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**IDENTIFICATION OF GEOPRESSURED OCCURRENCES  
OUTSIDE OF THE GULF COAST**

Final Report: Phase I

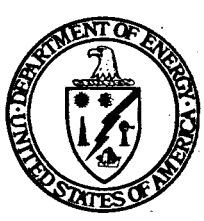
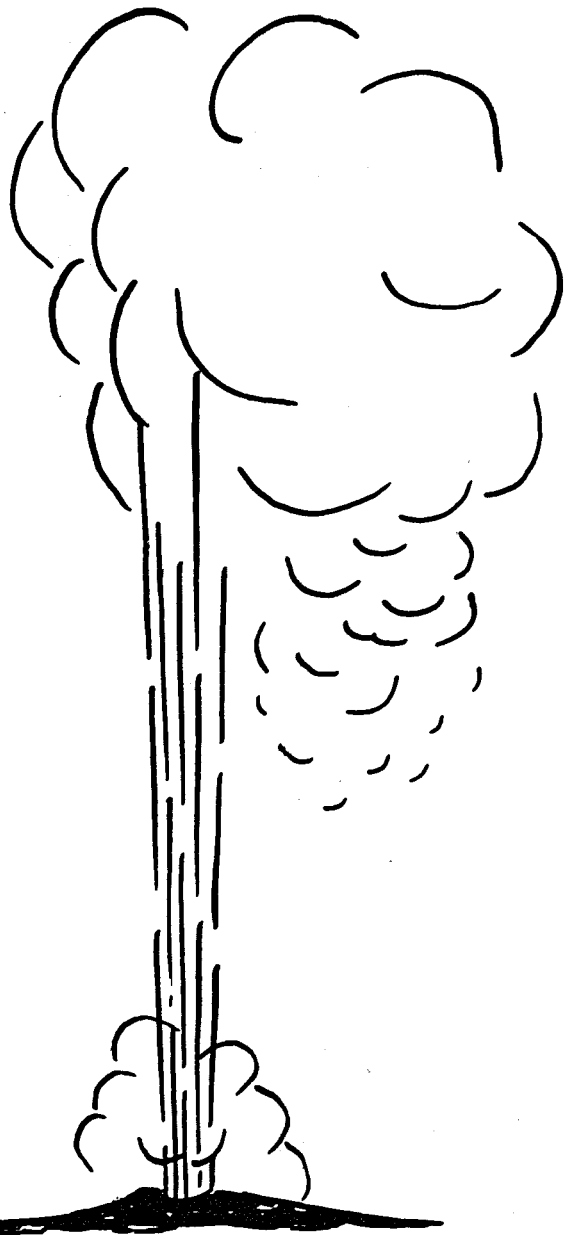
By  
Oscar Strongin

September 30, 1980

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**U. S. DEPARTMENT OF ENERGY**  
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FINAL REPORT  
PHASE I  
IDENTIFICATION OF GEOPRESSURED  
OCCURRENCES OUTSIDE OF THE  
GULF COAST

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Las Vegas, Nevada 89114

Under Contract

No. DE-1-AC08-80NV10133

September 30, 1980

ATLANTA • ANN ARBOR • BOSTON • CHICAGO • CLEVELAND • DENVER • HUNTSVILLE • LA JOLLA  
LITTLE ROCK • LOS ANGELES • SAN FRANCISCO • SANTA BARBARA • TUCSON • WASHINGTON

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TYPICAL PRESSURE PROFILE IN MIOCENE ROCKS,  
SANTA BARBARA CHANNEL, CA

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## ABSTRACT

As an extension of its efforts in the development of the geopressured resources of the Gulf Coast, the Division of Geothermal Energy of the U.S. Department of Energy is interested in determining the extent and characteristics of geopressured occurrences in areas outside the Gulf Coast. The work undertaken in this first phase of the project involved a literature search of available information documenting such occurrences.

Geopressured reservoirs have been reported from various types of sedimentary lithologies representing virtually all geologic ages and in a host of geologic environments, many of which are unlike those of the Gulf Coast. These include many Rocky Mountain basins (Green River, Big Horn, Powder River, Wind River, Uinta, Piceance, Denver, San Juan), Mid-Continent basins (Delaware, Anadarko, Interior Salt, Williston, Appalachian), California basins (Sacramento, San Joaquin, Los Angeles, Ventura, Coast Ranges), Alaskan onshore and offshore basins, Pacific Coast offshore basins, and other isolated occurrences, both onshore and offshore.



## 1. INTRODUCTION AND STUDY PURPOSE

There has been considerable interest and activity in the past five years by the Division of Geothermal Energy (DGE) of the U.S. Department of Energy (DOE) to determine and evaluate the geopressured brines of the Gulf Coast which are characterized by high temperature, high pressure gradient, and entrained methane. Field tests are currently underway in various areas of the Gulf Coast to specifically define the magnitude of the methane resource, nature and ultimate producing life of reservoirs, potential for energy utilization, and the technical and economic parameters.

In line with the above, DOE/DGE is also interested in learning of the extent of geopressured occurrences in areas outside of the Gulf Coast and this project is the initial effort in that direction. For study purposes, this project is being conducted in two phases:

Phase I - Literature search

Phase II - Field confirmation and expansion of results obtained in the first phase

This report represents the work performed in Phase I.



## 2. TERMINOLOGY

The terminology used in describing the state of pressures in rock formations at depths is set forth below.

Formation pressure refers to the pressure acting upon the fluids (water and hydrocarbons) in the pore space of a rock unit. A normal formation pressure is one in which the pressure is equal to the hydrostatic head of water from the surface to the subsurface formation and any departure from the normal trend is considered abnormal resulting in either:

- a) underpressured formation pressures or
- b) overpressured or geopressured or abnormally high formation pressures (in this report, the term geopressured and overpressured will be used interchangeably).

Hydrostatic pressure, another term for normal formation pressure, as indicated, refers to a unit weight and vertical height of a fluid column, the size and shape of which have no effect. However, the hydrostatic pressure gradient expressed in pounds per square inch per foot (or psi/ft.) is affected by the concentration of dissolved solids (or salts) in the fluid column as well as by the temperature gradients.

The following are the typical average hydrostatic gradients generally found in the United States:

<u>Region</u>	<u>Salinity of Water</u>	<u>Hydrostatic Gradient</u>
Mid-Continent and Rocky Mountains	Fresh Water and Brackish	0.433 psi/ft.
Gulf Coast	Salt Water	0.465 psi/ft.

Within this framework, overpressured or geopressured gradients will therefore commonly occur between .433-.465 and 1.0 psi/ft., although both the lower range of values and the upper value may be somewhat higher than the above.

The above pressure terms are generally applied to waters of varying salinities; however, in a number of basins, geopressured occurrences have been noted where formation waters are nearly completely absent as in the overpressured oil zones in the Williston Basin and certain gas-condensate zones in the Anadarko Basin. Further, it should be noted that information on the specific salinity of formation waters, where present, is extremely sparse as most investigators, even in areas of high salinity such as the Interior Salt Basin, have generally only employed qualifying descriptions rather than specific numeric values or analyses.



### 3. GENERAL CHARACTERISTICS

Abnormally high subsurface formation pressures have been observed in all types of geologic environments:

- at shallow depths below the surface, measured in hundreds of feet, to depth in excess of 25,000 feet
- in clastic sediments as well as massive evaporite and carbonate sections
- as rather isolated occurrences or on a basinal or regional basis
- in rocks of all ages - from indurated Cambrian formations to unconsolidated Recent sediments
- in oil reservoirs with little or no formation water, in high or low volume gas reservoirs with little or no condensate, and in high salinity and low salinity waters
- in one formation but not in the overlying or underlying formations
- accompanied by anomalously high temperature gradients as well as by normal temperature gradients

There are numerous causes of geopressuring and one or more of the following may be operative in a given area or basin:

- Rapid sedimentation and compaction of sands and shales in a subsiding basin often characterized by "undercompacted" overpressured shales and growth faults (e.g. Gulf Coast)
- Generation of hydrocarbons from source rocks such as shale, oil shale, coal, or other organic rich rocks (e.g. Williston Basin, Green River Basin, Uinta Basin and other Rocky Mountain Basins)
- Tectonic activities including faulting, folding, diapiric salt or shales intrusions, etc. (e.g. California Basins, Alaskan Basins)



- Chemical action of pore waters trapped in a sealed formation involving such reactions as salt recrystallization, secondary precipitation of cementation minerals, rehydration of anhydrite, etc.
- Thermal expansion or contraction of fluids reacting to temperature changes.
- Diagenesis of clay minerals.
- Electrochemical effects including osmosis.

The genesis of geopressures through geologic time is dependent on a number of factors including the environment of deposition, the form and lithology of the sediments, nature of faulting, basinal structure, burial and compaction, and subsequent tectonic activity. In view of the interaction of all of these processes, it is difficult, if not impossible to ascribe geopressuring in one area or one basin to a particular cause or origin. However, a dominant mechanism can be ascribed in certain basins, e.g. in California, tectonism in the Sacramento Valley and burial and "undercompaction" of shales in the San Joaquin Valley.

Geopressuring is a transient phenomenon that was probably characteristic of most, if not all, sedimentary basins at one time in their development, but over geologic time these high fluid pressures have stabilized and the reservoirs are now essentially either normally pressured or underpressured. In many cases, as in several of the Rocky Mountain Basins, there may be anomalously low and high pressures - the former at shallow depths while relict high pressures may be found at depths usually below 10,000 feet. In other basins, such as the Anadarko and Delaware, geopressured zones may occur in the 10,000 through 15,000 foot intervals while the formations below are normally pressured. The main focus of this project is on basins and areas that currently display overpressured reservoirs. One primary requirement for the existence and preservation of geopressures is a seal, otherwise the pressure would equalize to hydrostatic. This seal essentially requires impermeable



rocks separating more permeable rocks and the seal may be horizontal involving shales and evaporites or vertical consisting of fault displacements, fault gouges or lateral facies changes.



#### 4. STUDY METHODOLOGY

The effort involved in this phase of the project to identify and describe all of the occurrences of geopressured reservoirs in the U.S. outside of the Gulf Coast was indeed a formidable one for many reasons:

- Insofar as is known, aside from Wallace's, et al (1978) preliminary work, there has not been any formal effort to research and aggregate in one publication all of the known non-Gulf Coast occurrences. A number of authors (Fertl, 1976; Jones, 1977; Dickey, 1978; Hunt, 1979; and others) have cited various areas in the U.S. and abroad and provided representative samples but no attempt has been made to organize the material into a coherent and codified volume.
- The importance of geopressured or overpressured formations in the exploration and planning of deep drilling ventures was not recognized until about 15 years ago and consequently, there is little published information available prior to that time about reservoir pressure conditions.
- Most field descriptions payed little attention to initial reservoir pressures unless there was a blowout or where the overpressuring caused difficult drilling and/or completion problems. In many publications, such as The Oil and Gas Journal, which do provide limited descriptions of new discoveries or important development wells, formation reservoir pressures are rarely mentioned. Moreover, in many older fields developed 40-50 years ago, the pressure data was not too reliable given the state-of-the-art at that time; hence, the initial reservoir pressures in several well developed fields and basins cannot be determined.



- The available geologic abstracts do not reference the term "geopressures" or "overpressures" or "abnormally high pressures" and hence, this normally invaluable source for a researcher is not readily useful. In addition, most authors in dealing with field and basin description fail to mention or highlight the occurrence of geopressures unless it is an overriding phenomenon.

In view of the above, the use of computerized literature retrieval from available data banks was found to be rather fruitless and only a handful of applicable references was obtained. As a result, the literature search undertaken for this phase of the project was based on the reading and review of the following:

- 1) Publications previously mentioned as well as books and articles dealing with petroleum genesis and migration in which geopressuring is a significant phenomenon.
- 2) Articles and abstracts for the past ten years and more in such publications as the Bulletin of the American Association of Petroleum Geologists, Journal of Petroleum Technology, Journal of the Society of Petroleum Engineers, and World Oil.
- 3) Various special publications issued by the American Association of Petroleum Geologists such as Memoirs, Studies, Course Notes, Reprints, etc.
- 4) Guidebooks to various basins and areas issued by regional geologic societies and associations.
- 5) Numerous selected special papers of the Society of Petroleum Engineers dealing with abnormal pressures, deep drilling, specific basins, etc.
- 6) Citations in other publications extracted from the above.
- 7) Recent published papers obtained from authors.
- 8) Telephone discussions and written correspondence.



## 5. DATA ORGANIZATION

From an organizational viewpoint, the data and description of the various geopressedured occurrences has been aggregated on a basinal or areal basis and in Section 6 that follows, a separate subsection, numbered 1 to 14 has been prepared for each as follows:

<u>Basin or Area</u>	<u>Section No.</u>
Applachian Basin	1
Interior Salt Basin	2
Anadarko Basin	3
Delaware Basin	4
Rocky Mountain Basins	
Big Horn	5
Powder River	6
Wind River	7
Green River	8
Uinta	9
Others	10
Williston Basin	11
California Basins	12
Alaskan Basins	13
Other Occurrences	14

The basins and areas listed above as well as isolated occurrences have been identified in Figure 1, Index Map of U.S. showing the location of geopressedured occurrences outside of the Gulf Coast.





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**6.0 DESCRIPTION OF GEOPRESSURED  
OCCURRENCES BY BASINS AND AREAS**



## 6.1 APPALACHIAN BASIN

### Location

The Appalachian Basin, as illustrated in Figure 2, stretches in a northeasterly direction from Alabama to New York; the occurrence of geopressed formations, however, has only been reported from Kentucky, New York, Pennsylvania, Virginia, and West Virginia.

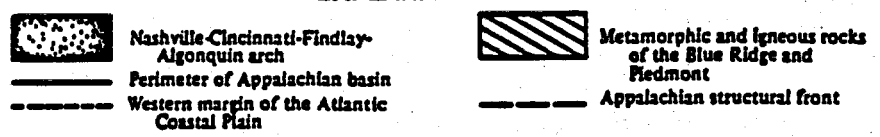
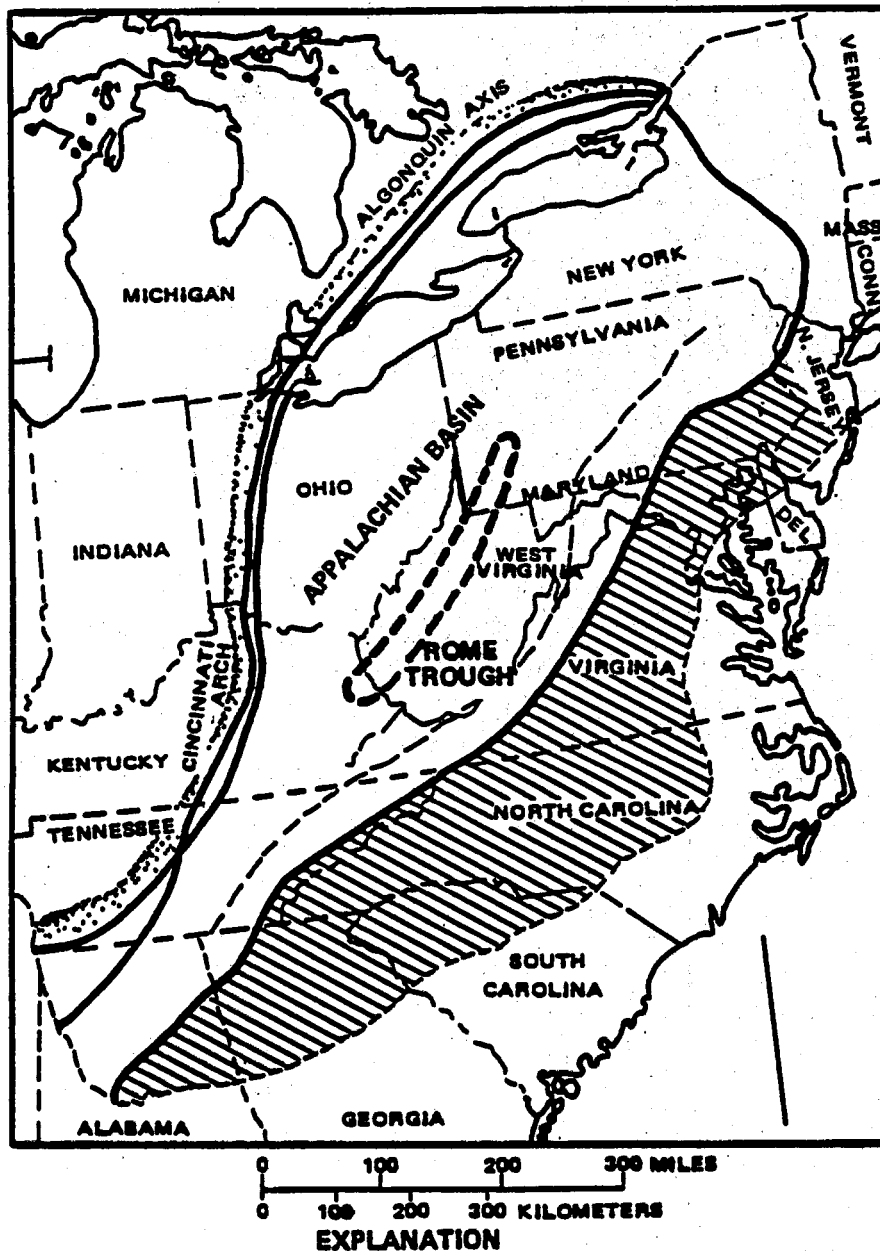
### Formations

The basin is composed of a sedimentary column composed wholly of Paleozoic rocks from the Cambrian to the Permian; a generalized section is depicted in Figure 3. However, as described below, geopressed occurrences are all confined to pre-Mississippian formations as follows:

#### A. Middle and Lower Devonian (Russell, 1972)

1. Oriskany sandstone slightly overpressured (0.491 psi/ft pressure gradient) in New York, Pennsylvania, and West Virginia
2. Onondaga chert overpressured (0.550 psi/ft pressure gradient) in Pennsylvania
3. The above are mean values in the Oriskany and Onondaga formations based on close to 80 determinations, of which 27 were above 0.600 psi/ft (in folded eastern areas of Pennsylvania)
4. In Sissonville (Elk-Poca) Gas field in Kanawha, Jackson and Putnam Counties of West Virginia, high rock pressures have been found in the Oriskany formation at depths of





**FIGURE 2. MAP OF APPALACHIAN BASIN SHOWING LOCATION OF ROME TROUGH AND OTHER GEOLOGIC FEATURES (EXCLUSIVE OF THE EASTERN OVERTHRUST BELT).**

SYSTEM	SERIES	GROUP	FORMATION OR MEMBER	GENERALIZED LITHOLOGY
PENN	POTTSVILLE			
MISS	POCONO			
DEVONIAN	UPPER		PINKROCK	
			CHEMUNG SAND AND SHALES	
	MIDDLE		TULLY	
			MARCELLUS SH.	
	LOWER		ONONDAGA	
			ORISKANY	
		HELDERBURG		
SILURIAN	CAYUGAN		BASS ISLAND	
			TONOLWAY	
	MAGARAN	SALINA	SALT SHALE	
		CLIN-LOCK-PORT	LOCKPORT	
	ALEXANDRIAN		CLINTON	
		ALBION	MEDINA TUSCARORA	
OROVOCIAN	CINCINNATIAN (UPPER)		JUNIATA (QUEENSTON)	
			REEDSVILLE (MARTINSBURG) (UTICA)	
	MICHAWICIAN (MIDDLE)	TRENTON		
		BLACK RIVER		
	CANADIAN (LOWER)	CHAZAN	GLENWOOD SH. ST. PETERS SS.	
		KNOX GROUP	SEEKMAINTOWN	
CAMBRIAN	ST. CROIXON	KNOX	ROSE RUN TREMPEALEAU-COPPER RIDGE	
	ALBERTON		ROME (THERESA)	
	WALCUBAN		SHADY DOLOMITE	
			ANTIETAM QTZITE	
			HARPERS WEVERTON LOUDDON	
			BASAL SS. (POTSDAM) (MT. SIMON)	

PRE C

Fig 3. Generalized composite columnar section and lithology—Appalachian Basin.

4000 ft to 4350 ft which are believed to be local lenses of rather permeable sandstone bounded by much less permeable rocks; original records indicate a rock pressure of close to 1900 psi and in a more recent well was as high as 1950 psi (Haight, 1972)

5. In the Leidy Gas field (currently a gas storage area) in Clinton County, Pennsylvania, the Oriskany is reported to be overpressured; also, the Marcellus shale overlying the Oriskany is likewise reported to be overpressured (Brown, 1980).

#### B. Lower Devonian Shales

The Burkett member of the Harrel shale penetrated in a test well at Morgantown, West Virginia, encountered abnormally high pressures at a depth of about 7100 ft; at that point, the formation shut-in pressure was 3700 psi (.520 psi/ft) while the minimum pressure gradient found was .489 psi/ft (Frohne, 1978).

#### C. Upper Ordovician

Reedsville-Utica-Trenton shales and limestone sections in southern West Virginia have reported high pressure-low volume gas zones requiring mud weights as high as 18 ppg (Bee, 1974).

#### D. Cambrian

1. In the Rome formation, on the southern flank of the Rome Trough, a deep well in Mingo County, West Virginia,



exhibited a near-lithostatic gradient of .940 psi/ft at depth intervals of 10,900 to 11,300 ft and 16,900 to 19,600 ft (Gates and Watson, 1979). The temperature was measured at 258°F and the salinity of the waters was reported to be very low -- about 45 ppm. Also, some gas was reported to be present in the formation waters (Brown, 1980).

2. Other deep wells in the Rome Trough in Calhoun County and Jackson County, West Virginia, found overpressured zones in Ordovician and Cambrian units with pressure gradients comparable to those found in the Mingo County well. A temperature of 272°F was reported from the Jackson County deep well while the salinity of formation waters in the Calhoun County well was only 53 ppm (Brown, 1980). (See Figure 2 for map of Appalachian Basin showing location of Rome Trough.)

E. Other Geopressured Occurrences (Brown, 1980; Overby, 1980)

Various unconfirmed reports suggest the presence of geopressured reservoirs in the following areas:

1. Oriskany sandstone in the Gladys field at depths of 6000 to 7000 ft in Randolph and Pocahontas Counties, West Virginia
2. Ordovician shales in recent wells drilled in the West Virginia-Ohio Panhandle
3. In recent wells drilled in the Eastern Overthrust Belt at Wise County, Virginia, and near Keyser, in Mineral County, West Virginia



### General Comments

1. The information on overpressured areas in the Appalachians is extremely scanty and very little has been published; much of the information is apparently available in company files.
2. According to Russell (1972) and others, the Appalachian Basin tends to be underpressured and each region has specific characteristics, e.g., lower Silurian sandstones of New York, Ohio, and Pennsylvania have abnormally low pressures, about .295 psi/ft, while lower and middle Devonian reservoirs of the same region have much higher pressure gradients, about .491 psi/ft. Also, there is a regional variation, e.g., pressures in the lower Silurian of West Virginia are about .423 psi/ft, while reservoirs in the eastern folded lower and middle Devonian rocks of Pennsylvania have a pressure of about .550 psi/ft as contrasted to .491 psi/ft in similar strata of the relatively undisturbed parts of western Pennsylvania.
3. Generally, the Appalachian Basin is cool and normal temperature gradients have been found in deep wells (Brown, 1980). However, in northern West Virginia, the temperature gradients range from .808 to 1.892<sup>o</sup>F/100' with a mean value of 1.108<sup>o</sup>F/100' in Mississippian and Pennsylvanian formations (Grisafi, et al 1974).



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## 6.2 INTERIOR SALT BASIN

### Location

The Interior Salt Basin refers to the arcuate trend of Jurassic sediments that extends from western Florida in a west-northwesterly direction across southwestern Alabama and south-central Mississippi and through to northern Louisiana and southern Arkansas and then heads in a southwesterly direction into eastern Texas (Figure 4). Though geologically considered part of the Gulf Coast basin, the geopressured occurrences within the Interior Salt Basin, as indicated in the sections that follow, are totally different.

### Formations

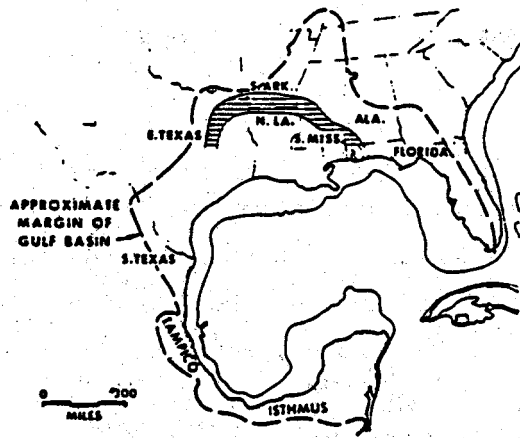
The geopressured formations are all of Jurassic and lower Cretaceous age as depicted in the generalized geologic column shown in Figure 5. Geopressures have been encountered in all of the formations listed (except for the Louann evaporites) in relatively shallow as well as at great depths. The various occurrences are described below on a geographic basis.

#### A. Western Florida - Southwestern Alabama

##### 1. Jay and Little Escambia Creek fields

The Smackover formation at a depth of 15,400 feet displays a reservoir pressure of 7850 psi and temperature of 285<sup>o</sup>F (Maxson, 1974). Other nearby fields with similar parameters include the Big Escambia field in Alabama and the Blackjack Creek field in Florida.





**Fig. 4. Index map of Interior Salt Basin**

SERIES	GROUPS AND FORMATIONS
LOWER CRETACEOUS	
UPPER JURASSIC	COTTON VALLEY
	UPPER HAYNESVILLE
	BUCKNER (L. HAYNESVILLE)
	SMACKOVER
MIDDLE JURASSIC	NORPHLET
	LOUANN

**Fig. 5. Generalized geologic column—Interior Salt Basin**

## B. Mississippi

1. In the Mississippi Salt Basin part of the Interior Salt Basin, geopressuring generally occurs in the Smackover sandstones and carbonates and the underlying Norphlet sandstone though overlying units such as the Buckner are likewise often overpressured (Parker, 1972). The Smackover, where productive, is characterized by "sour" gas which may contain 10 to 60% H<sub>2</sub>S and 5 to 60% CO<sub>2</sub>; according to Kirk (1972), the following factors are believed to be the primary contributors to the above:

- The Jackson Dome, a Cretaceous-age intrusion, exposed carbonates to volcanic action thereby producing CO<sub>2</sub>.
- The seal formed by the Buckner anhydrite in the western part of the region prevented the dissipation of H<sub>2</sub>S generated in situ as well as CO<sub>2</sub>; to the east, the Buckner grades into a salt-anhydrite zone in which overpressuring is still present but commonly either above the seal or within the unit itself.
- The underlying Louann salt is characterized by a rolling configuration which has formed structures of interest and may have influenced the occurrence of overpressures.

Three basic areas in the Mississippi Salt Basin have been defined (Klementich, 1977):

- Jackson Dome area characterized by high pressure salt water flows (13,000 psi at 20,000' depths) and ultra-high pressure sour gas (22,000 psi at 22,000' depths -- virtually lithostatic). According to Stuart and Kozik (1977), the Smackover is found at 12,000' on the north flank and plunges to about 27,000' at the synclinal axis of the basin (See Figure 6). Pressure gradients increase with depth from hydropressure in the 12,500' Loring field to near lithostatic at Southwest Piney



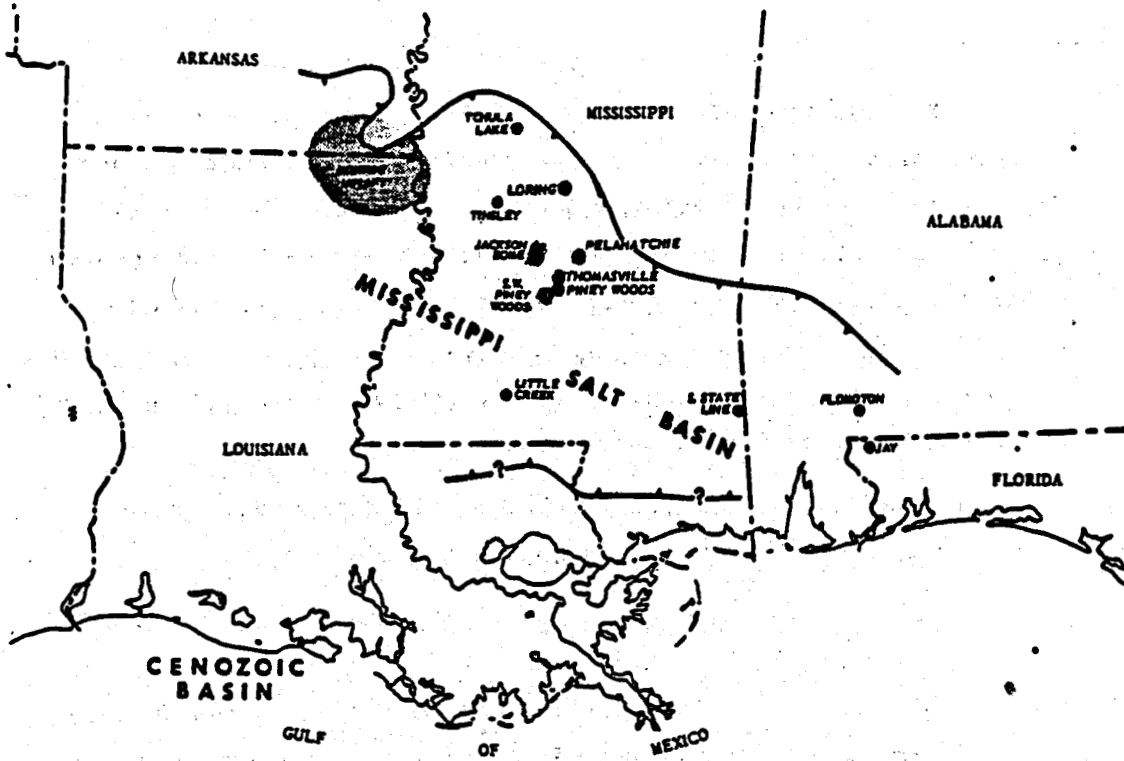


Fig. 6. Mississippi salt basin

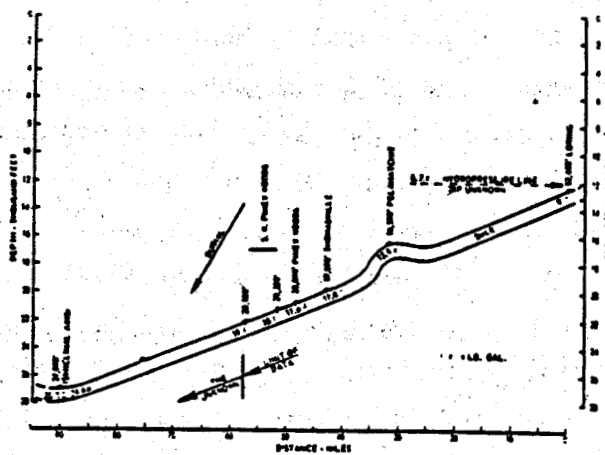


Fig. 7. Smackover regional geopressure profile extrapolated to synclinal axis (Stuart and Kozik, 1977)

Woods field. (Theoretically, at the synclinal axis, the geopressed gradient would exceed 1.28 psi/ft though it is not known if a rock can hold such a pressure gradient). The regional geopressure profile of the Smackover in this area is shown in Figure 7.

- Interdomal area in southern part of central Mississippi in which high pressure sweet gas is found in the Cotton Valley formation (18,000 psi at 23,000' depths).
- Area east of Mobile Embayment in Baldwin County, Alabama, in which the high pressured Buckner formation overlies the normally pressured Smackover.

Specific fields and occurrences include the following:

- (a) Thomasville, Piney Woods, and Southwest Piney Woods fields, Rankin County (Hamby, 1979 and Colvin, 1971).

These gas fields, developed in the late 1960's and early 1970's, exhibit extremely high pressures and temperatures in the Smackover formation which is comprised of dense, brown limestone with micro-laminated zones; e.g. at depths of 19,700 and 22,500 feet, reservoir pressures range from 17,500 to 22,000 psi (near-lithostatic) and bottom hole temperatures of 365 to 385°F. The Buckner formation above, comprised of anhydrite, shales, and colites, is normally pressured.

2. Pelahatchie field, Rankin County (Hartman, 1968)

Norphlet formation in this area is a geopressed oil reservoir at a depth of 17,100'



3. Tullala Creek field, Smith County (Kornfeld, 1966)

A sandstone zone in the Haynesville formation has a bottom hole pressure of 7933 psi at the 15,598 - 15,621' interval, i.e. pressure gradient of about .50 psi/ft.

4. Henderson area, Wayne County (Klementich, 1972)

Smackover geopressured gradient of about 1.0 psi/ft reported from salt water flow at 19,904' depth; the salt water comprised of mainly sodium and calcium chloride had a calculated density of 11.7 ppg and an estimated 1400 tons of salt was produced during an 18-hour flow test.

5. South State Line field (Parker, 1973)

Here the Smackover and Norphlet are normally pressured but the overlying Buckner has a pressure gradient of .75 psi/ft; these overpressures occur erratically throughout the immediate vicinity and are confined to porous rocks interbedded with evaporites (which may have served as a seal).

6. Hinds County

- A recent well drilled by Exxon Co. U.S.A. near Terry that bottomed in the Norphlet formation in which sour gas (with  $H_2S$  and  $CO_2$  was found) is believed to be the most expensive onshore well ever drilled (estimated cost \$42 million) and one that encountered one of the highest recorded bottom hole pressure in the United States (Anon., 1980); the parameters are as follows:

total depth	23,154'
bottom hole pressure	22,500 - 23,000 psi
bottom hole temperature	400°F

- An earlier well drilled by Placid Oil Co. to a depth of 25,640' encountered a bottom hole temperature of 425°F

and bottom hole pressure of about 24,000 psi in the lower Smackover; unlike other deep overpressured Smackover wells in the state, the gas contained little H<sub>2</sub>S (Anon., 1977)

C. Northern Louisiana - Southern Arkansas

1. Smackover field, Union and Ouachita Counties, Arkansas (Smith, et al 1972)

Nacotoch sand reservoir comprised of sandstone facies separated by shale stringers has an initial reservoir pressure of 1050 psi and temperature of 110°F at a depth of only 2000 feet

2. South Sarepta field, Bossier and Webster Parishes, Louisiana (Ellison and Russo, 1976)

Gray sandstone member of Smackover formation reported to be overpressured and extremely tight.

D. East Texas

1. Fallon-North Personville field, Limestone County

Cotton Valley lime formation is part of the Cotton Valley sand and lime trend that underlies more than 250,000 square miles, from central Texas through northeast Texas into northern Louisiana and southern Arkansas. In this area, the Cotton Valley lime is found below the Cotton Valley sand at about 11,000 feet and reservoir pressures of 6400 psi were measured (Anon., 1979). (One of the wells in this field was subjected to a massive hydraulic fracturing treatment partially funded by DOE under the Enhanced Gas Recovery Program).

Elsewhere in east Texas, the Cotton Valley sands are geopressured with a pressure gradient ranging from .50 to .55 psi/ft (Kozik, et al., 1979).



2. The temperature found in the Cotton Valley formation at depths of 10-11,000' ranges from 250 to 275°F for a gradient of 2.5°F/100' (Miller, 1980).

#### General Comments

As indicated above, the geopressured occurrences in the Interior Salt Basin, in contrast to those in the Gulf Coast Basin, have the following unique characteristics:

- Geopressures are confined to rocks of Jurassic and Cretaceous age (compared to Tertiary sediments in the Gulf Coast)
- Lithology is much more complex consisting of quartzites, carbonites, and evaporites (compared to overpressured shales and sandstones of the Gulf Coast Basin)
- There is no shale seal in these deep Jurassic formations
- The pressure gradients are extremely high and in certain instances approach the lithostatic gradient
- The Jurassic units are noted for their erratic porosity and their erratic geopressures since the porosity is secondary in origin and not a result of "undercompaction" as in the Tertiary Gulf Coast Basin sediments.



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### 6.3 ANADARKO BASIN

#### Location

The Anadarko Basin covers an area of approximately 35,000 square miles stretching across northwestern Oklahoma, the northeastern Texas Panhandle, southwestern Kansas, and southeastern Colorado. However, the deeper formations in which geopressuring occurs are confined to a relatively small area in western Oklahoma and the eastern Texas Panhandle (Figure 8). The basin, underlain by an extremely thick suite of Paleozoic sediments from Cambrian to Pennsylvanian in age, is the site of some of the deepest drilling and gas production in the world -- to 30,000' plus.

#### Formations

Geopressures have been found in various sedimentary units in the Anadarko Basin but principally in the lower-Pennsylvanian and upper Mississippian Atoka, Morrow, and Springer formations, occasionally in the overlying upper Pennsylvanian Tonkawa formation, and often in the underlying Siluro-Devonian Woodford shale and Hunton dolomite and the lower Ordovician Simpson formation (Lindsey, 1979).

The Hunton formation, a prime gas target in the Anadarko, is a solution limestone with dolomitic porosity zones that occurs at a depth of 17,000-23,000' and which is characterized by a pressure gradient of .65 to .73 psi/ft and temperature of 300-375<sup>o</sup>F (Barrett and Thompson, 1974). The underlying Arbuckle formation (lower Ordovician), another gas-bearing unit in the basin, is generally normally pressured.

The stratigraphic succession and lithology of the major formations in the western Anadarko Basin is depicted in Figure 9.



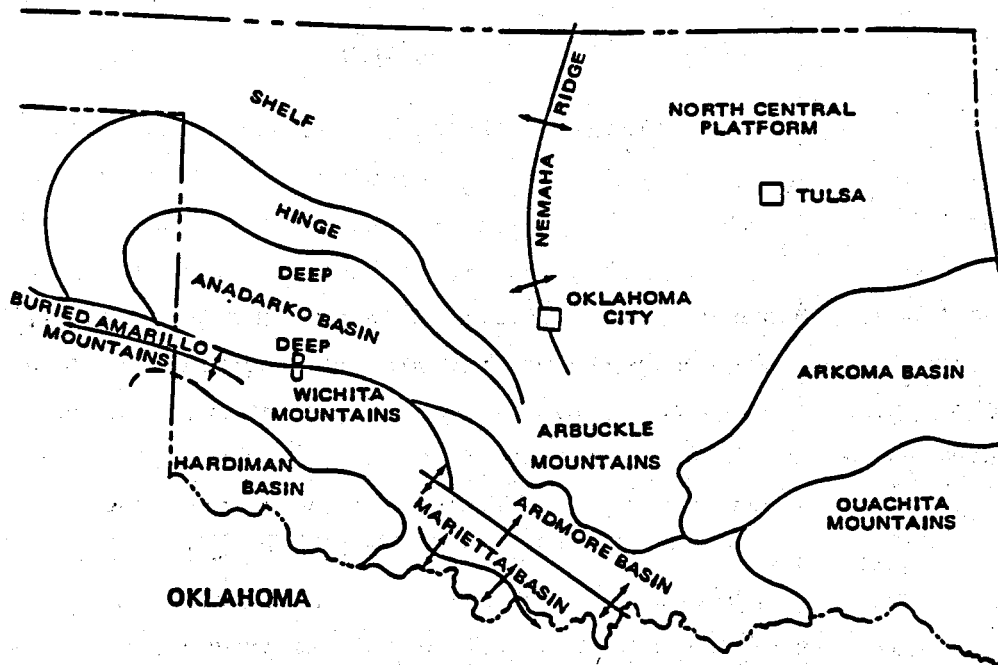


FIGURE 8. TECTONIC MAP OF DEEP ANADARKO BASIN REGION IN OKLAHOMA AND TEXAS (MODIFIED AFTER CLEMENT, 1977)

SYSTEM	SERIES	GENERAL LITHOLOGIES	TECTONIC ACTIVITY
LOWER PENNSYLVANIAN	ATOKA	SHALES, SANDSTONES AND THIN LIMESTONES DEPOSITED IN MARINE ENVIRONMENT	UPPER WICHITA OROGENY
	MORROW		LOWER WICHITA OROGENY
	SPRINGER		
UPPER MISSISSIPPIAN	?-?-? CHESTER	THIN LIMESTONES AND SHALES WITH OCCASIONAL SANDY ZONES, LIMESTONES BECOMING MASSIVE WITH DEPTH	VERY LITTLE TECTONIC ACTIVITY IN WESTERN OKLAHOMA

FIGURE 9. STRATIGRAPHIC SECTION - WESTERN OKLAHOMA - ANADARKO BASIN.

On a regional basis, the Morrow-Springer sequence is normally pressured throughout the Anadarko, but geopressed gradients are noted in a band extending from the eastern edge of the basin (around Blaine County, Oklahoma) westward into the eastern Texas Panhandle (Wheeler and Hemphill Counties). Figure 10 is a pressure gradient map of the Morrow-Springer in the western Anadarko Basin. A pressure-depth graph representative of the overpressuring found in this sequence is shown in Figure 11.

Specific fields and areas of geopressed occurrences are described below:

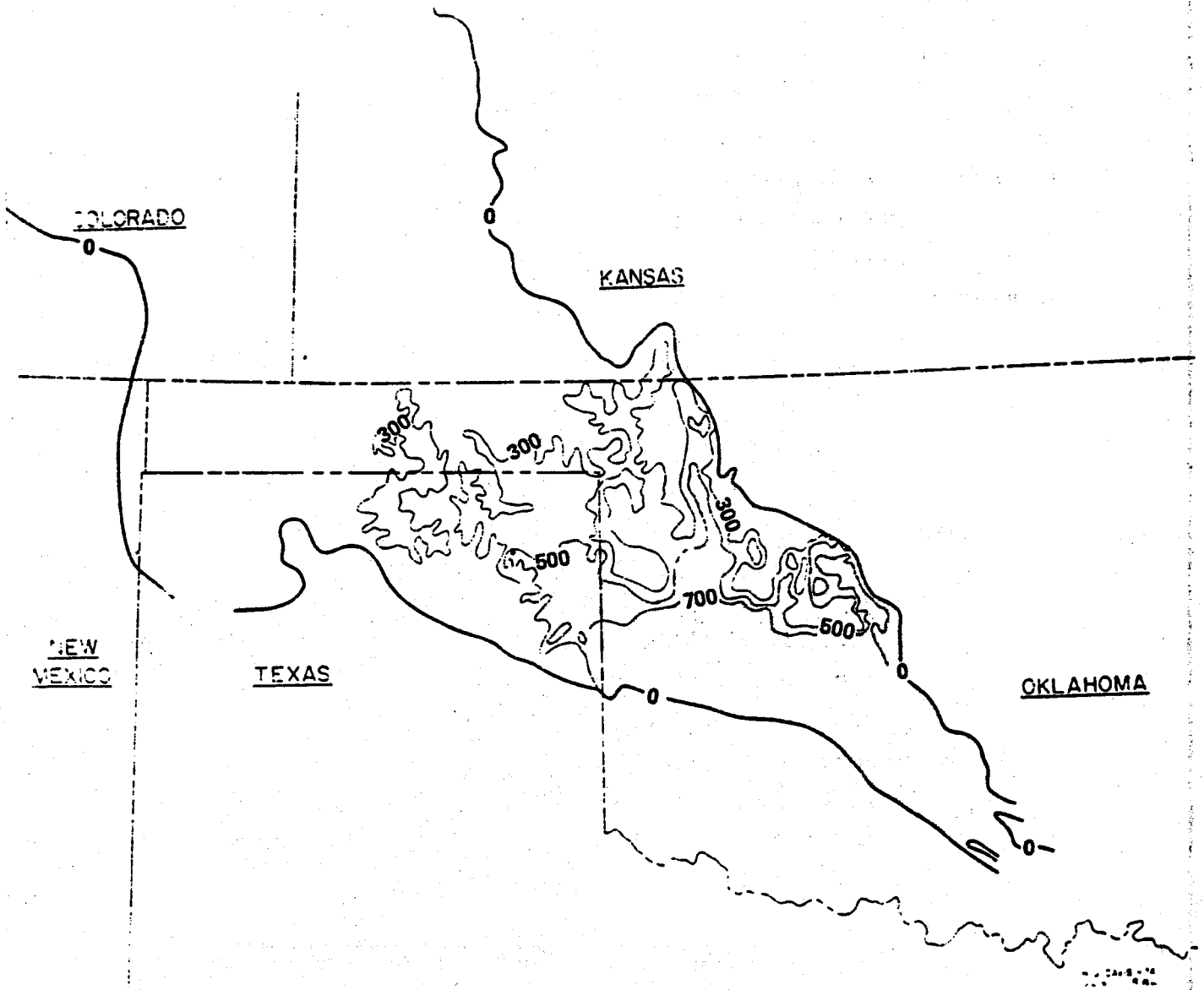
1. Hemphill and Wheeler Counties, Texas and Roger Mills, Beckham, and Washita Counties, Oklahoma

In this area, the upper Morrow formation (comprised of a sequence of fluvial/deltaic units consisting of alternating sands, chert conglomerates, and marine shales), one of the principal gas reservoirs in the western Anadarko, is usually overpressured in the deeper parts of the basin with gradients in excess of .81 psi/ft not uncommon. The temperature gradient is approximately 1.5<sup>o</sup>F/ft (Shelby, 1979).

- (a) Reydon field, Roger Mills County, Oklahoma and Hemphill County, Texas

This field, variously termed the West Reydon, Northwest Reydon, and Viking, has the following parameters (Borger, 1977):





**FIGURE 10.** — Anadarko Basin BHP gradient map, Morrow-Springer formations (Davis and Nondorf, 1974)

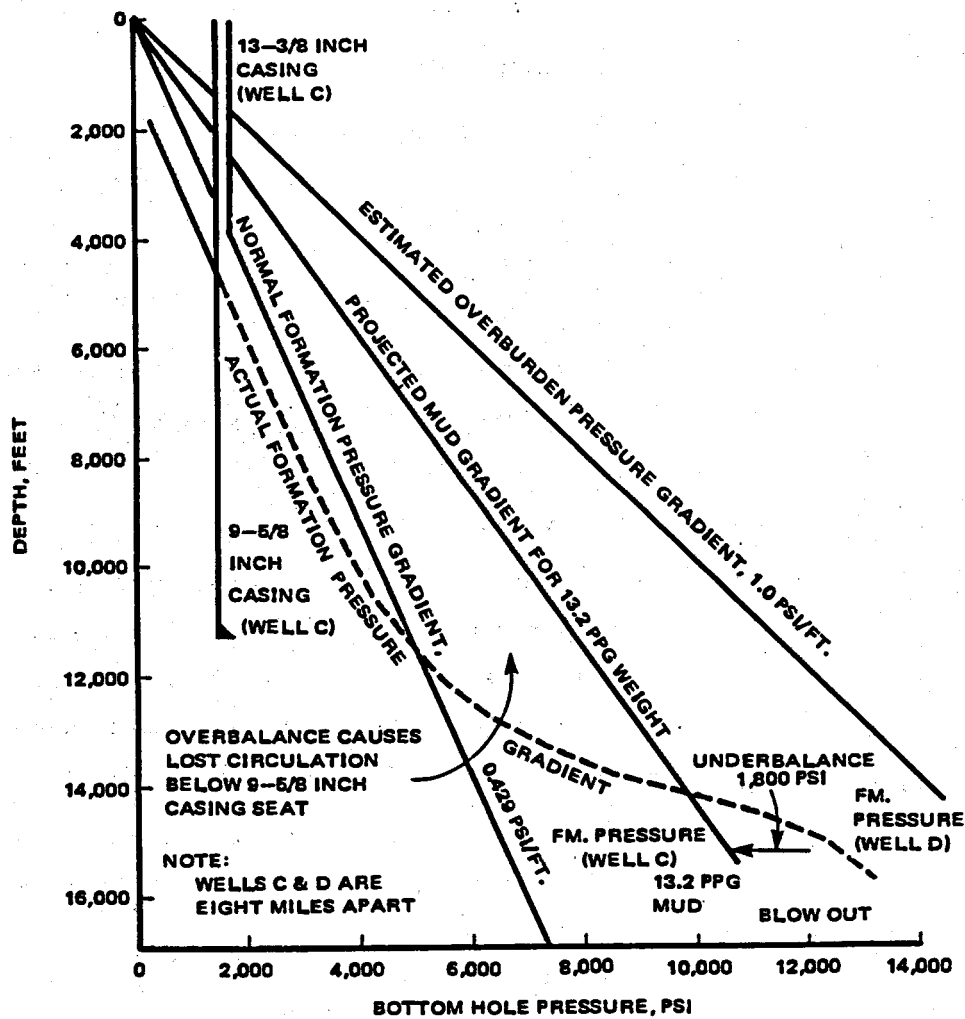


FIGURE 11. Pressure—depth graph of representative well in western Anadarko Basin indicating geopressures in the Morrow—Springer (Frederick, 1967)

Depth	15,000'
Initial reservoir pressure	12,550 psi
Pressure gradient	.838 psi/ft
Temperature	280°F

(b) West Cheyenne field, Roger Mills County

The pore pressure plot for the discovery well for this field (Figure 12) indicates a normal pressure gradient (.433 psi/ft) up to about 10,500' after which the gradient builds rapidly reaching the mud weight equivalents of 13.8 ppg at 11,600', 15.5 ppg at 15,000' in the Atoka, and 17.7 ppg further below in the upper Morrow (Calverly, 1977)

(c) Elk City field, Beckham County

Low volumes of gas accompanied by high pressure have been reported from intercalated shale layers in the Atoka at a depth of 16,000' while high volumes of gas likewise under high pressure occur in the Springer at 21,614' (Kornfeld, 1967)

(d) Other fields in this area in the upper Morrow which are similarly overpressured include the Southwest New Liberty and Carpenter in Beckham County and the Canute in Washita County.

2. Blaine County, Oklahoma

Located along the northeast flank of the Anadarko, Morrow sands contain water and gas under abnormally high pressures (.50 to .82 psi/ft) while to the northwest in Beaver County, they are subnormal, .22 to .30 psi/ft (Dickey and Soto, 1974).



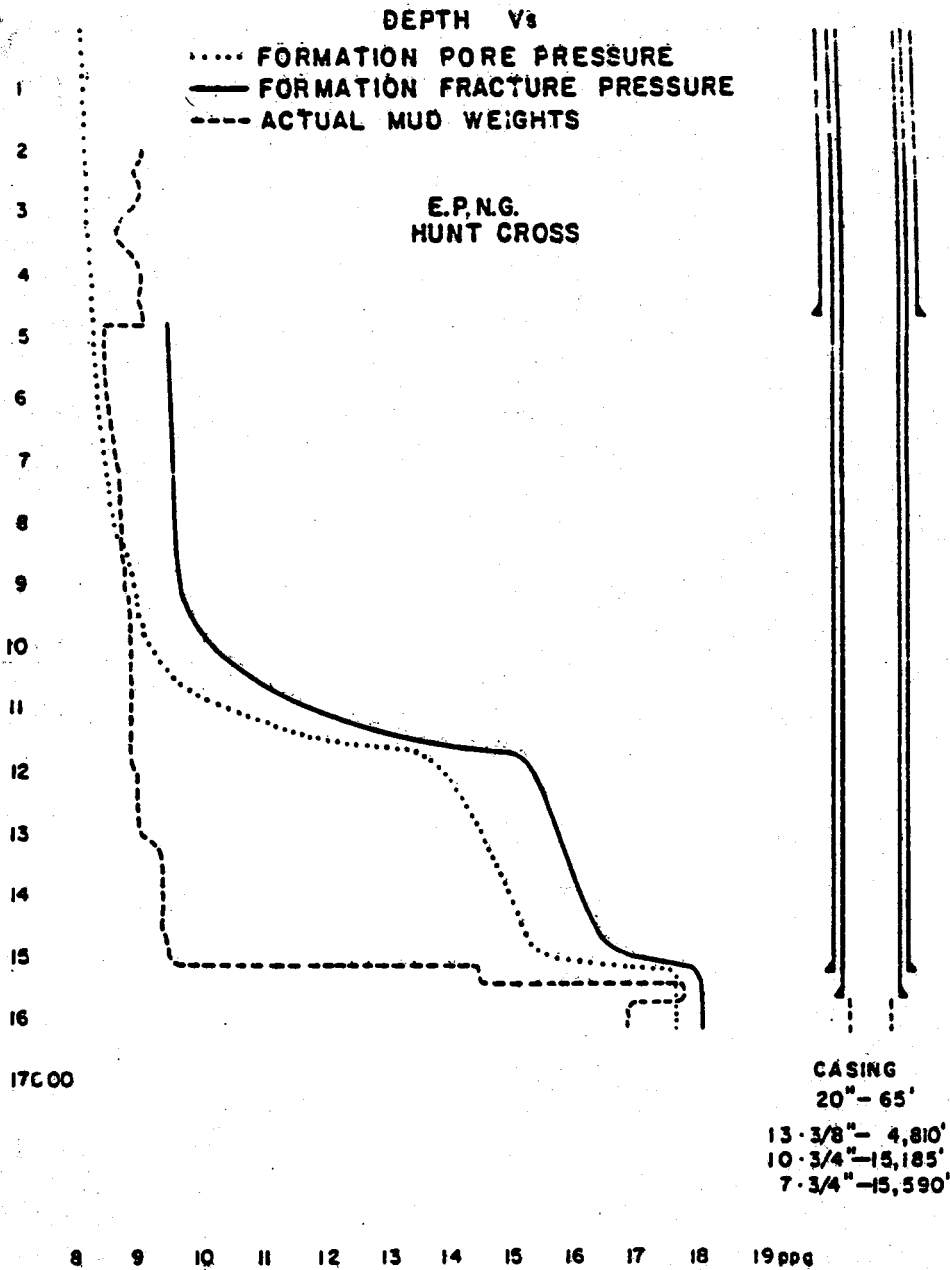


Fig. 12. Pore pressure plot for discovery well in West Cheyenne field, Roger Mills County, Oklahoma (Calverly, 1977)

In the Geary area, in the southeastern part of the county, a well completed in the basal Springer, composed of fine grained quartz sandstone overlain by carbonaceous mudstone and underlain by black mudstone, had a pressure of 8448 psi at 11,200' (pressure gradient of .754 psi/ft) and temperature of 200-230°F (Clement, 1977).

3. Caddo County, Oklahoma

Various wells encountered subnormal pressures between 0 and 10,000', abnormally high pressured shales between 10-15,000', and continued geopressures to 20,000'. The bottom hole temperature at about 19,300' was 300°F (Pratt, 1980).

4. Wheeler County, Texas

The Mills Ranch field exhibits overpressuring at 21,670' in the Hunton formation while the underlying Arbuckle is normally pressured at 22,800' (Leonard, 1977).

General Comments

1. The Atoka formation is overpressured in many places in the Anadarko Basin generally associated with fracture-type gas reservoirs and water-free condensate production (Koch and Meissner, 1979). The upper Morrow likewise has water-free condensate production and large gas flow rates (Shelby, 1980).



2. Normal temperature gradients appear to be prevalent in the Anadarko, e.g. at the Lone Star Baden #1 well drilled in Beckham County, Oklahoma to a depth of 30,050', the bottom hole temperature recorded was 427°F for a gradient of 1.16°F/100' (Zecchi and Scott, 1973).
3. Although steeper than normal temperature gradients occur in geopressed regions, as indicated above, this is not always the case.



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## 6.4 DELAWARE BASIN

### Location

The Delaware Basin is located in west Texas and southeast New Mexico and is geologically similar to the Val Verde Basin to the southeast. Figure 13 indicates the location of the two basins and other geologic structures and provinces in the region.

### Formations

The Delaware Basin is underlain by a thick sequence of Paleozoic sediments in which all systems from Cambrian to Permian are represented. A generalized stratigraphic and lithologic column is presented in Figure 14.

In general, high pressure (overpressured) gas has been encountered in the following formations and depths (Mahoney, 1966) though there are several exceptions:

<u>Approx. Depth</u>	<u>Lithology</u>	<u>Formation</u>
10,000'	limestone, shale	Wolfcamp
14,000'	sandstone, conglomerate limestone, sandstone	Atoka Morrow
20,000'	shale, sandstone dolomite, limestone	Simpson Ellenburger

A generalized geologic section indicating the formations, pressure variations -- from normal to high to normal -- that is characteristic of the Delaware Basin is shown in Figure 15.



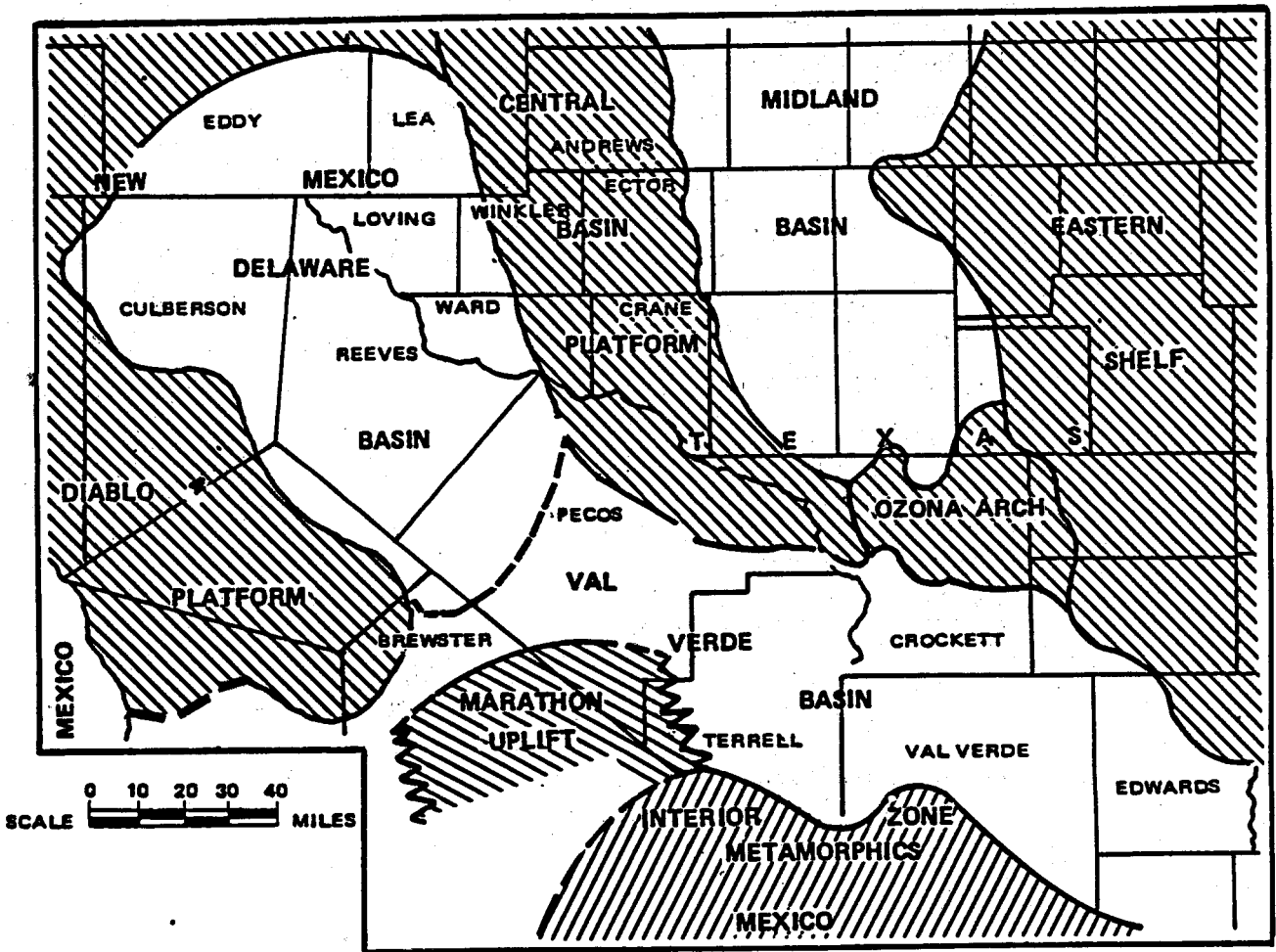


Fig. 13. Geologic provinces of West Texas—southeast New Mexico showing Delaware Basin, Val Verde Basin, and surrounding geologic structures (Holmquist, 1965)

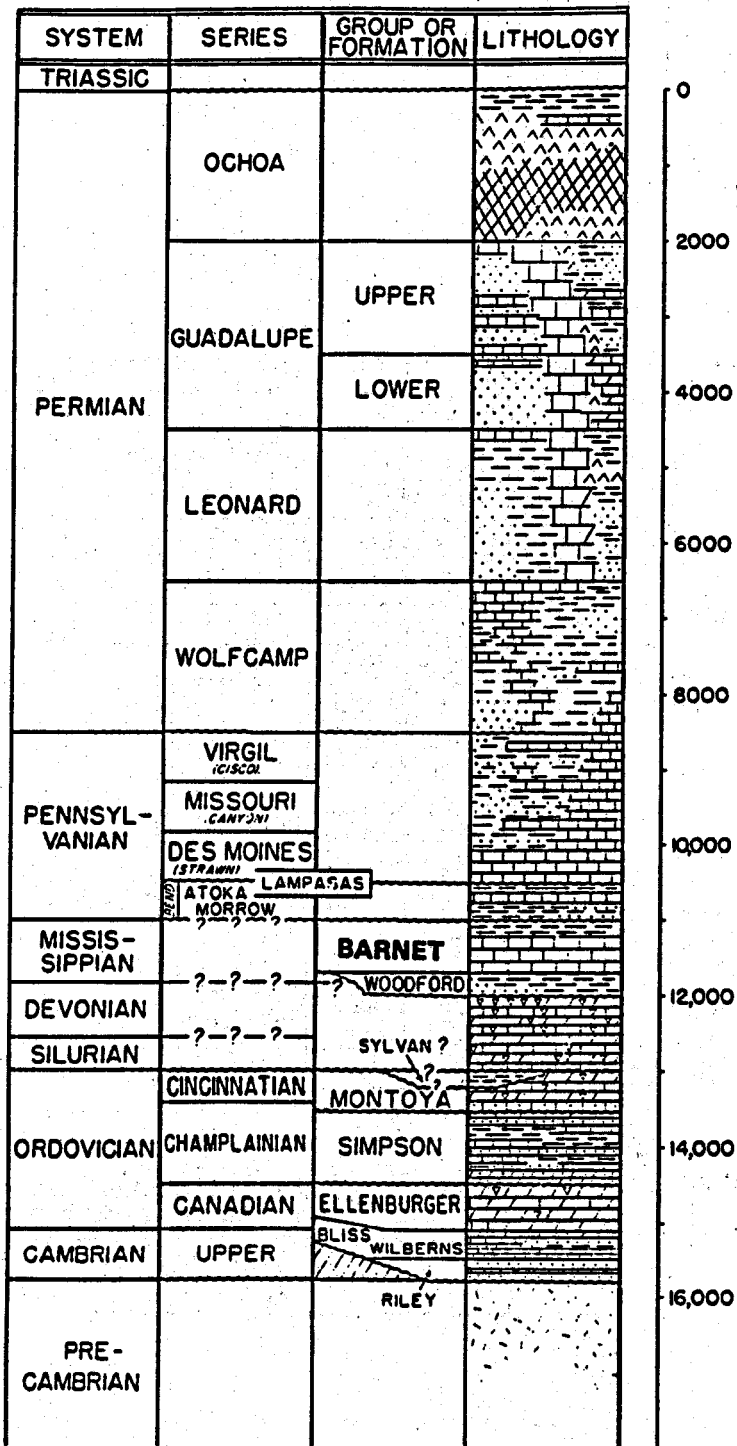


Fig. 14. Generalized stratigraphic and lithologic column—Delaware Basin (modified after Holmquist, 1965)

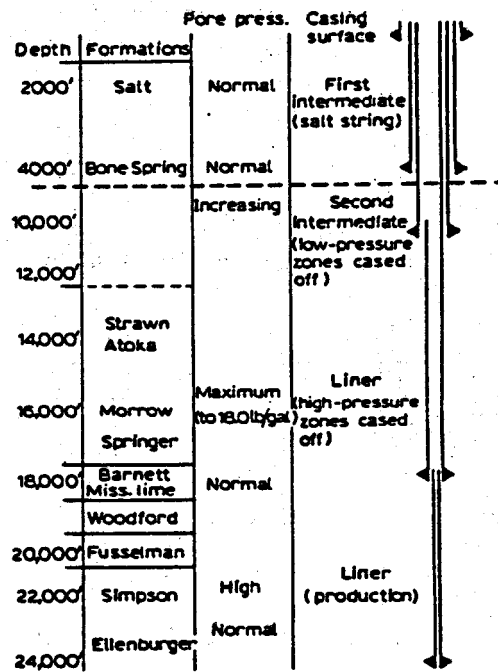


Fig. 15. Geologic section showing formations, pore pressure variations, and casing program for well in Delaware Basin, West Texas (Reid, 1970)

Specific areas and fields in the Delaware Basin where geopressures have been found are described below:

1. Pecos County, Texas (Holmquist, 1965)

Relict high pressures still remain in relatively discontinuous reservoirs of the Strawn-Atoka formations of the Coyanosa field, Atoka formation of the Rojo-Caballos field, and Wolfcamp formation of the Hershey field

2. Puckett Gas field, Pecos County, Texas (Frederick, 1966)

The normal pressure gradient for the area is .429 psi/ft. while the pressure gradient for the Ellenburger formation based on old pressure data from the 1950's is considerably higher as shown in the pressure gradient graph of Figure 16

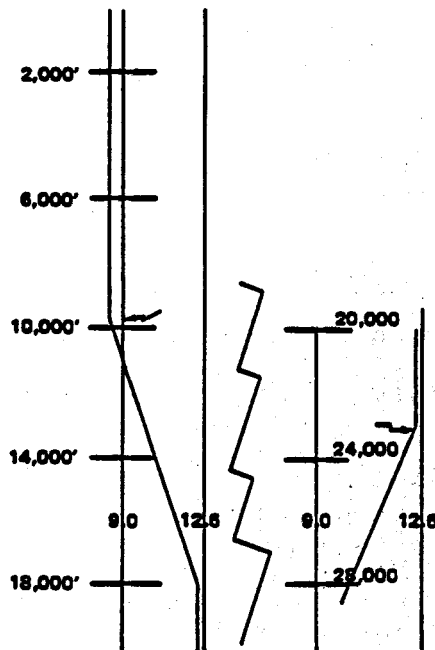
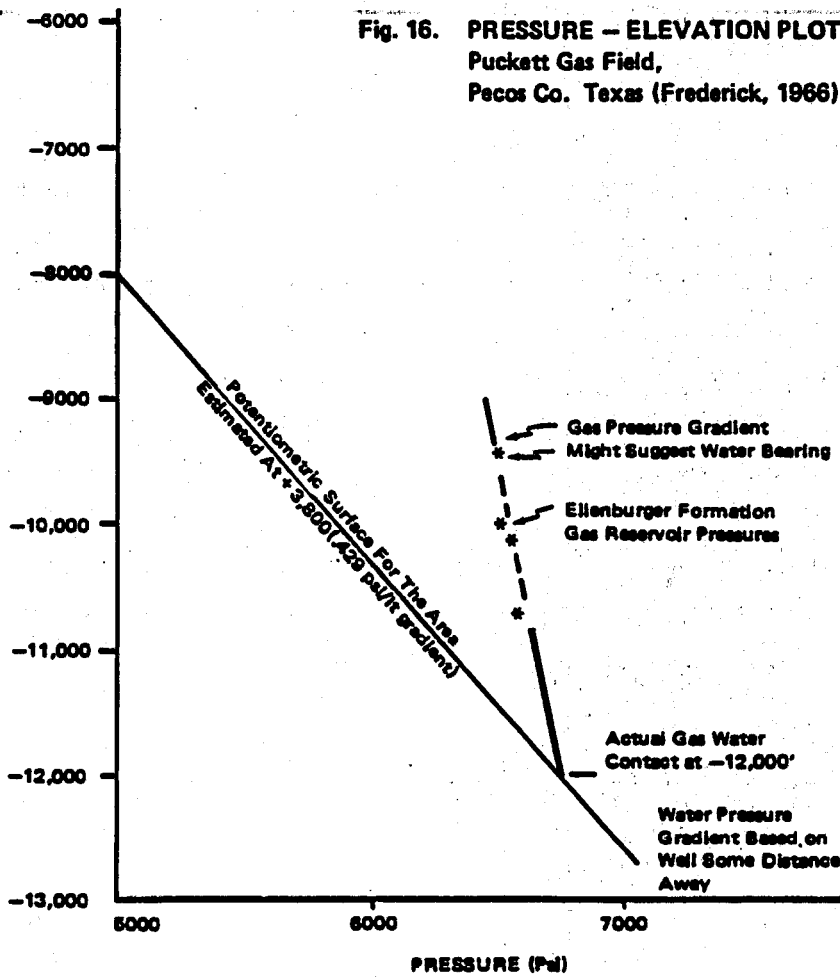
3. Ralph Lowe Estates University Well, Pecos County, Texas (Rehm, 1972)

Drilled to a depth of 28,500', this well displayed the onset of overpressuring at about 10,000', stabilized at 18,000', and decreased at 23,000' as shown in Figure 17. The highest pressures occurred in the center section of the well while production is from the normally pressured Ellenburger carbonates

4. Mentone area in southern Loving County, northwestern Ward County, and northern Reeves County, Texas



**Fig. 16. PRESSURE – ELEVATION PLOT**  
**Puckett Gas Field,**  
**Pecos Co. Texas (Frederick, 1966)**



**Fig. 17. Typical pressure profile,**  
**West Texas, Ralph Lowe**  
**Estate (Permian) mud**  
**weight. (Rehm, 1972)**

Abnormally high pressure gradients, the highest in the Delaware Basin are encountered in thick (5000' plus), predominantly shale sections in the Wolfcamp, Atoka, and Barnett formations. The pressure gradients for two representative wells in this area, depicted in Figure 18, indicate that mud weights in excess of 16 ppg needed to be employed (Bethancourt, 1977)

5. Other representative geopressured fields and formations in the Delaware and Val Verde Basins include the following (West Texas Geol. Soc., 1969):

<u>Field</u>	<u>County</u>	<u>Producing Formation</u>	<u>Initial Field Pressure</u>	<u>Depth</u>
Block II	Andrews	Devonian tripolitic chert	3200 psi	3,760'
Gomez	Pecos	Ellenburger dolomite	9718 psi	19,880'
Greg Ranch	Pecos	Wolfcamp	4960 psi	8,960'
JM	Crockett	Ellenburger dolomite	6330 psi	12,100'
Lockridge	Ward	Ellenburger dolomite	8715 psi	16,469'

#### General Comments

1. The Ellenburger formation, a highly soluble dolomite, is generally overpressured in the Delaware Basin and the pertinent parameters are as follows (Barrett and Thompson, 1974):



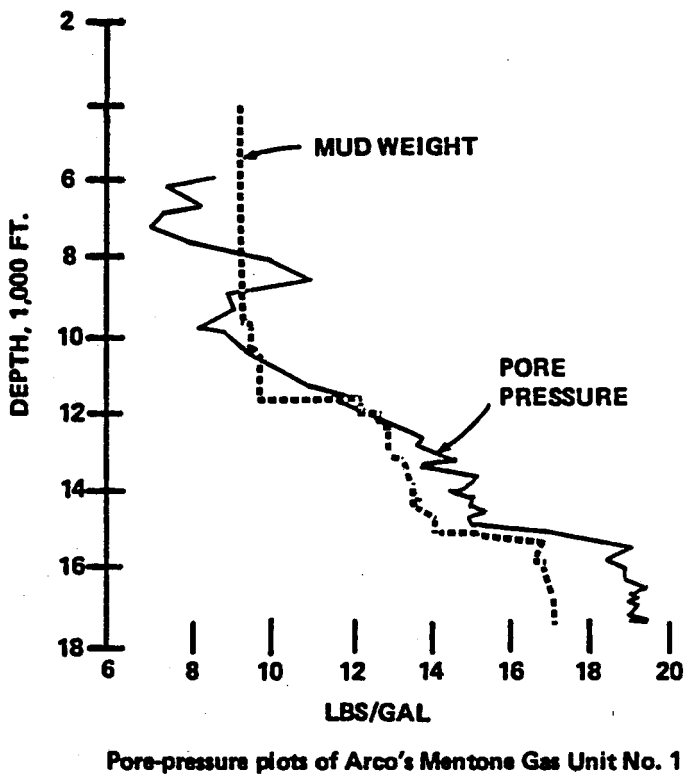
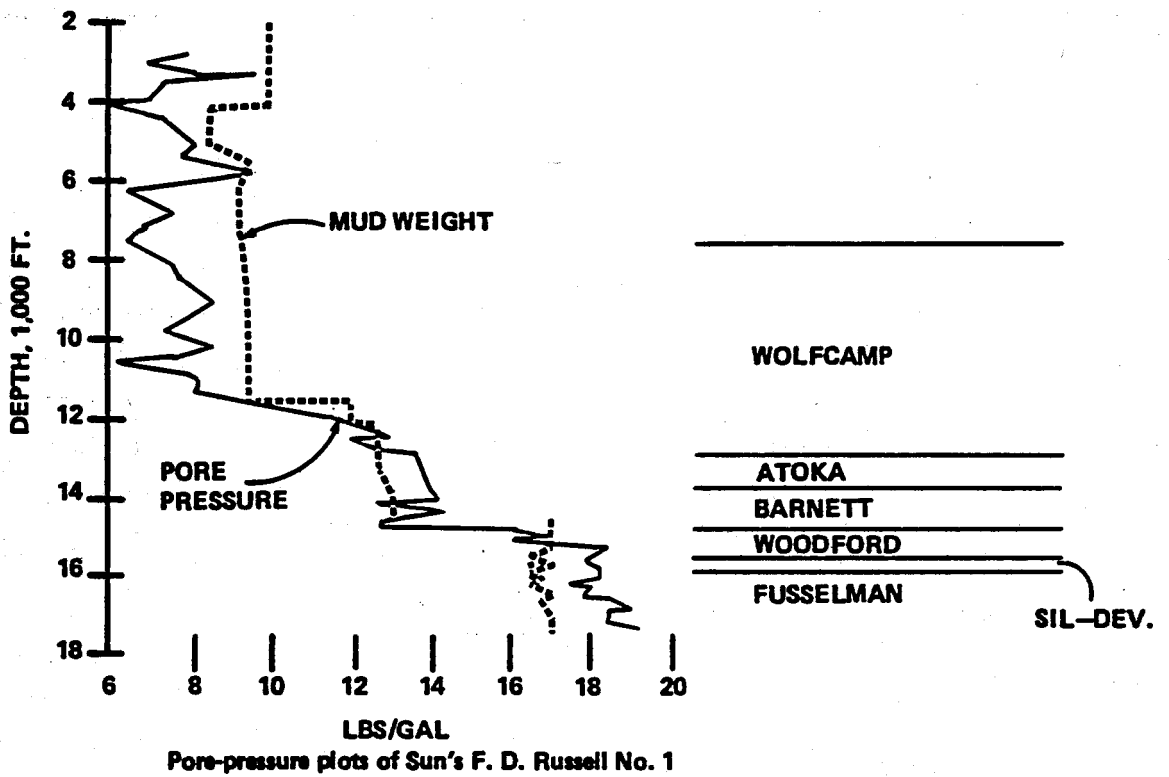


FIGURE 18. Pore pressure plots of two wells in Mentone area of Delaware Basin, Loving County, Texas (Bethancourt, 1977); stratigraphy shown for one well to indicate location of geopressed zones.

Depth	18-24,000'
Pressure gradient	0.65 to .80 psi/ft
Reservoir temperature	320-380°F

2. In general, at 25,000', the temperature expected ranges from 350 to 400°F while the pressure will be in the 12-15,000 psi range (Elliott, et al., 1966). As in the Anadarko Basin, the temperature gradients are apparently normal, e.g. in the Ralph Lowe University #1-17 well in Pecos County, Texas, drilled to 28,500', the bottom hole temperature was 428°F for a gradient of 1.24°F/100' (Zecchi and Scott, 1973).
3. The geothermal gradient increases in a southeasterly direction from New Mexico to Texas, e.g., in Chaves, Eddy and Lea Counties, New Mexico, the gradient is 0.7 to 0.9°F/100' (Summers, 1972) while to the southeast, in Texas, it is 1.4 to 1.7°F/100'.



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## 6.5-6.10 ROCKY MOUNTAIN BASINS

The basins of the Rocky Mountains are characterized by notable occurrences of geopressured reservoirs, for the most part at depths below 10,000 feet. Hence, where development of a particular basin has proceeded to the point where deep zones are being drilled, overpressured zones are most apt to be found, e.g. Uinta, Green River, and Wind River Basins. Elsewhere in the geologic section, the reservoirs are apt to be normally pressured or underpressured. Certain basins, such as the San Juan Basin and the Denver Basin, are generally characterized by underpressuring as a result of hydrodynamic influences but even there, isolated occurrences of geopressures have been reported. It is common, in fact, for Rocky Mountain Basins to have anomalously high and low pressures.

The various basins in this region that will be described in the sections that follow include the Uinta, Big Horn, Green River, Wind River, Powder River, and others; the location and relationship to each other are indicated in Figure 19. As most of the basins under discussion are located in Wyoming, a stratigraphic nomenclature chart for the various geologic areas of the state has been provided in Figure 20; it will be generally applicable to basins and structures in the immediately surrounding states.

Specific information on geopressured occurrences for each of these basins ranges from sparse to plentiful. In the case of the Uinta Basin, for example, the overpressured Altamont-Bluebell trend, discovered in the 1970's has been thoroughly described in the literature; by comparison, many fields in the Big Horn Basin were discovered 40-50 years ago and the means for pressure determination were neither as reliable nor as accurate as modern-day techniques and consequently, there is much uncertainty as to the initial reservoir pressures. Similarly, published information on the salinities of the geopressured waters of this region was unavailable but they have been reported to be relatively low.



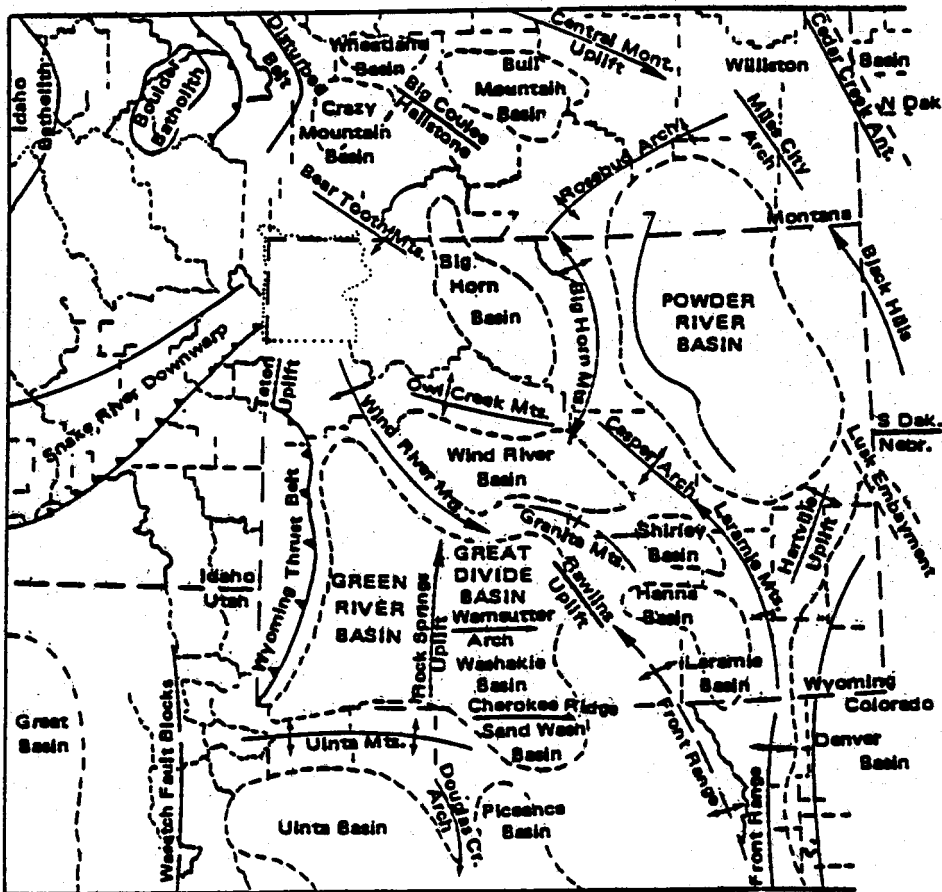
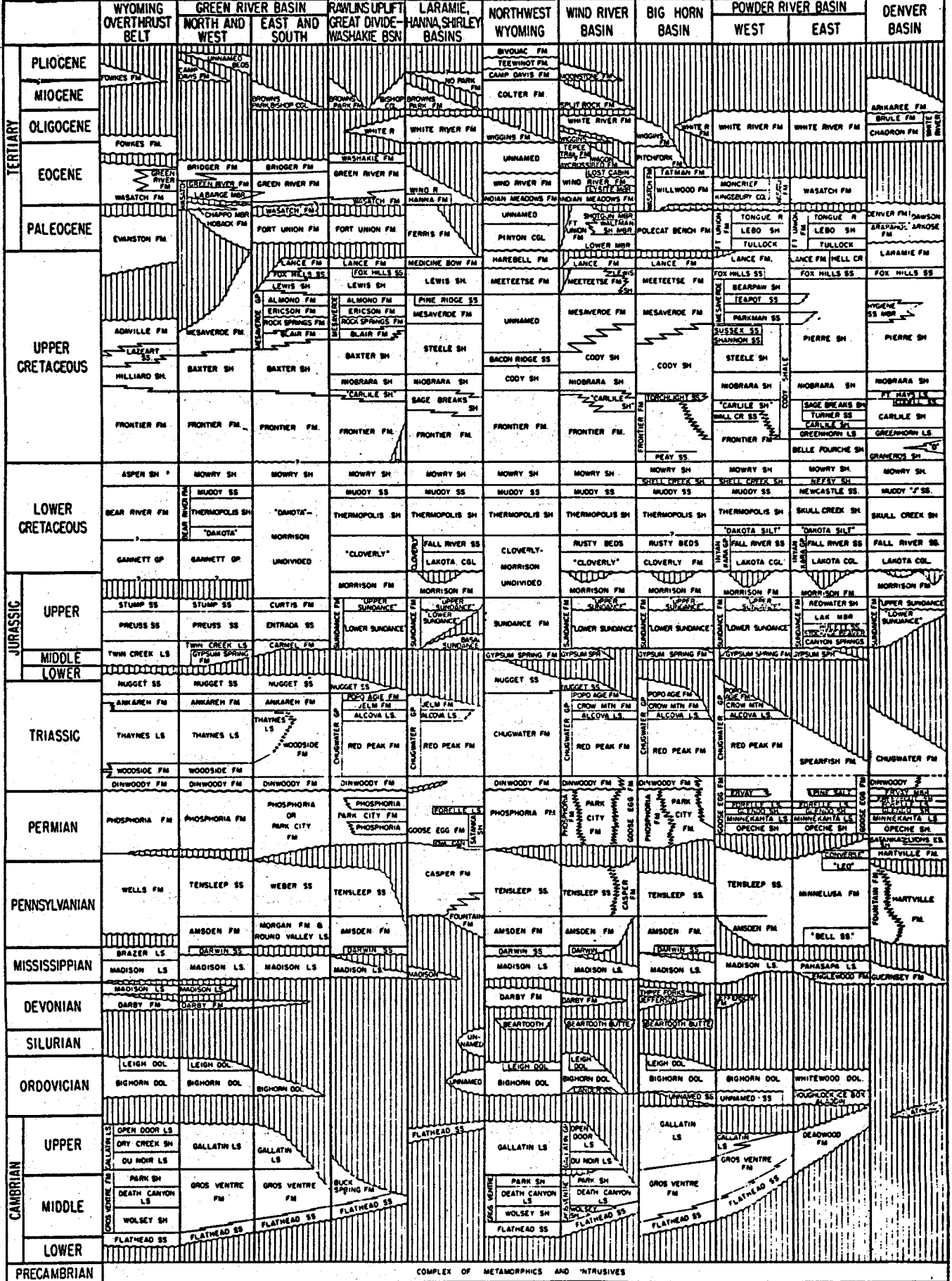


Fig. 19. Tectonic features and geologic provinces of northern Rockies

Fig. 20 WYOMING STRATIGRAPHIC NOMENCLATURE CHART



COMPLEX OF METAMORPHICS AND 'INTRUSIVES'

REVISED BY STRATIGRAPHIC NOMENCLATURE COMMITTEE, WYOMING GEOLOGICAL ASSOCIATION, 1969

## 6.5 BIG HORN BASIN

### Location

The Big Horn Basin is principally located in northwestern Wyoming and extends northward into southwest Montana (see Figure 19).

### Formations

Most of the oil fields in the Big Horn Basin have production from the Tensleep formation (Pennsylvanian) which is normally pressured or even underpressured; however, there are a number of fields cited below where this formation, the underlying Madison formation, and others are overpressured.

1. Bonanza field, Big Horn County, Wyoming (Hill, et al., 1961)

Drill stem tests indicate high datum pressures in the Tensleep (Pennsylvanian), Madison (Mississippian) and Gros Ventre (Cambrian) formations.

2. Grass Creek Oil field, Hot Springs County, Wyoming (Hill, et al., 1961)

Several high pressure reservoirs have been reported in the Tensleep, Madison, and overlying Cloverly formations.

3. Elk Basin field, Park County, Wyoming (McCaleb and Waydon, 1969)

This field is located at the north end of the basin straddling the Wyoming-Montana line and contains four producing zones in



the Madison limestone-dolomite sequence -- an upper zone characterized by extensive solution collapse, a shale unit below which has acted as a permeability barrier, and two zones below which have reduced porosity and sealed fractures. Differential pressures of 3000 to 3500 psi exist on the east side of the field and 1000 to 1500 psi on the west side.



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## 6.6 POWDER RIVER BASIN

### Location

The Powder River Basin is located in northeastern Wyoming and southeastern Montana (see Figure 19).

### Formations

This basin is generally characterized by normally pressured reservoirs but there are a few examples, discussed below, where overpressuring has occurred, usually in relation to the lower Cretaceous Mowry shale. The latter is believed to have been the major source rock for oil in the Powder River Basin and while it remains overpressured today, it is not sufficient for oil expulsion (Momper and Williams, 1979).

1. Kitty field, Campbell County, Wyoming (Larberg, 1976)

The field is located along the east flank of the basin where the lower Cretaceous Muddy formation forms a stratigraphic trap. The Muddy formation consists of interbedded sandstones, siltstones, and shales and is overlain by the Mowry shale and underlain by the Skull Creek shale. There are four separate reservoirs in the Muddy and two of these zones exhibit pressure gradients of .487 psi/ft as well as anomalously high temperature gradients of  $2.2^{\circ}\text{F}/100'$ . Other nearby fields where overpressures have been noted in the Muddy include the Mill Gillette and Kingsbury Creek fields.

2. Spearhead Ranch field, Converse County, Wyoming (Lange, 1976)

High pressure oil and gas have been reported from the upper Cretaceous Frontier sandstone; at a depth of 12,850', the reservoir pressure was 7400 psi.

3. The Ash Creek and South Ash Creek fields, Sheridan County, Wyoming; Lance Creek field, Niobrara County, Wyoming; and Porcupine Dome, Rosebud County, Montana have been determined to be overpressured based on hydrodynamic studies -- due to the presence of fault zones with low entry pressures which presumably indicates high formation pressures at depth (Price, 1976).

4. Powell-Ross field, Converse County (Hando, 1976)

Located in the southwest part of the county, the Frontier formation at about 11,700' has an indicated reservoir pressure of 8038 psi while the underlying Dakota at 13,374' had a pressure of 8575. The Steinle Ranch field, in Converse County, displays overpressuring in the lower Cretaceous Muddy sandstone, i.e. reservoir pressure of 5900' at a depth of about 10,700'.

5. Other fields where initial pressure analysis indicates high pressures (and probable geopressuring) include the LX Bar, Gas Draw, and Hilight fields (Larberg, 1976).

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## 6.7 WIND RIVER BASIN

### Location

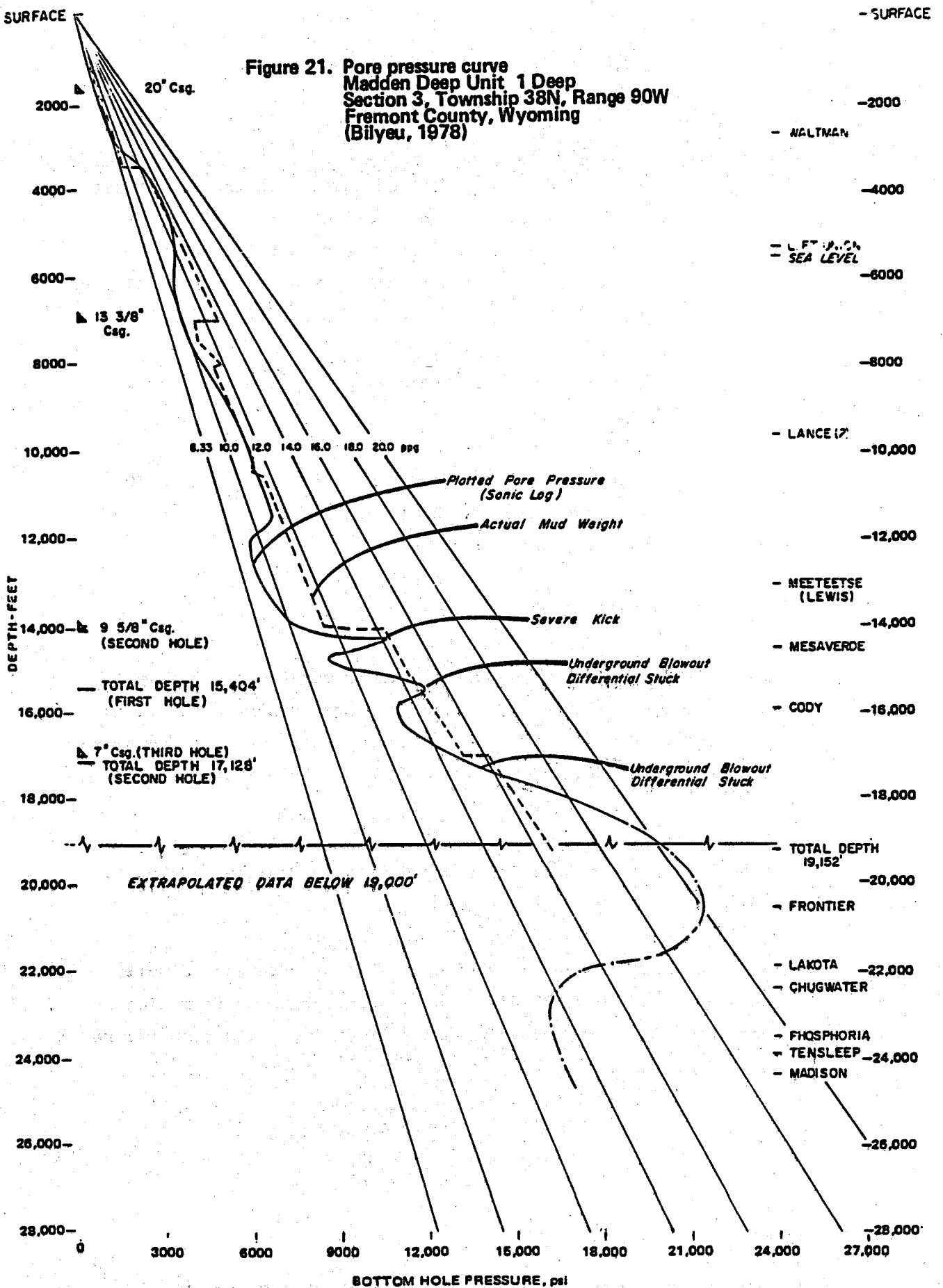
The Wind River Basin is located in central Wyoming encompassing parts of Sublette, Fremont, Natrona, and Washakie Counties as well as the Wind River Indian Reservation.

### Formations

The basin is underlain by a thick sequence of sediments ranging in age from Cambrian to Pliocene as depicted in Figure 20. Slightly overpressured zones have been encountered in shale beds at shallow depths but extremely high geopressures are found at depths below 10,000'. Several examples are described below.

#### 1. Madden Deep Unit # 1 Well, Fremont County (Bilyeu, 1978)

As indicated in the pressure-depth graph, Figure 21, slight overpressuring is noted in the Waltman shale and upper section of the Fort Union formation (Paleocene). Below that, high pressure-low volume gas is encountered in the upper Mesaverde and high pressure-high volume gas in the lower Mesaverde (upper Cretaceous) at about 14,000'. Further high pressures are encountered in the Cody formation (middle Cretaceous). Higher pressures are extrapolated for the Frontier formation (lower Cretaceous) and anticipated high pressures below 23,000' in the Madison formation (Mississippian).



**Figure 21. Pore pressure curve  
Madden Deep Unit 1 Deep  
Section 3, Township 38N, Range 90W  
Fremont County, Wyoming  
(Bilyeu, 1978)**

2. FRU # 22-25 Well, Fremont County (Bilyeu, 1978)

Slightly overpressured zones are encountered in the lower Fort Union, underpressured sections between 8000' to 10,000', subsequent geopressures in the Frontier-Nugget interval between 12,000 to 15,300', and apparent normal pressures to about 17,000' (total depth).

3. SHT # 334-10 Well, Wind River Reservation, Fremont County (Bilyeu, 1978)

Abnormally high pressures are noted starting at about 13,500' and continuing downward from the lower Cody to the Nugget formation at about 17,000'.

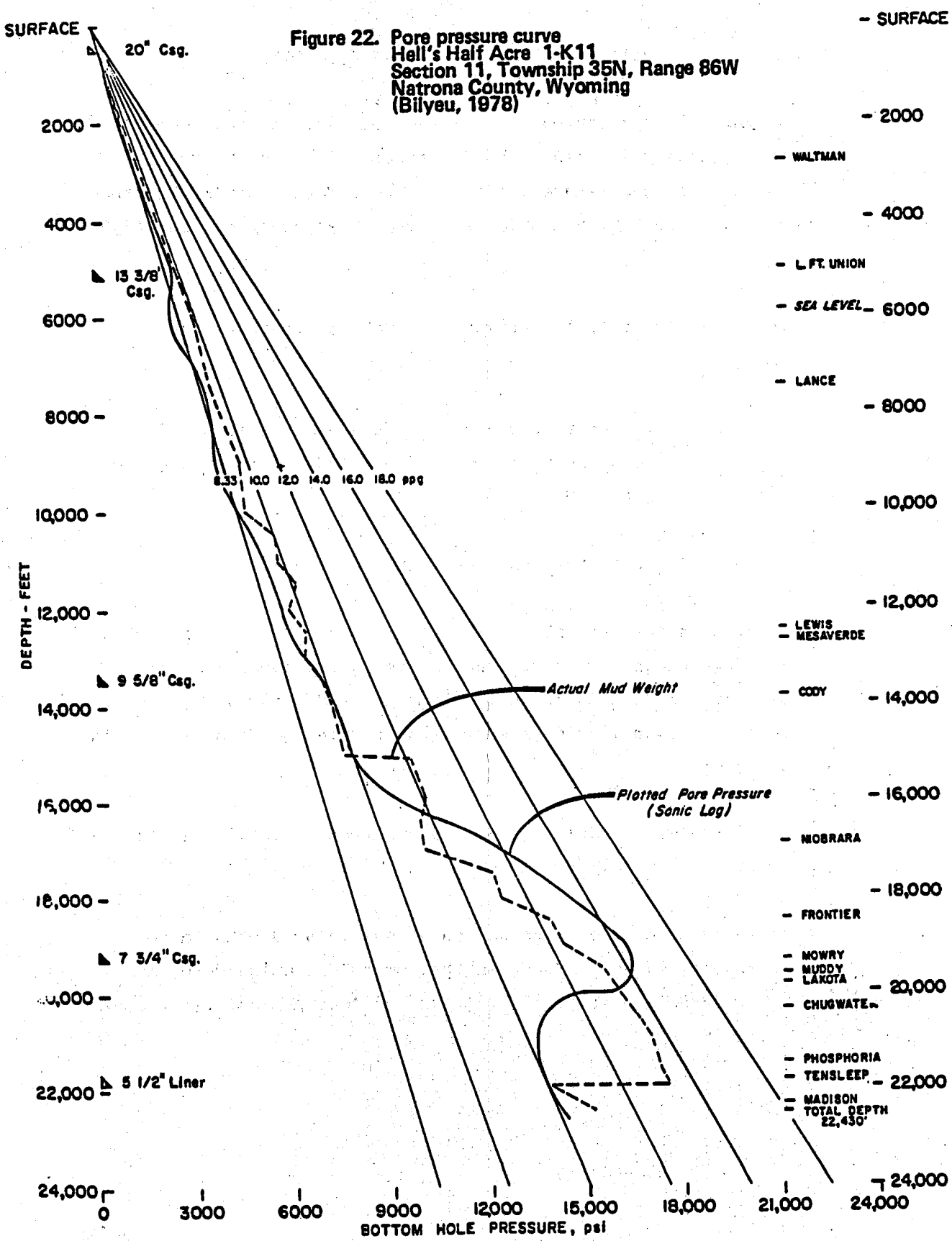
4. HHA # 1-K11 Well, Natrona County (Bilyeu, 1978)

Located on the east flank of the Wind River Basin, this well, as depicted in Figure 22, encountered overpressuring starting at about 15,000' in the Cody formation and progressing downward to a near lithostatic pressure gradient in the Frontier-Lakota interval.

5. Madden-Badwater field, Fremont and Natrona Counties (Schmitt, 1975)

As an example of overpressuring at shallower depths, a well at a depth of about 7500' in the lower Fort Union formation encountered a bottom hole pressure of 4625 psi and temperature of 190°F.





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## 6.8 GREEN RIVER BASIN

### Location

The Green River Basin is located primarily in southwestern Wyoming (see Figure 19) and consists of two major sections, the western half and the eastern half separated by the Rock Springs Uplift. The eastern section is comprised of three distinct sub-basins separated by structural highs, termed from north to south, the Great Divide Basin, Washakie Basin, and the Sand Wash Basin, the latter located in northwest Colorado.

### Formations

The occurrence of geopressed formations is almost wholly confined to deep zones in the eastern sub-basins of the Green River Basin where the following upper Cretaceous and Paleocene units have been found to have abnormally high pressures.

Paleocene	Fort Union fm.
Upper Cretaceous	Lance fm.
	Mesaverde Gp.
	Almond fm.
	Erickson fm.
	Rock Springs fm.
	Blair fm.

With the exception of the lower Mesaverde, all the units are non-marine lenticular sandstones.

Representative pressure and temperature gradients from several of these formations are shown below (Kuuskra, et al 1979):



<u>Formation</u>	<u>Depth</u> ft.	<u>Reservoir</u> <u>Pressure</u> psi	<u>Pres.</u> <u>Grad.</u> psi/ft	<u>Reservoir</u> <u>Temp.</u> °F	<u>Temp.</u> <u>Grad.</u> °F/100 ft
Fort Union	5700-9000	3150-6334	.55-.70	135-194	2.4-2.2
Almond A&B	8000-10,700	4200-6200	.53-.58	180-215	2.3-2.0
Erickson	8400-11,400	4400-6500	.52-.57	186-231	2.2-2.0
Rock Springs/Blair	9700-12,500	5000-7200	.52-.58	206-248	2.1-2.0
Other Mesaverde	9000-12,700	5850-8250	.65-.65	194-220	2.2-1.7

Recent deep drilling in the Washakie Basin beyond 15,000' has encountered pressure gradients up to .86 psi/ft in the Mesaverde. Also, the overlying Lance and lower Fort Union in this basin are overpressured with gradients in the .55 to .60 range. Similarly, the Lance in the deeper parts of the Red Desert Basin is overpressured (McPeck, 1980).

Other geopressured areas are as follows:

1. In the Pacific Creek area in Sublette County in the extreme northeastern part of the Green River Basin (north of the Rock Springs Uplift and at the base of the Wind River Mountains), two relatively deep wells indicate the onset of geopressuring at a depth of about 11,600' near the base of the Lance formation; at about 12,000', the pressure gradient is about .84 psi/ft while at the top of the overpressured zone, the temperature is 190°F (Law, et al., 1980).

In a third well, the deepest ever drilled in the Rocky Mountains, to 26,000' (still being tested as of this writing), geopressures were encountered in the Lance at about the same depth as above and it continued in the



underlying Erickson, Baxter, Frontier, and Morrison formations. At about 22,000', upon entry into the Nugget formation, normal pressures were again encountered (Arnold, 1979). A pore-pressure plot of this well is shown in Figure 23. At a depth of 21,670', the temperature recorded ranged from 289 to 310°F.

2. In the Wamsutter Arch area, oil and gas fields display considerable overpressuring in the Mesaverde especially below 10,000', as shown in Figure 24. Areally, the pressure gradients along the arch increase downdip to the east, as illustrated in Figure 25, where the depth is greater, permeability is lower, and the facies change from west to east from onshore to littoral to offshore, and the recharge area lies to the west of the map (Towse, 1980).
3. In the Barrel Springs field, located in the southeast part of the basin, upper Cretaceous Mesaverde rocks at a depth of about 8725' have an initial reservoir pressure of 4266 psi and a temperature of 195°F (Wanner, et al 1979).
4. In the Pinedale field, located in the northern part of the Green River Basin, and the proposed site of the Wagon Wheel Nuclear Stimulation Project, hydrostatic pressures are encountered in the aquifer above 8000'; beyond that depth geopressuring was observed including extremely high pressures in the Baxter shale at 17,940'. The average pressure gradient for the field (used for the proposed nuclear fracturing test) was considered to be .653 psi/ft and the geothermal gradient 1.252°F/100' (Shaughnessy and Butcher, 1974).



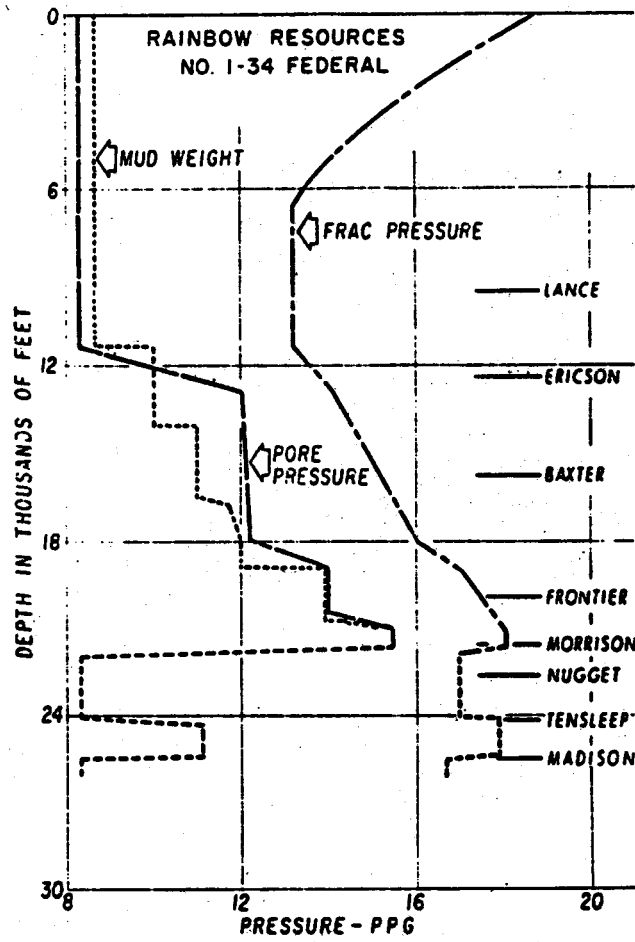


Fig. 23. Pore pressure plot of deep well in Pacific Creek area, northeast Green River Basin, Wyoming (Arnold, 1979)

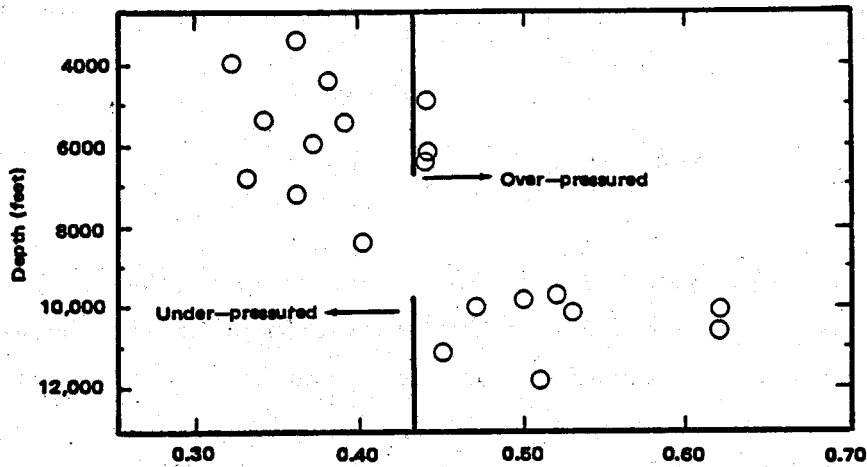


FIGURE 24. Apparent Pressure Gradient at Reservoir Depth (psi/ft) Wamsutter Arch Oil and Gas Fields (Towse, 1980)

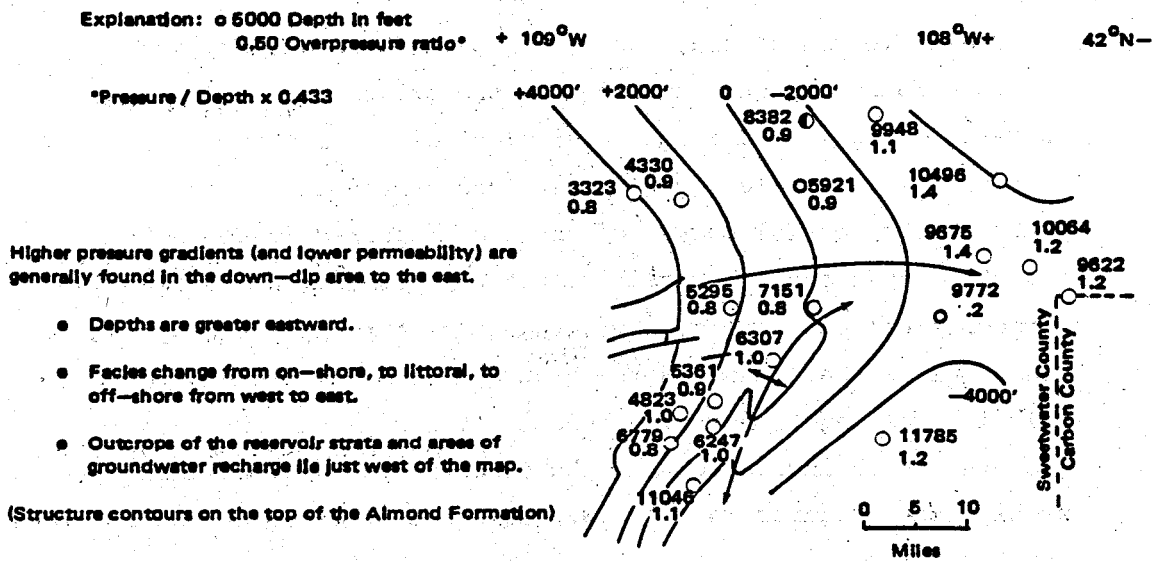


FIGURE 25. Areal Distribution of Pressure Gradient in Wamsutter Arch Oil and Gas Fields, Southwest Wyoming (Towse, 1980)

## General Comments

1. It has been postulated that overpressures in the Washakie and Red Desert Basin are due to the generation of gas from coal as each of the overpressured formations contains enclosed coal seams. As the conversion of each to gas is a volume-increasing process, this would account for the abnormally high pressures. Further, the overpressures would cause the formation of natural fracture systems that would trap the gas (McPeck, 1980). This phenomenon is comparable to the generation of oil from organic rich shales in the Uinta Basin and Williston Basin (as explained further in this report) each of which is manifested by overpressured reservoirs and production from fracture systems.
2. In the Pacific Creek area, the origin of the abnormally high pressures found has been ascribed to the presently active generation of gas in a thick interval of discontinuous, very low permeability shales, siltstones, and sandstones. The spontaneous potential curves of the overpressured zones indicate the presence of low salinity waters probably due to the thermochemical decomposition of organic matter and the dehydration of clays that caused a freshening of the formation waters. It is interesting to note the relatively low temperatures in this area which indicates that the coincidence of geopressuring and high temperatures is not always consistent (Law, et al., 1980).



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## 6.9 UINTA BASIN

### Location

The Uinta Basin is located in northeastern Utah and part of northwestern Colorado. The major structural elements and location of major hydrocarbon occurrences are depicted in Figure 26.

### Formations

The principal expression of geopressuring in the Uinta Basin occurs in the Altamont-Bluebell fields in Duchesne and Uintah Counties, Utah, where this trend covers an area of about 350 square miles in the northern, deeper part of the basin (Lucas and Drexler, 1976). The geologic section encountered here is comprised of a series of Paleocene to Eocene lacustrine sediments in which oil deposits are localized in highly overpressured, naturally fractured low-porosity sandstones (see Figure 27 for the stratigraphic column and geopressured section). Hydrostatic pressures are present to about 8000-10,000' after which the pressure increases dramatically to a maximum of over .80 psi/ft (equivalent to a mud weight of 16 ppg). In the transitional interval, the rate of pressure increase is as much as 3 psi/ft. A representative pressure-depth curve, Figure 28, indicates this accelerated increase in pressure in the Wasatch formation. Areally, as shown in Figure 29, the highest pressure gradients are localized in the center of the trend. The thermal gradient for the field is approximately  $1.5^{\circ}\text{F}/100'$ .

### General Comments

1. The Altamont-Bluebell trend suggests that pore pressure increases believed to be primarily caused by the generation of hydrocarbons from the overlying kerogen layers in the Green River



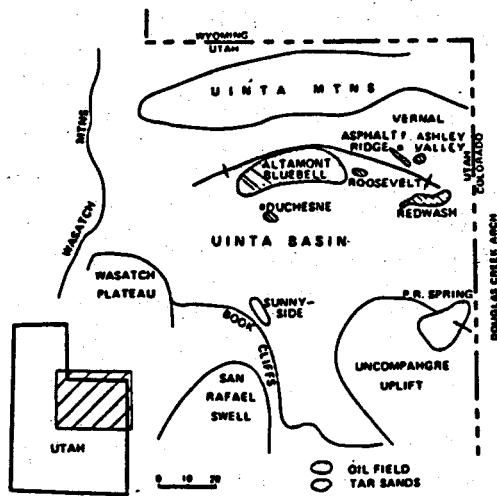


Fig. 26. Index map, Uinta basin, Utah, showing structural elements and location of major hydrocarbon occurrences (Lucas and Drexler, 1976)

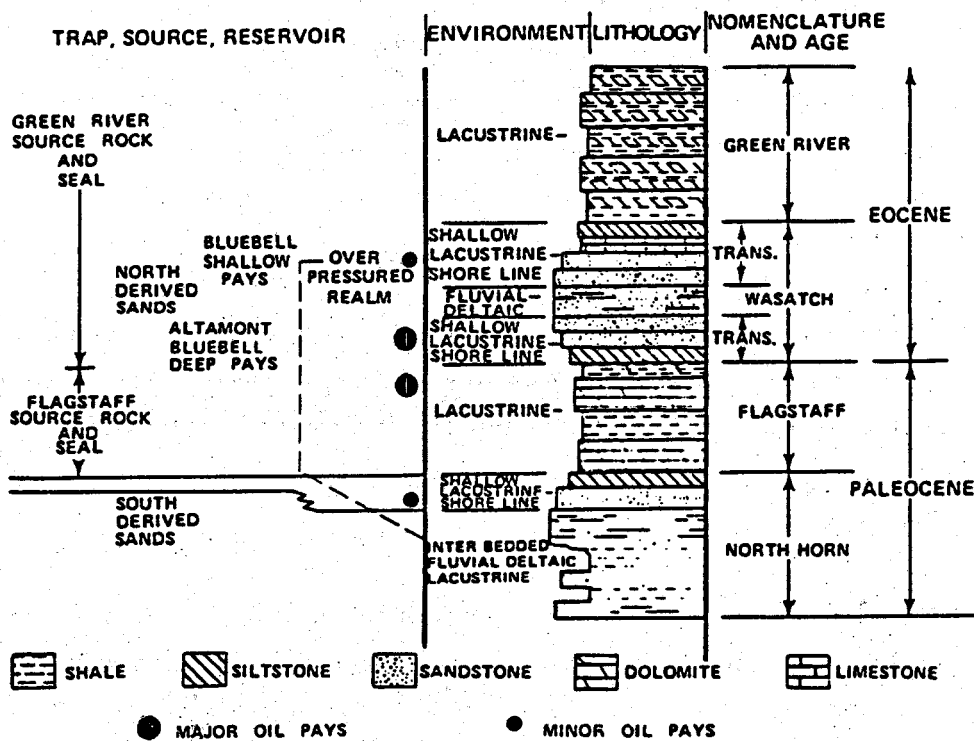
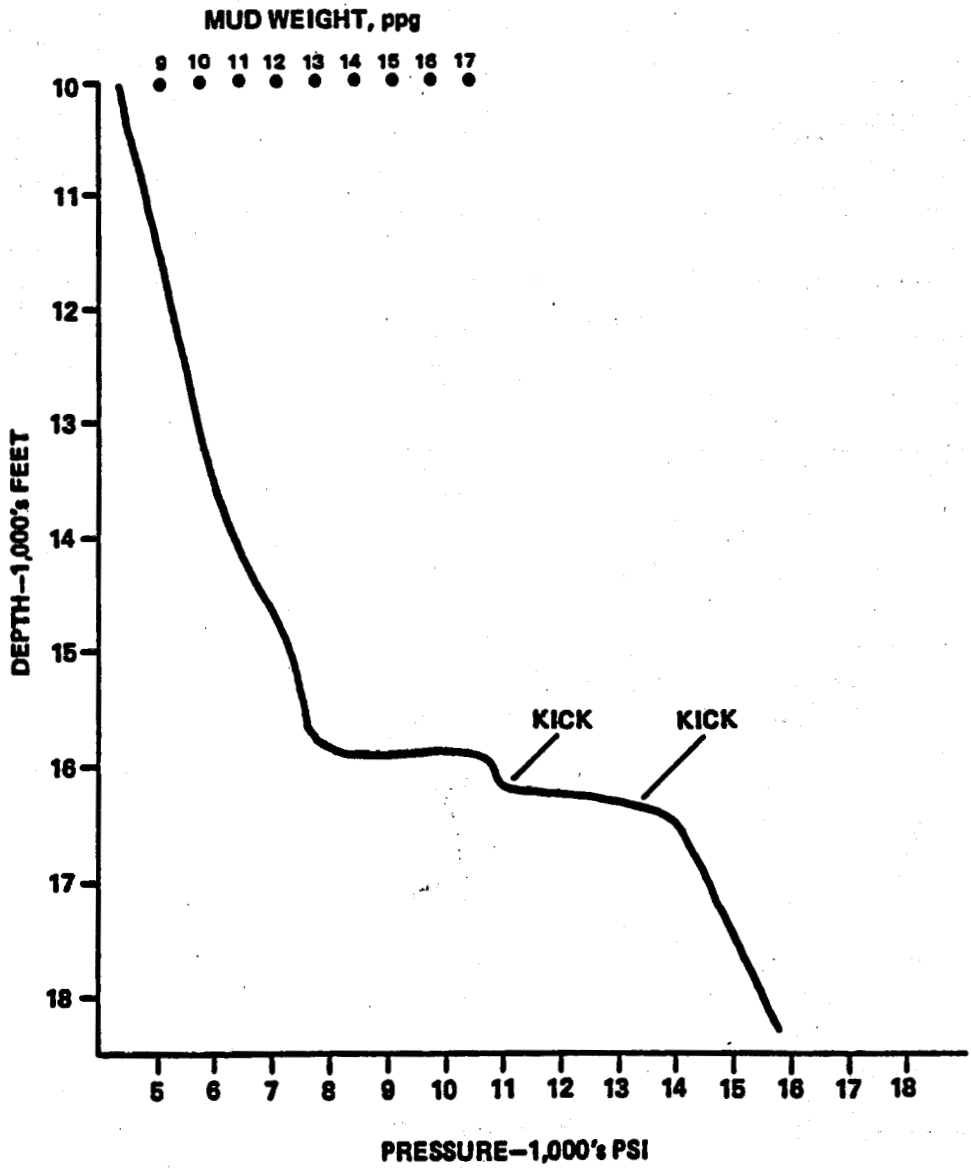


Fig. 27. Stratigraphy, nomenclature, and environmental relations of northern Uinta basin (Lucas and Drexler, 1976)



**FIGURE 28.** Pressure—depth graph of overpressured Wasatch formation (Collings and Layton, 1974).

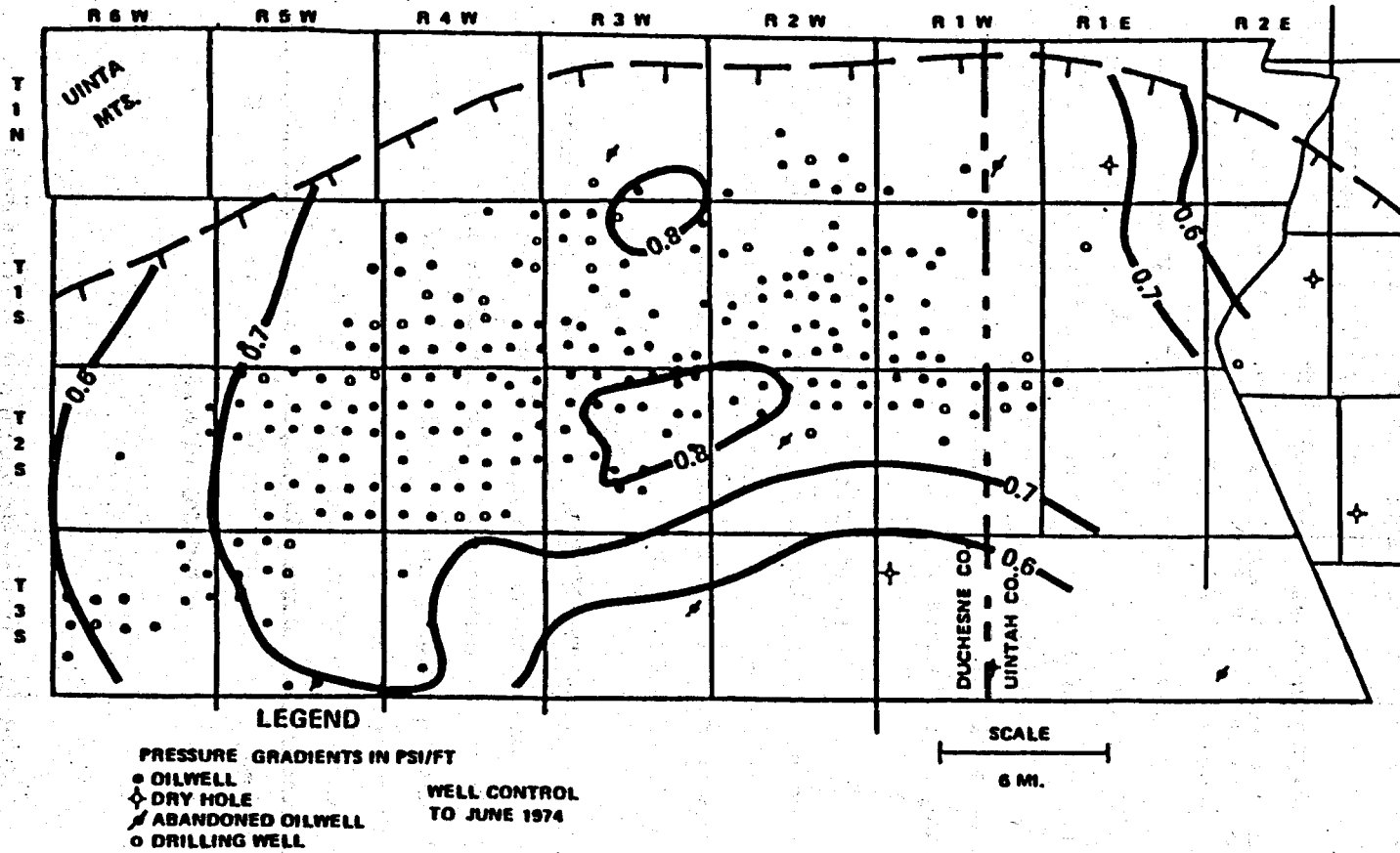


Fig. 29. Maximum observed pressure gradients, Altamont-Bluebell field, Utah. Data based on mud weights, hydrocarbon shows, lost circulation, and measured pressures. Maximum values occur at different stratigraphic levels within gross measured interval (Lucas and Drexler, 1976)

formation coupled with the expulsion of connate water during compaction, have been the principal migration mechanisms in this area (Lucas and Drexler, 1976). It has been further proposed that the effect of overpressuring has been critical in fracture genesis as oil production based on permeability is derived mainly from vertical fractures in sandstones and carbonate rocks (Narr and Currie, 1980). As will be noted elsewhere in this report, similar geopressed conditions in the Williston Basin have led to similar oil accumulations in fractured reservoirs as a result of the generation of hydrocarbons from overlying organic-rich shales.

2. Another example of overpressuring is the Red Wash area in the northeast corner of the Uinta Basin in Uintah County, Utah, where numerous wells have encountered high pressure, low volume gas pockets in channel sandstones of the Tertiary Uinta formation (Chatfield, 1965).
  
3. In the Bitter Creek field area, also located on the eastern flank of the Uinta Basin, the Wasatch (Tertiary) and Mesaverde (upper Cretaceous) formations, basically shale sections containing sand members ranging in thickness from stringers to 50', are overpressured. The pressure gradient is normal or hydrostatic to the middle of the Wasatch at which point it begins to increase linearly to about .50 psi/ft at the base of the Mesaverde (Short, 1978).



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## 6.10 OTHER ROCKY MOUNTAIN BASINS

### A. Piceance Basin and Northwest Colorado

The occurrence of geopressed formations in the Piceance Basin and surrounding areas of Northwest Colorado have been cited by a number of investigators (Towse, 1980; Momper, 1980; and others) but few specific details are available. Selected examples include the following:

1. Cattle Creek anticline near Glenwood Springs in the northern extension of the Piceance Basin has been ascribed to salt diapirism (a predominant feature of geopressing); it is believed to be only one of several examples of salt arching in the immediate area (Mallory, 1966)
2. In the Rangely field in Rio Blanco County located along the Douglas Creek arch separating the Piceance Basin from the Uinta Basin, high pressures and blow-outs have been reported from the lower Cretaceous Dakota formation (Treckman, et al., 1962)
3. A high pressured fractured shale pool in the Mancos shale has been reported from the Buck Creek field in Moffat County -- located in the Sand Wash Basin immediately north of the Piceance Basin (Polumbus, 1962).

### B. Denver Basin, Colorado (Weimer and Davis, 1976, 1977)

This basin is generally considered to be a prime example of underpressuring but recent seismic work indicates the presence of shallow growth fault systems and associated



overpressured shales of upper Cretaceous age along the western edge of the basin near Golden, Colorado, just east of the Front Range uplift in Boulder, Weld, and Adams Counties. Based on seismic surveys which revealed the presence of low-density, low-velocity overpressured shales in the upper 4000 feet of Pierre shales, the calculated pressure gradient at a depth of about 5000' was determined to be 0.7 psi/ft.

It has been postulated that late Cretaceous faulting along the east flank of the central Front Range is an example of a new type of Rocky Mountain tectonism involving the interrelation of shallow penecontemporaneous faulting with a basement controlled fault system. Along the western edge of the Denver Basin, a late Cretaceous center of deposition was formed followed by the rapid accumulation of sediments and recurrent activity on basement-controlled faults that resulted in the generation of overpressured shales.

Similar features involving growth faults and overpressured shales are believed to have occurred elsewhere in the Rocky Mountains, e.g.

- Frontier formation in western Wyoming
- Mesaverde formation in western Colorado and Utah
- Eagle and Judith River formations in Montana

#### C. San Juan Basin

This basin in northwest New Mexico and southwest Colorado is likewise generally considered a region where underpressuring is the norm; however, even here, overpressuring has been reported.

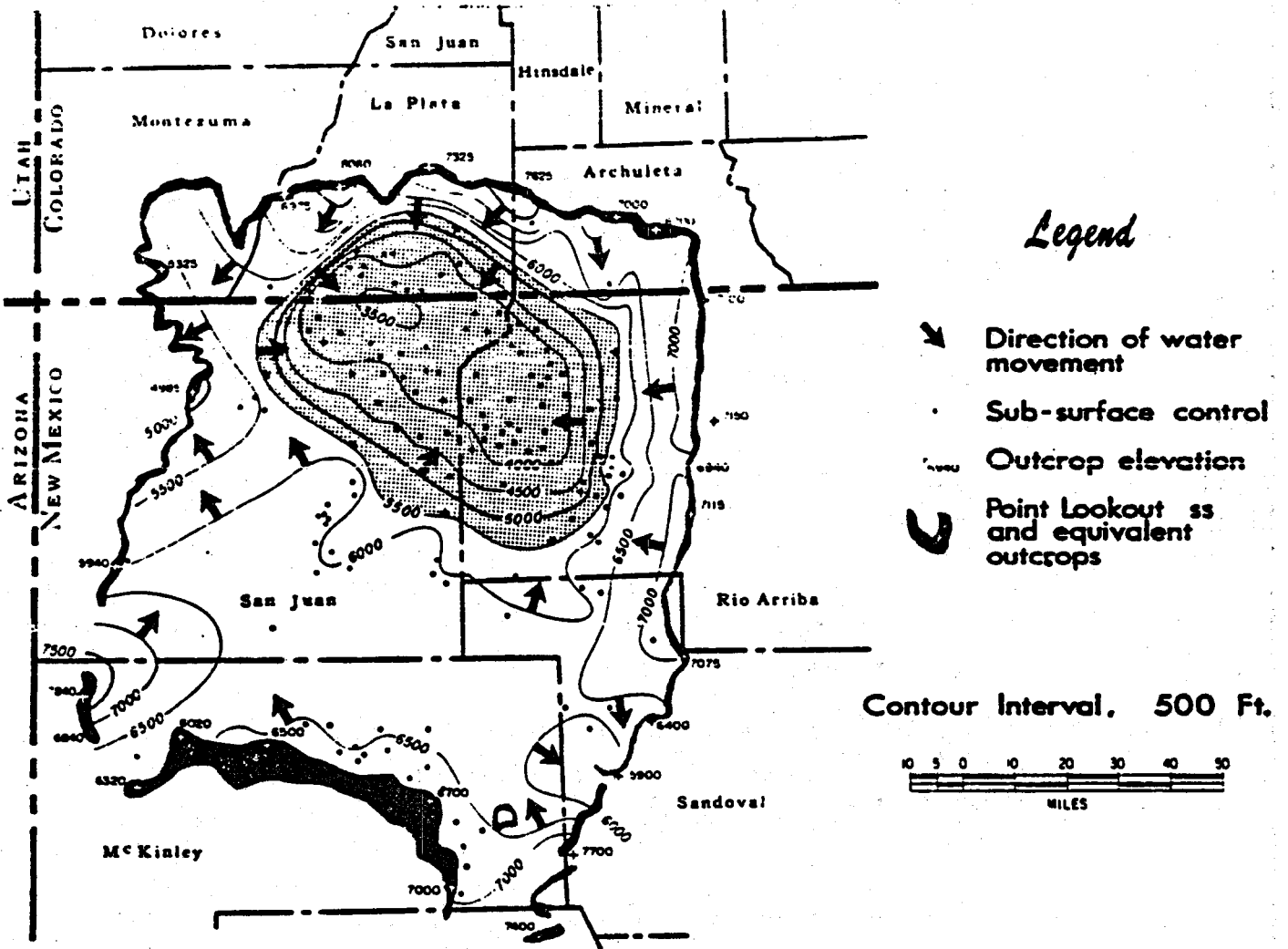


One example described by Hill, et al. (1961) involves the Cretaceous section of northwest New Mexico and southwest Colorado which is composed of a series of low-transmissibility sandstones and interbedded illite-rich shale zones. A potentiometric map was prepared of the Point Lookout sandstone (Figure 30), representative of other Mesaverde units which overlie it. As depicted, the flow under gravity influence should be from the high outcrops in the southern, eastern, and northern edges of the basin toward the low 5000' outcrops on the west flank. However, flow around the margin of the basin is affected by other conditions, because it is directed toward the basin center, which has potentials down to 3500' (or 1500' lower than the lowest topographic elevation in the basin). Hence, natural gas is trapped in the Mesaverde as a result of the steep pressure gradient created at the boundary of the low potential area.

A second example is in the Rattlesnake and Hogback oil fields of San Juan County in northwest New Mexico where a Pennsylvanian limestone and dolomite sequence is reported to be characterized by discontinuous (horizontally and vertically) zones of porosity, hydrocarbon gas content, and the presence of highly saline brines under high pressure (Wengerd, 1958).

#### D. Hanna Basin, Wyoming (Porter, 1979)

Although overpressuring has not been found here or in the contiguous intermontane Laramie and Shirley Basins, it is believed that the upper Cretaceous Mesaverde formation may be geopressed in the deeper portions of the Hanna Basin due to its geologic similarity with other Rocky Mountain Basins.



**FIG.30. POINT LOOKOUT SANDSTONE**  
 (Mesaverde Group)  
**POTENTIOMETRIC SURFACE** (Hill, et al, 1961)

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## 6.11 WILLISTON BASIN

### Location

The Williston Basin, located along the U.S. - Canadian border, occupies much of western North Dakota, northwestern South Dakota, west central Montana, and extends northward into southern Saskatchewan and southwestern Manitoba. A location map of the Williston Basin and its major structural features is shown in Figure 31.

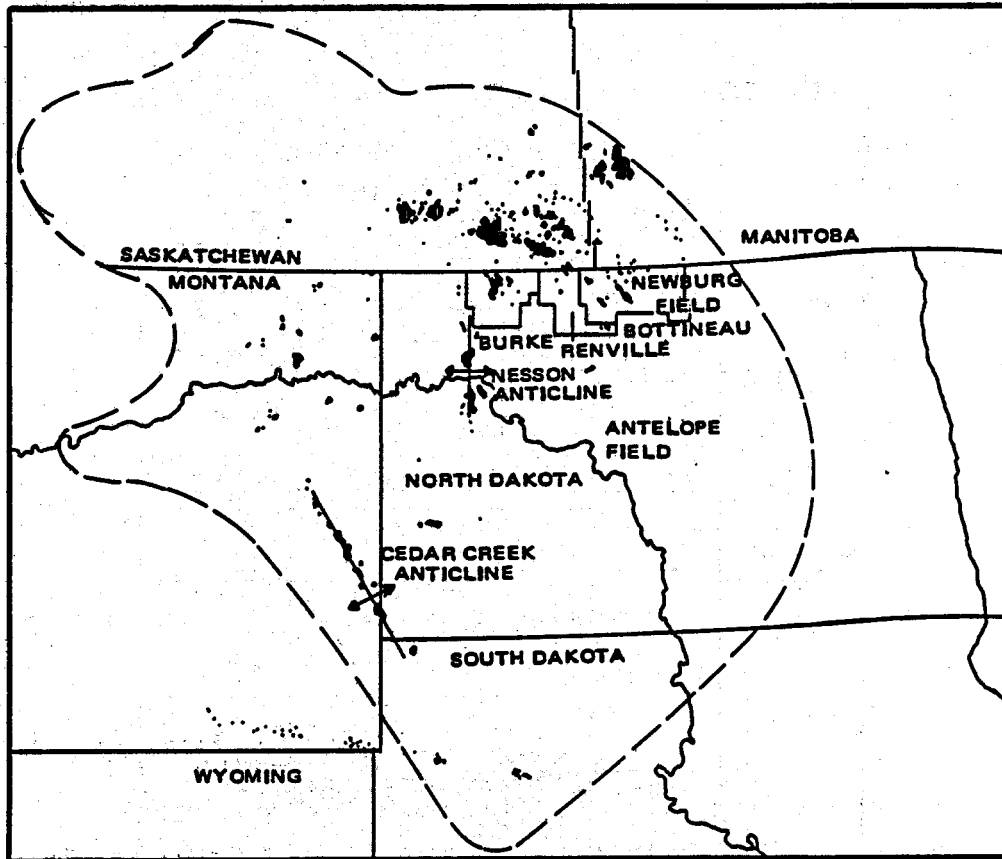
### Formations

The Williston Basin is underlain by an assemblage of sediments ranging in age from the Cambrian to the Tertiary as shown in the generalized stratigraphic and lithologic column of Figure 32.

From the viewpoint of geopressured occurrences, the most important formation is the lower Mississippian Bakken, a siltstone and shale, rich in organic matter, which is believed to be a major source rock of the oil accumulations found in the basin. Sandwiched between apparent impermeable rocks of the overlying Lodgepole and underlying Three Forks formations, it is believed that overpressures in the Bakken, with pressure gradients up to .80 psi/ft, are caused by the generation of oil from the latter (Meissner, 1976, 1978).

1. One example of this is the Antelope field in MacKenzie County, North Dakota, located on a southeast spur of the Nesson Anticline which produces oil from fractured Bakken shales and siltstones. These fractures are believed to be controlled by a combination of high pore fluid pressures and high differential rock stress. In this field, the Bakken is geopressured at about 7600 psi, for a pressure gradient of .73 psi/ft, while the formation above is underpressured at 4700 psi, for





**FIGURE 31.** Location map showing Williston basin, two of its major structural features, oil fields of North Dakota, and some oil fields of adjacent areas (Carlson and Anderson, 1965)

SEQUENCE	SYSTEM	GROUP OR FORMATION	DOMINANT LITHOLOGY		
Tejas	Tertiary	Glacial Deposits	Glacial Drift		
		White River	Clay, Sand and Limestone		
		Golden Valley	Clay, Sand and Silt		
		Fort Union Group	Langue River Cannonball Ludlow	Shale, Sandstone, Lignite Marine Sandstone, Shale Sandstone, Shale, Lignite	
		Zuni	Cretaceous	Hell Creek	Sandstone, Shale, Lignite
Montana Group	Fox Hills Pierre			Marine Sandstone Shale	
Colorado Group	Niobrara Carlisle Greenhorn			Shale, Calcareous Shale Shale, Calcareous	
Dakota Group	Belle Fourche Mowry Newcastle Skull Creek Fall River Lakota			Shale Shale Sandstone Shale Sandstone and Shale Sandstone and Shale	
Jurassic	Morrison			Shale, Clay	
	Sundance			Shale, green and brown and Sandstone	
	Piper			Limestone, Anhydrite, Salt and red Shale	
Abercrombie	Triassic			Spearfish	Siltstone, Salt and Sandstone
	Permian			Minnekahta	Limestone
				Oncha	Shale, Siltstone and Salt
	Pennsylvanian		Minnekahta	Sandstone and Dolomite	
Amsden			Interbedded Dolomite, Limestone, Shale & Sandstone		
Kaskaakia	Mississippian		Big Snowy Group	Heath Otter Kibbey	
		Madison	Shale, Sandstone and Limestone		
			Interbedded Limestone and Evaporites		
	Devonian	Bakken	Siltstone and Shale		
		Three Forks	Shale, Siltstone, Dolomite		
		Birdsbe	Limestone		
		Duperow	Interbedded Dolomite & Limestone		
		Souris River	Interbedded Dolomite & Limestone		
		Dawson Bay	Dolomite and Limestone		
		Prairie	Shale		
Winnipegosis	Limestone & Dolomite				
Tippecanoe	Silurian	Intariak	Dolomite		
		Stonewall	Dolomite and Limestone		
	Ordovician	Stony Mt. Fm.	Gunton Member Stoughton Member	Limestone & Dolomite Argillaceous Limestone	
		Red River	Limestone and Dolomite		
		Winnipeg Group	Roughlock	Calcareous Shale, Siltstone	
			Icebox	Shale	
		Blackland	Sandstone		
Sauk	Cambrian	Deadwood	Limestone, Shale and Sandstone		

FIGURE 32. North Dakota stratigraphic column (Carlson and Anderson, 1965)

a pressure gradient of .46 psi/ft , and the formation between is likewise underpressured at 5100 psi, for a pressure gradient of .47 psi/ft. The charts presented in Figure 33 indicate this pressure-depth relationship. It should be noted that in North Dakota, when saline waters up to 356,000 ppm occur, the normal pressure gradient is about .512 psi/ft (Finch, 1969). Other probable examples of fracturing related to oil generation include the Mission Canyon field and Niska field in Slope County, North Dakota (Meissner, 1976).

2. Another example is in the southwestern part of the Williston Basin in the Elkhorn Ranch field where geopressured zones similar to that of the Antelope field display a pressure of 6595 psi at subsea 8100' for a pressure gradient of .63 psi/ft.
3. Geopressures may also be present in the Bakken in Richland County, Montana, Billings County, North Dakota, and elsewhere in MacKenzie County where anomalous high hydrocarbon show indices in Mississippian, Devonian, and Silurian rocks suggest that fracturing due to fluid overpressuring allowed for the vertical migration of oil from the Bakken into under- and overlying formations (Stark, 1979).
4. Another geopressured occurrence recently reported is the MonDak field, which straddles the Montana-North Dakota line, where production is from vertically-fractured irregular intervals in a stratigraphic trap of slightly overpressured limestone (Parker and Hess, 1980).



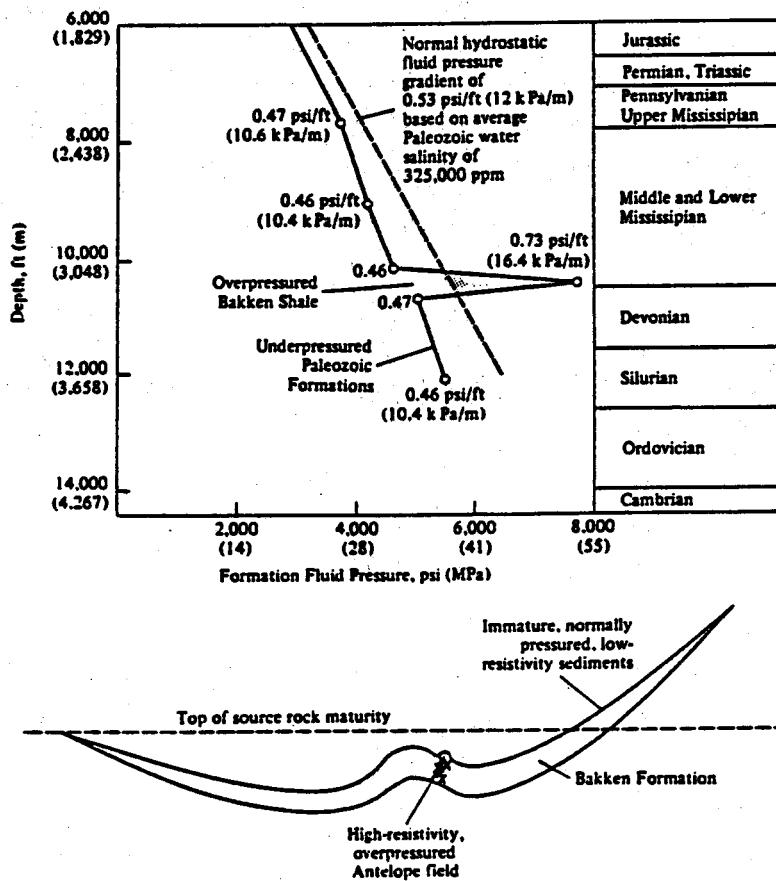


Fig. 33. Relation of Fluid Pressures to Oil Generation in Antelope Field, Williston Basin, North Dakota (Meissner 1978)

General Comments

1. Aside from these isolated occurrences, formations in the Williston Basin are either normally pressured or underpressured; however, it can be anticipated that geopressuring should be present where a permeable bed is in contact with the Bakken shale.
2. One interesting phenomenon of the geopressured occurrences in the Bakken shale is the almost complete absence of formation water.



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## 6.12 CALIFORNIA BASINS

### Location

There are numerous sedimentary basins and areas in California, both onshore and offshore, in which geopressured reservoirs have been reported. Berry's (1973) article on the subject provides the most comprehensive treatment on a state-wide basis; however, there are several other references in which specific occurrences have been noted. (See Figure 34, Index Map of California.)

The various geopressured basins and areas include the following:

- Great Valley (miogeosyncline) encompassing the Sacramento
- Valley and San Joaquin Valley
- Coast Ranges (eugeosynclinal Franciscan sequences) east of the San Andreas Fault and north of the Garlock Fault
- Los Angeles Basin
- Ventura Basin
- Offshore Santa Barbara Channel and Eel River Basin

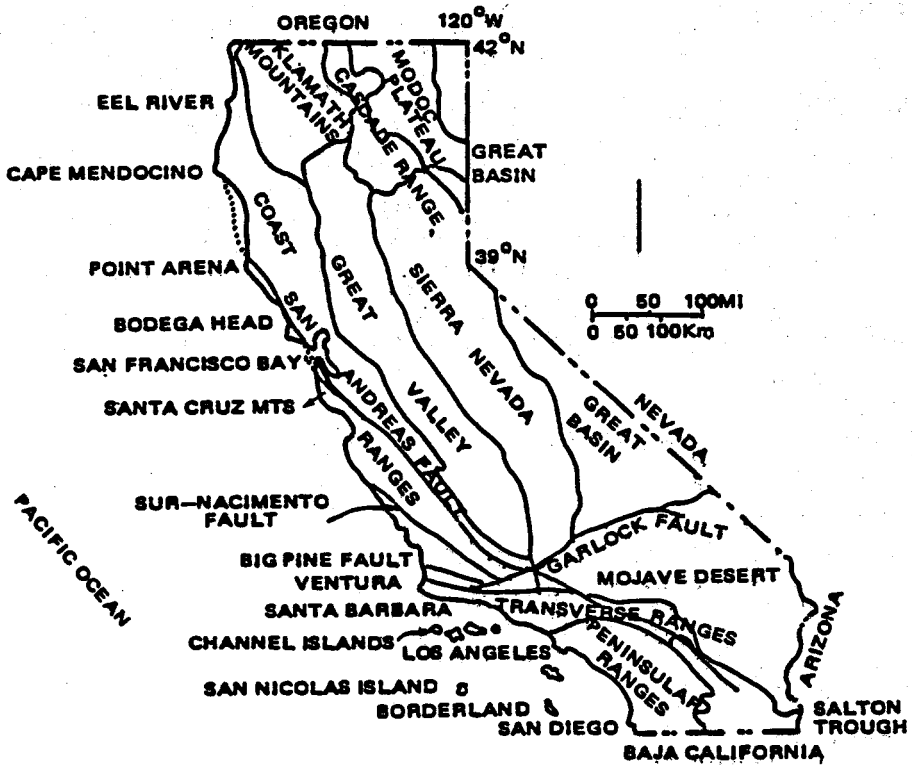
(See Figure 35 for map locations of hydrostatic (normally pressured), highly overpressured, and slightly overpressured areas.)

### Formations

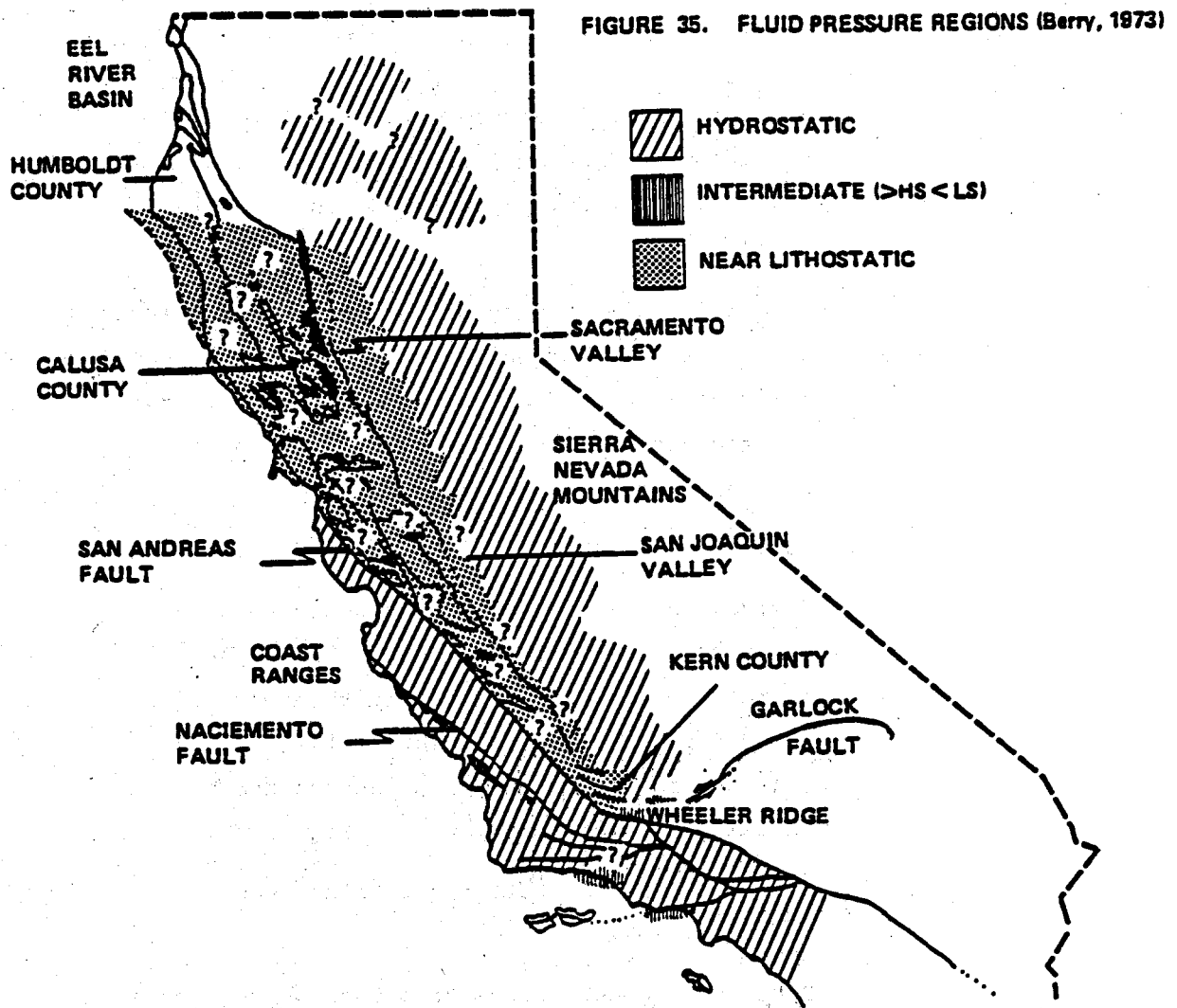
#### A. Northern California

##### 1. Sacramento Valley (see Figure 36 for reference points)

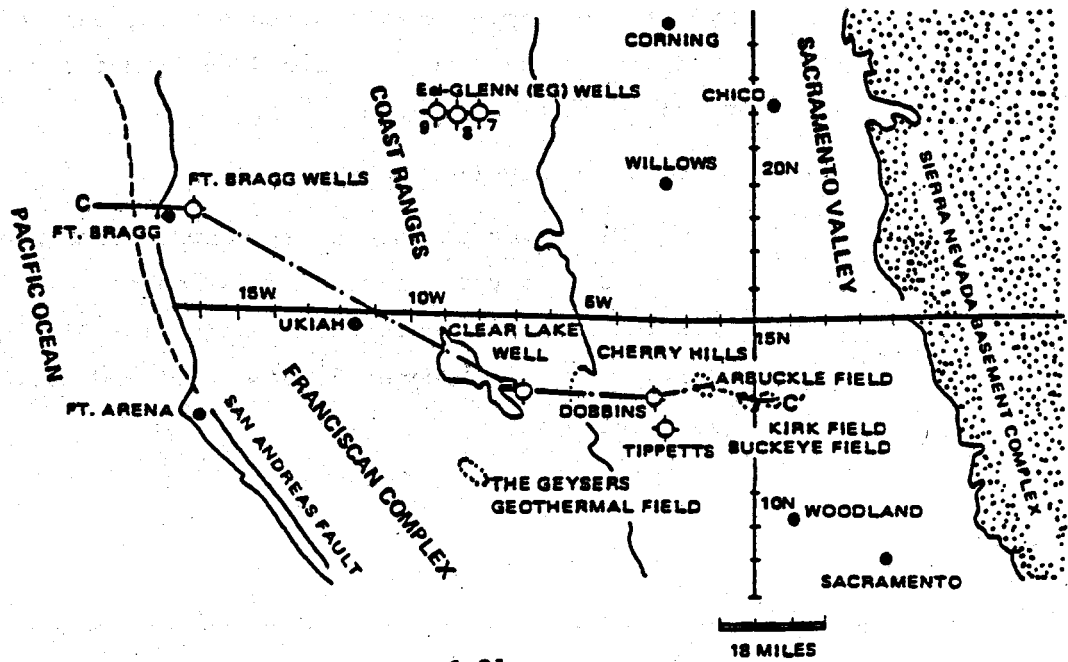
- (a) Kirk-Buckeye and Arbuckle fields (Berry, 1973)



**FIGURE 34.** Index map of California showing geomorphic and tectonic provinces



**FIGURE 36. REFERENCE AREAS IN NORTHERN CALIFORNIA (Berry, 1973)**



Abnormally high pressures occur in the Forbes formation (Cretaceous) starting at a depth of 6200' in Kirk-Buckeye and 3200' in Arbuckle fields.

(b) Selected wells (Cherry Hills, Dobbins and Tippetts) along west side of Sacramento Valley where geopressures have been reported from the Gunda formation (Cretaceous). (See Figure 37 for graphs of pressure gradients in these wells.)

(c) Calusa County (Rehm, 1972)

Typical sand-shale sequence changes to a massive calcareous shale at about 4000' accompanied by a pressure increase equivalent to a mud weight of 12.5 ppg at 8000'; at that point, a lime sequence in shales causes an abrupt increase in the Miocene-age formation (see Figure 38).

(d) Grimes Gas Field, Sutter and Calusa County (Weagant, 1972)

Upper Cretaceous Forbes formation which occurs at depths of 5500' exhibits average pressure of 4000 psi at 7200'. Formation pressures well above hydrostatic increase with depth but decrease eastward from western edge of field -- from fault block to fault block (see Figure 39).

(e) Humboldt County (Rehm, 1972)

In the Eel River Basin, three overpressured zones are noted in a typical sequence of sands and shales with intercalated calcareous shales (of Miocene Age) acting as a seal at 2000', 6000' and 10,000' (see Figure 40).



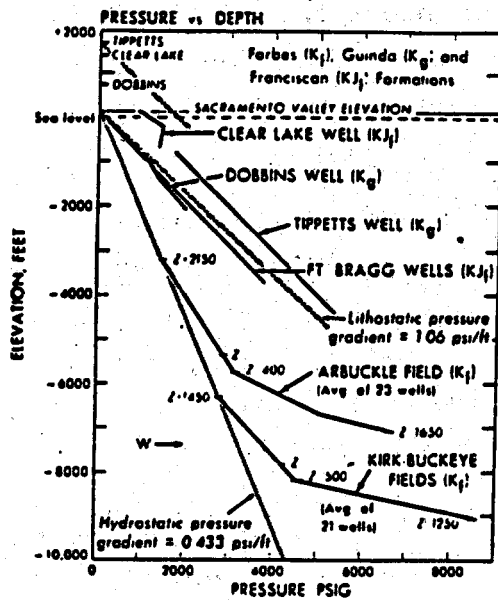


Fig. 37. Pressure gradients in selected wells and fields in Sacramento Valley (Berry, 1973)

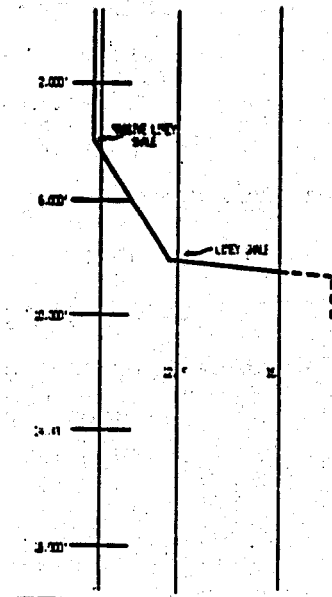


Fig. 38. Typical pressure profile in well drilled in Miocene rocks, Calusa County, California (Rehm, 1972)

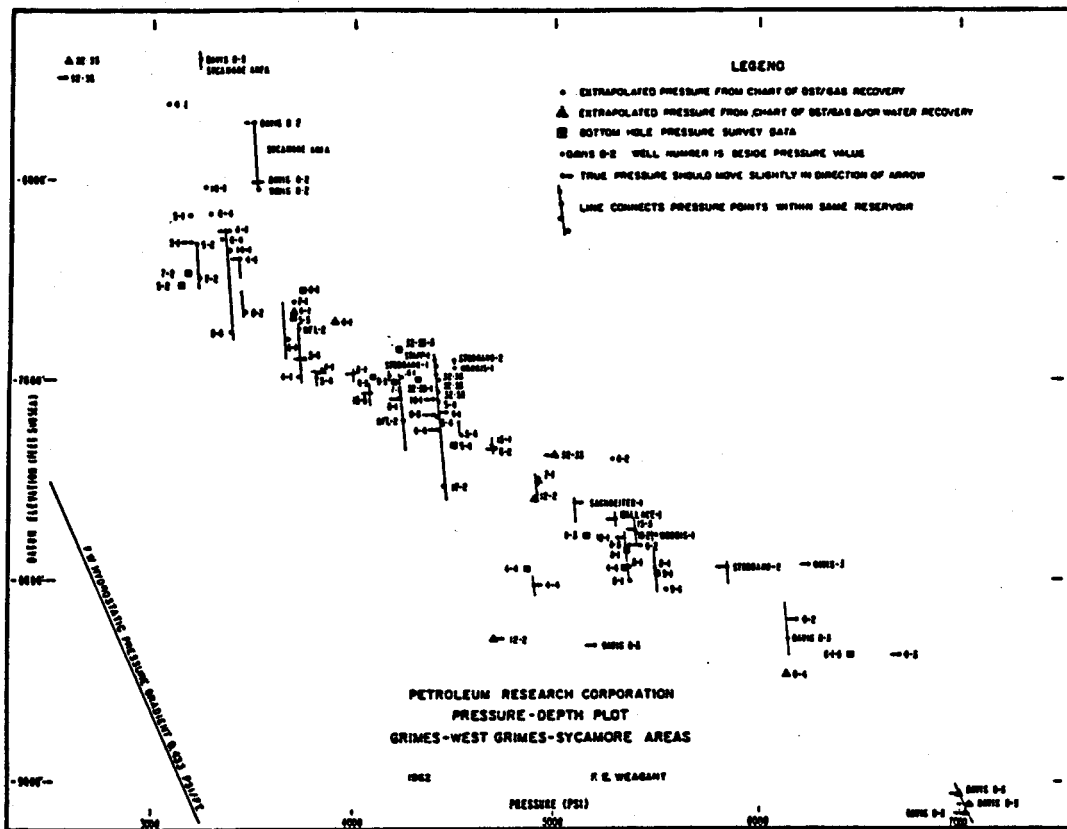


Fig. 39. Series of pressure—depth plots with data from many wells in area of Grimes, West Grimes, and Sycamore gas fields (Weagant, 1972)

## 2. Coast Ranges (Berry, 1973)

### (a) Fort Bragg Wells

Cretaceous-Jurassic Franciscan formation exhibits near-lithostatic values within a few hundred feet of surface (see Figure 41).

### (b) Clear Lake Wells

These wells likewise display near-lithostatic pressure gradients at very shallow depths.

### (c) Eel-Glen River Wells

In three shallow wells (with maximum depth of 4668', two had indications of geopressure, one at a total depth of 1350' in sheared Franciscan shale layers.

## B. Central and Southern California

### 1. San Joaquin Valley

(a) Cretaceous section overlain by 10,000' and more of Tertiary rocks has been rarely penetrated, but can be presumed to be geopressured as waters in the lower Tertiary sequences are similar in both the Sacramento and San Joaquin Valleys (Berry, 1973).

### (b) Coalinga-Kettleman-Lost Hills District (Berry, 1973)

Located along west side of San Joaquin Valley and representative of major anticlinal folds, this area displays noteworthy geopressured zones in several Tertiary zones -- Pliocene, Miocene (McClure and Temblor formations), Oligocene (Leda formation) and



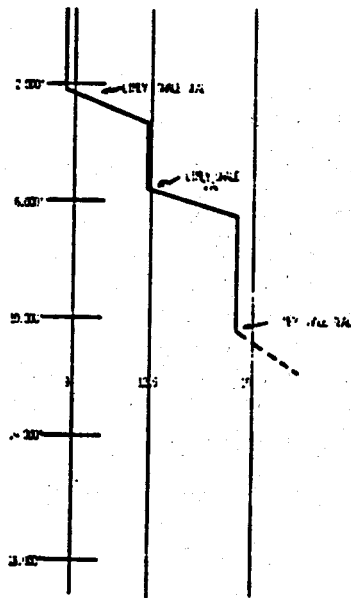


Fig. 40. Typical pressure profile in well drilled in Miocene rocks, Humboldt County, California (Rehm, 1972)

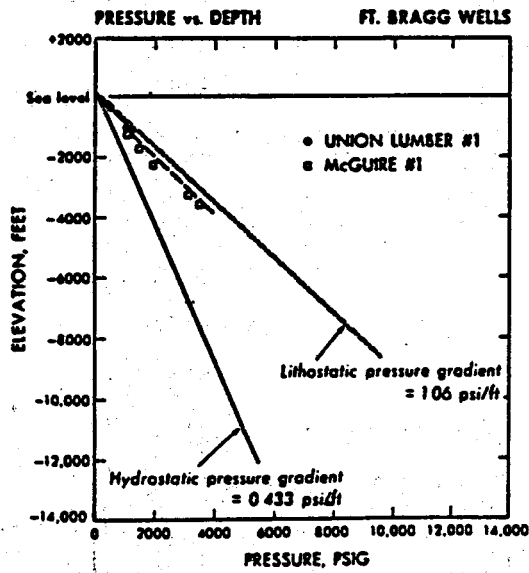


Fig. 41. Pressure gradients in wells at Fort Bragg, Coast Ranges, California (Berry, 1973)

Cretaceous beds. The average pressure gradient is 0.700 psi/ft, though it is close to lithostatic in the North Dome anticline at 13,500' depth and (in King County) in the Leda sandstone, a subsurface lens enclosed within shale and siltstone at 8000' and 11,000' depths. The Temblor formation at Lost Hills Field has an indicated pressure of 3200 psi at 4400' depth. (See Figure 42 for graphs of pressure gradients of wells in this district.)

(c) Wheeler Ridge Anticline (Berry, 1973)

Located near the southern end of the San Joaquin Valley, slightly overpressured zones are found in Eocene and Oligocene beds at 8000' depth (see Figure 43 for graph of pressure gradient).

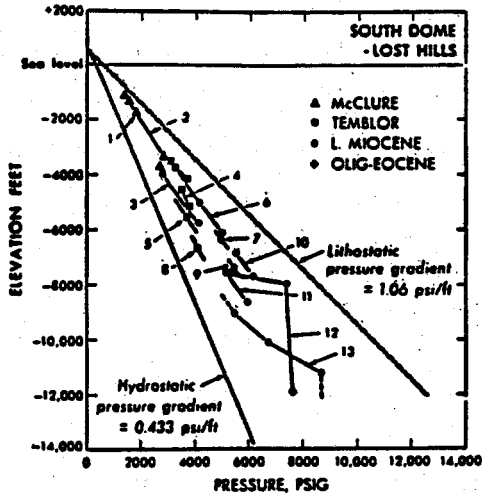
(d) Cal Canal Gas Field (Collins, 1980)

Located in Kern County approximately midway between the Lost Hills and Elk Hills Fields, very high geopressures and temperatures were encountered in the Stevens formation (Upper Miocene); with an average depth of 11,800', the initial reservoir pressure was 7350 psi and the temperature was 290°F (see Figure 44 for location of field). The pressure and temperature gradients are determined to be .623 psi/ft and 2.45°F/100', respectively.

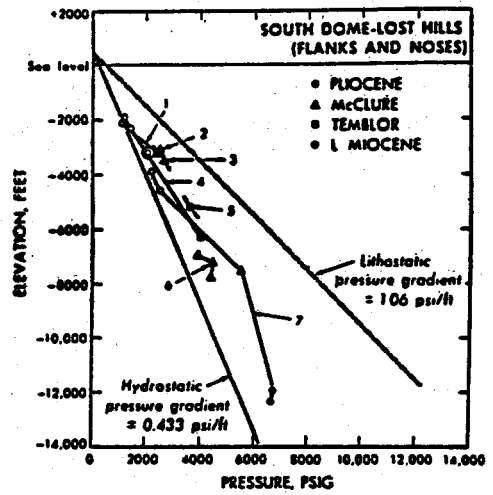
(e) Elsewhere in the San Joaquin Valley, the Stevens formation (actually a group name applied to an aggregate thickness of some 5000' of deep marine sandstones and shales) can be expected to be geopressured because of the presence of intra-



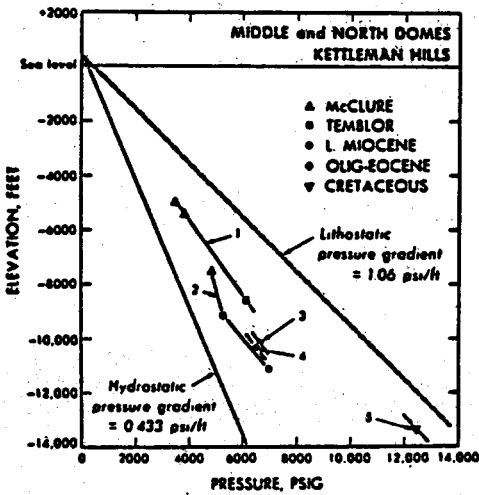
Fig. 42. Pressure gradients in Kettleman Hills-Coalingua-Lost Hills District (Berry, 1973)



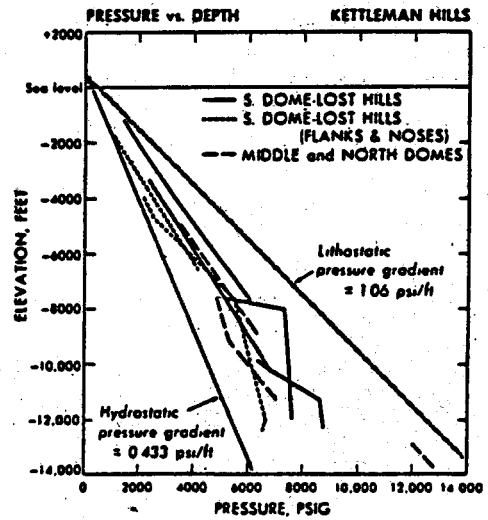
a. South Dome-Lost Hills anticlines (axis)



b. South Dome-Lost Hills anticlines (flanks and noses)



c. Middle Dome and North Dome anticlines



d. Composite of a, b, and c.

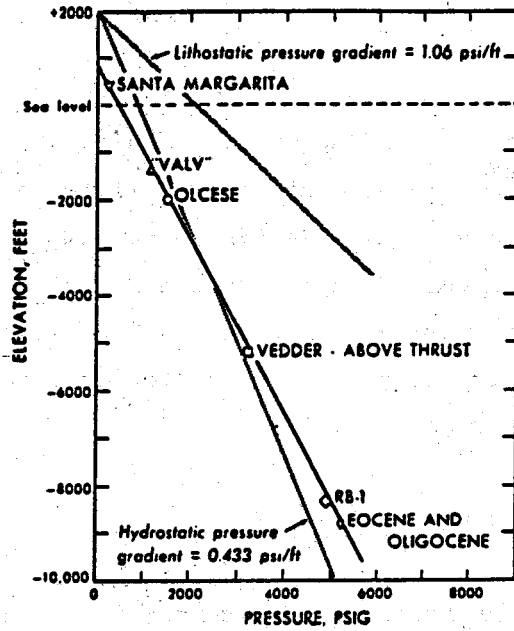


Fig. 43. Pressure gradient at Wheeler Ridge anticline (Berry, 1973)

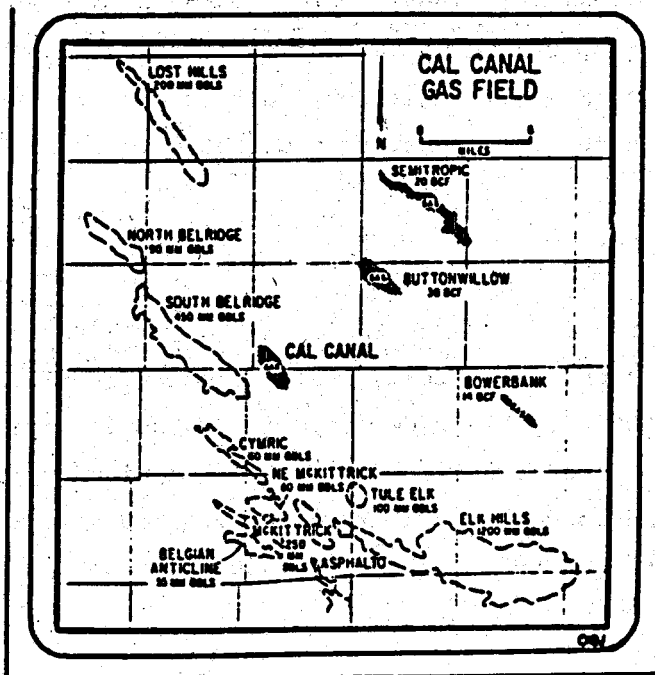


Fig. 44. Location of Cal Canal Gas Field in relation to nearby fields (Collins, 1980)

basinal contemporaneous faults (analogous to Gulf Coast growth faults) as well as compaction anticlines. These features are commonly associated with turbidite deposition in the mid-fan facies of a submarine fan which has been interpreted as the sedimentary environment for this formation (MacPherson, 1978).

#### C. Los Angeles Basin

Slightly overpressured zones, comparable to the Wheeler Ridge Anticline, have been noted along the southern edge of the Santa Monica Mountains (Berry, 1973). Another possible example is from the Wilmington field where differential pressures exist across fault blocks, i.e. subsurface pressures varied by as much as 400 psi (Mayuga, 1970) presumably indicating the effectiveness of certain faults as seals or barriers to migration. The temperature gradient in this basin based on an average of seven fields has been calculated at  $2.15^{\circ}\text{F}/100'$  (Phillipi, 1965); however, in certain areas extremely high temperatures have been reported, e.g. in a well piercing the Newport-Inglewood fault at a depth of 7000' in Huntington Beach, the temperature of the water was  $482^{\circ}\text{F}$  (Price, 1976).

#### D. Ventura Basin

In the Ventura Avenue oil field, near-lithostatic values (8300 psi at 9200' depth) as depicted in Figure 45 were measured in the Pico formation (Pliocene) comprised of alternating sands and shales (Watts, 1948). The temperature ranges from  $200^{\circ}\text{F}$  at 8900',  $208^{\circ}\text{F}$  at 9430', and  $262^{\circ}\text{F}$  at



13,180' (Young, et al, 1977) while the average temperature gradient based on six fields has been determined to be 1.46<sup>o</sup>F/100' (Phillipi, 1965). See Figure 45 for pressure gradient graph of this field in relation to other overpressured fields.

## E. Offshore

### 1. Santa Barbara Channel

(a) The Dos Cuadros field, site of the famous 1969 blowout, represents the offshore extension of a group of onshore fields termed the Rincon trend (which includes the Ventura field) which is characterized by pressure gradients of 0.6 to 0.9 psi/ft at depths of minus 4000 to 9000'. Offshore, the gradients range from .493 to .555 at depths of about 3350 to 3825'. Apparently, below 3440', minor thin sandstone beds of the Repetto reservoir are charged with fluids at notably greater pressures (McCulloh, 1969).

(b) A second example of overpressuring in the channel occurs at 10,000 to 14,000' where a massive shale (of Miocene age) has apparently formed a seal on a pressured section equivalent to a weight of 17 ppg, as depicted in Figure 46 (Rehm, 1972).

### 2. Eel River (Field, et al, 1980)

This basin off the coast of northern California and southern Oregon (from Eureka northward along the coast for about 125 mi.) contains a relatively thick section of Miocene, Pliocene, and Quaternary sediments. The



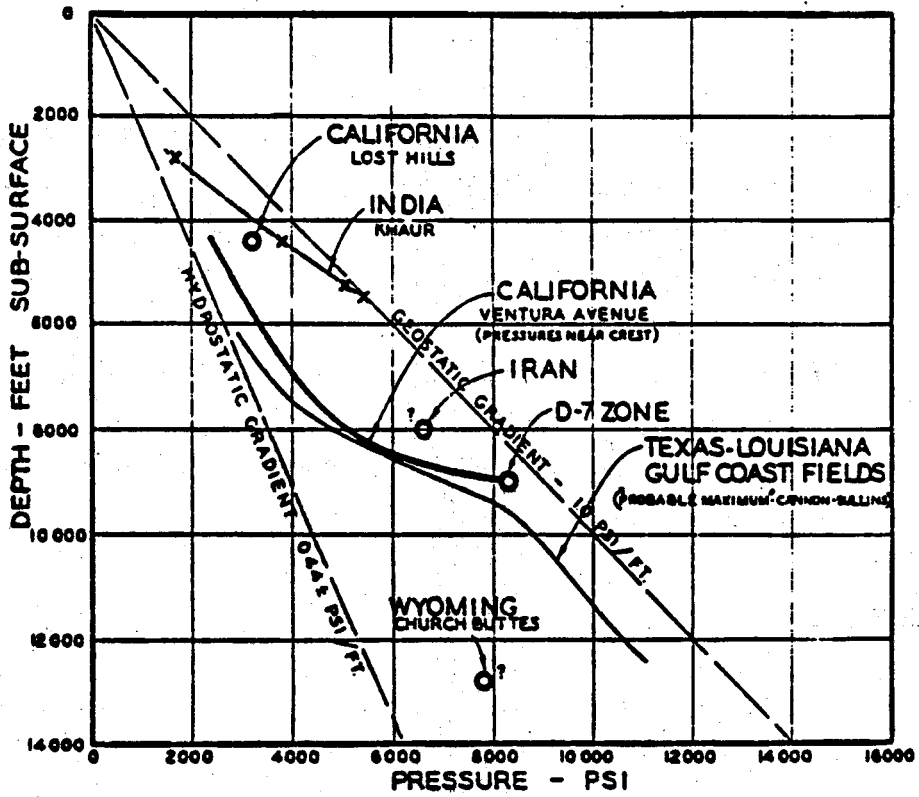


Fig. 45. Pressure gradient in Ventura Avenue oil field, Lost Hills field, and other areas (Watts, 1948)

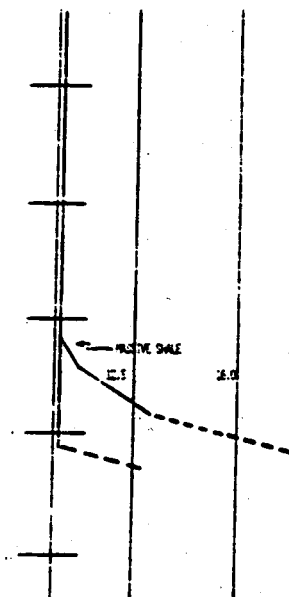


Fig. 48. Typical pressure profile in Miocene rocks, Santa Barbara Channel, California (Rehm, 1972)

western margin of the basin, defined by an uplift zone along the continental slope, is characterized by a series of north-south trending ridges that have been seismically determined to be diapiric in origin. The latter is commonly considered to be an indication of a geopressured zone but, as further evidence, cores (of Pliocene Age) from the crests of these ridges contain significant amounts of gasoline-range hydrocarbons and gas in the methane-butane range.

#### General Comments

1. In northern California, the pore pressure increases westward from the Sacramento Valley to the Coast Ranges; moreover, in the Coast Ranges, near-lithostatic pressure gradients are found at shallow depths whereas in the Great Valley, geopressures are located at much greater depths, in places exceeding 10,000' (Berry, 1973).
2. The temperature gradients in the normally pressured zones of the Great Valley are estimated at 1.0 to 1.5°F/100' up to 2.5°F/100' while geopressured zones are apt to be twice as high (Kharaka and Berry, 1980). Higher temperature zones are present along the west side of the San Joaquin Valley and Coast Ranges than in the Sacramento Valley and it is estimated that the 400°F isotherm will range between depths of 25,000' and 16,500' (Ziegler and Spotts, 1978).
3. Salinities of the waters in the geopressured zones are lower than in the Gulf Coast -- generally less than 20,000 mg/l, and in places less than 10,000 mg/l of dissolved solids, though occasionally they may be as high as 70,000 mg/l (Kharaka and Berry, 1980).



4. Two causes for geopressuring have been ascribed to these California occurrences (Berry, 1973):

- (a) In the San Joaquin Valley, geopressuring is due to the compaction of shales and siltstones under the weight of a rapidly deposited overburden accompanied by thermal expansion of formation water at rates higher than that of the enclosing sediments (analogous to the Gulf Coast).
- (b) In the Franciscan Coast Ranges and Sacramento Valley, geopressuring is believed to be due to tectonic compression of the Sierra-Klamath and Salinas blocks.



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## 6.13 ALASKAN BASINS

### 1. Gulf of Alaska

In all wells drilled in the Gulf of Alaska, geopressures were encountered at relatively shallow depths with pressure gradients up to .890 psi/ft. The first occurrence of abnormally high pressures, the onset of which appears to be related to major lateral compressive forces (such as at the point of transition from normal to thrust faulting), was at depths ranging from 6000 to 10,700' (Hottman, et al, 1979).

### 2. Beaufort Sea (Grantz and Dinter, 1980)

Along the continental slope and rise of the Beaufort Sea, east of 147°W Longitude, seismic surveys have detected the presence of diapirs which have disturbed Tertiary sediments and which, in places, have arched the seabed. These diapirs apparently consist of overpressured shales which have originated beneath the continental shelf and slope in beds that apparently have low seismic interval velocities. It is estimated that these possible source beds (for hydrocarbons) lie about 9800' below the sea floor.

### 3. Bering Sea

Various offshore basins in the Bering Sea, such as the Navarin Basin and the Aleutian Basin, contain Cenozoic sediments that are characterized by diapirs and acoustic phenomena (velocity amplitude features) probably caused by gas pockets and other hydrocarbons trapped in sedimentary sections (Marlow, et al, 1980; Cooper, et al., 1980).



4. Geopressuring has also been reported in Alaska from the following areas (but no specifics are available):

Copper River Valley (Dickey, 1978)

Cook Inlet area (Jones, 1977)



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## 6.14 OTHER OCCURRENCES

1. Continental Slope of Atlantic Coast offshore Cape Hatteras (Grow, et al, 1977)

Recent seismic surveys have discovered seven diapiric structures along the base of the continental slope southeast of Cape Hatteras in a discontinuous band 6 to 12 miles wide from  $32-1/2^{\circ}$  to  $35^{\circ}$  N. While diapirs are common off Nova Scotia, this is the first systematic group of diapirs to be detected in the U. S. Atlantic coast with the exception of an isolated diapir which intrudes Tertiary sediments off the New Jersey coast.

2. Washington (McFarland, 1979)

In the Ocean City field in Grays Harbor County near the Pacific Ocean 1.5 miles south of Ocean City, numerous wells have encountered very high pressures below 10,000'.

3. Offshore Oregon and Washington (Zieglar and Cassell, 1978)

Eleven out of 12 wells drilled offshore Oregon and Washington encountered sloughing shales and abnormal subsurface pressures although only minor shows of oil and gas were found.

4. South Carolina (Marine, 1974)

Near Aiken, South Carolina, a buried Triassic basin has been found. This basin, termed the "Dunbarton Basin" is about 30 miles long and 6 miles wide and is comprised of about 5300' of Triassic sediments. Two wells drilled into the basin were



found to be slightly overpressured with gradients of .453 and .473 psi/ft in contrast to the normal pressure gradient in the area of .411 psi/ft. (The latter value varies from the commonly accepted measure of .433 psi/ft for freshwater which is not applicable here because the water level in aquifers of the coastal plain do not rise to the land surface.)

5. Illinois Basin, Kentucky (Reynolds and Vincent, 1972)

In the southern part of the Illinois Basin, known as the Moorman syncline in western Kentucky, there appears to be slight overpressuring in the Bethel Channel sandstone of the Bethel shale (Mississippian - lower Chesterian).

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## 7. SUMMARY AND CONCLUSIONS

Geopressured occurrences outside the Gulf Coast have been encountered during drilling operations in numerous onshore and several offshore sedimentary basins. In undrilled offshore areas, seismic surveys have detected shale diapirs (presumably due to methane generation) in various deep-water basins off Alaska, Pacific coast from northern California northward, and isolated areas of the Atlantic OCS. These geopressured reservoirs in many cases differ from that found in the Gulf Coast in terms of lithology, geologic age, temperature gradient, genesis, salinity of water, and other parameters. In at least two basins, formation water is nearly absent in certain geopressured zones. In addition, certain basins, such as those in the Rocky Mountains, are characterized by anomalous overpressured and underpressured areas; elsewhere, there may be alternating geopressured formations interspersed between normally pressured strata.

The principal features of the geopressured occurrences in each of the major basins are summarized below.

### Appalachian Basin

- Slightly overpressured zones in selected moderately shallow Devonian and Ordovician sediments
- Abnormally high pressures prevalent in deep Cambrian rocks of the Rome Trough in West Virginia apparently characterized by very low salinity waters with contained gas

### Interior Salt Basin

- Various Jurassic carbonates at great depths (below 20,000') are highly overpressured in places approaching the lithostatic pressure gradient
- Commonly accompanied by highly saline waters and large quantities of sour gas

### Anadarko Basin

- Abnormally high pressures are generally concentrated in the western Oklahoma-eastern Texas Panhandle region of the basin in various Paleozoic sediments
- Geopressured formations are usually gas-bearing and in selected fields, formation waters are apparently lacking in gas-condensate zones
- Temperature gradient is normal
- Salinity values are unavailable

### Delaware Basin

- Geopressured zones are found at moderate to great depths in various Paleozoic formations throughout this basin and the geologically similar Val Verde Basin
- Temperature gradients are normal
- Salinity values are unavailable

### Rocky Mountain Basins

- Characterized by anomalously normal, underpressured, and overpressured formations, the latter are generally encountered at moderate to great depths
- Geopressured zones are commonly found accompanied by gas, but there are various exceptions such as the oil fields of the Altamont-Bluebell trend of the Uinta Basin, oil fields of the Wamsutter Arch area of the Green River Basin, etc.
- Abnormally high temperature gradients (over 2°F/100') have been generally encountered but there are numerous exceptions
- Specific data on salinity of formation waters are unavailable but based on SP curves of selected wells, it appears to be relatively low



### Williston Basin

- Geopressures are localized in the Bakken shale, the major presumed oil source rock in the basin, especially where in contact with a permeable bed
- Waters in the basin are generally highly saline but in the over-pressured Bakken formation, formation waters are almost completely absent

### California Basins

- Abnormally high pressures are found at moderate depths in Cretaceous formations in the gas fields of the Sacramento Valley and at shallow depths in the Franciscan formation of the Coast Ranges
- Geopressures have been encountered in numerous fields and wells in Tertiary formations of the San Joaquin Valley, Los Angeles Basin, Ventura Basin, and offshore Santa Barbara Channel
- Temperature gradients in the geopressured zones are generally relatively high, over  $2.0^{\circ}\text{F}/100'$ , though there are some exceptions
- Salinity of geopressured waters are commonly considerably lower than those of the Gulf Coast

In conclusion, it is apparent that geopressured occurrences are rather common throughout the U.S. though the conditions and parameters, for the most part, are unlike those found in the Gulf Coast. It is further evident that in most basins there is a dearth of published information available on the nature and composition of the contained associated waters in terms of the salinity, temperature, methane content, etc. To amplify the data base thus far developed the second phase of this study will be undertaken in order to obtain access to proprietary



records, files and material that it is believed will provide the necessary information for a preliminary assessment of the energy potential of these geopressured reservoirs outside the Gulf Coast.

