, v. 22, p. 13-15

Vine, J. D., 1960, Recent domal structures in southeastern New Mexico: American Association of Petroleum Geologists, Bull., v. 44, p. 1903-1911

, 1976, Breccia pipes and burial metamorphism in Permian evaporites of the Delaware Basin, New Mexico (abs.): Geological Society of America, Abstracts with Program, v. 8, p. 1154

TRANSITIONAL NATURE AND SIGNIFICANCE OF THE CASTILE-BELL CANYON CONTACT

by John M. Cys, *Mapco, Inc., 723 Western United Life Building, Midland, Texas 79701*

Abstract

The nature of the Bell Canyon-Castile contact has not been previously recognized because of the lack of adequate surface exposures and subsurface well cores that include the contact. The contact had been considered unconformable, primarily on the basis of the sharp distinction between the two units on mechanical well logs. However, a recent well core from Winkler County, Texas, shows that the contact is transitional; in approximately 3 ft the sequence changes from laminated siltstone and shale, to siltstone and limestone, to anhydrite and limestone. A recently described (Wilde and Todd, 1968; Wilde, 1975) surface section at a little-studied locality in the northern Apache Mountains, Culberson County, Texas, has a 10-20-ft transiton zone of thinly bedded alternating limestone, siltstone, and gypsum. Because the Bell Canyon is believed to be a deep-water deposit, the transitional contact implies that Castile evaporite deposition was in deep water, at least initially, and not in shallow water as some workers have postulated.

Introduction

The Bell Canyon-Castile contact is a significant one in the Permian Basin area because it represents a major, rapid change from siltstone and limestone to cyclic evaporite deposition. The abrupt change in depositional regime has been considered by some workers as suggestive of an unconformity. The exact nature of the contact has not been previously recognized because of the lack of adequate surface exposures and subsurface well cores that include the contact. However, a core recently cut from the Union Oil Company of California No. 4 University "37" well (fig. 1), Winkler County, Texas, included the contact and shows that it is transitional. This core was noted by Cys (1975), but no details were given. Wilde and Todd (1968, p. 23) briefly mentioned a surface locality in Seven Heart Gap (fig. 1), in the northern Apache Mountains, where the contact is exposed. Wilde (1975) gave a general description of the contact. This paper gives detailed descriptions of the contact at both localities.

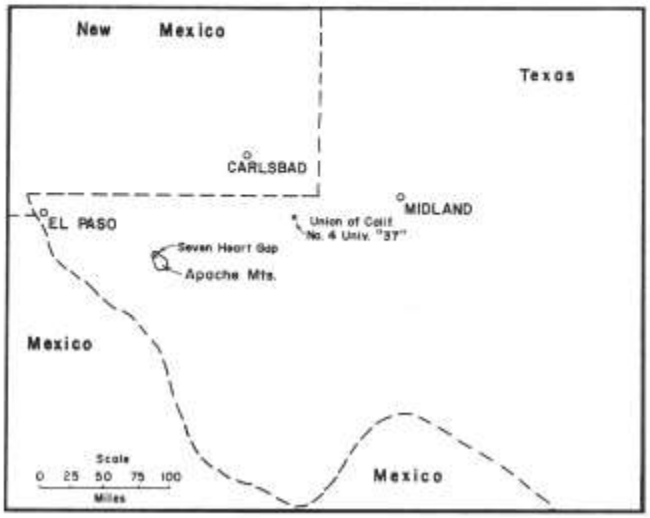


FIGURE 1—LOCATION INDEX MAP.

ACKNOWLEDGMENTS—Special thanks go to Garner L. Wilde, Exxon Company, U.S.A., Midland, Texas, for helpful information, advice, and field assistance in the Apache Mountains. Thanks also go to Mary Louise Rhodes, Chevron Oil Company, Denver, Colorado, for allowing me to examine core photographs and descriptions before the core itself was available to me. S. J. Mazzullo, Faculty of Earth Science, University of Texas of the Permian Basin, Odessa, Texas, very kindly reviewed an earlier draft of this paper and made laboratory facilities available to me for study of the core.

Union No. 4 University "37" well core

A number of wells have penetrated the Bell Canyon-Castile contact, but very few have taken cores that included the contact. One of the wells that did include it is the Union No. 4 University "37," Winkler County, Texas. As Wilde (1975) indicated, the contact on mechanical well logs is sharp (fig. 2) and is suggestive of an unconformity. The core in the Union No. 4 University "37" shows the contact to be transitional. The reasons that it appears sharp on mechanical logs are: 1) the transition interval is thinner than the minimum thickness resolution of the logging tool, and 2) anhydrite and limestone-siltstone have markedly different log-curve responses. The contact interval in the core is shown in figs. 3 and 4 and described below:

Depth (in ft)	**Lithology**
Castile	
4984-4991	Nodular anhydrite in dark-gray to black calcite matrix
4991-4992	Discontinuous and contorted anhydrite-calcite laminae interlayered with and grading into nodular anhydrite in upper 6 inches. Bottom 6 inches consists of thin, alternating laminations of anhydrite and dark, organic-rich calcite
Bell Canyon	
4992-4996	Laminated siltstone and lime mudstone with scattered anhydrite crystals oriented parallel to laminae at 4,994-4,995 ft
4996-4997	Small, elongate, rounded limestone pebbles in a calcareous siltstone matrix
4997-5003	Laminated shale and siltstone with scattered anhydrite and calcite crystals at 5,002 ft
5003-5016	Finely laminated, black, gray, and tan calcareous siltstone and shale with a few interbedded fine-grained sandstone laminae. Scattered calcite and anhydrite crystals oriented parallel to the laminae at 5,015-5,016 ft

The contact in the core is abrupt but definitely transitional. The sequence changes from laminated siltstone and shale, to siltstone and limestone, to anhydrite and limestone. This is a thinly laminated sequence with no evidence of erosion. I fail to recognize the 50-cm-thick basal limestone member interval that Anderson and others (1972) identified at the base of the Castile in this core. I place the contact at 4,992 ft, at the base of the first lamina of anhydrite.

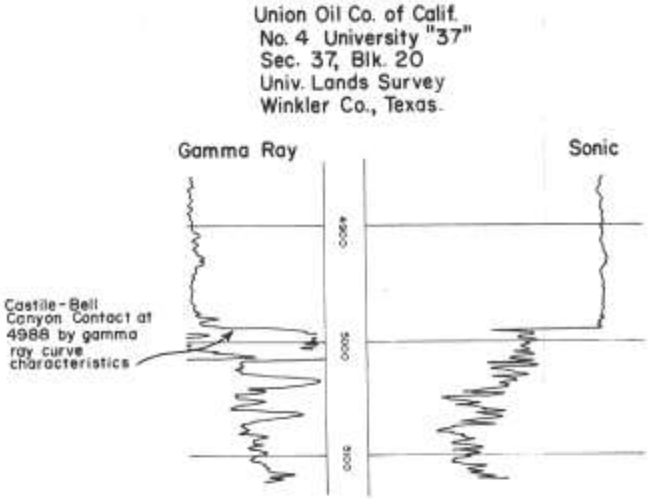


FIGURE 2—MECHANICAL LOG OF THE UNION NO. 4 UNIVERSITY "37" WELL SHOWING THE ABRUPT CONTACT BETWEEN THE BELL CANYON AND CASTILE FORMATIONS.

Seven Heart Gap

The Castile is easily weathered and eroded and, as a result, the contact with the underlying Bell Canyon is almost always covered. The only exception known to me is the eastern end of Seven Heart Gap in the northern Apache Mountains. Based on field observations in 1955, Wilde (1975) described the sequence here as 10-20 ft of decidedly alternating platy limestone, gypsum, and calcareous siltstone.

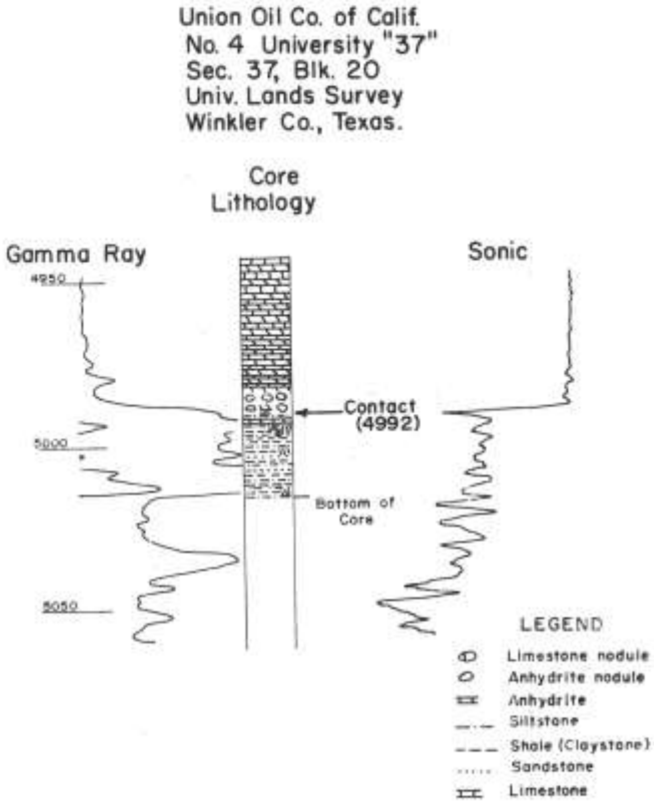


FIGURE 3—DIAGRAM OF THE BASAL 70 FT OF THE UNION NO. 4 UNIVERSITY "37" WELL CORE SHOWING THE CONTACT AT A DEPTH OF 4,992 FT.

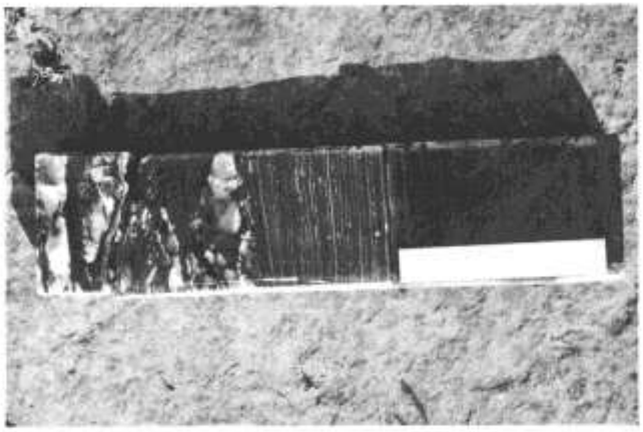


FIGURE 4—PHOTOGRAPH OF THE CONTACT INTERVAL IN THE UNION NO. 4 UNIVERSITY "37" WELL CORE. The contact is at the upper edge of the 6-inch plastic ruler.

Unsuccessful attempts to relocate this sequence were made both by myself and with Garner Wilde in the spring of 1977; we concluded that post-1955 weathering and erosion had covered the sequence that he had previously observed. However, a second exposure of the contact was discovered during our search for the first. To facilitate its location and study by other workers, the contact is documented in photographs and a detailed locality map (figs. 5-7). The contact interval is described as follows:

Bed No.	Thickness (inches)	Lithology
Castile		
4	8-12	Broadly laminated dark-gray limestone and gypsum. Laminations not always visible on weathered surfaces
3	4	Grayish-white, friable, sucrosic, slightly calcareous gypsum
Bell Canyon		
2	6	Black micritic limestone with very abundant rusty colored (limonite-stained), very thin, discontinuous laminae and blebs of very fine silt grains. Numerous calcite-filled vertical fractures
1	12-24	Gray to dark-gray calcirudite

The contact described above is abrupt; however, it is also transitional with no evidence of erosion. It is noteworthy that the lithology of this sequence is different from that of the Union No. 4 University "37" well core and that the basal limestone member of Anderson and others (1972) is absent.

Other areas

I have examined cores of the Castile-Bell Canyon contact in the shallow subsurface of the Rustler Hills (approximately 30 mi north-northeast of the Apache Mountains). In this area also, the contact is both abrupt and transitional with a generalized sequence as follows:

Castile
5 Alternating thin laminae of calcite and anhydrite. 30 + ft thick
4 Laminated, slightly (at base) to very (at top) anhydritic, gray to dark-gray limestone. 1 1/2-2 ft thick
3 Thinly laminated dark-gray limestone. 1 1/4-2 ft thick

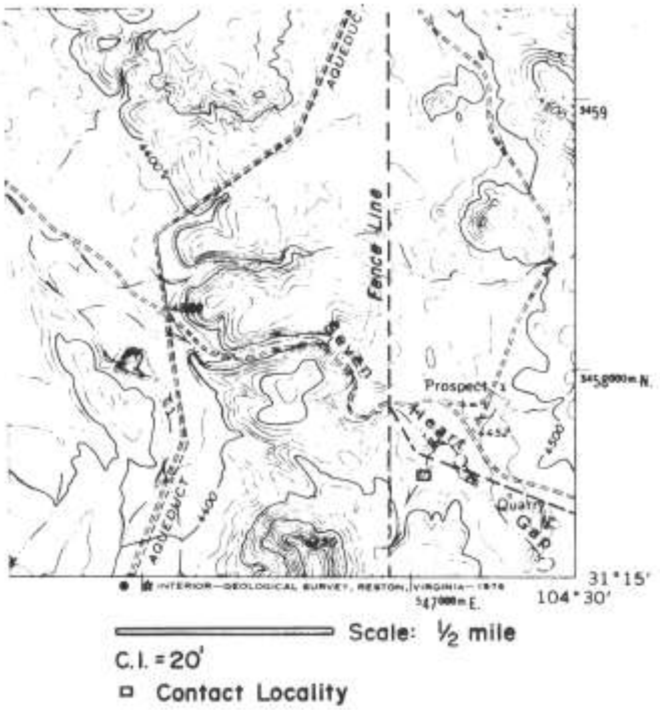


FIGURE 5—DETAILED TOPOGRAPHIC MAP SHOWING THE LOCATION OF THE CASTILE-BELL CANYON CONTACT EXPOSURE AT THE EAST END OF SEVEN HEART GAP.

Bell Canyon

2 Very silty, laminated to very thin bedded, black limestone. 2-3 ft thick

1 Black, slightly calcareous, thin-bedded siltstone. 6-10 ft thick

The lithology is different from the previous two localities discussed. I would assign Units 3 and 4 to the basal limestone member of Anderson and others (1972).

Anderson and others (1972) also described five well cores from eastern Culberson County, Texas, and concluded the contact was both abrupt and transitional. They described a general lithologic sequence of thin organically laminated siltstones, organically laminated claystones (Bell Canyon Formation), organically laminated calcite (basal limestone member of the Castile), and thin alternating laminae of anhydrite and calcite.

FIGURE 6—PHOTOGRAPH OF THE CONTACT LOCALITY AT THE EAST END OF SEVEN HEART GAP SHOWING THE GEOGRAPHIC RELATIONSHIP TO PROMINENT TOPOGRAPHIC FEATURES IN THE IMMEDIATE AREA. Garner Wilde is kneeling next to a flat-surfaced outcrop of bed no. 2. View is toward the north.

FIGURE 7—PHOTOGRAPH OF THE EXPOSURE OF THE BELL CANYON-CASTILE CONTACT AT THE EAST END OF SEVEN HEART GAP. The sample bag is on bed no. 1, and Garner Wilde is standing on bed no. 4. View is toward the east-southeast.

Significance

The Bell Canyon Formation, primarily on the basis of projected dips away from the Capitan reef, is considered to have been deposited in marine waters at a depth of 1,200-1,800 ft (Newell and others, 1953). Additional evidence for deep-water deposition at the Seven Heart Gap locality described earlier in this paper is relatively complete hexactinellid sponges found approximately 20-30 ft below the top of the Bell Canyon Formation (to be described in a later paper not in this volume). Also suggestive, but not unequivocal, of deep water are possible flow-roll and pillow structures (fig. 8) found in the upper Bell Canyon Formation.

FIGURE 8—POSSIBLE FLOW-ROLL AND PILLOW STRUCTURES IN A LIMESTONE OF THE UPPER BELL CANYON FORMATION AT THE EAST END OF SEVEN HEART GAP.

As Dean and others (1975) have pointed out, a sabkha origin may be postulated for the Castile primarily on the basis of the presence of nodular anhydrite, which is supposedly diagnostic of a subaerial sabkha environment. If this interpretation is correct, then a rapid relative lowering of sea level of 1,200-1,800 ft would have been required between the end of Bell Canyon deposition and the start of Castile deposition. With such a drop in sea level, evidence of an unconformity should be expected; however, there is none. Instead, the transitional nature of the contact with the underlying deep-water Bell Canyon Formation indicates that the Castile, at least initially, was deposited in deep water. Anderson and others (1972) and Dean and others (1975) present sedimentological evidence for the Castile being deposited in deep water.

Conclusions

The lithologic sequence at the Castile-Bell Canyon contact is extremely variable; however, at all localities it is both transitional and abrupt. There is strong evidence to support a deep-water origin for the Bell Canyon Formation. Hence, the transitional nature of the contact strongly implies that the lower Castile was deposited in deep water and not in a subaerial sabkha environment.

References

Anderson, R. Y., Dean, W. E., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved evaporite sequence, west Texas and New Mexico: Geological Society of America, Bull., v. 83, p. 59-86

Cys, J. M., 1975, New observations on the stratigraphy of key Permian sections of west Texas, *in* Permian exploration, boundaries, and stratigraphy: West Texas Geological Society and Society of Economic Paleontologists and Mineralogists, Permian Basin Sec., p. 22-42

Dean, W. E., Davies, G. R., and Anderson, R. Y., 1975, Sedimentological significance of nodular and laminated anhydrite: Geology, v. 3, p. 367-372

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

Wilde, G. L., 1975, Fusulinid-defined Permian stages, *in* Permian exploration, boundaries, and stratigraphy: West Texas Geological Society and Society of Economic Paleontologists and Mineralogists, Permian Basin Sec., p. 67-83

Wilde, G. L., and Todd, R. G., 1968, Guadalupian biostratigraphic relationships and sedimentation in the Apache Mountains region, west Texas, *in* Guadalupian facies, Apache Mountains area, west Texas: Society of Economic Paleontologists and Mineralogists, Permian Basin Sec., p. 10-31

STRATIGRAPHY AND MINERAL RESOURCES OF GUADALUPIAN AND OCHOAN ROCKS IN THE TEXAS PANHANDLE AND WESTERN OKLAHOMA

by Kenneth S. Johnson, *Oklahoma Geological Survey, University of Oklahoma, Norman, Oklahoma 73019*

Abstract

Permian strata of Guadalupian and Ochoan age in the Texas Panhandle and western Oklahoma comprise a thick sequence of evaporites and red-bed shales and sandstones deposited north and northeast of the platform bounding the Midland Basin. These strata are 400 to 600 ft thick in much of the area, but they reach 2,000 to 3,000 ft in the major depositional basins. The study area embraces the Palo Duro, Anadarko, and Dalhart Basins and the Matador, Wichita-Amarillo, Cimarron, and Bravo uplifts. Lithostratigraphic studies enable correlation of the fossiliferous sequence of west Texas and southeast New Mexico with the sparingly fossiliferous red beds and evaporites of the Texas Panhandle and western Oklahoma. The early Guadalupian San Andres Formation of the Palo Duro Basin is correlative with the San Angelo (Duncan), Flowerpot, Blaine, and Dog Creek Formations of the El Reno Group farther north and east. The late Guadalupian Artesia Group of the Palo Duro Basin is equivalent to the Whitehorse Group and part of the overlying Cloud Chief Formation of the Anadarko Basin. Ochoan strata in the western and central parts of the Palo Duro Basin include the Salado, Rustler, and Dewey Lake Formations. The Salado salts pinch out northward within the basin, whereas the upper part of the Rustler extends northward and is correlative with the Alibates Bed. The Dewey Lake is believed equivalent to the Doxey Shale of western Oklahoma. The youngest Ochoan unit is the Elk City Sandstone, which apparently is limited to the axis of the Anadarko Basin. Mineral resources that have been developed include salt, gypsum, copper, uranium, petroleum, dolomite, sandstone, shale, and flint. Other minerals present in small quantities include potash and celestite.

Introduction

Guadalupian and Ochoan rocks of the Texas Panhandle and western Oklahoma are a thick sequence of red beds and evaporites laid down in and near a broad, shallow inland sea that extended north and northeast of the platform that bordered the Midland Basin (Mills, 1942; Clifton, 1944; Ham, 1960). Evaporites, chiefly salt (halite) and gypsum (or anhydrite), were precipitated from evaporating sea water as layers on the sea floor or grew as coalescing crystals in a host of mud just below the depositional surface. Thick red-bed shale and sandstone units were deposited on the perimeter of the evaporite basins, and some of these also extended as blanket deposits across the entire area; many thin red-bed clastic units are interbedded with the evaporites.

Major tectonic features in the area include the Palo Duro, Anadarko, and Dalhart Basins and the Matador, Wichita-Amarillo, Cimarron, and Bravo uplifts (fig. 1), all of which were developed mainly during the Pennsylvanian Period (Roth, 1955; Galley, 1958; Nicholson, 1960; Ham and Wilson, 1967; Hartman and Woodard, 1971; Adler and others, 1971). Although tectonic activity had largely subsided by the end of Pennsylvanian time, most of these features still exercised some control on sedimentation and facies distribution during the Permian.

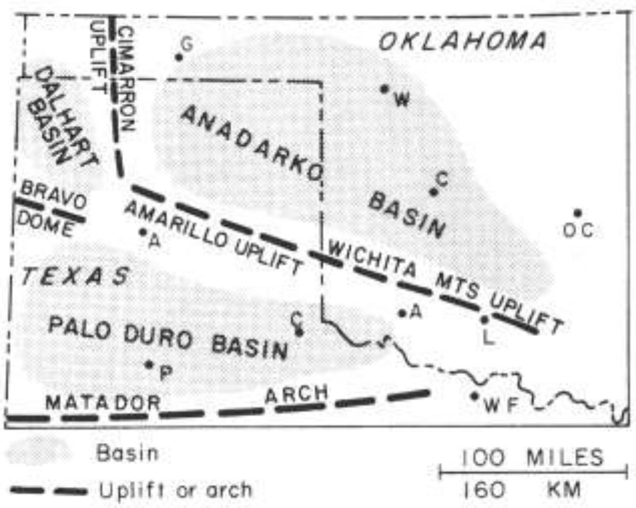


FIGURE 1—MAP SHOWING MAJOR TECTONIC FEATURES OF TEXAS PANHANDLE AND WESTERN OKLAHOMA. City names (single letters) are spelled out in fig. 2.

Since Permian time, there have been some continued minor tectonic adjustments in these provinces, with the basins subsiding slightly in comparison to the surrounding uplifts. The minor vertical movements have resulted partly from post-tectonic adjustments along preexisting zones of weakness and partly from differential rates of compaction where a thicker column of Permian and pre-Permian strata in the basins permitted a greater amount of settlement in the basins. Thus, although the pre-Permian rocks are locally faulted and complexly folded, the Permian strata are virtually free of major structural deformation and in most areas have a regional dip of less than one-half degree. The gentle regional dip is disrupted at many places where outcropping strata have collapsed owing to dissolution of underlying Guadalupian and Ochoan salt beds (locally, collapse is due to dissolution of gypsum).

Present-day outcrops are principally along the east side of the study area, whereas to the west the Late Permian strata are largely covered by 500 to 2,000 ft of Mesozoic and Cenozoic sedimentary rocks of the High Plains (fig. 2).

ACKNOWLEDGMENTS—Publication of this report is authorized by the Director of the Oklahoma Geological Survey. The report is an outgrowth of the Survey's ongoing study of Permian rocks in Oklahoma and of a study of salts and other evaporites in the Permian Basin conducted for the Office of Waste Isolation, Union Carbide Corp., Nuclear Division, under contract to the U.S. Energy Research and Development Administration.

Appreciation is expressed to Robert 0. Fay and the late William E. Ham, who have done much of the recent work on Permian rocks in the study area and with whom I have discussed many of the geologic data herein described. Illustrations were drafted by Roy D. Davis and Wendy Oberlin, cartographers with the Oklahoma Geological Survey.

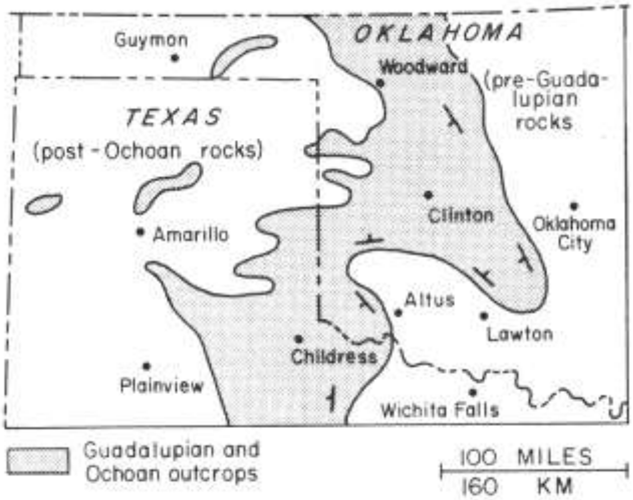


FIGURE 2—Map showing outcrops of Guadalupian and Ochoan strata.

Stratigraphy

The Guadalupian and Ochoan sequence of red beds and evaporites is typically 400 to 600 ft thick in much of the Oklahoma Panhandle and in the northern part of the Texas Panhandle. These strata thicken southward to nearly 3,000 ft across the Palo Duro Basin, and they thicken eastward to nearly 2,000 ft in the Anadarko Basin.

Age assignments of the largely unfossiliferous strata in the study area are based primarily upon lithostratigraphic correlation with equivalent strata at the south boundary of the area. The stratigraphic sequence and age of these formations in the western and central parts of the Palo Duro Basin (fig. 3) have been well established (Tait and others, 1962; McKee and others, 1967; Summers and Kottlowski, 1969; Jones, 1974), owing to intensive study of the same strata in the nearby Midland Basin and adjacent platform areas where they are fossiliferous. Thus, one of the major results of the current study is establishment of regional lithostratigraphic correlations between the fossiliferous sequence of west Texas-southeast New Mexico and the sparingly fossiliferous red-bed-evaporite sequence of the Texas Panhandle-western Oklahoma area.

Early Guadalupian

Early Guadalupian strata are a thick sequence of evaporites that grade laterally into red-bed shales and sandstones to the east and west and into carbonates (dolomite and then limestone) to the southwest on the northern platform of the Midland Basin (fig. 4). Outcropping early Guadalupian strata in north-central Texas and western Oklahoma include the San Angelo (Duncan), Flowerpot, Blaine, and Dog Creek Formations of the El Reno Group (Scott and Ham, 1957; Fay, 1964; Johnson, 1967), which have also been referred to in Texas as the Pease River Group (Roth, 1945).

The San Angelo Sandstone consists of 50-200 ft of light-gray and red-brown sandstone, siltstone, and mudstone conglomerate interbedded with greenish-gray shale. It has an interfingering contact with the overlying Flowerpot Shale and is a deltaic and alluvial deposit that grades into shale westward a short distance back from the outcrop (fig. 4). The name San Angelo is applied to the unit south of the Wichita Mountains, whereas equivalent and similar strata north of the Wichitas are called Duncan Sandstone.

The overlying Flowerpot Shale is 100 to 300 ft of red-brown shale with thin interbeds of gypsum, dolomite, siltstone, sandstone, and green-gray shale on the outcrop. In subsurface to the west, the upper part of the formation contains several hundred feet of rock salt (halite) and salty shale, referred to as the Flowerpot salt (Jordan and Vosburg, 1963).

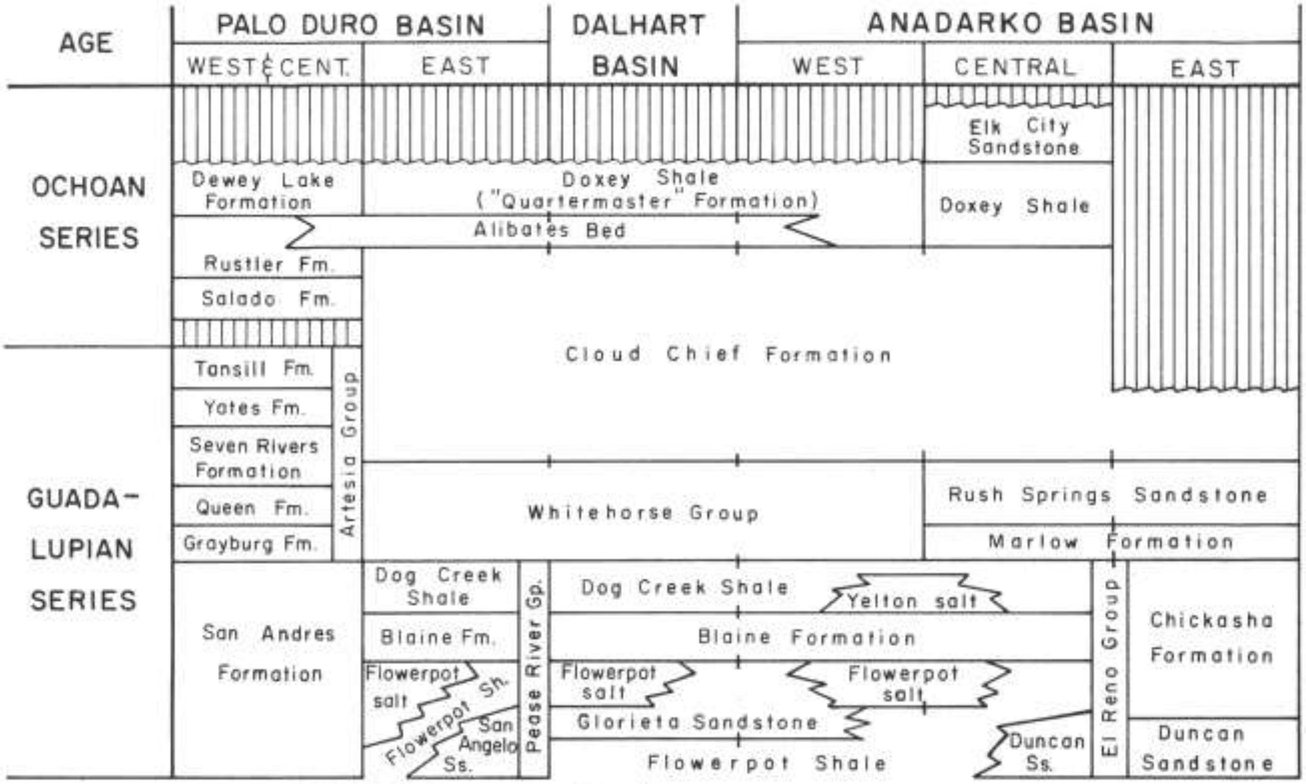


FIGURE 3—Chart showing Late Permian stratigraphic nomenclature.

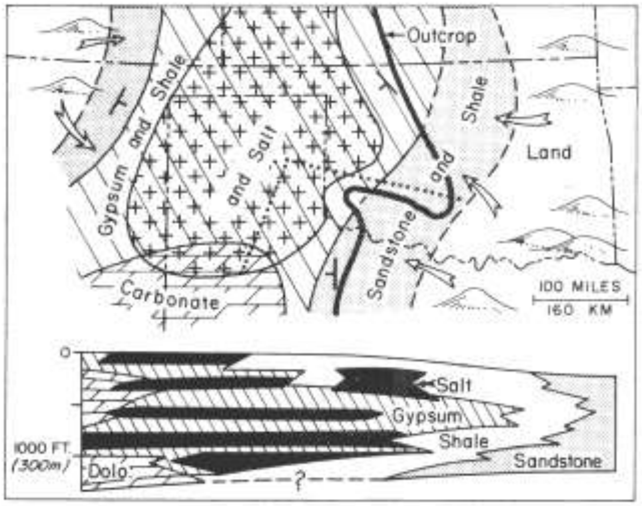


FIGURE 4—MAP SHOWING EARLY GUADALUPIAN PALEOGEOGRAPHY AND SCHEMATIC CROSS SECTION. Line of cross section shown by row of dots.

Overlying the Flowerpot is the Blaine Formation, which consists chiefly of thick beds of pure gypsum interstratified with red-brown shale. Thin beds of dolomite and green-gray shale typically underlie each of the gypsum beds. Evaporites in the Blaine were deposited during the maximum transgression of the shallow sea during early Guadalupian time, before regression of the sea in later Dog Creek time. The Blaine Formation is about 200 ft thick in most of the study area but is about 100 ft thick on the north flank of the Anadarko Basin, where the upper Blaine gypsums were not deposited. Individual gypsum and shale beds are commonly 5 to 30 ft thick, and dolomite beds are generally 1 to 10 ft thick. Gypsum, dolomite, and (in subsurface) salt beds are thicker to the west and south, whereas shale beds are thinner.

The overlying Dog Creek Shale is 50 to 200 ft of red-brown shale interbedded with thin layers of gypsum, dolomite, and green-gray shale. Several hundred feet of salt (Yelton salt of Jordan and Vosburg, 1963; Johnson, 1967) and salty shale are present in the lower part of the Dog Creek in subsurface along the axis of the Anadarko Basin and west of the outcrop in the eastern Palo Duro Basin. At the southeast end of the Anadarko Basin, the Dog Creek, Blaine, and Flowerpot Formations all grade laterally into alluvial and deltaic red beds of the Chickasha Formation (fig. 3).

The El Reno Group of the outcrop extends westward and southwestward in subsurface into the San Andres Formation in the western and central parts of the Palo Duro Basin. The San Andres consists chiefly of interbedded anhydrite, salt, dolomite, and shale, with thick beds of dolomite being abundant in the bottom 200 to 300 ft of the formation. Total thickness of the San Andres ranges from about 1,200 ft in the west to less than 800 ft in the east-central part of the basin, where many of the salt beds have been dissolved. The same lithologies extend westward into east-central New Mexico (Jones, 1974), but they grade into a thick sequence of limestones and dolomites south and southwest of the Palo Duro Basin (Summers and Kottlowski, 1969).

The regional relationship of the Glorieta to the San Andres and Blaine Formations and other early Guadalupian units is not fully established. The Glorieta underlies the Blaine Formation in parts of the Dalhart and western Anadarko Basins and must be equivalent in part to the Flowerpot Shale and possibly the Duncan-San Angelo. To the southwest, in New Mexico, Glorieta sandstone beds are placed in the lower San Andres (Summers and Kottlowski, 1969); however, in the Palo Duro Basin sandstone referred to as Glorieta is below the basal dolomites of the San Andres.

Late Guadalupian

Late Guadalupian strata are mostly red-bed sandstones and shales, with some interbeds of salt and gypsum (fig. 5). The Whitehorse Group is predominantly orange-brown cross-bedded sandstone with minor amounts of red-brown shale in eastern outcrops and in subsurface of the Anadarko and Dalhart Basins. The thickness of the Whitehorse Group ranges from about 225-300 ft in much of the Texas Panhandle and northern Anadarko Basin (Fay, 1965) to as much as 400-600 ft along the depositional axis in the central and eastern parts of the Anadarko Basin. The Whitehorse Group is divided into the Marlow Formation and overlying Rush Springs Sandstone in most of the Anadarko Basin: the Marlow is typically 100 to 120 ft thick, whereas the Rush Springs ranges from 125 to nearly 500 ft.

Overlying the Whitehorse Group is the Cloud Chief Formation, which consists mainly of red-brown to orange-brown shale interbedded with some sandstone and gypsum. A bed of massive gypsum 100 ft thick is at the base of the formation in the eastern part of the Anadarko Basin. The thickness of the Cloud Chief ranges from about 125 to 200 ft over much of the Texas Panhandle and western Oklahoma (Fay, 1965), but it reaches 300 to 350 ft near the axis in the central part of the Anadarko Basin.

I believe that the lower part of the Cloud Chief is Guadalupian in age and that the upper part is Ochoan. This is based upon my correlation of the base of the Cloud Chief in eastern Palo Duro Basin outcrops with strata in the Seven Rivers Formation just back from the outcrop (Tait and others, 1962, p. 509, well 9) and upon the equivalence of basal Doxey-Alibates-upper Rustler strata (fig. 3). This latter equivalence is affirmed by correlation of the Alibates dolomite (gypsum or anhydrite, in places) with the thick evaporites shown in the upper Rustler (Tait and others, 1962, p. 508-509) in the Palo Duro Basin and farther southwest and by the correlation of the Alibates with the base of the Doxey in western Oklahoma (Fay, 1965).

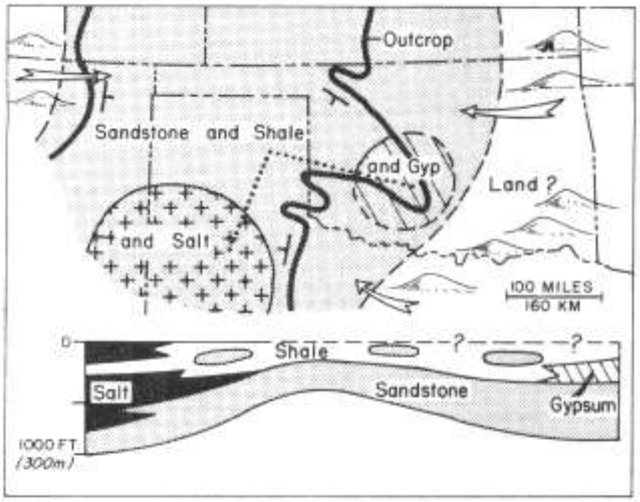


FIGURE 5—MAP SHOWING LATE GUADALUPIAN PALEOGEOGRAPHY AND SCHEMATIC CROSS SECTION.

The Artesia Group of the western and central parts of the Palo Duro Basin is about 800 to 1,200 ft thick and consists of red-bed shales and sandstones interbedded with salt and some anhydrite and dolomite (Tait and others, 1962). The thick salt deposits occur chiefly in the Seven Rivers and Tansill Formations. It was originally thought that the Artesia and Whitehorse Groups were correlative (Tait and others, 1962); but, as mentioned above, I believe that only the Grayburg, Queen, and lower Seven Rivers are equivalent to the Whitehorse, whereas the upper Seven Rivers, Yates, and Tansill are equivalent to the lower Cloud Chief.

Ochoan

Ochoan rocks are mainly red-bed sandstones and shales, but they contain some gypsum and dolomite in the northern Texas Panhandle and a thick salt unit farther south (fig. 6). The upper part of the Cloud Chief Formation and regional correlations of the late Guadalupian-Ochoan strata were discussed previously. Rocks equivalent to the upper Cloud Chief in the western and central parts of the Palo Duro Basin are the Salado Formation and the lower part of the Rustler Formation. The Salado is a wedge of salt and thin shale interbeds that thickens southward to about 300 ft in the south-central Palo Duro Basin: the hiatus beneath the Salado Formation represents presumed nondeposition in the area while the Castile Formation was being laid down farther southwest in the Delaware Basin of west Texas and southeast New Mexico. The Rustler Formation consists mainly of red-brown shales in the lower part, overlain by a pair of gypsum (anhydrite) or dolomite beds. The thickness of the Rustler is typically 50 to 100 ft.

The Alibates Bed in most parts of the Texas Panhandle consists of two beds of dolomite or gypsum, each 5 to 30 ft thick, separated by 5 to 20 ft of red-bed shale. The Alibates is equivalent to the upper part of the Rustler Formation farther south and is believed by Fay (1965) and me to be approximately correlative with the base of the Doxey Shale to the east.

The Doxey Shale is red-brown to maroon shale with thin beds of siltstone and sandstone. It is 180 to 200 ft thick in the central part of the Anadarko Basin and is typically much thinner farther west, where it is truncated in the Anadarko and Dalhart Basins. The Doxey (referred to as the Quartermaster Formation in much of the Texas Panhandle) is correlated with the Dewey Lake Formation to the southwest, owing to lithologic similarities and the correlation of the Alibates Bed with the upper Rustler (fig. 3); the Dewey Lake is about 200 ft thick in the central part of the Palo Duro Basin.

Overlying the Doxey Shale in the central part of the Anadarko Basin is the Elk City Sandstone (fig. 3). The Elk City is therefore younger than the Ochoan rocks of west Texas and southeast New Mexico, and thus it appears to be the youngest Permian rock unit in North America. Elk City strata are mainly cross-bedded orange-brown sandstones that range in thickness from 50 to 185 ft (Fay, in press).

Mineral resources

Mineral resources in the Guadalupian and Ochoan evaporite sequences include major deposits of salt and gypsum and minor amounts of potash and celestite. Clastic sequences contain stratiform copper deposits and uranium occurrences in outcrops along the east side of the area. Other resources developed on a local or limited scale are oil and gas, dolomite, sandstone, shale, and flint.

SALT—Salt resources of the region are vast and are widely distributed (fig. 7). Earlier reports by Jordan and Vosburg (1963) and Johnson (1972) indicated reserves in the trillions of tons and showed that the deeper Leonardian strata also contain major salt deposits (Hutchinson salt, Lower Cimarron-Lower Clear Fork salt, and Upper Cimarron-Upper Clear Fork salt). Principal salt-bearing units of the Guadalupian and Ochoan are the San Andres Formation and the equivalent Flowerpot and Yelton salts, the Seven Rivers and Tansill Formations of the Artesia Group, and the Salado Formation.

Individual salt beds are typically 5 to 30 ft thick. Salt is interbedded principally with thin layers of red-brown shale, although gypsum or anhydrite or both are present in some sequences. Each of the basins contains one or more salt-bearing sequences, 50 to 300 ft thick, wherein halite makes up 60 to 90 percent of the rock. At no place are there salt domes or salt anticlines such as in the Gulf Coast or Paradox Basin.

Salt beds range from 30 to 4,000 ft below the land surface in various parts of the region, although at most localities the shallowest salt is 500 to 2,000 ft below the surface

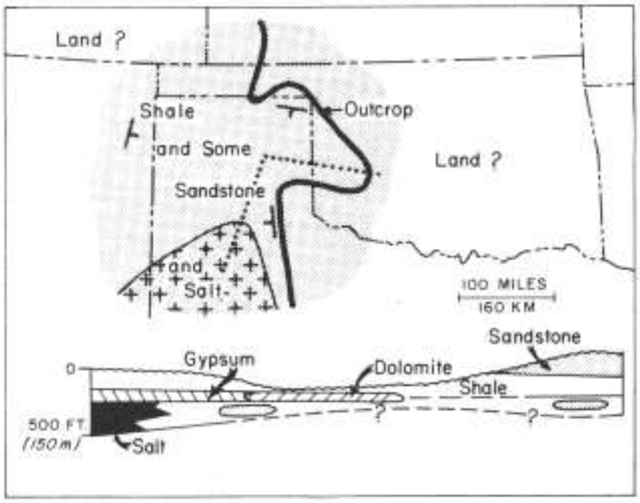


FIGURE 6—MAP SHOWING OCHOAN PALEOGEOGRAPHY AND SCHEMATIC CROSS SECTION.

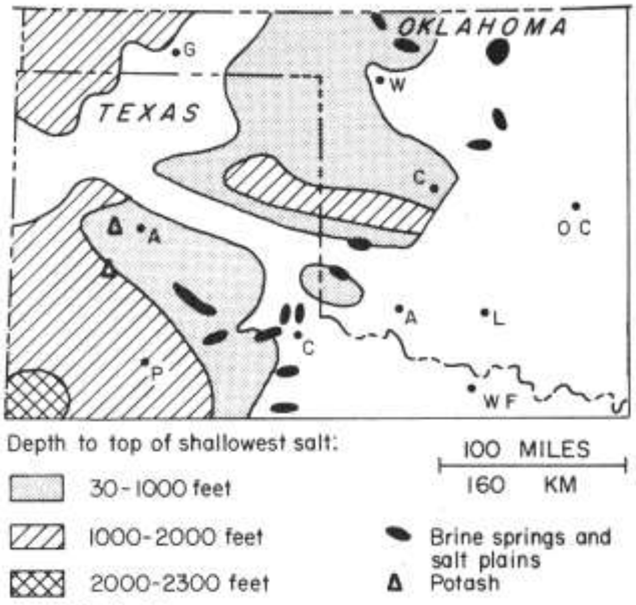


FIGURE 7—MAP SHOWING DISTRIBUTION OF SALT AND POTASH RESOURCES AND LOCATIONS OF NATURAL BRINE SPRINGS AND SALT PLAINS.

(fig. 7). Saturated brine, formed by dissolution of salt in the shallow subsurface, is emitted at 14 natural salt springs or salt plains in the area, with emissions ranging from 150 to 3,000 tons of salt per salt plain per day.

The depth and thickness of salt beds make them suitable for either underground or solution mining, but to date the small amount of production has been by solar evaporation of brine on the salt plains. Chemical and petrographic data on the salt are lacking, but analysis of brine and of salt produced from the brine indicates a fairly high purity.

POTASH—Although potash is being mined underground from the Salado Formation near Carlsbad in southeast New Mexico, there is no evidence that significant amounts of potash salts were deposited in the Texas Panhandle and western Oklahoma region. Udden (1915) reported traces of potash in tests drilled in Texas at Boden, Potter County, and at Miller Ranch, Randall County (fig. 7). In the Boden test, potash was reported at a number of levels between 390 and 2,010 ft, which ranges from 225 ft above the San Andres to several hundred feet below the San Andres. In the Miller Ranch test, potash occurred in samples 1,500 to 2,100 ft deep, in the top half of the San Andres Formation.

GYPSUM—Large reserves of high-purity gypsum and anhydrite are present at and near the surface, chiefly in the Blaine and Cloud Chief Formations in the east half of the area (fig. 8). Reserves of stone available to open-cut mining (maximum overburden, 30 ft) in Oklahoma alone are estimated to be 48 billion short tons (Johnson, 1972), and additional near-surface reserves in the southeastern part of the Texas Panhandle are probably several billion tons.

Gypsum beds in the Blaine Formation are typically 10 to 30 ft thick and 95 to 99 percent pure (Scott and Ham, 1957; Ham, 1962). The number of massive gypsum beds in the Blaine ranges from 3 to 9 in different districts, whereas the total thickness of the formation ranges from 100 to 200 ft. The Cloud Chief gypsum is a single massive bed of gypsum that is 20 to 100 ft thick and is 92 to 97 percent pure (Ham and Curtis, 1958). Anhydrite lenses and beds occur locally a short distance back from gypsum outcrops, and in some areas they could be mined after removal of 20 to 40 ft of overburden (Ham and Curtis, 1958; Ham, 1962).

Open-pit mining of gypsum is now being done by eight companies in Oklahoma (Johnson, 1969) and one company in Texas. Most of the stone is used in making wallboard, but large quantities also are used for plaster, as a retarder in portland cement, and as a soil conditioner.

CELESTITE—Celestite and minor amounts of strontianite are associated with dolomite and gypsum locally in eastern Washita and Custer Counties, Oklahoma (fig. 8). They are present in the top part of the Rush Springs Formation (in and above the thin Weatherford Dolomite Bed) and in the basal part of the Cloud Chief Formation. The celestite occurs as thin, subhorizontal veins and layers several inches to perhaps 1 ft thick and as crystals scattered in other host rocks. The deposits apparently are small, and no commercial production has been attempted.

COPPER—Scattered occurrences of copper minerals in the upper Permian red beds of western Oklahoma and Texas have been known for more than a century. Most deposits are small and consist of chalcocite and malachite as encrustations, impregnations, veinlets, or small nodules in shale and sandstone. Early attempts at commercial production were unsuccessful.

Discovery of thin but extensive copper shales containing 1 to 3 percent copper and some silver values (Ham and Johnson, 1964) led to strip mining of the deposit at Creta, Oklahoma, from 1965 through 1975. Further studies by Smith (1974) described deposits in north Texas, and a recent symposium (Johnson and Croy, 1976) dealt with various aspects of stratiform copper deposits in the Guadalupian sediments of the midcontinent.

The principal known copper occurrences are in the Flowerpot Shale and the San Angelo-Duncan Sandstones in southwestern Oklahoma and north Texas (fig. 9). The Creta deposit consists of 6 to 12 inches (average, 8 inches) of copper shale in the upper part of the Flowerpot along a 3-milong outcrop; the grade is about 2.5 percent copper, with small amounts of recoverable silver. Between 15 and 60 ft of overburden was removed by Eagle-Picher Industries, Inc., in its strip mine, and almost 2 million tons of ore was mined during its 11 years of operation. Similar deposits have been discovered in the Flowerpot near Mangum, Medicine Mounds, and Crowell, but these deposits are lower grade (1 to 2 percent copper) and have not been considered economical. Mineralization in the San Angelo-Duncan at Crowell and other locations south and north of the Wichita Mountains is chiefly irregular deposits associated with channels and fossil wood.

URANIUM—Descriptions of uranium-bearing sandstones and siltstones in Guadalupian and Ochoan strata in the

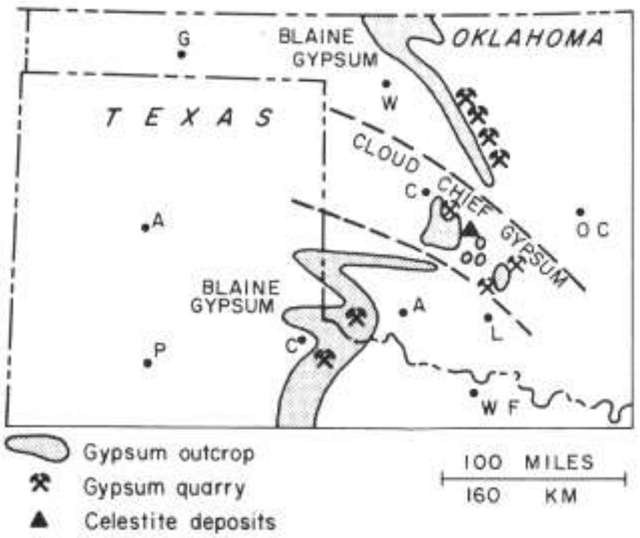


FIGURE 8—MAP SHOWING DISTRIBUTION OF GYPSUM AND CELESTITE RESOURCES.

FIGURE 9—MAP SHOWING DISTRIBUTION OF COPPER-BEARING AND URANIUM-BEARING STRATA.

eastern and central parts of the Anadarko Basin (fig. 9) were summarized recently by Al-Shaieb and others (1977). Carnotite and tyuyamunite are the chief uranium minerals, and they occur in white, gray, or yellow sandstones that generally are surrounded by red-colored sediments.

The only commercial production was about 13 tons of ore, averaging 2.2 percent uranium, mined in the 1950's from the upper part of the Rush Springs Sandstone at Cement, Oklahoma (Al-Shaieb and others, 1977). The ore was in a series of small pods along a fracture for a distance of 150 ft along the crest of the oil-productive Cement anticline. Other radioactivity anomalies occur in pink shales in the upper part of the Cloud Chief Formation and in siltstones of the Doxey Shale.

OTHER MINERALS-Oil and gas are produced from pre-Guadalupian rocks in many parts of the study area, but production from Guadalupian and Ochoan strata is limited to the San Andres Formation along the Matador arch in the extreme south. Dolomite, calcareous sandstones, and other stone are mined locally for road and construction material (Johnson, 1969). Shales in the Flowerpot, Chickasha, and Cloud Chief Formations are being mined for brick manufacture. The highly prized Alibates flint was quarried north of Amarillo by early Indians for making scraping tools, knives, and points for spears and arrows.

References

Adler, F. J., and others, 1971, Future petroleum provinces of the Midcontinent, Region 7, *in* Future petroleum provinces of the United States-their geology and potential: American Association of Petroleum Geologists, Mem. 15, v. 2, p. 985-1120

Al-Shaieb, Z., and others, 1977, Uranium potential of Permian and Pennsylvanian sandstones in Oklahoma: American Association of Petroleum Geologists, Bull., v. 61, p. 360-375

Clifton, R. L., 1944, Paleoecology and environments inferred for some marginal middle Permian marine strata: American Association of Petroleum Geologists, Bull., v. 28, p. 1012-1031

Fay, R. 0., 1964, The Blaine and related formations of north western Oklahoma and southern Kansas: Oklahoma Geological Survey, Bull. 98, 238 p.

, 1965, Geology and mineral resources of Woods County, Oklahoma: Oklahoma Geological Survey, Bull. 106, 189 p.

, in press, Geology and mineral resources of Custer County, Oklahoma: Oklahoma Geological Survey, Bull. 114

Galley, J. E., 1958, Oil and geology in the Permian Basin of Texas and New Mexico, *in* Habitat of oil: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 395-446

Ham, W. E., 1960, Middle Permian evaporites in southwestern Oklahoma: 21st International Geological Congress, Copenhagen, Part XII, Regional Paleogeography, p. 138-151

, 1962, Economic geology and petrology of gypsum and anhydrite in Blaine County, *in* Geology and mineral resources of Blaine County, Oklahoma: Oklahoma Geological Survey, Bull. 89, p. 10-11, 100-151

Ham, W. E., and Curtis, N. M., 1958, Gypsum in the Weatherford-Clinton district, Oklahoma: Oklahoma Geological Survey, Mineral Rept. 35, 32 p.

Ham, W. E., and Johnson, K. S., 1964, Copper in the Flowerpot Shale (Permian) of the Creta area, Jackson County, Oklahoma: Oklahoma Geological Survey, Circ. 64, 32 p.

Ham, W. E., and Wilson, J. L., 1967, Paleozoic epeirogeny and orogeny in the central United States: American Journal of Science, v. 265, p. 332-407

Hartman, J. K., and Woodard, L. R., 1971, Future petroleum resources in post-Mississippian strata of north, central, and west Texas and eastern New Mexico, *in* Future petroleum provinces of the United States-their geology and potential: American Association of Petroleum Geologists, Mem. 15, v. 1, p. 752-800

Johnson, K. S., 1967, Stratigraphy of the Blaine Formation and associated strata in southwestern Oklahoma: Ph.D. thesis, University of Illinois, 247 p.

, 1969, Mineral map of Oklahoma (exclusive of oil and gas fields): Oklahoma Geological Survey, Map GM-15, scale 1:750,000

, 1972, Gypsum and salt resources in Oklahoma: Industrial Minerals, no. 62, p. 33-39

Johnson, K. S., and Croy, R. L., eds., 1976, Stratiform copper deposits of the Midcontinent region, a symposium: Oklahoma Geological Survey, Circ. 77, 99 p. [1977]

Jones, C. L., 1974, Salt deposits of the Clovis-Portales area, east-central New Mexico: U.S. Geological Survey, Open-file Rept. 74-60, 22 p.

Jordan, L., and Vosburg, D. L., 1963, Permian salt and associated evaporites in the Anadarko basin of the western Oklahoma-Texas Panhandle region: Oklahoma Geological Survey, Bull. 102, 76 p.

McKee, E. D., and others, 1967, Paleotectonic maps of the Permian System: U.S. Geological Survey, Misc. Geol. Inv. Map 1-450, 164 p.

Mills, J. M., 1942, Rhythm of Permian seas-a paleogeographic study: American Association of Petroleum Geologists, Bull., v. 26, p. 217-255

Nicholson, J. H., 1960, Geology of the Texas Panhandle, *in* Aspects of the geology of Texas: a symposium: University of Texas, Bureau of Economic Geology, Pub. no. 6017, p. 51-64

Roth, Robert, 1945, Permian Pease River Group of Texas: Geological Society of America, Bull., v. 56, p. 893-907

, 1955, Paleogeology of Panhandle of Texas: American Association of Petroleum Geologists, Bull., v. 39, p. 422-443

Scott, G. L., Jr., and Ham, W. E., 1957, Geology and gypsum resources of the Carter area, Oklahoma: Oklahoma Geological Survey, Circ. 42, 64 p.

Smith, G. E., 1974, Depositional systems, San Angelo Formation (Permian), north Texas-facies control of red-bed copper mineralization: University of Texas, Bureau of Economic Geology, Rept. Inv. 80, 73 p.

Summers, W. K., and Kottlowski, F. E., eds., 1969, The San Andres Limestone, a reservoir for oil and water in New Mexico: New Mexico Geological Society, Spec. Pub. 3, 51 p.

Tait, D. B., and others, 1962, Artesia Group of New Mexico and west Texas: American Association of Petroleum Geologists, Bull., v. 46, p. 504-517

Udden, J. A., 1915, Potash in the Texas Permian: University of Texas, Bull. 17, 59 p.

CONVENTIONAL POTASH MINING

by Clark H. McNaughton, *International Minerals and Chemical Corp., P.O. Box 71, Carlsbad, New Mexico 88220*

Abstract

Conventional potash mining at the International Minerals and Chemical Corporation mine near Carlsbad, New Mexico, presently consists of the following cycle: Sixteen to twenty-four deep holes are drilled in the working face with a two-boom Joy CD73 Jumbo drill. At floor level a kerf is cut across the width of the face with a Joy 15RU undercutter. The drill holes are charged with an electric delay blasting cap, one stick of dynamite and prilled AN/FO (ammonium nitrate with about 6 percent fuel oil) and then blasted. After blasting, the broken ore in each room is loaded into a diesel ram car with a Joy gathering-arm loader. The back and ribs are scaled as loading progresses, and after the room is mucked clean, expansion-shell roof bolts are installed on a standard pattern. The ore is hauled to a Jeffrey ratio feeder in the panel, which feeds a conveyor belt that connects the area to the ore hoisting shaft. Each major area is presently producing with a crew of 6 miners, 1 foreman, and 1 maintenance man each per shift. The mine operates 7 days a week, with 3 shifts a day. Production crews average about 200 tons per manshift. Thirty-foot by fifty-foot pillars are left for support, and no pillar recovery is in progress at this time.

Introduction

International Minerals and Chemical Corporation's New Mexico potash operation is located approximately 25 mi east of Carlsbad. Surface facilities, besides the headframe (fig. 1), consist of office buildings, a large refinery and chemical plant, product warehouses, and the supporting electrical, machine, and carpenter shops.

Mining levels are serviced and ventilated by four mine shafts. All ore is hoisted through a single shaft located near the surface refinery. Ore is recovered by standard room-and-pillar techniques, using conventional coal-mining face equipment and belt haulage.

A primary concern of management has been mine safety. IMC is pleased that our Mine Production Department worked a 423-day period without lost-time injury during 1975-76. Our entire plant lost-time frequency rate during 1976 was 2.64, compared to a national average of about 20.

ACKNOWLEDGMENTS—The author expresses appreciation and gratitude to R. W. Hougland, Vice-President, Carlsbad Operations, International Minerals and Chemical Corp., for permission to present this paper and for his expert advice. Steve D. Birckett, Mining Engineer, International Minerals and Chemical Corp., reviewed the manuscript and offered constructive suggestions.

FIGURE 1—THE NO. 1 HEADFRAME AT THE IMC POTASH MINE NEAR CARLSBAD, NEW MEXICO.

IMC operations

Conventional potash mining presently consists of the following cycle: Sixteen to twenty-four 1-7/8-inch diameter by 11-ft-deep holes are drilled in a 32-ft wide by 72-108-inchhigh working face with a two-boom Joy CD73 Jumbo drill (fig. 2). Two rows of 8 holes each are drilled, with the top row 6-12 inches below and parallel to the mud seam at the top of the ore. The second row is collared about waist high and angled downward to bottom about 12 inches above the undercut. In faces over 100 inches high, 3 rows of 8 holes each are drilled.

Auger drill steel is used with tungsten carbide-tipped rotary-drill bits that are resharpened after drilling. Area production foremen mark the drill pattern and spacing for each round on the face with spray paint. If the placement of drill holes is carefully controlled, the later loading operation is faster and more efficient.

At floor level a 6-inch kerf is cut 11 ft deep across the width of the face with a Joy 15RU undercutter (fig. 3). About 65 bits in a set are used in a cutter chain and must be changed after 2 to 6 cuts. These bits are also sharpened and reused. The skill with which the cutter is operated results in a smooth or rough floor for later haulage and is critical in controlling the grade of the ore mined. If the cut is below the ore, the feed grade of the crude ore mined is reduced rapidly.

The drill holes are charged with an electric delay blasting cap, one stick of 1-inch-by-6-inch dynamite, prilled AN/FO, and then blasted. AN/FO is a mixture of ammonium nitrate and about 6 percent fuel oil. Four delays are used with the center waist-high holes first, the waist-high rib holes second, the center back holes third, and the corner rib holes last. The primer stick with electric cap is placed in the mouth of the drill hole and pushed to the back of the hole with a semiconductive loading tube; AN/FO prills are then blown into the hole as the tube is withdrawn (fig. 4). About 2 ft of unloaded hole is left at the collar. At IMC the advance is about 9 1/2 ft to 10 ft per round.

After blasting, about 150 to 180 tons of broken ore in each room are loaded into a 404-HP1A-1E Jeffrey diesel ram car with a 14 BU10-41BH Joy gathering-arm loader (fig. 5). Two ram cars are normally operated behind one loader, so one car is being loaded while the other is discharging at the end of the belt. Each ram car will haul about 11 tons per trip.

FIGURE 2—A TWO-BOOM JOY JUMBO DRILL PUTTING 16-24 HOLES INTO THE MINED SEAM

[New Mexico Bureau Mines & Mineral Resources, Circular 159, 1978]

FIGURE 3—THE JOY UNDERCUTTER USED TO PUT IN A 6-INCH KERF, 11 FT DEEP, ACROSS THE WIDTH OF THE MINED FACE.

The back and ribs are scaled as loading progresses, and after the room is mucked clean, 5/8 inch diameter by 2- to 6-ft expansion-shell roof bolts are installed on a standard pattern. Additional spot bolting is installed where the condition of the back appears to require more support. The ore is hauled to a Jeffrey ratio feeder in the panel at the end of a 42-inch-wide conveyor belt (fig. 6), which connects the production area to the ore hoisting shaft.

At IMC, each major area is presently producing with a production crew of 6 miners, 1 foreman, and 1 maintenance man each per shift. The mine is operated 7 days a week, 3 shifts a day. Production crews average about 200 tons per manshift. Thirty-feet-by-fifty-feet pillars are left for support (fig. 7), and no pillar recovery is in progress at this time. In a normal panel, 2 miners operate ram cars, 1 undercuts faces, 1 drills rounds, 1 loads ore, and 1 charges drill holes and does miscellaneous face work.

Mining is on three levels. On the 800-ft level a mixed sylvitelangbeinite ore is mined from the Fifth Ore Zone. On the 850-ft level a langbeinite ore is taken from the Fourth Ore Zone, and on the 900-ft level mixed ore is mined from the First Ore Zone.

Carlsbad district

In the Carlsbad area the 7 current underground operations produce an average of about 9,000 tons per day of sylvite (KCl) crude ore at a feed grade averaging 14.5 percent K$_2$0 as sylvite. Average sylvite-ore grades for the Carlsbad mining district have declined rapidly during the past few years—from about 21 percent in 1955 to the present 14.5-percent average. 1MC is presently mining the lowest-grade sylvite ore in the hemisphere and thus must continue to be efficient in order to compete with other producers.

FIGURE 4—AMMONIUM NITRATE AND FUEL OIL (AN/FO) IS BLOWN INTO THE DRILL HOLES AS THE TUBE IS WITHDRAWN.

FIGURE 5—A DIESEL-POWERED JEFFREY RAM CAR IS LOADED BY A JOY GATHERING-ARM LOADER.

FIGURE 6—ORE IS HAULED TO A JEFFREY RATIO FEEDER AT THE END OF A 42-INCH CONVEYOR BELT, WHICH CONNECTS THE PRODUCTION AREA TO THE ORE HOISTING SHAFT.

FIGURE 7—THIRTY- BY 50-FT PILLARS ARE LEFT FOR SUPPORT.

CATIONIC FLOTATION OF SYLVITE

by M. P. Scroggin, *Duval Corporation, P.O. Box 511, Carlsbad, New Mexico 88220*

Abstract

The cationic chemical used to float sylvite is a tallow amine consisting primarily of C18 saturated and unsaturated straight-chain amines with some C16 saturated amine. The most logical explanation of the attachment of the amine to sylvite is that aminium ion fits in the place of potassium at a sylvite surface. Sylvinite ore must be deslimed thoroughly before the addition of the amine collector, because the cationic reagent coats the slimes in preference to sylvite. Desliming is accomplished by scrubbing and separating the slime from the sands through the use of hydrocyclones, rake classifiers and thickeners. A reagent with a large number of attached hydroxyl ions that is compatible with the absorptive surface of the slimes is used to blind the small amount of slimes remaining. Reagentizing is accomplished first by adding a slimes blinder, second, by adding the cationic collector, and last by adding a frother. The sylvite ore is floated in two steps: First the sylvite is floated in two banks of rougher cells, and then the overflow of the rougher cells is transported by gravity to 2 banks of cleaner cells and reflotated, because some fine salt is floated in the rougher cells, making this additional separation step necessary. After flotation, the concentrate is centrifuged, dried, and sized.

Introduction

Armour Chemical Division (no date) defines cationic flotation as flotation accomplished by means of cationic chemicals. These chemicals consist of molecules that, upon ionizing in a water circuit, liberate a long-chain fatty ion carrying a positive charge. The fatty cation will attach itself to those minerals that possess a high concentration of negative surface charges providing a hydrophobic surface, which permits flotation. This definition does not apply to cationic flotation of sylvite, because sylvite has a positively charged surface.

Gaudin (1957) states that "it is remarkable that two isomorphous minerals such as sylvite and halite can be separated by flotation, and . . . it is all the more remarkable to note that the best separations between these minerals, which differ only in the cation, are obtained with collectors having an active cation." Gaudin further states that "the only interpretation that makes sense is that the aminium ion fits in the place of potassium at a sylvite surface but does not fit in place of sodium at a halite surface."

The cationic chemical used to float sylvite is a tallow amine consisting primarily of C18 saturated and unsaturated straight-chain amines with some C16 saturated amine. Amines are organic bases and are neutralized with acetic or hydrochloric acid. The resulting amine acetate or hydrochloride ionizes in water, resulting in an increased ability to be used in flotation.

Cationic reagents coat slimes first, in preference to sylvite; therefore, it is necessary to deslime as thoroughly as possible before adding the amine collector. However, even with good desliming, there is a small amount of slimes left in the ore that must be treated to nullify its affinity for the collector. Even a small amount of slimes, without treatment, is detrimental to good flotation. The clay material associated with the ores in the Carlsbad area and that produces the slime in processing, predominantly consists of the smectite (montmorillonite) group of clay minerals. The two most common reagents used to blind the remaining slimes are starch (hydrolyzed or causticized) and mannogalactan gums. According to G. E. Atwood and D. J. Bourne (1953):

> "In tailoring a blinding agent for the process, numerous characteristics are important. The reagent must be extremely compatible with the adsorptive surface of the montmorillonite, hence a hydrophillic or hydroxyl-laden molecule. Molecular structure should be non-ionic to prevent electrostatic interference. Configuration of the reagent must permit easy access between the clay sheets when they are normally extended by hydration. Individual attractive forces will at best be relatively weak; therefore, the molecule should be as large as possible so that a mass bounding effect will be obtained. Additionally, high molecular weight, long chain molecules, by virtue of their protruding bulk, could temporarily armor the clay particle against penetration by the cationic collector. Hydroxyl configuration should be such that the free groups are cis, thus augmenting the weak bonding forces by chelation as suggested by A. M. Gaudin. From the practical and operational standpoint, the material should be cheap, naturally occurring, and of dependable quality and quantity."

Process

GRINDING—In Duval Corporation's mill, the initial grinding is accomplished with a Pennsylvania Impactor. The impactor discharge is mixed with saturated brine and is passed over a wet screen on which the oversize material is separated from the on-size material, with the on-size material going to scrubber tanks by gravity flow and the oversize material being pumped to a rod mill for further grinding. The rod-mill discharge is pumped to another wet screen, with the on-size material going to the scrubber tanks and the oversize being pumped back to the rod mill. The grinding section is a closed circuit that assures proper sizing of all material for flotation.

SCRUBBING—The ore is slurried in saturated brine and is passed through a series of tanks that contain agitators with attrition-type blades. The scrubbing is accomplished by the particles being scrubbed in contact with other particles. Scrubbing accomplishes two main purposes: freeing the slimes for separation and obtaining clean surfaces on the sylvite particles for reagentizing.

DESLIMING—Desliming is accomplished in hydrocyclones, rake classifiers, a hydroseparator, and thickeners (fig. 1). The first three separate the slimes from the ore and the fourth thickens the slimes for removal from the circuit.

REAGENTIZING—After desliming, the first reagent added is the slimes blinder, which is a mannogalactan gum. Contact between the gum and remaining slimes is made in a tumbler. Prior to the material entering a second tumbler, the cationic collector (amine hydrochloride) is added. In the second tumbler, the attachment of the collector to the sylvite crystals is accomplished as previously discussed. After the ore is conditioned with the collector, a frother is added just prior to pumping the slurry to the flotation cells.

FLOTATION—Flotation is achieved in two steps: The first is the rougher step where the initial separation is made. In this step, the sylvite and some fine halite are floated. In the Duval Mill, the rougher cells consist of 2 parallel banks of five 100-cu-ft cells with the overflow from the first 3 cells of each bank being moved by gravity to 2 parallel banks of cleaner cells where a further separation of the sylvite and halite is made (fig. 2). The underflow from the cleaner cells along with the overflow from the last 2 cells from each rougher bank flows by gravity to a pump box. Here the combined flows are

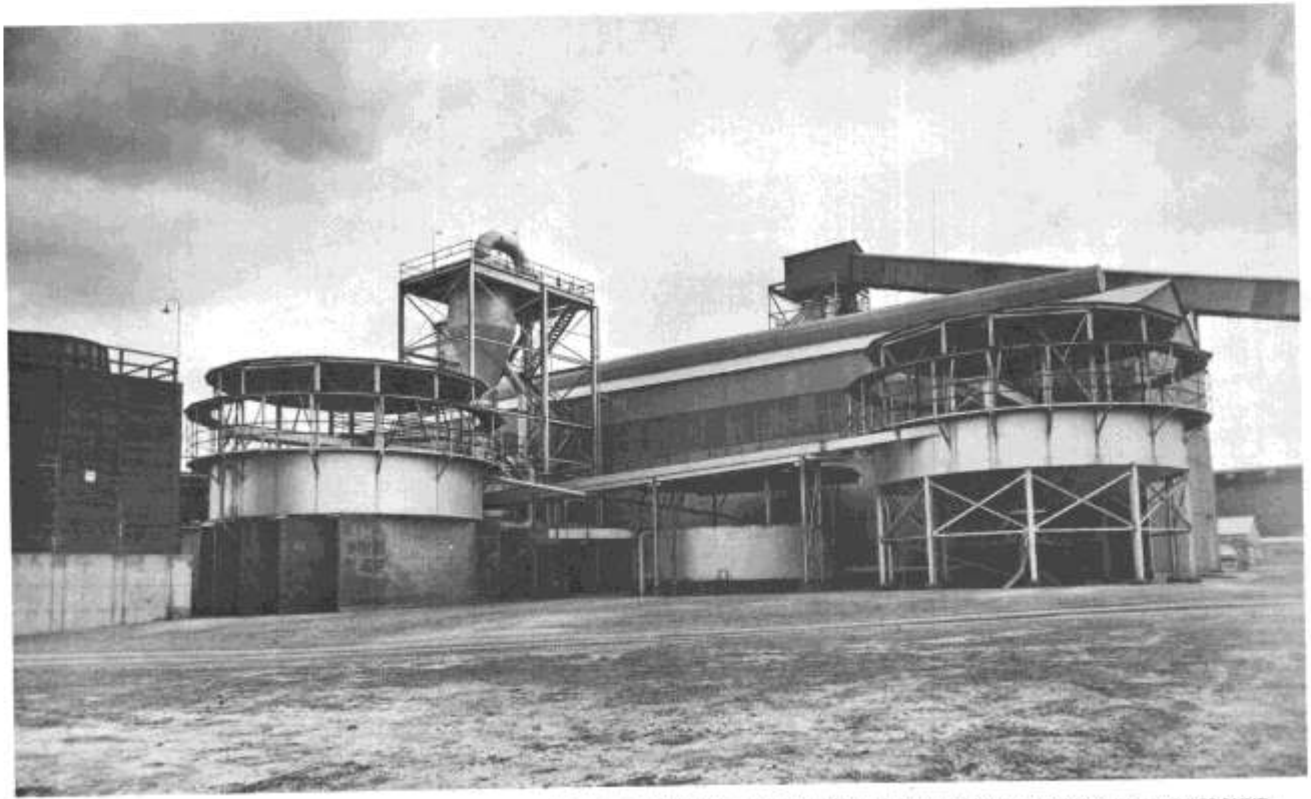


FIGURE 1—PORTION OF THE DESLIMING SECTION OF THE DUVAL PLANT WITH THICKENERS (METAL CYLINDRICAL TANKS) IN THE FOREGROUND.

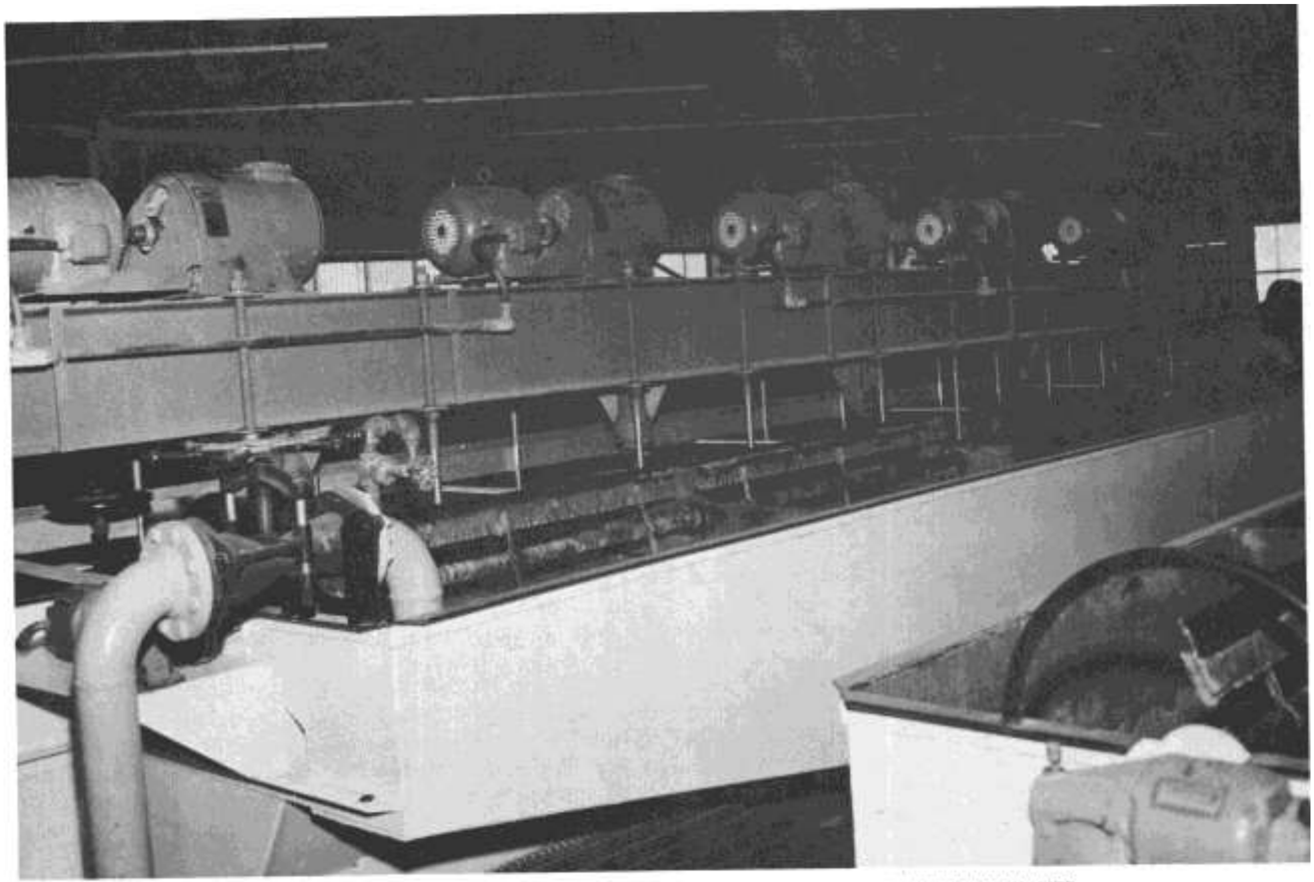


FIGURE 2—FLOTATION CELLS AT THE DUVAL PLANT USED TO SEPARATE SYLVITE FROM HALITE.

pumped to wet screens from which the overflow (middlings) flows to the product retention tank, and the underflow, containing mostly halite but some fine sylvite, is moved to the leach section for recovery of the contained sylvite. (The middling circuit is a process patented by Duval Corporation.) The combined middlings and overflows from the cleaner cells are centrifuged (fig. 3), with the cake being dried and sized and the brine being returned to the circuit.

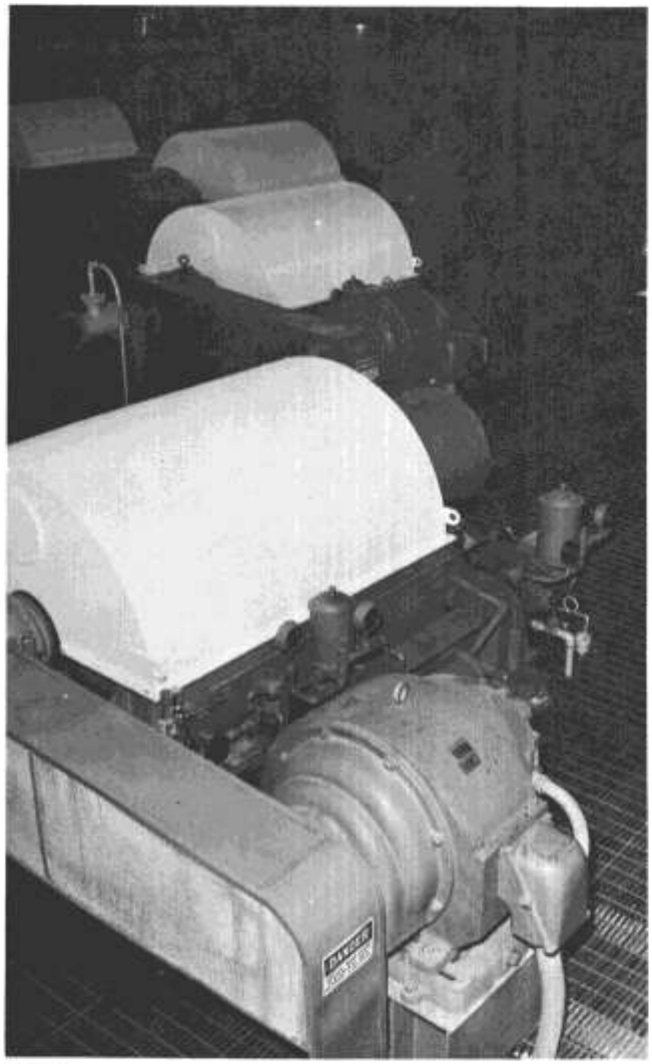


FIGURE 3—CENTRIFUGE DECK WHERE SYLVITE IS SEPARATED FROM BRINE. THE BRINE IS RETURNED TO THE CIRCUIT, AND THE SYLVITE CAKE IS DRIED AND SIZED.

References

Armour Chemical Division, no date, What is cationic flotation?: Armour Chemical Division, trade paper

Atwood, G. E., and Bourne, D. J., 1953, Process development and practice of the Potash Division of the Duval Sulphur and Potash Co.: Mining Engineering, v. 5, p. 1099-1104

Gaudin, A. M., 1957, Flotation: 2nd ed., New York, McGraw-Hill, 573 p.

LEACH/CRYSTALLIZATION-PROCESS FOR POTASH PRODUCTION

by Walter S. Case, *Jr., Kerr-McGee Chemical Corporation, P.O. Box 610, Hobbs, New Mexico 88240*

Abstract

The high clay content of Kerr-McGee's ore and the technology existing in the early 1960's dictated the use of a leach/crystallization flow scheme to economically recover potash from the ore. The process depends on the difference in solubility of potash and salt in hot and cold brines. The resulting product is somewhat higher in potash content and is snow white because more impurities are removed than when a flotation process is used.

Introduction

The Kerr-McGee Chemical Corporation's Hobbs Potash Facility is the newest of seven operations in the Potash Basin with production beginning in 1965. Approximately 3 million tons of ore per year is mined exclusively from the Tenth Ore Zone. The ore contains 21-27 percent sylvite (KCl) with halite (NaCl), clay, and several sulphate minerals as the other major ore constituents. Potash in the ore is processed to a finished product containing 98 percent or more KCl, or as it is more commonly designated in the fertilizer industry, 62 percent or more K_2O equivalent. This is at a production capacity of about 600,000 tons per year; the Kerr-McGee mill is roughly average in size. About 450 people are employed, with about two-thirds in underground and one-third in topside operations. As is the case with the other processing plants, over 90 percent of the production finds its end use as plant food. The largest acreage crops planted in the U.S. require about 200 lbs of potash per acre per year.

The process

The Kerr-McGee operation is the only Carlsbad area plant using exclusively leach/crystallization to recover potash values. Other mills' processes depend on flotation for the separation of potash from the other ore constituents. What is the reason Kerr-McGee uses crystallization? The high clay content of the ore necessitates this approach. The ore contains 6-7 percent montmorillonite-type clay. Most of the other mines in the area have less than half of this amount. At the time when Kerr-McGee's process was developed, it was found that the clay acted as an absorbent, or sponge, for flotation reagents and resulted in prohibitively high reagent costs. There was no economic way to remove the amount of clay required to make flotation economic and to realize adequate recovery of potash values. Consequently, in the late 1950's and early 1960's Kerr-McGee developed a process around differential solubility concepts that were known as early as 1900 by Vant Hoff (d'Ans, 1933), detailed by d'Ans (1933), and further quantified in the early 1950's by Autenrieth (1954, 1955). When the process was developed using fairly elaborate heat recovery systems, the fuel cost roughly offset reagent costs of other manufacturers, and potash recovery was much greater than if a flotation technique had been applied to the high clay ore.

To detail the concept of leach/crystallization, the Kerr-McGee process uses hot unsaturated brine to dissolve or leach potash away from the rest of the ore, making a solid-liquid separation; the liquid is then cooled to precipitate or crystallize potash from solution. For example, a barrel will contain about 350 lbs of water. At room temperature, this amount of water will dissolve about 53 lbs of potash or KC1 and 87 lbs of salt or NaCl. If this brine is heated to boiling, the same 350 lbs of water would dissolve a total of 110 lbs of KC1 while NaCl solubility decreases slightly to 84 lbs; potash solubility more than doubles while salt solubility decreases. The other members of the suite of potassium, sodium, magnesium, calcium, and sulphate minerals in the ore have varying solubilities and do effect the absolute potash-salt-solubility relationships to make processing interesting, but do not change the concept appreciably.

Mill operations

After the ore is hoisted to the surface, it is first crushed to a size that allows complete dissolution of the largest potash particles in the time available in the system's tanks. Next, most of the clay is removed. This is necessary because potash is blended with other plant nutrients. Consumers need consistent, specified product sizes to eliminate segregation of the plant foods after they are blended. If clay were left, its presence in the crystallization step would result in extremely fine potash crystals that would not be consistent with sizes of the other fertilizer components. The clay is removed mainly by hydrocyclones and then is washed in six 240-ft-diameter thickeners to recover finely divided and soluble potash values. The clay is then discarded.

The potash is dissolved away from the remaining ore constituents in the step called leaching. This is done in agitated tanks with heat supplied through steam coils submerged in these tanks. Next, the hot potash-laden brine is separated from the coarse waste materials, using hydrocyclones and continuous centrifuges. After washing to remove entrained brine, these coarse solids are reslurried and pumped to a disposal area. During the leaching step, more clay is liberated from the ore, and it follows the liquid in the solid-liquid separation step. The hot brine is then clarified in a 150-ft diameter hot thickener; the separated clay is combined with the clay removed earlier.

Next, this clear liquor, at approximately 3,000 gpm (gallons per minute) and about 200 °F, is fed to the first of 6 crystallizers in series. Each crystallizer cools the brine about 20°, which precipitates potash from the solution. Cooling is achieved by evaporation of water to give the required temperature drop. This is not the same as evaporation to dryness, which would result in crystallization of salt as well as potash. In fact, the water evaporated must be replaced to maintain the delicate double-saturation of KCl and NaCl at the different crystallizer temperatures. In each of the 6 crystallizers, evaporation is accomplished by boiling at the progressively lower temperatures, which are achieved by increasing vacuum or decreasing absolute pressure. In the hotter units, vacuum is obtained using steam jet ejectors. In the cooler units, vacuum is obtained using barometric condensers. Heat is transferred from vapors to brine destined for the leaching step using shell and tube heat exchangers. As brine cools in the upper part of the crystallizer, it becomes supersaturated and is then circulated through a bed of crystals suspended in the lower portion of the crystallizer body. The supersaturation is relieved on these crystals, causing them to grow. A slurry of these crystals is being removed continuously at a rate of about 13 tons per hour from each unit. Kerr-McGee's crystallizers are 70 ft high, 32 ft in diameter, and have a nominal volume of 130,000 gallons. Internal circulation rates are about 20,000 gpm. Finally, the product slurry is thickened, filtered, and the crystals are dried, sized, and stored for future shipment.

Because there is a premium for larger-sized products, a portion of the smallest or "standard"-sized product is converted to one of the larger-sized materials, either "coarse" or "granular." This is done in the last process step. Small particles are fed between hydraulically loaded rolls to produce a compacted board about 3/8 inch thick and 2 ft wide. The board is broken down in several crushing stages and particles sized. Oversized material is returned to the crushing step, and undersized material is returned to the compactor.

To give a better concept of the magnitude of the material handled at the Kerr-McGee plant, the normal ore feed rate to the mill is between 350 and 400 tons per operating hour; this is enough ore to fill 4 average railroad cars each hour. In the plant, brine flows are in the range of 3,000 gpm, which would fill a normal-sized highway tank transport in 2-3 minutes. Processed sylvite leaves the process at a rate of nearly one railroad car full each hour.

References

Autenrieth, H., 1954, Die stabilen und metastabilen gleichgenichte des reziproken salzpaars $K_2Cl_2 + MgSO_4 \rightleftharpoons K_2SO_4 + MgCl_2$ ohne und mit NaCl als Bodenkörper, sowie ihre Anwendung in der Praxis: Kali u. Steinsalz 1, H. 7, p. 3-22

Autenrieth, H., 1955, Neue, für die kalirohsalzuerarbeitung wichtige untersuchungen am quinären, NaCl-gesähigten system der salze ozeanischer salzablagerungen: Kali u. Steinsaltz 1, H. 11, p. 18-32

d'Ans, J., 1933, Die lösungsgleichgewichte der systeme der salze ozeanischer salzablagerungen: Kali-Forschungsanstalt, Berlin, Verl. Ges. F. Ackerbau, 254 p.

SULFUR DEPOSITS IN OCHOAN ROCKS OF SOUTHEAST NEW MEXICO AND WEST TEXAS

by A. Richard Smith, *Olin Corporation, P.O. Box 10680, Houston, Texas 77018*

Abstract

Elemental sulfur is common in gypsum and gypsiferous rocks of Ochoan age in the Delaware Basin, Eddy County, New Mexico, and in Culberson and Reeves Counties, Texas. The sulfur presumably formed in two steps: Hydrocarbons migrated vertically or laterally from source beds or traps into the gypsum (possibly anhydrite) strata, there to be attacked by anaerobic bacteria, which used the hydrocarbons for energy and reduced the sulfate ion in the gypsum, forming hydrogen sulfide as one product and limestone as the other. Alternatively, the hydrogen sulfide migrated into the gypsum beds from hydrocarbon accumulations elsewhere. In the second step the hydrogen sulfide was oxidized to elemental sulfur where conditions were appropriate: by oxygen-rich ground water, by sulfate-rich ground water, or by sulfide-oxidizing bacteria. The crystalline sulfur is usually found in the secondary limestone. Sulfur in Delaware Basin rocks occurs along faults and joints in the Castile Formation, usually near the base, and as irregular masses and lenses in the Salado residuum. Deposition of sulfur is guided and localized by: 1) fractures permitting migration of hydrocarbons or hydrogen sulfide into gypsum beds, 2) suitable ground water flow patterns, and 3) an impermeable confining bed. All known deposits also occur west of the updip edge of salt in the Castile.

Sulfur was strip mined in the late 1800's and early 1900's in Culberson County for use as a soil conditioner. Prior to the late 1960's sporadic sulfur exploration followed discoveries of sulfur in oil tests or was an attempt to drill below surface occurrences. From about 1966 through 1970 the major sulfur companies and several oil companies drilled more than 1,300 sulfur test holes in the 3 counties. A few modest deposits were found, most with less than 2 million long tons each, but only the giant Rustler Springs deposit (60 to 90 million long tons) found by Duval Sulphur Company was considered suitable for Frasch mining. Duval commenced production there on September 30, 1969, and had produced 11,236,824 long tons through December 31, 1976. Sulfur leasing and drilling activity has continued intermittently, but no more elephants have been found.

Introduction

The Rustler Springs (Culberson) sulfur mine near Orla, Texas, is the world's largest producer of sulfur by the Frasch method. Duval Corporation, a subsidiary of Pennzoil Corporation, began mining there on September 30, 1969, and had mined 11,236,824 long tons through December 31, 1976; production continues at rates of more than 1.7 million long tons per year. Operating capacity of the mine is about 2.5 million long tons annually. Reserves in place were originally estimated to be about 60 million long tons, and subsequent drilling has confirmed and increased the reserve tonnage.

Other sulfur deposits have been discovered in this area. Like the Rustler Springs deposit, they are associated with Ochoan evaporitic rocks in the Delaware Basin. All these others are much smaller, from which the question arises: Is there only one very large sulfur deposit in the Delaware Basin? That question leads naturally to other questions, such as: Why is the Rustler Springs deposit so large and in its particular location? How and why does it differ from the smaller deposits? And ultimately: How did these sulfur deposits form? These questions, none of which can be answered now with certainty, are the topic for my paper. The speculations and conclusions contained here are my own, based on field work, on the literature, and on the enjoyed discussions of Delaware Basin geology in its broadest sense with friends and colleagues.

ACKNOWLEDGMENTS—In particular I thank Stewart H. Folk, geological consultant, who guided much of my early work in sulfur exploration when we were both employed by Jefferson Lake Sulphur Company; Stewart also kindly reviewed this paper. A. G. Bodenlos, U.S. Geological Survey, provided valuable input to the paper and served as a sounding board for some of these ideas. Jefferson Lake Sulphur Company agreed to my use of some materials from its files, all of which is public information or derived from it.

Stratigraphy

The Delaware Basin and its contained Ochoan rocks have been capably described in several recent publications (Anderson and others, 1972; Payne, 1976). Fig. 1 shows the approximate outline of the basin as it probably existed at the beginning of Ochoan time. Presumably, the basin was then everywhere floored with clastic sediments of the Bell Canyon Formation. Water depth remains controversial but probably was several hundred feet.

The lowermost rock unit of Ochoan age in the basin is the Castile Formation, consisting mainly of anhydrite with thin organic-rich calcite laminae; massive halite is interbedded with the laminated anhydrite. Anderson and others (1972) have shown that the laminae in the Castile and overlying Salado can be correlated individually over most of the basin.

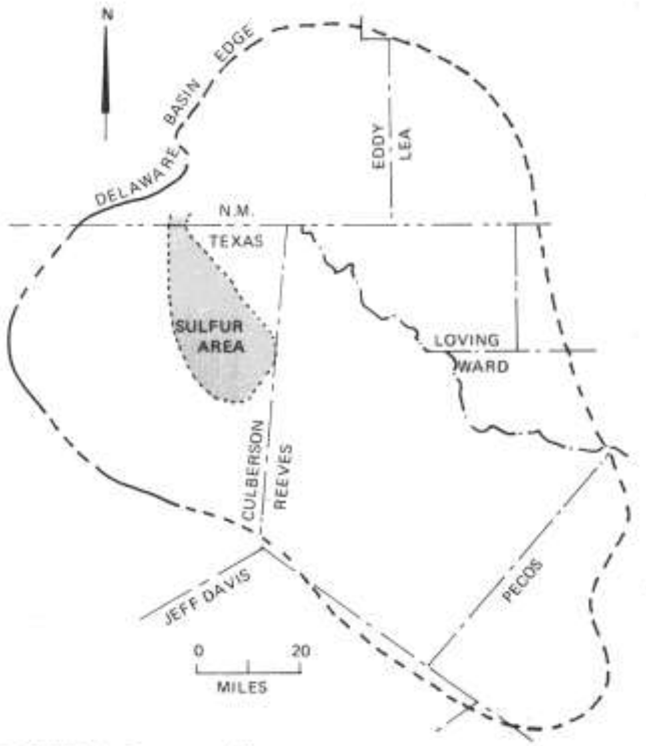


FIGURE 1—DELAWARE BASIN SHOWING APPROXIMATE POSITION OF AREA WHERE SULFUR OCCURS IN OCHOAN ROCKS.

Anderson and others (1972) subdivide the Castile into the following members: Basal Limestone, 1 to 3 ft thick; Anhydrite I, ranging from 170 to 350 ft thick; Halite I, pure halite, up to 500 ft thick; Anhydrite II, 90 to 150 ft thick; Halite II, halite with 5 thin anhydrite marker beds, up to 225 ft thick; Anhydrite III, 280 to 300 ft thick; Halite III, interbedded halite and anhydrite, 200 to 400 ft thick; Anhydrite IV, anhydrite with some interbedded halite, 300 to more than 600 ft thick. The basis of the subdivision is the presence of the major halite beds; where they are absent, it is difficult to separate the anhydrite units. The Halite III and Anhydrite 1V members are present only in the deepest part of the basin, well east of the sulfur-bearing area.

In the western part of the basin Halite I and Halite II are absent, and in their place is a much thinner anhydrite breccia bed. Anderson and others (1972) believe that the breccia consists of the undissolved anhydrite laminae remaining after solution of the salt in the halite members. Fig. 2 shows the western and southern limits of Halite I and Halite II in Culberson County and part of Reeves County.

Within the Castile Formation are masses of secondary limestone, apparently the result of local replacement of Castile gypsum by calcite. Outcrops of these masses form more or less circular hills ranging from a few feet high to buttes rising several tens of feet above the plain. Adams (1944, p. 1606) refers to the limestone hills as "castiles," a confusing term but one that remains in use. Kirkland and Evans (1976) refer to the same features as limestone buttes, and suggest that they are related to a part of the sulfur-forming process. In the subsurface, secondary limestone occurs in the Castile and Salado; some of the limestone contains sulfur.

Overlying the Castile Formation is the Salado Formation, predominantly halite in the subsurface with lesser amounts of anhydrite and, locally, potash salts. In the outcrop and shallow subsurface the salt is absent, presumably removed by solution, and the Salado consists mainly of anhydrite or gypsum breccia, commonly red-orange. In the Rustler Hills this zone is visible as red gypsum underlying Rustler dolomite. Some of the medium-bedded unbrecciated anhydrite and gypsum west of the Rustler Hills may be lower Salado (Snider, 1965).

Clastic rocks, including metaquartzite, chert, and older Permian limestone pebbles, green silty shale, and banded anhydrite fragments, occur irregularly in the Salado interval

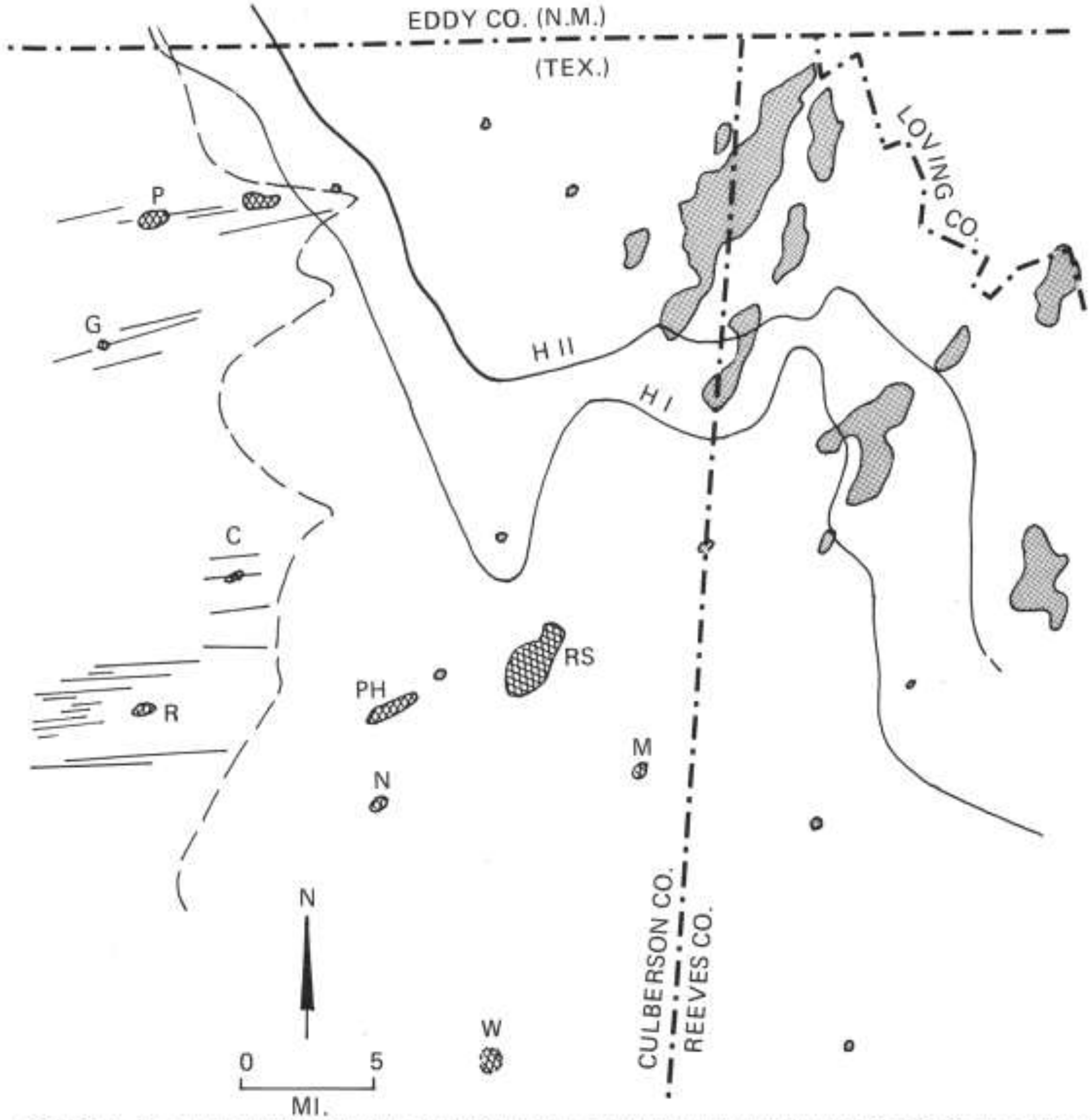


FIGURE 2—Larger-scale map of sulfur area shown in fig. 1. HI and HII are southwest limits of Halite I and Halite II in Castile Formation; dashed line is eastward limit of solution-subsidence troughs shown by fine east-west lines; oil fields are screened but unlabeled. Sulfur deposits, from northwest to southeast, are: P, Pokorny; G, Grant; C, Covington; R, Rounsaville; PH, Phillips Ranch; N, Nevill; RS, Rustler Springs; M, Minerals Exploration; W, Weigel.

and in the upper Castile. They may represent: 1) fall-in of overlying rocks through sinkholes in the Rustler (and some of the rocks could then be Cretaceous); 2) clastic sediments deposited on top of the Castile and in the Salado, perhaps as a tongue from back-reef areas; or 3) pre-Rustler or early Rustler clastic sediments filling in lows formed by pre-Rustler post-Salado erosion or solution. A southerly trend from the reef for these clastics suggests the second possibility to be likely. In the vicinity of the Rustler Springs sulfur deposit, the clastic unit may be several tens to 300 ft thick.

Interbedded dolomite, anhydrite, red beds, and salt of the Rustler Formation overlie the Salado in the deep subsurface on the east side of the basin. In outcrop, notably in the Rustler Hills, the Rustler is dolomite with subsidiary clay beds. Collapse and solution brecciation are abundantly evident in outcrops.

Cretaceous rocks occur in a few collapse areas and distinct sinkholes. Quaternary sediments partly fill valleys and sinkholes; they are anomalously thick in the Black River valley along the Guadalupe Mountain front and in other large troughlike areas, such as the Pecos Trough, in the eastern part of the basin where salt has been dissolved at depth (Maley and Huffington, 1953; Hiss, 1976).

Structure

Just prior to deposition of the Castile Formation, the top of the Capitan Reef ringing the Delaware Basin was probably essentially at sea level and thus horizontal. The basin itself continued to subside through Ochoan time, mainly along the eastern side (Ochoa Trough of Snider, 1965); the basin shelf on the west subsided much more slowly. Following Hayes (1964) and others, Snider (1965) suggests that uplift prior to Triassic deposition modified the Delaware Basin, Midland Basin, and intervening Central Basin Platform into a single shallow saucer-shaped basin. Adams (1940) postulates some pre-Rustler uplift in the western part of the basin.

The major deformation of the basin was its eastward tilting during Tertiary tectonism and possibly both earlier and later. The western edge of the basin was raised as much as 4,500 ft, resulting in the fairly uniform east dip in most of the evaporites.

Faults of small displacement have been mapped or inferred in the Castile. The most obvious group are the bounding fractures of solution-subsidence troughs (Olive, 1957); these faults are described by King (1949) in the map explanation as "Linear features in Castile anhydrite (possible fracture zones, in places forming low scarps . . .)." Several of these faults are shown in fig. 2 to indicate the almost uniform east-west trend. The eastern limit of the faults is everywhere west or south of the area where halite remains in the subsurface Castile.

Origin of the solution-subsidence faults is still not clear, but their direct downdip trend and their restriction to now salt-free areas of the Castile suggest that they are somehow related to solution of Halite I and Halite II. Logs of sulfur exploration tests drilled along these fractures would shed light on this problem if they were released.

A second group of faults has been delineated only by sulfur test drilling, as far as I know. These faults, with displacements on the order of 25-75 ft, are nearly vertical and trend about N. 65 E. Good examples are the graben-boundary faults shown in fig. 3. Clearly, the displacement affects the upper Bell Canyon and the lowermost Castile, at least Anhydrite I, but well-log data have not been released that would show more details. It is possible that these faults are in the same system mapped by King (1949) in the Bell Canyon along the west edge of the Castile; although most that King mapped are in the Bell Canyon, a few continue east into the lower Castile outcrop.

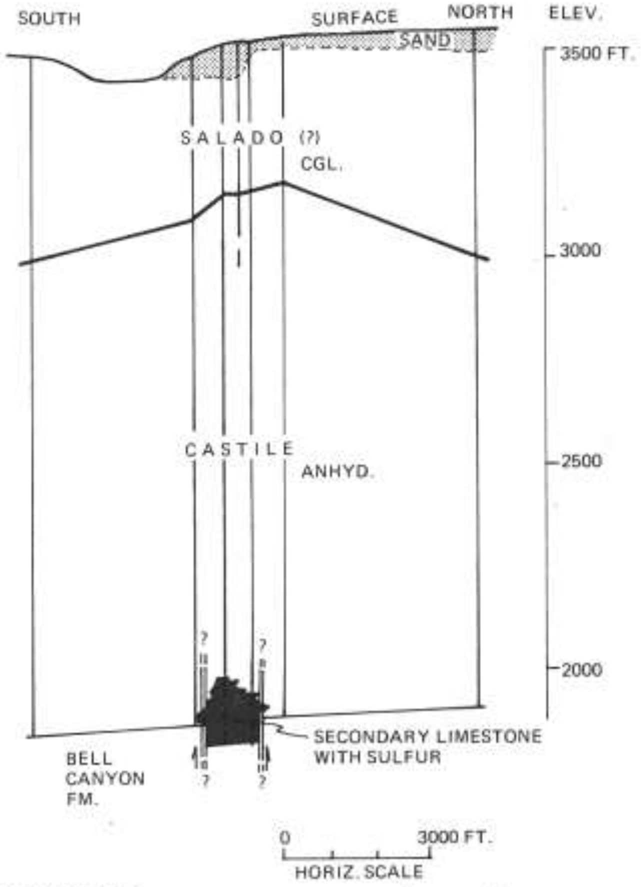


FIGURE 3—North-south cross section, Phillips Ranch deposit; vertical lines represent selected sulfur tests drilled by Texas Gulf Sulphur Company (line of section is shown on fig. 4).

Photogeologic studies by Trollinger-Gosney & Associates, Inc. (1970) suggest two "possible faults at depth" trending northeast near the Eddy-Reeves-Culberson Counties junction and one "probable fault at depth" trending about N. 25 E. This last fault lies only about two miles east of the Rustler Springs sulfur deposit. One other possible major fault zone suggested by TGA, Inc., would extend from just east of the Rustler Springs deposit east-northeast across Reeves, Loving, and Winkler Counties.

Sulfur deposits

Native sulfur has been known in the western Delaware Basin since at least the mid-1800's. Richardson (1904; 1905), Porch (1917), Evans (1946), and others described and discussed the surface and near-surface deposits in the region. Except for sporadic exploration by a few sulfur companies and accidental discovery of sulfur by oil companies, little was known about sulfur in the subsurface of the region until the latter 1960's. Practically all the surface and subsurface deposits associated with Ochoan rocks in the basin are in the Sulfur Area marked on fig. 1.

Castile Formation deposits

At least five subsurface sulfur deposits are known from the Castile. All occur at or near the base of the formation in Anhydrites I and 1I and in the Halite I breccia zone. Each of the deposits consists of brown, laminated to unlaminated to brecciated limestone containing crystalline sulfur, often reported as "secondary" or "brown" limestone on drillers' logs. (Sulfur companies rarely mention sulfur in any drillers' logs released to the public domain.) Laterally, the brown limestone interfingers with laminated gypsum, which grades into laminated anhydrite.

In the deposits for which information is available—Phillips Ranch, Pokorny, and Covington—and probably in the others in the Castile, the sulfur-bearing rocks are oily, or there are oil-bearing zones within the secondary limestone. The oil composition in the Pokorny deposit, about 75 percent naphthenes and 16 percent aromatics, is "strikingly similar to the oil produced from the Castile Formation (Rustler Hills Field). . . ." (Davis and Kirkland, 1970, p. 115-116). Oil from the upper Bell Canyon Formation is usually more than 50 percent paraffins.

The faults of moderate displacement in the upper Bell Canyon-lower Castile and trending about N. 65 E. probably localized the basal Castile deposits. Because of lack of well data it is hard to be sure of this, but drilling patterns in most deposits indicate such a trend. The possible exception is the Grants deposit, which is very shallow but still in the basal Castile; and this deposit may be related to a limestone butte or castile.

The Phillips Ranch deposit, discovered by Texasgulf Inc. (formerly Texas Gulf Sulphur Company), is an excellent example of the basal Castile sulfur deposits. The probable relationship between the sulfur-bearing secondary limestone and the Castile, as well as the graben-bounding faults, is shown in fig. 3. In places between the faults the Castile is unreplaced but is surrounded by secondary limestone. The maximum thickness of the sulfur-bearing limestone is about 235 ft (fig. 4).

The top of the Castile, picked from drillers' logs as "top of banded anhydrite" (fig. 3), is arched over the deposit. It is possible that this structural anomaly is a result of volume increase from replacement of anhydrite by limestone and gypsum; on the other hand it may have some other cause, such as conversion of anhydrite at the top of the Castile to gypsum by ground water.

The deposit is aligned along and beween 2 faults forming a graben about 800 ft wide (figs. 4 and 5). Displacement on the faults is about 50 ft. Close-spaced drilling has permitted delineation of the graben for more than a mile and a half along its N. 65 E. trend, and the faults probably continue farther.

Of the basal Castile deposits, the Phillips Ranch is probably the largest, with reserves in excess of 6 million long tons. The other deposits—Rounsaville, Pokorny, Covington, and Nevill—range from 300,000 to perhaps 3 million long tons (depending upon who's talking), although exploration is not complete.

The Grant deposit, if indeed much sulfur is in the subsurface, is (or was) remarkable. According to Porch (1917) a natural shaft on one of the 2 adjacent limestone buttes, or castiles, was reported to be 100 ft deep and lined with a 4-inch layer of crystalline sulfur. The shaft is still there, most of the sulfur having been mined, but hydrogen sulfide issues from it in copious quantities. Texaco investigated the area with geophysics and several drill holes, but there have been no reports of any subsurface deposit.

Salado Formation deposits

Two sulfur deposits have been found in the Salado Formation in the Delaware Basin: the Rustler Springs deposit and a small one explored by Minerals Exploration Company. The latter probably contains about a half-million long tons of sulfur, and not much information about it is public.

The Rustler Springs deposit (called the Culberson Mine by Duval) is more or less saucer-shaped or bowl-shaped, with the center much thicker than the edges. The ore zone, like that in the basal Castile deposits, consists of vuggy secondary limestone; sulfur occurs as vug linings and as vug and fracture fillings. This deposit lies along the east side of the Rustler Hills and beneath Virginia Draw, a valley cutting through the Rustler Hills. Underlying rocks are mostly masked by Quaternary and Recent alluvium, but Rustler carbonates are exposed on the west side in the edge of the Rustler Hills. Duval filed the following log for its sulfur test C-37 with the Texas Railroad Commission:

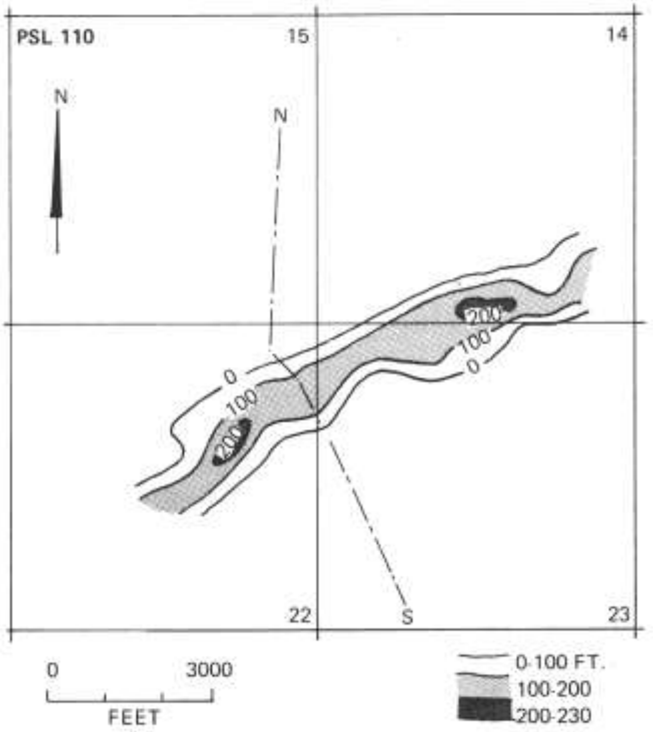


FIGURE 4—Isopachous map of secondary, sulfur-bearing limestone, Phillips Ranch deposit.

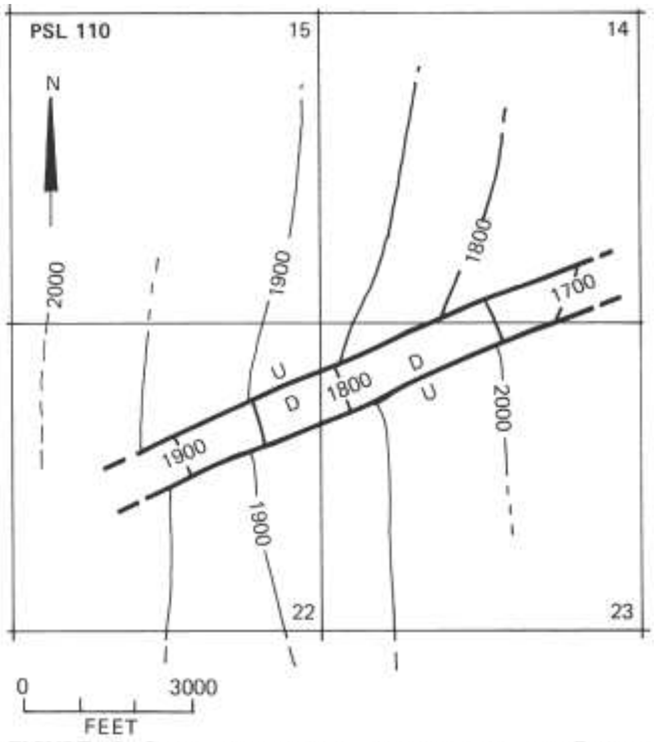


FIGURE 5—Structure contour map of base of Castile Formation, Phillips Ranch deposit; contour interval is 50 ft.

Depth (in ft)	Reported rock type
0-325	Sandstone, conglomerate
325-395	Anhydrite
395-405	Clay
405-515	Dolomite
515-560	Sandstone, dolomite
560-810	Anhydrite with sandstone stringers
810-1000	Banded anhydrite

The upper 325 ft may be Cretaceous to Quaternary, and the banded anhydrite below 810 ft is Castile. The remaining interval, 325 to 810 ft, probably includes lower Rustler and Salado or Salado residuum. The interval between the clay bed and the banded anhydrite is the principal sulfur-bearing section in the Rustler Springs deposit. Correlations of lithic units above the top of the Castile (banded anhydrite) with the driller's logs that have been filed are difficult. The extremely poor quality of the correlations enhances the interpretation that the interval represents material that slumped badly as salt (and possibly gypsum) in the Salado and Rustler was dissolved.

The clay bed shown in the driller's log is an important feature. Ranging from a few inches to 100 ft thick, it overlies the entire deposit. Clearly, the clay acted as an upward limit of mineralization. No data are available to determine whether or not the clay is absent beyond the edges of the deposit. In the southwest part of the deposit, secondary limestone extends downward through the Castile to the top of the Delaware. The "pipe" apparently contains very little sulfur, but nearby the secondary limestone extending down into the upper banded anhydrite is heavily mineralized.

Fig. 6 shows the general shape of the deposit and the variation in the amount of sulfur in the orebody. The usual measure of the sulfur volume among sulfur geologists is the "equivalent foot of solid sulfur" or E.F.S.S. For example, a 50-ft section of rock with 15 percent sulfur would contain 7.5 E.F.S.S. One of the better wells in the Rustler Springs deposit was estimated to contain 48 E.F.S.S.; if the mineralized interval averaged 25 percent sulfur, the interval was at least 192 ft thick.

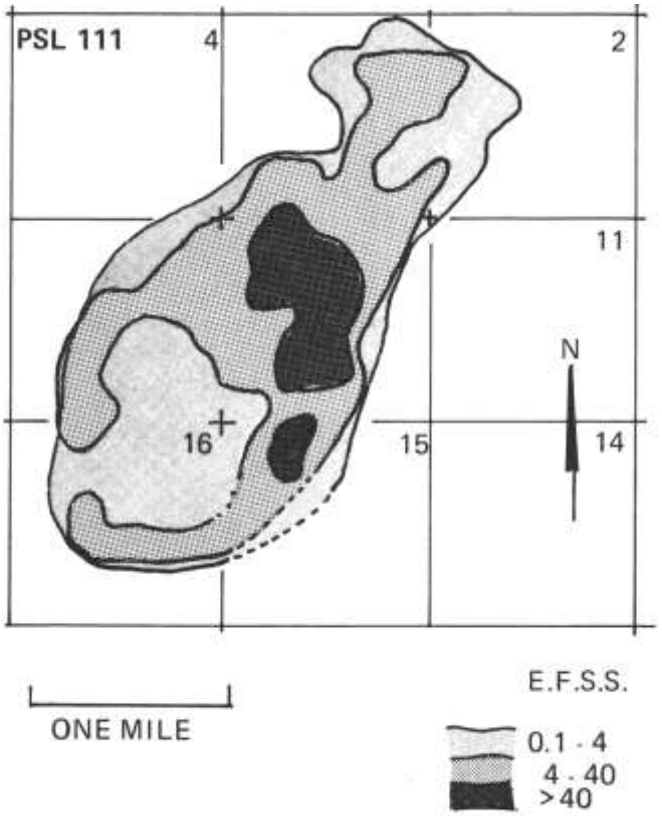


FIGURE 6—Generalized sulfur mineralization map, Rustler Springs deposit; E.F.S.S. means equivalent feet of solid sulfur.

Although the basal Castile deposits are oily or have oil-bearing zones, the Rustler Springs deposit is practically oil-free. Only a little asphaltic material and minor amounts of oil have been found. Another notable characteristic of the deposit is a section of barite, up to a few tens of ft thick, overlying part of the sulfur section. The relationship of the barite to the sulfur is not clear from the public well logs.

Structure of the rocks in and around the deposit appears from very limited control to be an east or northeast dipping homocline. A structural terrace or monocline might be present, superimposed on the regional dip, but it is not obvious. No evidence is available to indicate that a structural high in the evaporites pre-dated the deposit and controlled its location.

Faulting, on the other hand, is strongly suggested. The graben-bounding faults described in the Phillips Ranch deposit trend N. 65 E. and, if extended, would intersect the northern part of the Rustler Springs deposit. A possible major fault zone interpreted from aerial photography extends from the Rustler Springs deposit east to Winkler County, and a probable fault trending N. 25 E. lies about two miles east of the deposit.

The Rustler Springs deposit is more or less in line with two prominent trends of upper Bell Canyon oil fields. One is the Screwbean north-northeast trend, and the other is the Sabre/Olds northeast trend. Grauten (1965) shows that oil in these upper Bell Canyon fields occurs in clean sandstone stratigraphic traps bounded above and below by shale and siltstone and laterally by shaly or carbonate-cemented sandstone. William F. Grauten (personal correspondence, 1970) thinks the clean sandstone trends continue into the Rustler Springs area, but oil is generally absent in the trends west and south of the updip limits of Halite I (fig. 2).

Deposition and localization

Davis and Kirkland (1970) discuss the origin and deposition of native sulfur in the Delaware Basin. They use as an example the Pokorny deposit in the basal Castile, but their ideas apply generally to all of the deposits. According to their hypothesis, oil migrated into porous parts of the Castile sulfate rocks where sulfate-reducing bacteria generated hydrogen sulfide and carbon dioxide. Calcite was precipitated, and ultimately the hydrogen sulfide, if not lost to the surface or carried away, was oxidized by oxygenated ground water to elemental sulfur. Kirkland and Evans (1976) think that natural gas, rather than oil, was used by sulfate-reducing bacteria as an energy source.

Some geologists have suggested that as many as 12 factors must coincide for sulfur deposition. Based on the ideas of Davis and Kirkland (1970) and on other work, we can select 6 factors which are important in the origin and localization of sulfur deposits in the Castile and Salado Formations. These factors are: 1) presence of sulfate rocks, 2) presence of hydrocarbons, 3) fracturing or brecciation of rocks to permit fluid flow, 4) oxygenated ground water or other agents capable of oxidizing H2S, 5) sealing bed to prevent loss of H2S to surface, and 6) absence of salt.

1) Sulfate rocks make up most of the Castile and Salado in the western part of the Delaware Basin. On the surface the Castile is gypsum, and drilling shows the gypsum normally to grade downward into anhydrite 50-100 ft below the surface. In the vicinity of the basal Castile sulfur deposits (especially adjacent to the secondary limestone), the Castile is gypsum, apparently altered from anhydrite.

2) Oil is locally abundant in the upper Bell Canyon Formation; outlines of the major fields near the sulfur area are

shown on fig. 2. Minor amounts of oil have been found in the Castile and Salado. Gas is much less common in the upper Bell Canyon, Castile, and Salado.

The API (American Petrolum Institute) gravity of oil in the upper Bell Canyon fields is 34 or higher, averaging about 40; in the Castile and Salado fields, it ranges from about 23 to 33. Gravity of the oil in the upper Bell Canyon generally increases updip, "probably because of an escape of the lighter fractions into other structurally higher traps farther west" (Jones and Smith, 1965). If the Castile and Salado oil was originally from the lighter fraction of the Bell Canyon oil, then further migration and alteration of the oil has occurred. Such a suggestion fits well with the idea that the oil has been modified by chemical reactions and bacterial action.

Oil in the upper Bell Canyon fields is generally reported to be sweet, but that in the Castile and Salado is sour. Small volumes of very sour gas ranging to almost pure hydrogen sulfide have been reported by drilling crews. This usually unexpected sour gas is a severe hazard during drilling and has resulted in a few deaths.

Sulfur geologists seem now inclined to think that natural gas, probably from the Bell Canyon, was the hydrocarbon devoured by anaerobic bacteria to generate hydrogen sulfide that ultimately became the sulfur deposits. That hypothesis explains the general lack of hydrocarbon gases in the area. Whether oil or gas, an enormous volume of hydrocarbons was required for deposition of the Rustler Springs deposit, equivalent to more than 200 million barrels of oil!

3) In order for hydrocarbons, whether oil or gas, to migrate into the sulfate rocks and for the metabolic products of sulfate-reducing bacteria to move to appropriate sites of calcite precipitation and sulfur deposition, permeable zones must have existed in the Castile Formation. Similarly, if oxygenated meteoric ground water was required to oxidize the hydrogen sulfide, there must have been permeable zones in the upper Castile and overlying rocks. In the discussion of stratigraphy, I have pointed out the possibly permeable breccia beds in the Castile, which remained after solutional removal of the salt; these breccias do not appear to be very permeable in exposures, however. The Salado residuum overlying the Castile is certainly permeable. Faulting and fracturing in the Castile probably post-dated removal of the salt, especially in the Rustler Springs area. Fractures through the salt probably would have healed by flowage and recrystallization unless fluid flow was large.

4) Sulfur in the deposits is presumed to have formed by oxidation of hydrogen sulfide. Davis and Kirkland (1970, p. 120) state, "Oxygenated ground waters may well have had a role in the oxidation of hydrogen sulfide to sulfur in salt-dome caprocks. . . . This is very likely the oxidative mechanism in the west Texas area where porosity and permeability of the Castile Formation are evident." In a later paper Kirkland and Evans (1976) concur in the earlier statements. It is not yet clear if the hydrogen sulfide was oxidized by oxygenated meteoric water moving downward through the Castile and the Salado residuum or upward from the underlying but poorly permeable Bell Canyon sandstone, or if the oxidation of hydrogen sulfide might not have been by other kinds of reactions not yet known, observed, or suspected.

5) Hydrogen sulfide generated in the subsurface by sulfate-reducing bacteria has a tendency to rise—to the surface, if possible. If it does go to (or near) the surface, then it will be lost to the atmosphere or be dispersed by ground water systems, perhaps depositing small amounts of sulfur, which is later destroyed by sulfur-oxidizing bacteria. To prevent the loss of hydrogen sulfide, to provide an upper limit on sulfur deposition, and possibly to prevent loss of sulfur by bacterial action, a seal or barrier must be present. In the Rustler Springs deposit the seal is a clay bed. In the basal Castile deposits along faults, the seal might be upward termination of the fractures or of fracture permeability. The former would be important as an indicator of the age of faulting in the upper Bell Canyon and lower Castile.

6) All of the subsurface sulfur deposits now known lie west and south of Halite I. This may be coincidental, or it may indicate that the requisite migrations of hydrocarbons, hydrogen sulfide, and/or oxygenated ground water are prevented by the salt and its sealing action.

I would not be surprised, nor would it surprise active sulfur exploration geologists, to find that other factors are a necessity for deposition of large sulfur deposits. When the Delaware Basin sulfur area is satisfactorily explored, we can hope that the sulfur companies will be free to publish their opinions on sulfur deposition along with their supporting data.

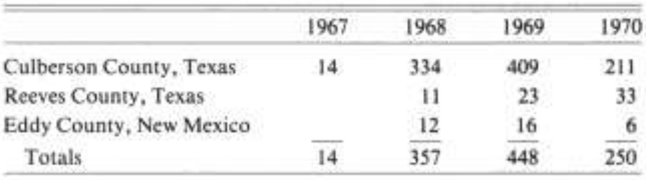
Sulfur exploration and development

Early development of sulfur resources in the Delaware Basin was limited to shallow strip mining of sulfur occurring in gypsite and to the sulfur lining of the natural shaft in the Grant deposit. Richardson (1905) and Porch (1917) describe the early mining operations in detail. According to Hinds and Cunningham (1970, p. 1):

> The most noteworthy mining effort between 1918 and 1966 was an open pit operated for 12 years as a one-man venture near Rustler Springs, Tex., by Mr. Thad Sanford of Carlsbad, N. Mex. Sanford recovered 800900 tons per year of "sulfur soil," which he shipped by rail from Orla, Tex., and sold as a soil conditioner. . . .

Exploration for subsurface sulfur deposits was not very active until the last half of the 1960's. Freeport Sulphur Company drilled several test holes in the late 1940's, and a few other sulfur tests were drilled before 1965 with no promising results. With sulfur in short supply beginning about 1964, sulfur companies began active exploration in west Texas. Frasch sulfur mining in bedded evaporites was proven by Duval and Sinclair Oil Corporation in Pecos County, Texas, southeast of the Delaware Basin sulfur area. Exploration by Duval in the vicinity of the old Michigan surface mine discovered the Rustler Springs deposit, and research drilling by University of New Mexico geologists inadvertently found the Pokorny deposit. All the sulfur companies and several major and independent oil companies joined the search. Table 1 shows the numbers of sulfur exploration wells drilled in the Delaware Basin for the period 1967-1970; the totals shown include only the wells reported to regulatory agencies as sulfur tests. By 1971 drilling had practically ceased. Drilling was renewed by at least 4 companies in the last 3 years and continues at a moderate level by Duval, Leonard Resources, and Texasgulf.

TABLE 1—SULFUR EXPLORATION WELLS, DELAWARE BASIN, 1967-70.



	1967	1968	1969	1970
Culberson County, Texas	14	334	409	211
Reeves County, Texas		11	23	33
Eddy County, New Mexico		12	16	6
Totals	14	357	448	250

Other exploration methods were used in the Delaware Basin, based on a variety of hypotheses about sulfur deposition and localizing factors. The most obvious was gravity, presuming a density contrast between the limestone-sulfur orebody and the surrounding Castile anhydrite. This method, although supported by the marked gravity low over the Rustler Springs deposit, had poor results because most of the basal Castile deposits were too deep; other features—caverns, gypsum-also produced gravity lows; and the detailed gravity coverage needed for success was generally too expensive. Also used were aeromagnetic, electrical, and seismic surveys, soil and soil-gas chemistry, ground water chemistry, and color and color infrared photography. To date none of these has provided more than a guide to drilling targets and, worse, apparently none has led directly to discovery of a deposit.

Although exploration of the sulfur area in the Delaware Basin has been locally thorough, areas remain that have not been drilled at all or not been drilled to the base of the Castile. Continuing modest exploration and occasional bursts of leasing activity indicate that some of the sulfur companies still hope to find economic deposits in the area. Duval also has recently acquired the Phillips Ranch deposit (a few miles west of the Rustler Springs deposit), but no plans for mining have been announced.

References

Adams, J. E., 1940, Structural development, Yates area, Texas: American Association of Petroleum Geologists, Bull., v. 24, no. 1, p. 134-142

, 1944, Upper Permian Ochoa Series of Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists, Bull., v. 28, no. 11, p. 1596-1625

Anderson, R. Y., Dean, W. E., Jr., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved evaporite sequence, west Texas and New Mexico: Geological Society of America, Bull., v. 83, no. 1, p. 59-86

Davis, J. B., and Kirkland, D. W., 1970, Native sulfur deposition in the Castile Formation, Culberson County, Texas: Economic Geology, v. 65, p. 107-121

Evans, G. L., 1946, The Rustler Springs sulphur deposits as a source of fertilizer: Texas Bureau of Economic Geology, Rept. Inv. I, 13 P.

Grauten, W. F., 1965, Fluid relationships in Delaware Mountain sandstone: Fluids in subsurface environments: American Association of Petroleum Geologists, Mem. 4, p. 294-307

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey, Prof. Paper 446, 69 p.

Hinds, J. S., and Cunningham, R. R., 1970, Elemental sulfur in Eddy County, New Mexico: U.S. Geological Survey Circ. 628, 13 p.

Hiss, W. L., 1976, Structure of the Permian Ochoan Rustler Formation, southeast New Mexico and west Texas: New Mexico Bureau of Mines and Mineral Resources, Resource Map 7

Jones, T. S., and Smith, H. M., 1965, Relationships of oil composition and stratigraphy in the Permian Basin of west Texas and New Mexico, *in* Fluids in subsurface environments: American Association of Petroleum Geologists, Mem. 4, p. 101-224

King, P. B., 1949, Regional geologic map of parts of Culberson and Hudspeth Counties, Texas: U.S. Geological Survey, Oil and Gas Inv. Prelim. Map 90

Kirkland, D. W., and Evans, R., 1976, Origin of limestone buttes, Gypsum Plain, Culberson County, Texas: Geological Society of America, Bull., v. 60, no. 11, p. 2005-2018

Maley, V. C., and Huffington, R. M., 1953, Cenozoic fill and evaporate *[sic]* solution in the Delaware Basin, Texas and New Mexico: Geological Society of America, Bull., v. 64, no. 5, p. 539-546

Olive, W. W., 1957, Solution-subsidence troughs, Castile Formation of Gypsum Plain, Texas and New Mexico: Geological Society of America, Bull., v. 68, no. 3, p. 351-358

Payne, M. W., 1976, Basinal sandstone facies, Delaware Basin, west Texas and southeast New Mexico: American Association of Petroleum Geologists, Bull., v. 60, no. 4, p. 517-527

Porch, E. L., Jr., 1917, The Rustler Springs sulphur deposits: University of Texas, Bull. 1722, p. 1-71

Richardson, G. B., 1904, Report of reconnaissance in Trans-Pecos Texas north of the Texas and Pacific Railway: University of Texas, Bull. 24 (Min. Surv. Ser. 9), p. 1-119

, 1905, Native sulphur in El Paso County, Texas: U.S. Geological Survey, Bull. 260, p. 589-592

Snider, H. I., 1965, Stratigraphy and associated tectonics of the Upper Permian Castile-Salado-Rustler evaporite complex, Delaware Basin, west Texas and southeast New Mexico: Ph.D. thesis, University of New Mexico, 196 p.

Trollinger-Gosney & Associates, 1970, Photogeologic-geomorphic evaluation map of the Delaware Basin area, Texas-New Mexico

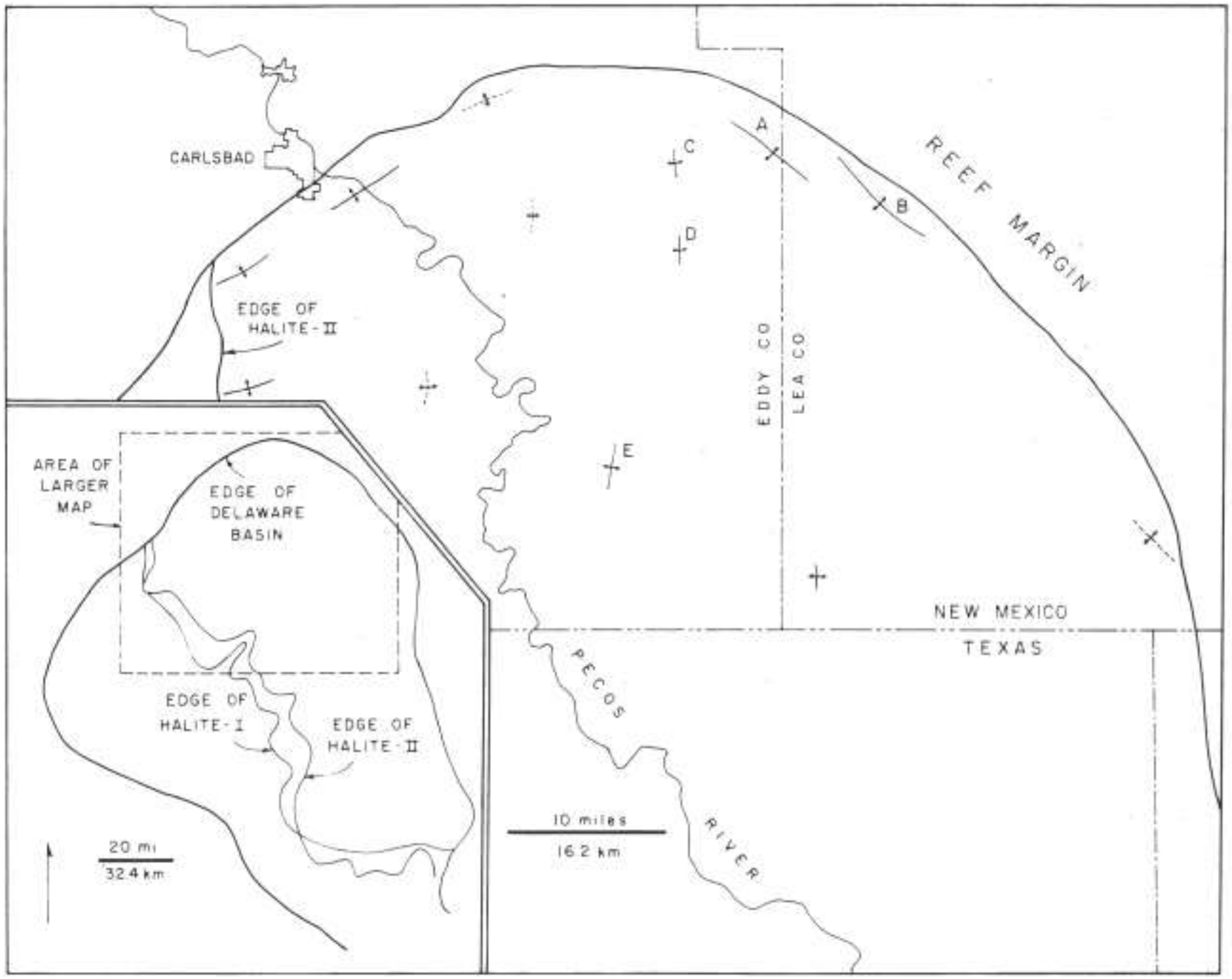


FIGURE 1—INDEX MAP SHOWING THE DISTRIBUTION OF THE LOWER TWO HALITE BEDS (I AND II) OF THE CASTILE FORMATION AND THE LOCATION OF ANTICLINAL STRUCTURES DEVELOPED WITHIN THOSE SALTS. Structures with dashed pattern were located with only one data point. ERDA No. 6, AEC No. 7, and AEC No. 8 are wells drilled on top and on the flanks of structure A.

SALT ANTICLINES IN CASTILE-SALADO EVAPORITE SEQUENCE, NORTHERN DELAWARE BASIN, NEW MEXICO

by Roger Y. Anderson, *Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131*
and
Dennis W. Powers, *Sandia Laboratories, Albuquerque, New Mexico 87115*

Abstract

A number of structures have been encountered within the body of the Castile-Salado evaporites that can reasonably be interpreted as salt anticlines. One such structure, associated with brine, H_2S, and dissolution effects, was found during exploratory coring for the proposed nuclear waste disposal site near Carlsbad, New Mexico. Correlation of stratigraphic units in the recovered core with cores and logs from nearby boreholes shows that the middle anhydrite unit (A-II) of the Castile Formation, which attains dips of as much as 70°, has been displaced vertically by as much as 950 ft (290 m). Extension fractures in the A-I1 unit suggest that it has been stretched above a pod of exceptionally thick salt of the lower halite unit (H-I) of the Castile Formation that moved into the axis of the anticlinal structure. Exceptionally thick and thin units of lower salt (H-I) occur in other nearby boreholes in a zone of deformation marginal to the reef. Suspected salt anticlines also occur at scattered localities in the northern part of the Delaware Basin. The association of extension fracturing to microfolding in the middle anhydrite unit (A-II) suggests that salt deformation accompanied or followed Cenozoic uplift and tilting of the basin.

Introduction

In the summer of 1975, during an exploratory coring program in southeastern New Mexico (sec. 35, T. 21 S., R. 31 E.) carried out by Sandia Laboratories to locate a site for radioactive waste disposal, a steeply dipping bed of laminated anhydrite from the Castile Formation was encountered at a depth of 2,550 ft (777 m) (fig. 1). At a depth of 2,711 ft (845 m), the coring operation encountered a dissolution horizon with pressurized brine containing 16 percent H_2S in the gas phase (Lambert, this volume). The coring operation in this hole (called ERDA No. 6) was terminated after penetrating an underlying salt bed at 2,733 ft (833 m).

Investigation of the core from ERDA No. 6 and of logs and cores from elsewhere in the Delaware Basin shows that the structure encountered in the ERDA No. 6 borehole could reasonably be interpreted as an anticlinal structure associated with the movement of salt in the evaporite sequence. This report briefly describes the ERDA No. 6 core, interprets the nature of the associated structure, and relates the structure to similar structures elsewhere in the Delaware Basin.

ACKNOWLEDGMENTS—Funding for this work was provided by Energy Research and Development Administration (ERDA) as part of the Waste Isolation Pilot Plant (WIPP) program at Sandia Laboratories. Among the people who either worked on the project or discussed various matters are George Barr, Fred Donath, Ken Kietzke, Doris Rhodes, and Joe Tillerson. The manuscript was reviewed by Allen Lappin and Wolfgang Wawersik.

ERDA No. 6 anticline

Brief description of core

The relevant stratigraphic and structural features in the ERDA No. 6 core are summarized in fig. 2. Beneath the Cowden Anhydrite, at a depth of approximately 2,275 ft (703 m), the part of the core of interest can be divided into four major units: 1) an upper halite, 2) an upper anhydrite, 3) a thin lower anhydrite, and 4) a lower halite. The laminations in the core show dips in excess of 80° in some places, so the 182 ft (55.5 m) of core between the upper halite and a "corroded" zone near the base actually comprise about 103 ft (31.5 m) of stratigraphic thickness.

The anhydrite units are composed of "Castile type" calcite-anhydrite laminae couplets, with the pairs having an average thickness of 2.0 mm; this implies that the upper anhydrite unit represents about 14,000 years of deposition (Anderson and others, this volume). The upper anhydrite also contains a large number of cyclets, each consisting of a thick anhydrite lamina overlain by an unusually thick calcium carbonate lamina. These cyclets are similar to those described by Anderson and Kirkland (1966) as "irregular laminations," but they do not appear to have an internal laminated character. The cyclets are much more common near the base of the anhydrite bed. Several nodular zones occur in the upper anhydrite, and nodular development is particularly strong in the lower anhydrite (fig. 2).

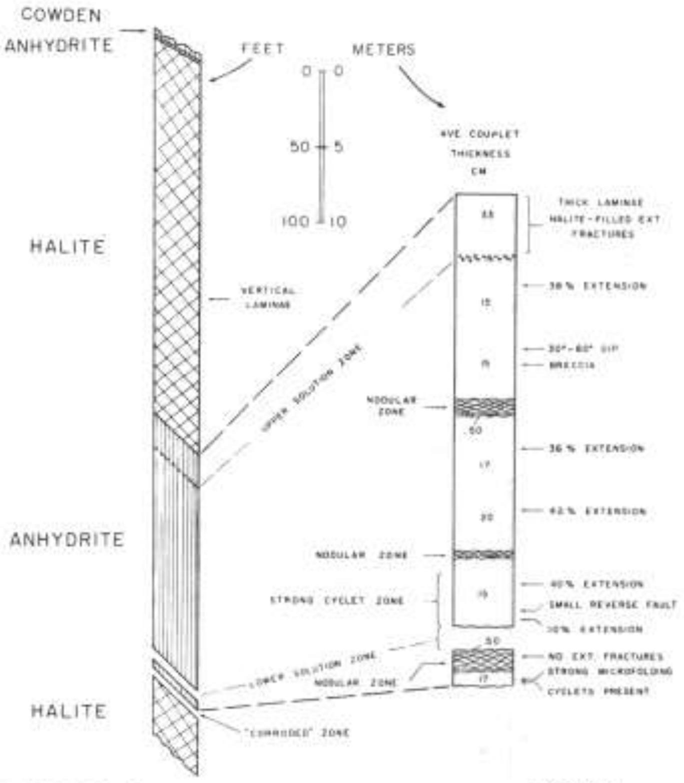


FIGURE 2—Section showing the relevant beds from ERDA No. 6. Beds below the Cowden Anhydrite include: the upper halite, upper anhydrite, lower anhydrite, and lower halite. The section on the right is corrected for dip and expanded from the upper and lower anhydrites.

An unusual type of fracturing has affected the entire upper anhydrite. Thick calcite laminae, behaving as competent units, have been "snapped apart" normal to bedding planes and the intervening voids filled in by calcium sulfate (fig. 3). In addition to the "pull apart" or extension type fractures, thick calcite-anhydrite laminae have been fractured to form a cross-hatched pattern (fig. 3). The basal meter of the upper anhydrite unit has been extended by about 10 percent, as determined by measuring the void space between the "pulled apart" calcite laminae. The remainder of the upper anhydrite has been subjected to extension of approximately 40 percent (fig. 2). No extension fractures were observed in the lower anhydrite unit. Microfolding, as described by Kirkland and Anderson (1970), is well developed in the lower anhydrite unit, and weak microfolding also occurs in the lower part of the upper anhydrite.

Both upper and lower halite units are composed primarily of medium-gray recrystallized halite; halite laminae are set off by thin sulfate layers with poorly defined boundaries. Halite laminae thicknesses range from about 4-15 cm, with most between 10 and 15 cm thick. The basal part of the Cowden Anhydrite consists of about 0.5 m of white, massive, non-laminated anhydrite. The overlying unit has alternating dark-gray and powdery white laminae couplets averaging about 2.5 mm in thickness.

A "corroded" zone (fig. 2) separates the lower halite from the lower anhydrite; a well-developed solution horizon, containing vugs lined with halite crystals, also separates the lower and upper anhydrites. A second solution horizon, less than 0.5 m thick and with associated weak brecciation, occurs near the top of the upper anhydrite. The "corroded" zone at the base of the lower anhydrite unit shows evidence of solution activity. This contact is sharp and irregular with about 40 cm of relief. Laminations above the corroded zone reach dips in excess of 80° (some are even overturned), while laminae in the halite about 20-30 cm below the contact dip only about 30°. Laminae in the halite appear to have "fitted" themselves to conform to the relief of the corroded contact with the overlying anhydrite. Just beneath the contact, the sulfate laminae formerly within the halite have accumulated as a residue; the thickness of this zone indicates that at leapt 10-20 halite-sulfate couplets (2-4 ft; 0.6-1.2 m) have been dissolved out in a process of retrograde metamorphism (Borchert and Muir, 1964).

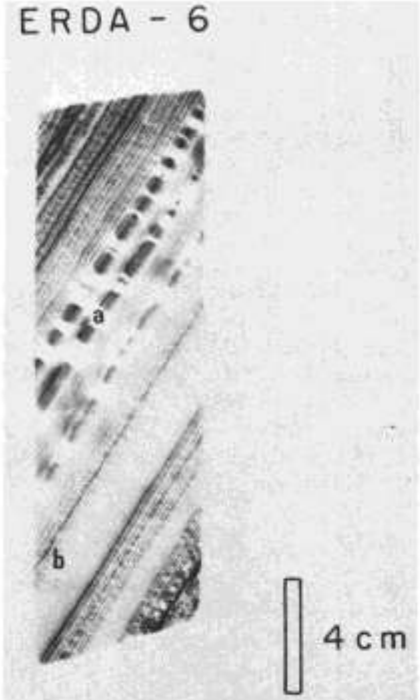


FIGURE 3—Slabbed and polished section from the upper anhydrite shown in fig. 2. **a** indicates calcium sulfate filling "pull-apart" structures; **b** indicates zone of cross-hatched fracture pattern.

Identity of stratigraphic units

The upper and lower anhydrite beds encountered in ERDA No. 6 have been identified as the middle anhydrite unit (Anhydrite I1 of Anderson and others, 1972) of the Castile Formation (Anderson, 1976). Identification was initially a problem; the rapidly changing character of the calcite-anhydrite laminae near the margin of the Delaware Basin did not allow a lamina by lamina correlation as has been accomplished elsewhere in the basin (Anderson and Kirkland, 1966). A comparison of the material with cores collected from the AEC No. 8 location (sec. 11, T. 22 S., R. 31 E.), however, showed that the anhydrite units above the second halite unit (Halite II) of the Castile Formation do not contain Castile-type laminae; the Anhydrite II unit (below Halite II) contains laminae similar in character to those encountered in ERDA No. 6. In addition, the degree of nodular development and the spacing of nodular zones in the section is essentially the same in the Anhydrite II unit of AEC No. 8 and in the anhydrite bed of interest in ERDA No. 6. Nodular development has been shown to be correlative over wide areas of the basin (Anderson and others, this volume).

Interpretation of structure

The identification of the stratigraphic units, the degree of development of extension fracturing, and the thickness of halite in nearby boreholes permit an interpretation of the nature of the structure encountered in ERDA No. 6. After adjustments for elevation and regional dip, the vertical displacement between the top of the Anhydrite 1I unit in ERDA No. 6 and nearby AEC No. 8 is about 950 ft (290 m). This implies that the lower halite (Halite I) beneath the tilted anhydrite bed in ERDA No. 6 is thickened to about 1,200 ft (366 m) in a regional trend of salt thickness that is 350 ft (107 m). Seismic profiles in the area do not show a structural involvement of the Bell Canyon sequence beneath the evaporites; therefore, flowage of the Halite I salt of the Castile must form the underlying core of the structure (fig. 4).

Extreme extension fracturing, similar to that observed in the ERDA No. 6 core, where competent beds have been "pulled apart" during the flow of less competent, enclosing materials have been found in other evaporites; for example, see Borchert and Muir, 1964, fig. 20.9. Anticlinal or diapiric structures tend to develop in evaporites where two or more types of stratigraphic units (materials) are interlayered and subjected to stresses perpendicular to the bedding. Even in relatively undeformed and flat-lying rocks, flowage can increase the thickness of an incompetent salt unit to several times the normal value. Theoretically, a stratigraphic unit that has been stretched upward into a simple flexure with a dip of 45 ° will have become stretched by 40 percent. The dips in ERDA No. 6 are slightly greater than 45 °, but the close agreement to the theoretical value suggests that flowage of the underlying salt has stretched the Anhydrite I1 unit (fig. 4).

The Cowden Anhydrite is conformable with the upper salt in ERDA No. 6 (fig. 2). The lower salt, by inference, is the Halite I member of the Castile. A correlation with the stratigraphic section encountered nearby at AEC No. 7 (sec. 31, T. 21 S., R. 32 E.) shows that about 500 ft (152 m) of stratigraphic section above the anticlinal structure has been moved out to produce the relationships observed (fig. 4).

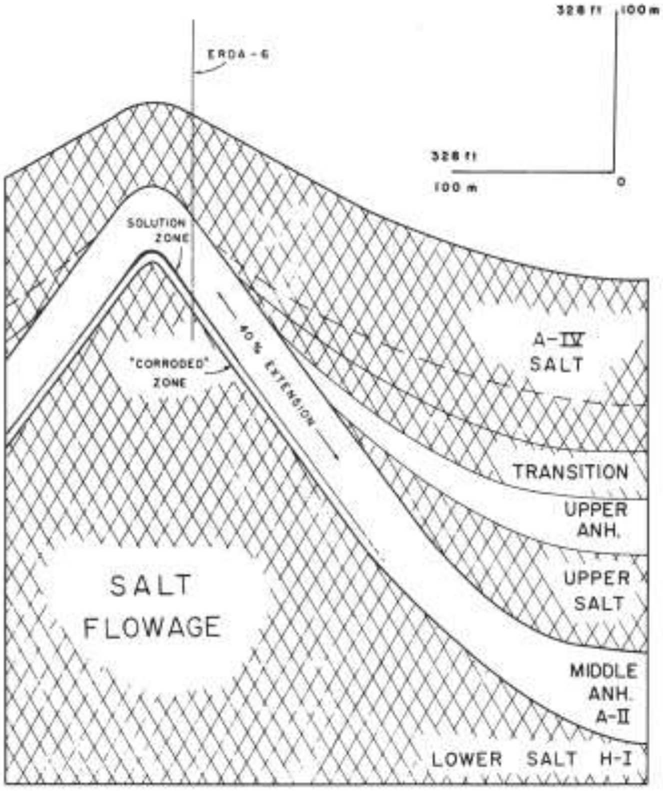


FIGURE 4—Diagrammatic cross section of structure at ERDA No. 6, illustrating loss of stratigraphic section and flowage in Halite I of Castile Formation. The middle anhydrite was encountered at a depth of 2,550 ft.

A possible analog to the structure encountered at ERDA No. 6, where flat-lying beds are involved, is illustrated by Lotze (1957, fig. 116). The structure in ERDA No. 6, however, may not be as simple as depicted by fig. 4 or by Lotze; the lower anhydrite in ERDA No. 6, below the corroded zone, has not been involved in the stretching, suggesting that this unit has in some way moved separately or become detached.

Finally, the solution zones in ERDA No. 6 depicted in fig. 4 have been placed only near the axis of the structure, because Borchert and Muir (1964) note that such solution processes are commonly induced along anticlinal axes, either by ascending waters from below or by downward percolating meteoric waters.

Other salt anticlines

Distribution of salt anticlines

The distribution and features of other salt anticlines within the Delaware Basin were examined as analogs to the ERDA No. 6 structure. A structure map made on the top of the Halite II unit of the Castile Formation reveals that the anticline encountered at ERDA No. 6 has a southeasterly trending axis that is more or less parallel to the margin of the basin (fig. 1, location A and fig. 5). C. L. Jones, in a similar unpublished map prepared in 1975, has recognized a deformation belt or zone encircling the inner margin of the basin and extending into the basin for a distance of about 5 mi (8 km). Anticlinal structures that somewhat parallel the basin margin (fig. 1 and fig. 5) are common in this zone, and the structure encountered in ERDA No. 6 is one of these.

Jones also shows a number of other smaller structures within the basin that can also be interpreted as salt anticlines. Some of these are illustrated in fig. 5, although this is not a complete map of such structures. When only one data point is available, the contours are dashed and the structures are inferred, owing to possible errors and differences in log interpretation.

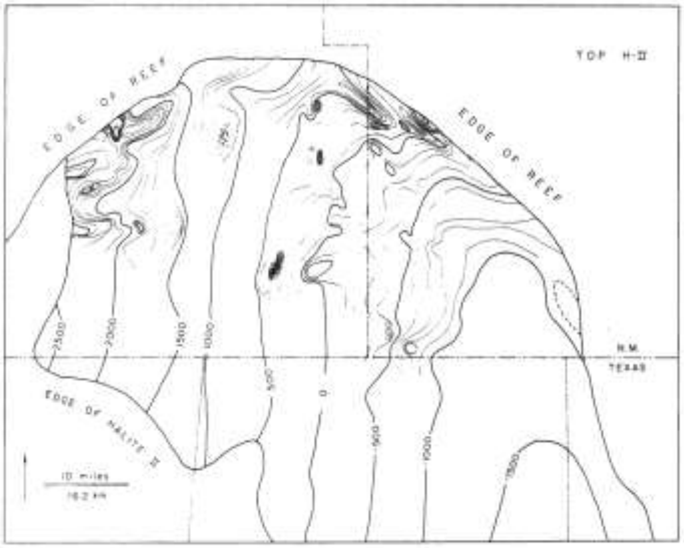


FIGURE 5—Structure contour map on the top of second halite of Castile Formation (Halite II). General N-S strike of the bed and gentle (1°) eastward dip is also reflected very well by the Bell Canyon Formation underlying the Castile Formation, but the Bell Canyon Formation does not have the smaller anticline and syncline pattern. Structures with dashed pattern were located with only one data point.

The smaller anticlinal structures inferred for the basin appear to have a discernible trend parallel to the regional structure contours, particularly the underlying Bell Canyon Formation. A good example of one of the anticlines within the basin is the Poker Lake anticline (fig. 1, location E and fig. 5), where there is sufficient well control to define the structure quite accurately.

Poker Lake anticline

The Poker Lake anticline (fig. 6) involves salt movement and thickening in both the Halite I and Halite II units. The contours on the top of the Bell Canyon Formation show no evidence of an anticlinal structure, and it may be inferred that the structure is entirely confined to the evaporite sequence.

Poker Lake anticline is associated with a depression in the structure contours on the top of the Halite II unit along its southwestern flank. The isopach maps (fig. 6) show that both Halite I and Halite II are thinned to produce the depression. Similar depressions are associated with most of the salt anticlinal structures within the basin proper and also in the zone of deformation marginal to the basin. Trusheim (1960) discusses similar features in the Zechstein of the northern German Basin. The Delaware Basin salt anticlines and adjacent depression, as illustrated at Poker Lake, may be analogous to the "salt pillow" stage and "primary peripheral sinks," respectively, of Trusheim.

Age and origin of anticlinal structures

Inasmuch as anticlinal structures within the basin tend to parallel the regional structure contours, it can be inferred that the structures are synchronous with or postdate the development of the regional structural grain or pattern. This pattern is generally thought to have developed with the uplift and tilting of the basin in early to mid-Cenozoic time (King, 1948). Further evidence of the timing is provided by the relationship

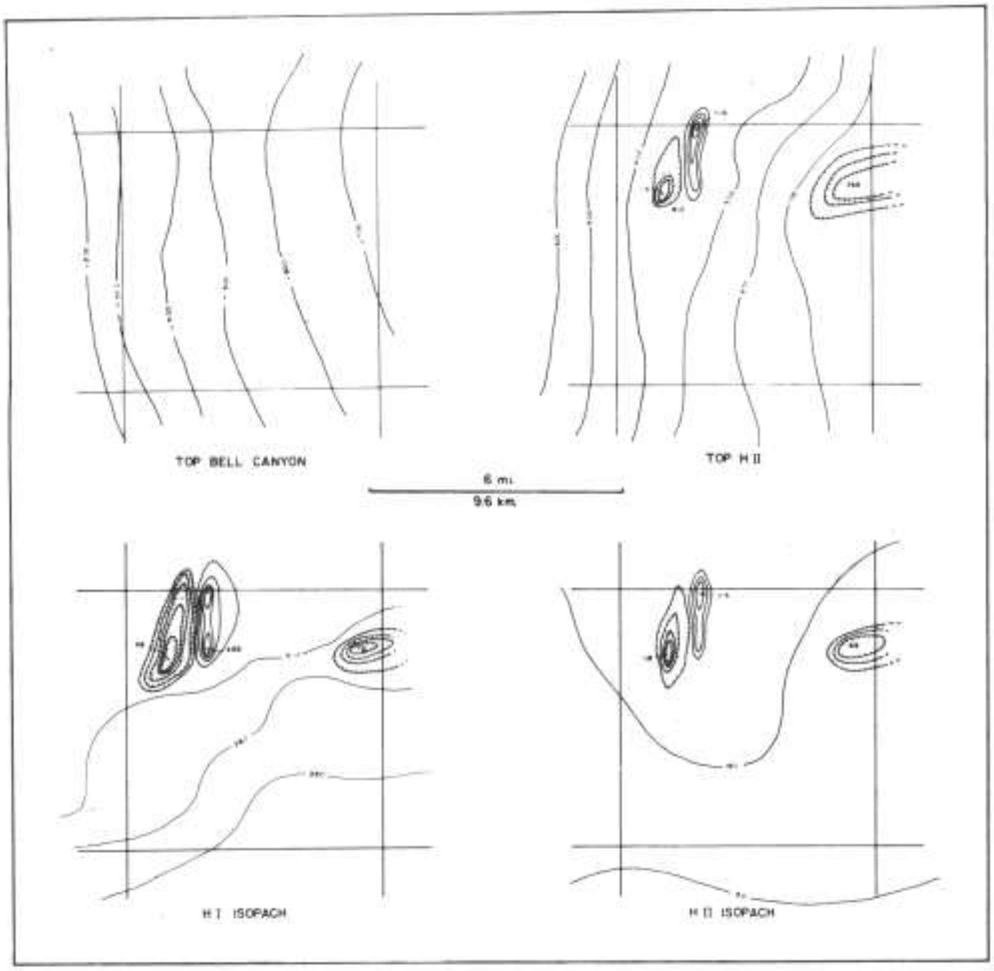


FIGURE 6—DETACHED MAPS OF POKER LAKE ANTICLINE SHOWING WELL CONTROL, STRUCTURE CONTOURS ON HALITE II, AND ISOPACH MAPS OF HALITE I AND II. The peripheral sink, which presumably supplied salt to the anticline, is well displayed, as is the parallel direction of the structure with the strike on the Bell Canyon Formation.

of microfolding to extension fracturing. Microfolding in the basin also follows Cenozoic structural trends (Kirkland and Anderson, 1970), and, because microfolded layers are later subjected to extension fracturing in the core collected from ERDA No. 6, the salt structure there is inferred as post-microfolding.

Origin

The prevailing conditions under which the deformation of the Castile occurred may be approximated to a fair degree, though the specific conditions for each anticline are not known. The stratigraphic section in the basin above the lower halite units of the Castile Formation was a minimum of 3,700 ft (1,128 m) at the time of Cenozoic deformation; that is the present thickness in AEC No. 8. The Cretaceous sediments in the area presumably were only a few hundred feet thick at most before being stripped away. Forty-five hundred ft (1,371 m) may be a reasonable estimate of the total overburden at the initiation of deformation, which implies gravity loading of about 300 bars. The present temperatures measured in AEC No. 8 (Manure and Reiter, 1977) are 30.5°C at 3,700 ft (1,128 m) and 33°C at 4,500 ft (1,371 m). Nothing within the mineralogy of the evaporite sequence suggests the temperatures were significantly higher in the past. If the mid-Cenozoic date of the general structural trend is correct, the time of formation of the anticlines within the basin might be inferred to have taken as long as 30 m.y. Some time may be subtracted since the Ogalalla Formation (Miocene-Pliocene) does not appear to be involved in these structures; 25 m.y. may be a reasonable estimate.

The strain within an anticline-syncline pair, as at Poker Lake, may be crudely estimated. Assuming none of the halite leaked through the enclosing anhydrite layers, a line drawn across the upper surface would show strain of about 0.2, or 20 percent. An equivalent steady-state strain rate for 25 m.y. would be about 2.5 x 10^{-16}/sec. Heard (1972) graphically illustrates domains for expected large-scale flow for the Gulf Coast area. The conditions of temperature and depth discussed above do not appear to place the northern Delaware Basin in this domain. The strain rate crudely calculated may be increased by an order of magnitude or more if the formation time is reduced to one or two million years or if the total strain is greater than estimated above. Even with higher strain rates, the apparent depths and temperatures for the formation of the salt anticlines fall outside of the range of values assumed by Heard (1972) for massive halite flow. Because conditions of formation of the anticlinal structures in the Delaware Basin do not match the strain conditions suggested by Heard for massive halite flow, further work is needed to reconcile the difference in observations.

The common association of deep depressions and loss of Halite I and Halite II in small localized areas adjacent to the anticlinal structures (fig. 5) may be interpreted in several ways. These depressions may have been the source for the salt that moved into the core of the anticlinal structure as for Trusheim's "primary peripheral sinks," although the reason why the salt source should be so localized is unclear. Alternatively, the depressions may represent deep dissolution associated with the movement of meteoric waters that post-dated the formation of the anticlinal structure. It is even conceivable that original dissolution, particularly around the margin of the basin, may have developed the differential loading required to initiate salt movement.

Conclusions

1) The structures found in the Castile salt beds do not involve the underlying beds; they are the result of massive halite flow and are associated with nearby sinks or depressions.

2) Structures in the basin proper are aligned parallel to the strike of the underlying Bell Canyon Formation; structures around the margin are subparallel to the Capitan Reef.

3) Formation of the anticlinal structure at ERDA No. 6 resulted in the stretching and fracturing of an overlying more competent anhydrite bed and the loss of some stratigraphic section.

4) The structures are mid-Cenozoic or later.

5) Massive flowage of halite occurred, though the conditions of formation do not seem sufficient compared to other areas.

References

Anderson, R. Y., 1976, Correlation and structural relationships of the Castile-Salado evaporite sequence in ERDA #6, AEC #7, and AEC #8 boreholes, Eddy and Lea Counties, New Mexico: Open-file report to Sandia Laboratories, 33 p.

Anderson, R. Y., Dean, Walter E., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved evaporite sequence, west Texas and New Mexico: Geological Society of America Bull., v. 83, p. 59-86

Anderson, R. Y., and Kirkland, D. W., 1966, Intrabasin varve correlation: Geological Society of America Bull., v. 77, p. 241-256

Borchert, H., and Muir, R. 0., 1964, Salt deposits: Von Nostrand and Co., Ltd., London, 338 p.

Heard, H. C., 1972, Steady-state flow in polycrystalline halite at pressure of 2 kilobars, *in* Flow and fracture of rocks: Geophysical Monograph Series, v. 16, p. 191-209

King, P. B., 1948, Geology of the Southern Guadalupe Mountains: U.S. Geological Survey, Prof. Paper 215, 183 p.

Kirkland, D. W., and Anderson, R. Y., 1970, Microfolding in the Castile and Todilto evaporites, Texas and New Mexico: Geological Society of America Bull., v. 81, p. 3259-3282

Lotze, F., 1957, Steinsalz and Kalisalze, I Teil: Gebruderborn Traeger, Berlin

Mansure, A., and Reiter, M., 1977, An accurate equilibrium temperature log in AEC #8, a drill test in the vicinity of the Carlsbad disposal site: New Mexico Bureau of Mines and Mineral Resources, Open-file Rept. 80, 7 p.

Trusheim, F., 1960, Mechanism of salt migration in northern Germany: American Association of Petroleum Geologists, v. 44, p. 1519-1540

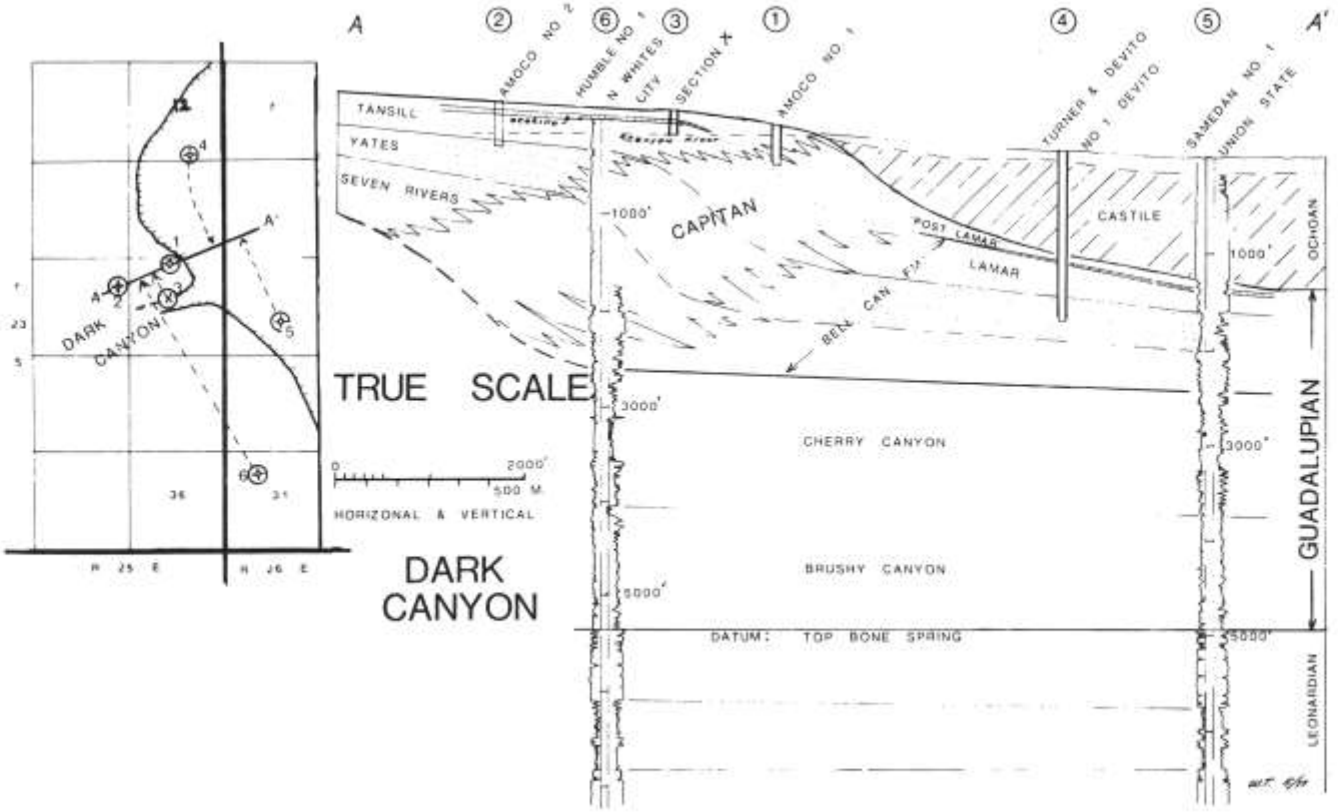


FIGURE 1—True-scale stratigraphic section showing relationships of Amoco core holes to nearby well control in Dark Canyon, Guadalupe Mountains, Eddy County, New Mexico.

LATE GUADALUPIAN CORRELATIONS, PERMIAN REEF COMPLEX, WEST TEXAS AND NEW MEXICO

by Willis W. Tyrrell, Jr., *Amoco International Oil Company, Chicago, Illinois,*
Donald H. Lokke, *Southern Methodist University, Dallas, Texas,*
George A. Sanderson, *Amoco Production Company, Tulsa, Oklahoma* and
George J. Verville, *Amoco Production Company, Denver, Colorado*

Abstract

The Tansill Formation (shelf deposit), upper Capitan Formation (shelf margin deposit), and Lamar Limestone (basinal deposit) are the uppermost carbonate units of the Permian Reef Complex. The Lamar Limestone Member of the Bell Canyon Formation is separated from the overlying Castile Formation by the "post-Lamar beds" consisting of Capitan debris at the margin of the Delaware Basin and a thin sandstone unit further basinward. The generally accepted correlation of the middle and lower Tansill with the Lamar (Tyrrell, 1969) has been questioned by Achauer (1969) and Kelly (1971), who correlate the Lamar with the Seven Rivers Formation. Their correlations contradict the exceptionally fine fusulinid zonation first established by Skinner and Wilde (1954, 1955) for the Lamar.

Fig. 1 shows the location and stratigraphic relationship of two Amoco Research core holes and a section measured along the north wall of Dark Canyon. The Amoco No. 2 Dark Canyon cored 399 ft of the Tansill Formation and the upper 70 ft of the underlying Yates Formation. The Ocotillo Silt Member is present from 86-118 ft. Fusulinid occurrences in this core include (from top to bottom):

Fusulinid	Depth (in ft)
Poorly preserved *Paraboultonia(?)*	15-80
Reichelina	106-232
Paradoxiella	242-324
Codonofusiella	332-469 (total depth)
Yabeina texana	391 (one bed)

In the Amoco Nb. 1 Dark Canyon core hole, the upper 220 ft consists mostly of Tansill lithology with a few units of Capitan lithology; the section from 220-290 ft is transitional with alternating Tansill and Capitan lithologies; and the section from 290 ft to total depth (400 ft) is massive Capitan. *Paraboultonia* is common from 40-394 ft, and no *Reichelina* were found.

The small Tethyan fusulinid genera in the two core holes and in measured sections and well cuttings of Tansill and Lamar between Dark Canyon and McKittrick Canyon reconfirm: 1) *Paraboultonia* is restricted to the Ocotillo Silt Member and the overlying upper Tansill beds, as well as to the uppermost Capitan, uppermost Lamar and post-Lamar beds; 2) *Reichelina* slightly overlaps the lower part of the *Paraboultonia* zone, but otherwise is restricted to the middle Tansill and to all except the lower Lamar; 3) *Paradoxiella* is present in the middle Tansill and middle and lower Lamar; 4) *Yabeina texana* is restricted to the lowermost Tansill and lowermost Lamar; *5) Codonofusiella* ranges as high as the lower Tansill and lower Lamar; 6) *Polydiexodina*, the large fusulinid characteristic of the upper Guadalupian in west Texas, does not range as high as the Tansill or Lamar.

References

Achauer, C. W., 1969, Origin of the Capitan Formation, Guadalupe Mountains, New Mexico and Texas: American Association of Petroleum Geologists, Bull., v. 53, p. 2314-2323

Kelley, V. C., 1971, Geology of the Pecos Country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Mem. 24, 75 p.

Skinner, J. W., and Wilde, G. L., 1954, The fusulinid subfamily Boultoniinae: Journal of Paleontology, v. 28, p. 434-444

, 1955, New fusulinids from the Permian of west Texas: Journal of Paleontology, v. 29, p. 927-940

Tyrrell, W. W., Jr., 1969, Criteria useful in interpreting environments of unlike but time-equivalent carbonate units (Tansill-Capitan-Lamar), Capitan Reef Complex, west Texas and New Mexico: Society of Economic Paleontologists and Mineralogists, Spec. Pub. No. 14, p. 8-97

(five abstracts follow)

SOLUTION OF PERMIAN OCHOAN EVAPORITES, NORTHERN DELAWARE BASIN, NEW MEXICO

by J. W. Mercer, *U.S. Geological Survey, Albuquerque, New Mexico 87125*
and
W. L. Hiss, *U.S. Geological Survey, Menlo Park, California 94025*

Abstract

Solution of salt from the Castile, Salado, and Rustler Formations, which compose the Permian Ochoan evaporite sequence in the Delaware Basin, has resulted in the formation of numerous solution-collapse features. In many places, these depressions are filled with collapsed Triassic and Cretaceous strata and/or younger alluvium. Two distinctive types of salt-solution features have been recognized.

Linear lens-shaped depressions follow an arcuate trend above and parallel to the Capitan aquifer of Guadalupian age along the north and east margins of the Delaware Basin. Ground water moving eastward from the Guadalupe Mountains and northward from the Glass Mountains through the Capitan and shelf-aquifer systems dissolved and removed salt from the adjacent and overlying Castile and Salado Formations. Fractures and joints caused by differential compaction and regional tectonism probably aided this process. Collapse of the overlying beds and filling of the resulting depressions probably occurred simultaneously or followed shortly after removal of the salt.

Salt-solution features of a distinctly different type are located along the present westernmost extension of soluble beds in the Ochoan Series in the northwestern part of the Delaware Basin. This set of solution-collapse features extends from near Balmorhea in Pecos County, Texas, northward to the vicinity of Loving in southeastern Eddy County, New Mexico. In this part of the Delaware Basin, Ochoan evaporites were exposed and removed by erosion related to the Pecos River and uplift of the Guadalupe Mountains. The western limit of the soluble beds in the Castile, Salado, and Rustler Formations has been determined by the effects of both surface and ground water. In places, dolomite beds in the Rustler Formation are water bearing. Ground water moving through the Rustler aquifer has apparently dissolved and removed halite from salt-bearing members of the Rustler.

Because the Rustler Formation is in the uppermost salt-bearing unit, a map of the top of this formation depicts the configuration of the collapse features formed by removal of underlying salt beds. Recent detailed mapping of the Rustler Formation in eastern Eddy County, New Mexico, has revealed the chaotic nature of these solution features and further defined the relation of salt solution to the movement of water in the major surface drainage and aquifer systems.

LOG EVALUATION OF NONMETALLIC MINERAL DEPOSITS

by M. P. Tixier and R. P. Alger, *Schlumberger Well Services, Houston, Texas 77001*
(originally published March 1967 by Society of Professional Well Log Analysts)

Abstract

Well logs can be used to locate and evaluate deposits of various commercially important minerals. It is only necessary that the mineral of interest represent a significant fraction of the formation bulk volume and that it exhibit characterizing properties measurable by logs. Because modern logging methods measure electrical, density, acoustic, radioactivity, and certain nuclear characteristics of formations, they may be used to identify many minerals.

For evaluation of sulfur deposits, either density or sonic logs provide god resolution when compared with porosity computed from neutron or resistivity logs. Trona beds are identified by a sonnic reading of approximately 65 microsec/ft, neutron porosity index of about 40 percent, low natural radioactivity, and pronounced hole enlargement. Gamma-ray logs provide important information in the location, identification, and evaluation of potash mineral deposits. Neutron, sonic, and density logs, in various combinations, augment the gamma-ray data in such studies. Coal beds are characterized by high resistivities and by high apparent porosities on sonic, neutron, and density logs. Density logs are particularly suited for evaluation yield from oil shales. In all such explorations for nonmetallic mineral deposits, well-logging methods provide a fast, detailed, and economical reconnaissance of the entire length of drilled hole. Results compare well with core assays.

CONTINUOUS MINING: THE PROBLEM AND THE ANSWER

by C. C. Wynne, *Mine Engineering Dept., Ideal Basic Industries, Potash Company of America Division, Carlsbad, New Mexico 88220*

Abstract

Potash producers who have converted to rock-breaking machinery for ore extraction make liberal use of technology developed in coal mines during the last three-quarters of a century. Conversion of coal-extracting machinery to use in the harder ores of potash mines required considerable efforts in mechanical engineering. Some of the engineering occurred on site in the mine, sometimes through trial and error. Other modifications were developed by manufacturers who saw the value of a noncoal market. "Continuous mining" is the term applied to the practice of cutting, loading, and transporting ore in simultaneous and interrelated operations, theoretically without halting the extraction process at any point. Mine operators use the term as opposed to "conventional mining," which is an extractive method involving the use of explosives. Rock-cutting machines vary in design depending on type of ore, mining methods used, power requirements, and other mining and mechanical engineering considerations. Four of the seven potash producers in the Permian Basin break ore with mining machines purchased from several manufacturers. One of those four companies developed and patented a unique continuous miner at its mine site near Carlsbad, New Mexico. Ore-cutting machines are used in potash production in several other areas of the world, including Canada and Spain. While some potash ores, such as langbeinite, do not lend themselves to extraction by continuous-mining methods, and while some mine operators will not convert to machine extraction because of economic or other considerations, this form of potash mining maintains a strong foothold in the industry.

UNDERGROUND ORE-HAULAGE METHODS IN NEW MEXICO POTASH MILLING

by W. N. Ellett, *National Potash Company, Carlsbad, New Mexico 88220*

Abstract

Adapted from coal-mining technology over twenty-five years ago, belt conveyors have proven to be an efficient and competitive method for rapid transport of potash ore from active panels to shaft-bottom loading bins. Actual selection of the size and type of installation will vary according to the desired production rate and mining method used. The flexibility offered by belt conveyor systems gives the mine operator a method by which to adapt his haulage to meet changing ore grade and production requirements.

SOLUTION FEATURES IN DELAWARE BASIN EVAPORITES

by A. J. Bodenlos, *U.S. Geological Survey, Reston, Virginia 22092*

Abstract

Surface water percolating downward in the evaporites of the Delaware Basin has produced many isolated depressions, sinkholes, and shallow-seated caverns. Elsewhere, laterally moving ground water has leached and removed the most soluble evaporite beds; overlying strata by collapsing into resulting voids have produced thin, areally extensive blanket breccias. Slow but unequal dissolution of evaporites has commonly led to tilting of large blocks of younger formations. In addition, ground water moving upward from underlying aquifers has dissolved large cavities in the evaporites; roof failures have then produced chimneys of breccias. All such solution features are found in the anhydrite sequence west of the Pecos River.

Surface and near-surface karst is found in the Gypsum Plain and east of the Rustler Hills. Blanket dissolution of anhydrite produced widespread brecciated dolomite in the Rustler Hills, and breccia chimneys are found from the Pecos River to the west edge of the Gypsum Plain. The surface expressions of the breccia chimneys differ: 1) chimneys filled with postanhydrite rocks form mounds of uncemented rubble or in higher hills contain steeply dipping postanhydrite strata; 2) chimneys filled with recemented anhydrite may be topographically featureless or may form low mounds; and 3) breccias altered to limestone and perhaps containing small amounts of sulfur form knolls, hills, or high conspicuous buttes. Some subsurface anhydrite-calcified breccias contain minable concentrations of sulfur; surfaces overlying these concentrations are devoid of topographic expression.

Because brecciation of anhydrite was a precursor to sulfur mineralization and calcification in the Delaware Basin, the broad distribution of such structural features west of the Pecos suggests that large unexplored areas remain in which minable concentrations of that mineral could be found. Total ground-water requirements to produce the solution features in the basin indicate that the bulk of dissolution began after the Laramide disturbance, rather than in the late Cenozoic.

Typefaces: Text in 9-pt. English Times, leaded one point
References in 8-pt. English Times, leaded one point Display heads in 18-pt. English Times bold

Presswork: Miehle Single Color Offset
Harris Single Color Offset

Binding: Smyth sewn with softbound cover

Paper: *Cover* on 65 lb. Hopsack Ivory
Text on 60 lb. white Offset

Ink: Cover—PMS 179
Text—Black