A SUBSURFACE INTERPRETATION USING THREE-DIMENSIONAL SEISMIC METHODS OF A PORTION OF THE ERAWAN GAS/CONDENSATE FIELD, GULF OF THAILAND

CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

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Geology

by

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ABSTRACT

A SUBSURFACE INTERPRETATION USING THREE-DIMENSIONAL SEISMIC METHODS OF A PORTION OF THE ERAWAN GAS/CONDENSATE FIELD, GULF OF THAILAND

by

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Master of Science in Geology

Geological and geophysical data were combined to conduct a highly detailed interpretation of the southern third of the Erawan gas/condensate field in the Gulf of Thailand. Data included three-dimensionally migrated seismic lines, horizontal time slices through the 3-D data volume, time and amplitude maps generated on an interactive computer interpretation system, and borehole data. Using these data, six seismic horizons were mapped in the study area: (1) top of acoustic basement (Paleozoic or Mesozoic rocks); (2) near top of Cycle I (within the lower Miocene); (3) an arbitrary reflector within Cycle II (within the lower Miocene); (4) near top of Cycle II

(within the lower Miocene); (5) near the middle Miocene unconformity, near top of Cycle III (within the upper Miocene); and (6) a very continuous reflector within Cycle IV (within the upper Miocene). The regional geologic history included several different tectonic settings from the Cambrian to the Recent. Subduction from the east commenced in the Silurian to Lower Devonian and continued until continental collision occurred in the Triassic. Subduction from the west commenced in the Jurassic and has continued to the present. Associated with the subduction was the formation of large granitic bodies which were intruded throughout most of the region. The Tertiary section within the Pattani trough was dominantly controlled by backarc spreading in the early Tertiary which initiated subsidence along older zones of weakness. Most of the faulting associated with the study area developed in the Miocene as the result of increased sediment load and basin subsidence.

The configuration of the horizons mapped demonstrates the presence of a complex, faulted graben. Fault blocks of less than a quarter mile (half a kilometer) in width were mapped. Faults generally strike north-south in the northern part of the study area and trend eastward in the southern half. The structure contains major east-dipping faults which cut basement and associated west-dipping antithetic faults. The axis of the graben shifts from the

center of the study area in the north to east of the area in the southern part. In the southwest corner of the area, the west-dipping flank of another graben structure is present. Stratigraphic mapping performed on and between these horizons revealed a complex stratigraphy. Most sand bodies are thin and lenticular with limited lateral extent. Most of the section is fluvial in origin with only minor amounts of marine influence. Reservoir beds are mainly meandering channel sandstones and bars, rather than extensive sheet sands. With each fault block acting as a separate unit in controlling hydrocarbon accumulations, it is critical to encounter these small faulted sand bodies in an optimum structural position. The use of three-dimensional seismic methods have aided in defining these structural positions.

INTRODUCTION

Purpose and Objectives

The initial exploration which defined the Erawan structure occurred from 1968 to 1972. The first well was drilled in 1972 and encountered hydrocarbons. Consequently, eight additional delineation wells were drilled on the structure from 1972 to 1979. Based on the geologic information obtained in these wells, the Erawan field was considered to be a commercial producer. In 1979, a three-dimensional seismic survey was deemed necessary for the development of the field because of the structural complexity observed on the two-dimensional data.

This geological and geophysical interpretation of the southern third of the Erawan field was conducted to: (1) define the structural style at various depths; (2) determine potential environments of deposition and their role in controlling hydrocarbon accumulations; and (3) give a general background into the geology of the region to show what factors have acted upon the study area. In so doing, the author: (1) proposed tectonic models based on all available geological and geophysical information; (2) generated synthetic seismograms to correlate seismic and borehole data; (3) constructed six structure contour maps to establish the extent and nature of faulting and

also to define structural traps; and (4) conducted stratigraphic mapping using three-dimensional seismic methods to define the geometry of individual reservoir beds.

The geophysical data used included 142 three-dimensionally migrated seismic lines displayed in the east-west direction, numerous north-south and radial lines, and 1,125 horizontal time slices displayed from 0 to 4.5 seconds. Borehole data used included various electric, radioactive, and mud logs along with several well velocity surveys.

Geographic Setting

The study area is concentrated in the southern third of the Erawan (gas/condensate) field, which is located in the Gulf of Thailand between north latitudes 9° 15' and 8° 57' and between east longitudes 101° 15' and 101° 23' (Figure 1). The area is located 93 miles (150 kilometers) from Peninsular Thailand and encompasses 50 square miles (129 square kilometers). The field is in close proximity to a disputed area claimed by the governments of Thailand, Kampuchea, and Vietnam. The study area contains parts of blocks 12 and 13 of the original lease tracts awarded by the government of Thailand in 1968.

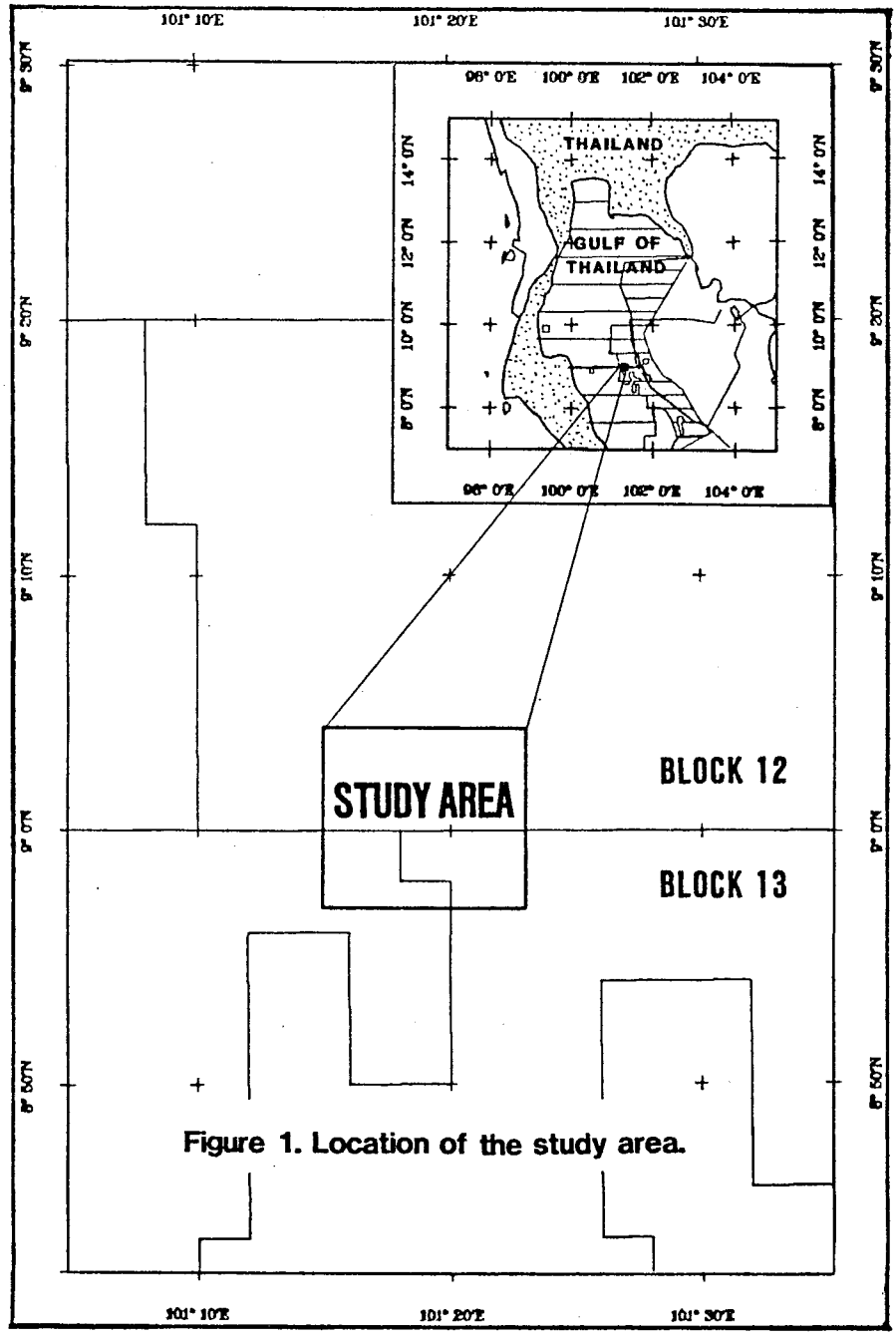

Figure 1. Location of the study area.

Climate and Oceanography

The Gulf of Thailand has a tropical climate with an average rainfall of approximately 40 to 60 inches (100 to 150 centimeters). Temperature varies only slightly from 77° to 85° F. (25° to 29° C.). Monsoonal wind systems control both the wet and dry seasons. The monsoon begins in May and continues through October, during which time nearly all of the annual rainfall occurs.

The Gulf is a relatively shallow basin with a maximum depth of 282 feet (86 meters), and the average water depth in the study area is approximately 200 feet (61 meters). The Chao Phraya River is the main river which flows into the Gulf at the northernmost extension. The tidal range of approximately eight feet (2.4 meters) classifies the coastline as mesotidal.

Prior Seismic Surveys

A series of seismic surveys have been undertaken over this area between 1968 and 1979 (Table 1).

TABLE 1. LIST OF SEISMIC SURVEYS CONDUCTED OVER THE ERAWAN FIELD BETWEEN 1968 AND 1979

Date	Company	Source Type
August 1968	Delta	12 fold Vibroseis
October 1969	G.S.I.	24 fold airgun
February 1973	Ray	48 fold airgun
July 1974	G.S.I.	48 fold airgun
April 1976	Western	High resolution, 48 fold Aquapulse
June 1979	Prakla	Low frequency, 48 fold airgun
October 1979	G.S.I.	3-D, 48 fold airgun

A total of six different surveys were shot prior to the 3-D survey used in this interpretation. Four of the surveys used airgun arrays as the source. The earliest survey used a marine Vibroseis and one survey used Aquapulse, a sleeve exploder, as the source. Early surveys collected such poor data that only structure form maps could be made. The complexity of the structure was not realized until after the shooting of the high resolution survey. This survey enhanced the response from thin beds by high frequency resolution giving a better definition of reflection termination caused by faulting and abrupt stratigraphic changes. Then, a low frequency survey was conducted because the high frequency survey showed that most of the mappable reflectors deeper in the section were more resolvable by low frequency energy.

Previous Investigations

A very limited amount of geologic information has been published on the Gulf of Thailand. Of the small number of the papers published on Thailand and its neighboring countries, few investigators discuss the geologic nature of the Gulf.

Klompe (1962) described the igneous and structural features of Thailand. He presented some models for the formation of the Gulf. Burton (1967) described the wrench

faulting in Malaya and extended one fault into the Gulf. Garson and Mitchell (1970) described the transform faulting of the Thai Peninsula and extrapolated the location of these faults into the Gulf. Burton (1974) described four Paleozoic and Mesozoic zones on Peninsular Thailand and correlated them across the Gulf to the mainland using limited well control.

The first paper specifically written on the Gulf of Thailand was by Achalabhuti (1974). Using information obtained from aeromagnetic and seismic data, and from the initial thirteen wells drilled in the Gulf, he described the petroleum potential of the Gulf. Paul and Lian (1975) reviewed the geologic history of the Gulf of Thailand. Hutchinson (1975) described the ophiolites present in southeast Asia and at least one which may extend out into the Gulf.

Woollands and Haw (1976) conducted a detailed study on the Tertiary sedimentation and stratigraphy of the Gulf based on British Petroleum wells in the Gulf. A plate tectonic model was described by Asnachinda (1978) for the Burmese-Malayan Peninsula while attempting to explain the origin of tin deposits found in the region.

Stump (1981) described the sedimentological evolution of the Tertiary rocks of the Gulf of Thailand based on over thirty wells drilled in the Gulf. In 1981, the Asian Council on Petroleum (ASCOPE) reviewed the stratigraphy,

structure, and hydrocarbon occurrence within the Thai basin. This review was done as part of a general regional study. Trevena (1981) described the petrography of the reservoir rocks within the Pattani trough (refer to Figure 3, page 16). Kimbell (1982) made a geophysical investigation of the deltaic environments within the northern part of the Pattani trough. Dahm and Graebner (1982) gave a case history of field development within a portion of the Gulf, using three-dimensional seismic methods.

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DESCRIPTION OF DATA USED

General

Three-dimensional seismic surveys collect data using the same methods as two-dimensional surveys. The main differences between 2-D and 3-D surveys are in the amount of data collected over a particular area and the way the data is processed. Three-dimensional surveys may collect over ten times the amount of seismic line data as a 2-D survey over the same area. A dense seismic data volume is needed so that processing may be performed not only in the direction the seismic sections were acquired but also between adjacent lines.

Acquisition

Over 2,800 miles (4,500 kilometers) of 48-fold reflection data were acquired in 1979. A total of 427 east-west lines, with a 246 foot (75 meter) spacing between each line were collected over an area covering 128 square miles (330 square kilometers). The cost of the survey was over three million dollars. An airgun array was the energy source with 48 geophone groups encased in a 7,874 foot (2,400 meter) streamer cable. A sample rate of 4 milliseconds was used for a record length of 5 seconds.

Positioning

The position of the survey was 93 miles (150 kilometers) offshore. Because of this extreme distance from shore, an Argo navigation system along with long-range Shoran was used for lane count verification. The accuracy of these combined systems is between 33 and 164 feet (10 to 50 meters). It was important to have very good positioning so that sufficient data would be collected for full-fold coverage throughout the survey.

Processing Sequence

The processing sequence is shown in Table 2. Three-dimensional migration (migration along the shot-line and between adjacent lines) is an important advantage over two-dimensional migration. A significant improvement in the signal to noise ratio is produced. The seismic sections appear much cleaner because diffractions from out of the plane of the section were removed (Brown and McBeath, 1980).

TABLE 2. THE 13 STEPS PERFORMED IN THE DIGITAL PROCESSING OF THE 3-D DATA

Static Corrections
True Amplitude Recovery
Predeconvolution Ramp
Deconvolution
Scaling
Velocity Analysis
Normal Moveout Corrections
First Break Suppression
Common Depth Point Stacking
Deconvolution
3-D Migration (F-K)
Time Variant Filtering
Time Variant Scaling

Data Quality

A major problem which affects the interpretation of over 25 percent of the 3-D data volume is the presence of shallow bright spots. These high amplitude reflectors generate multiple wave trains which were not removed by the digital processing sequence. The result is a cone of interference which severely distorts the data. An example is shown on the left hand side of Plate I. In areas where this problem is absent, data quality is very good and the complexity of the structure can be adequately interpreted.

REGIONAL GEOLOGIC SETTING

Thailand can be divided into three major geologic provinces: (1) a northern and western mountain belt; (2) an eastern highland, the Khorat Plateau; and (3) a central depression, the Chao Phraya, and associated offshore extension, the Gulf of Thailand. Figure 2 shows the distribution of these provinces.

The first province includes the Thai-Malay Peninsula, a Paleozoic-Mesozoic folded belt. The Peninsula is moderately folded and heavily intruded by granites. Burton (1974) described four zones on the Peninsula which he extended across the Gulf to the mainland. From east to west, the first is an internal positive zone of Paleozoic sedimentary rocks intruded by granites. The second is a eugeoclinal zone in which a Paleozoic/Mesozoic series with volcanics has been strongly folded and overlain by later Mesozoic rocks. The third zone is a miogeoclinal zone of mildly metamorphosed Paleozoic rocks. The fourth is a miogeoclinal zone with the Paleozoic layers overlain by thin Mesozoic rocks. Some shelf-like sediments within Zone 4 have been distinguished as sub-Zone 4A.

The second province is the Khorat Plateau which is a broad fairly flat highland in the northeastern part of Thailand. Outcrops on the Plateau are dominantly Mesozoic continental rocks. Thick Paleozoic and Mesozoic sections

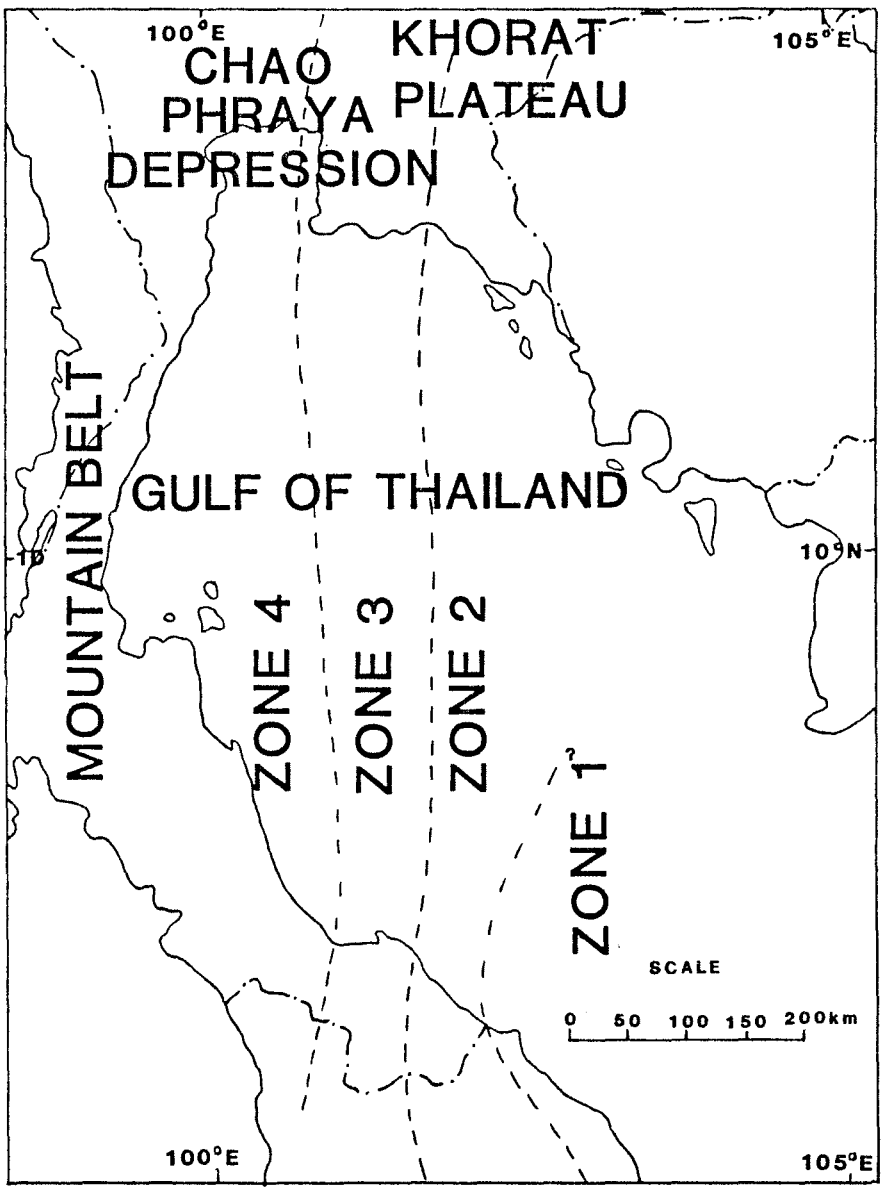


Figure 2. Distribution of the major provinces and zones of the region. Modified from Burton(1974).

are also present within the Plateau.

The third province consists of the Tertiary Chao Phraya and Gulf of Thailand depressions. Thick accummulations of predominantly continental rocks fill these depressions. Outcrops are mainly Quaternary alluvium. Paul and Lian (1975) stated that within the Gulf this province is bounded on the east by the Khorat swell. The swell, which crops out from southeast Thailand to southwest Vietnam, appears to consist of a complex of Paleozoic igneous, metamorphic, and sedimentary rocks unconformably overlain by Mesozoic continental deposits and intruded by Mesozoic plutons.

Major Structures

Many major structural features are present on the Thai-Malay Peninsula and most of them extend offshore into the Gulf of Thailand. Figure 3 shows the major structural features of the region.

Six major fault zones have been recognized, four of which occur on the Thai-Malay Peninsula. The largest is the Khlong Marui fault zone, a northeast-southwest left-lateral strike-slip fault zone first identified by Garson and Mitchell (1970). Displacements of at least 93 miles (150 kilometers) have been observed. The Ranong fault is also a northeast-southwest left-lateral strike-

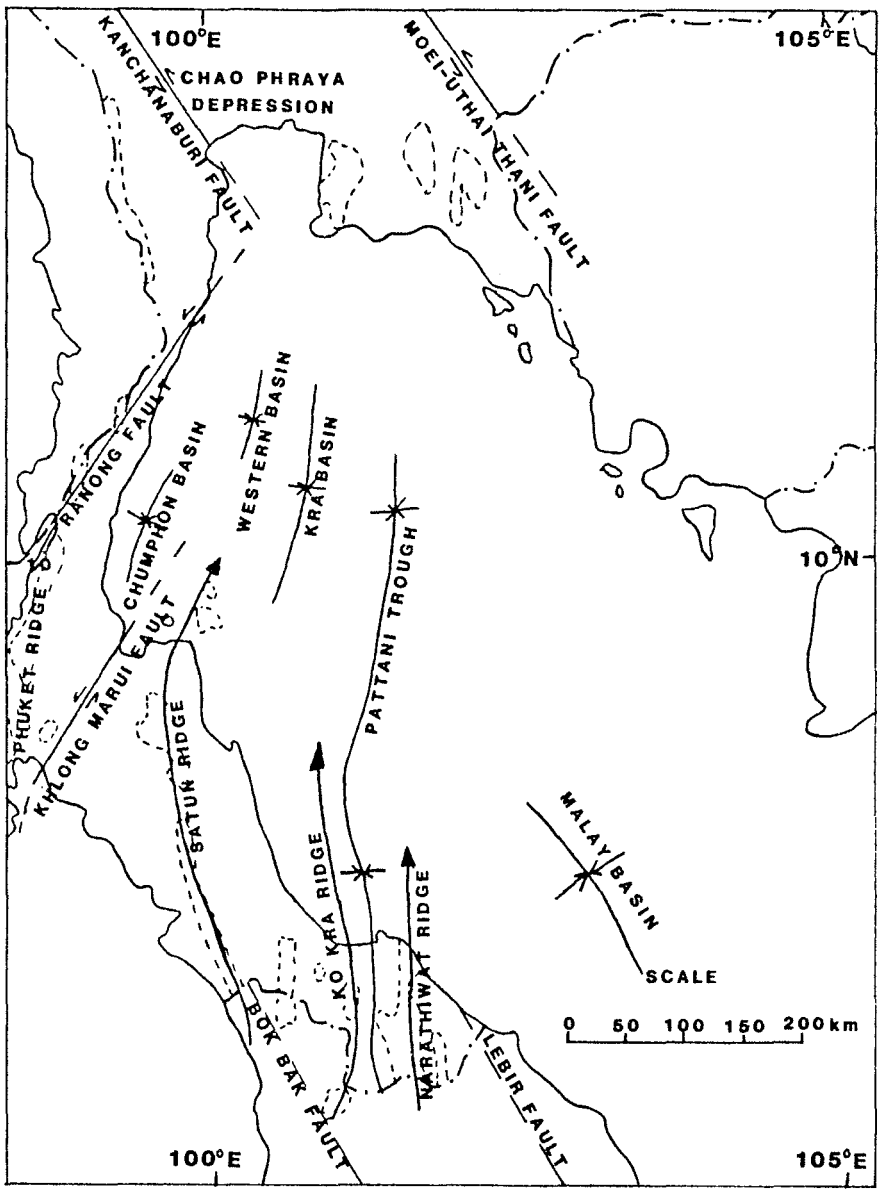


Figure 3. Major structural features of the region. Modified from Achalabhuti(1974).

slip fault with displacements of at least 12 miles (20 kilometers). Garson and Mitchell stated the age of faulting is post late Carboniferous to Triassic. The age of cessation of movement is unknown. Burton (1974) described two other left-lateral strike-slip faults. The Bok Bak fault trends northwest-southeast with a displacement of 32 to 36 miles (52 to 58 kilometers). Burton suggested that movements commenced in the Upper Triassic to Cretaceous and ceased in the Late Jurassic to early Quaternary. He also described the north-northwest to south-southeast trending Lebir fault along which large left-lateral movements took place. The age and the amount of movement is unknown.

Two other, large left-lateral strike-slip fault zones have been observed on the mainland and both may extend into the Gulf. Both trend northwest-southeast; the age and amount of movement is unknown. The zone cutting southwest of Bangkok has been called the Kanchanaburi, the Kwae Noi, or the Three Pagoda-Ratburi fault zone. The zone cutting northeast of Bangkok is called the Moei-Uthai Thani fault zone.

Three major Late Cretaceous to early Tertiary granitic ridges extend from the Thai-Malay Peninsula out into the Gulf of Thailand. These are, from east to west, the Narathiwat, the Ko Kra, and the Satun ridges. A fourth ridge, the Phuket ridge, lies along the Peninsula. These

ridges are important because they control the position of the two major troughs in the Gulf of Thailand. One of these, the Pattani trough, is bounded on the west by the Ko Kra ridge and on the east by the Narathiwat ridge. The Narathiwat ridge separates the Pattani trough from the Malay basin on the east. Smaller basins to the west include the Kra, the Western, and the Chumphon basins.

Regional Geologic History

No Precambrian rocks crop out or have been drilled in the general vicinity of the Gulf of Thailand. According to Burton (1974), recorded geologic history begins in the Cambrian when shallow marine sediments were being deposited onto a stable platform. This platform, similar to an Atlantic-type margin, probably existed in the position of the Thai-Malay Peninsula and over the western part of the present day Gulf of Thailand (Figure 4). The platform can be distinguished by the presence of shallow water miogeoclinal deposits. Much of the sediments were derived from a stable landmass to the west, probably India. Burton's (1974) evidence for India being the landmass included the presence of diamond clasts in Mississippian and Pennsylvanian sediments, which are totally out of geological context on the west coast of Thailand but could be from the Indian Golconda diamond

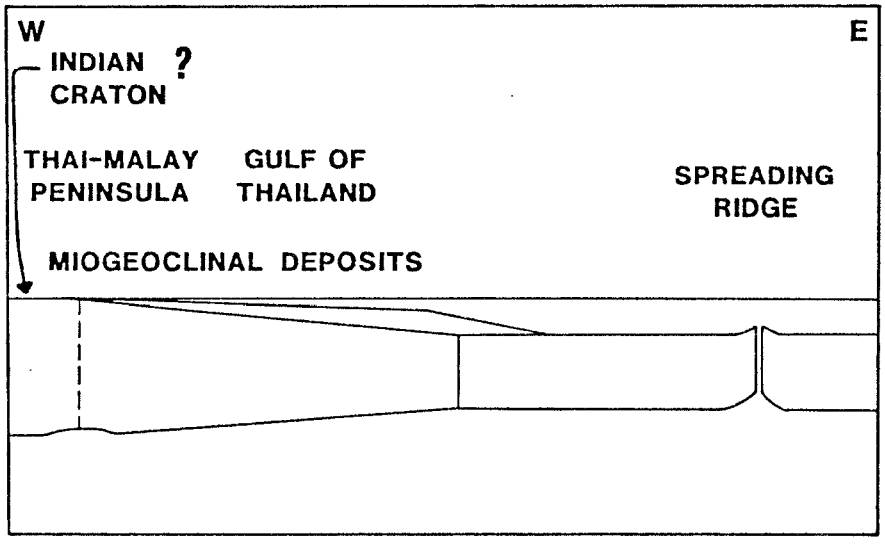


Figure 4. Cambrian to Silurian tectonic setting.

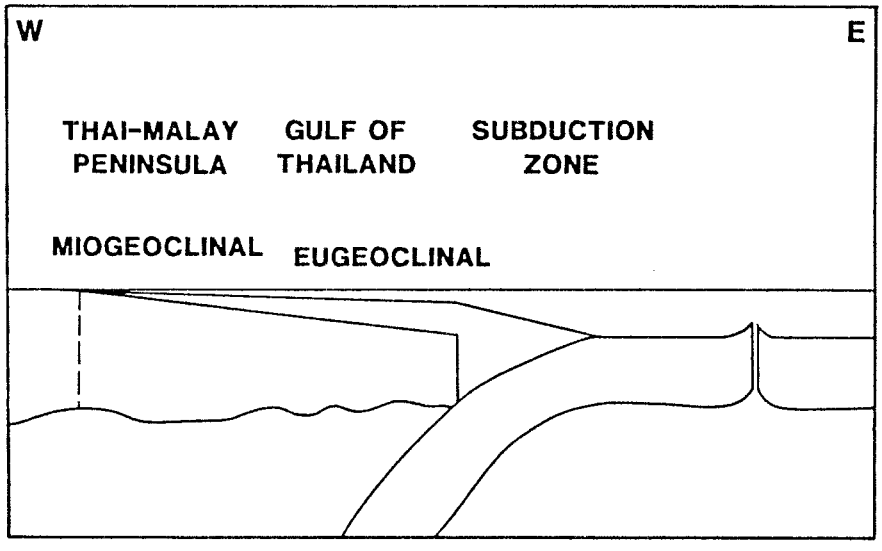


Figure 5. Silurian to Lower Devonian tectonic setting.

field. The extent of continental rifting to the east is unknown, although it may have just been initiated as suggested by the occurrence of rhyolitic and rhyodacitic flows (probably Ordovician in age).

In the Silurian to Lower Devonian subduction may have begun in the east with a west dipping subduction zone. Eugeoclinal deposits of this age are found onshore which, when projected offshore, are in the position of the present day Gulf. Meanwhile, miogeoclinal deposits continued to be deposited in the position of the Thai-Malay Peninsula (Figure 5). In 1975, Hutchinson described several ophiolite zones as evidence for subduction in the region of the Gulf of Thailand. One of these, the Bentong-Raub belt on the Thai-Malay Peninsula, appears to extend offshore into the Gulf along the general trend of the Pattani trough. Hutchinson describes the emplacement time of this ophiolite belt as Ordovician to Mississippian.

As subduction progressed, the generation of magma led to the development of granitic batholiths across most of the region. This tectonism led to the formation of an arc in the position of the central region of the present day Gulf and the development of separate forearc and backarc basins (Figure 6). Associated with these intrusions was the development of flysch-like deposits (marine argillaceous rocks) in the Early Devonian to Lower

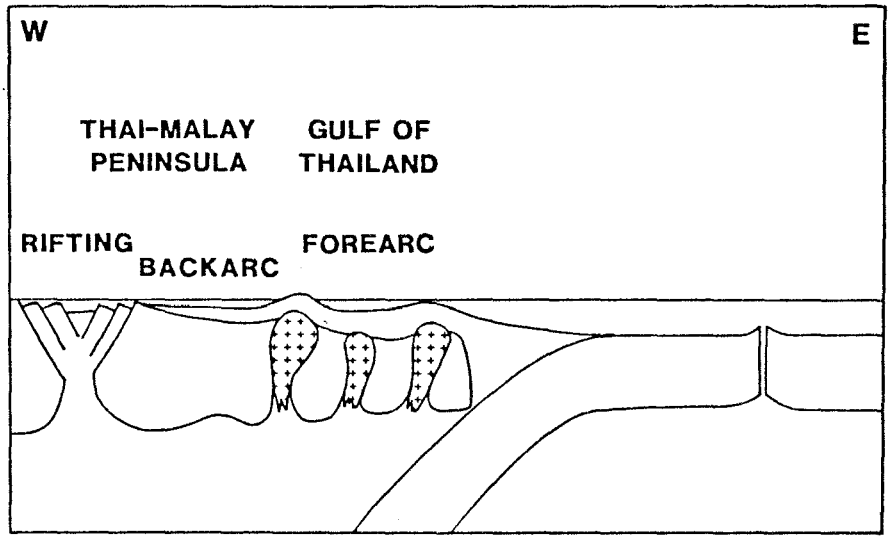


Figure 6. Early Devonian to Early Permian tectonic setting.

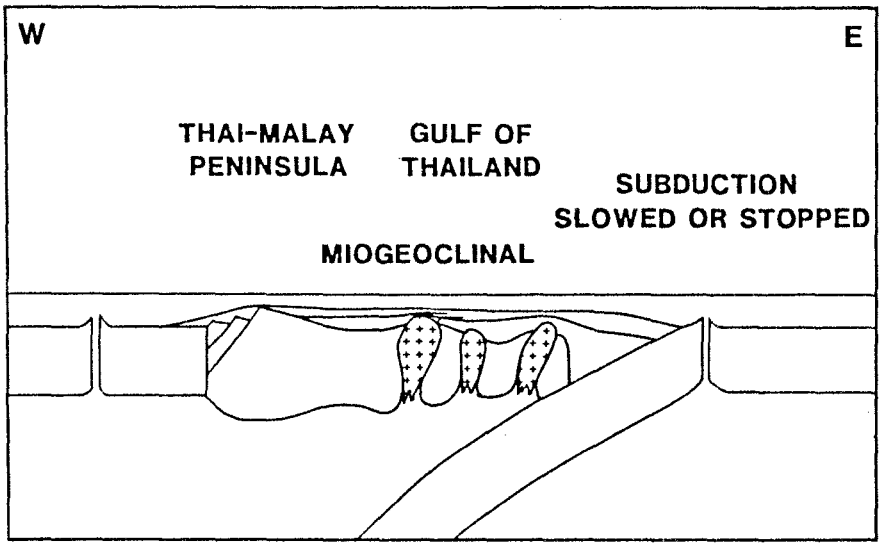


Figure 7. Early Permian to Lower Triassic tectonic setting.

Mississippian, and molasse deposits (nonmarine arenaceous and argillaceous rocks) in the Upper Mississippian to Early Permian. These sediments were probably derived from preexisting sediment eroded off the intrusions. Backarc spreading may have helped to initiate continental rifting between India and the Thai-Malay Peninsula in the Late Devonian to Mississippian forming a new microcontinent. Asnachinda (1978) suggested that the aforementioned diamond deposits were associated with this rifting.

The arc region was very subdued in the Early Permian to Lower Triassic. This situation may have been due to a young light ridge approaching the subduction zone which slowed or even stopped the subduction process (Figure 7). This setting allowed the deposition of miogeoclinal deposits in both the backarc and forearc basins. To the east some of these deposits were interbedded with volcanics. Possibly, the subduction may have switched to the east side of the ridge at this time or subduction may have been taking place on both sides of the ridge prior to this time (Figure 8).

During the Middle to Upper Triassic, deposition was occurring only in the west with flysch-like sediments. This evidence suggests that collision between the microcontinent, including the Thai-Malay Peninsula and the Gulf of Thailand, and the Indo-China block had commenced.

In the Late Triassic, collision culminated with

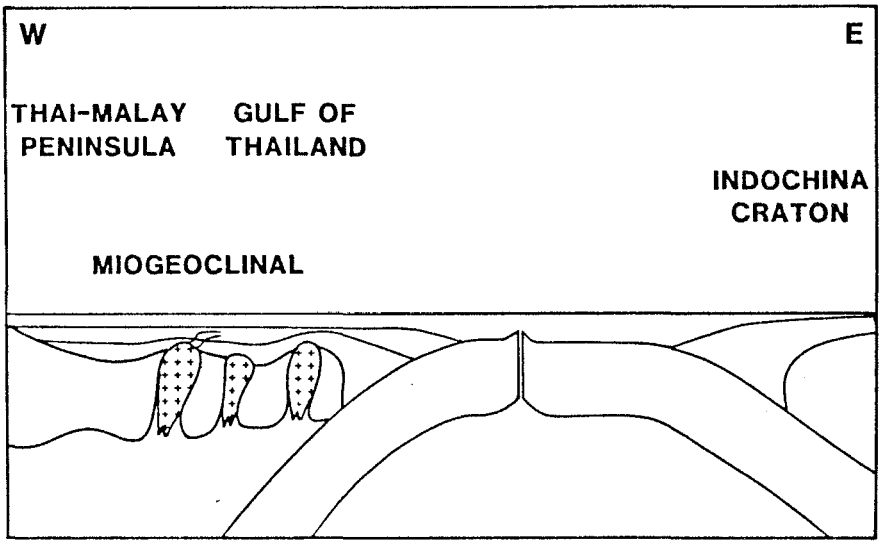


Figure 8. Early Permian to Lower Triassic tectonic setting.

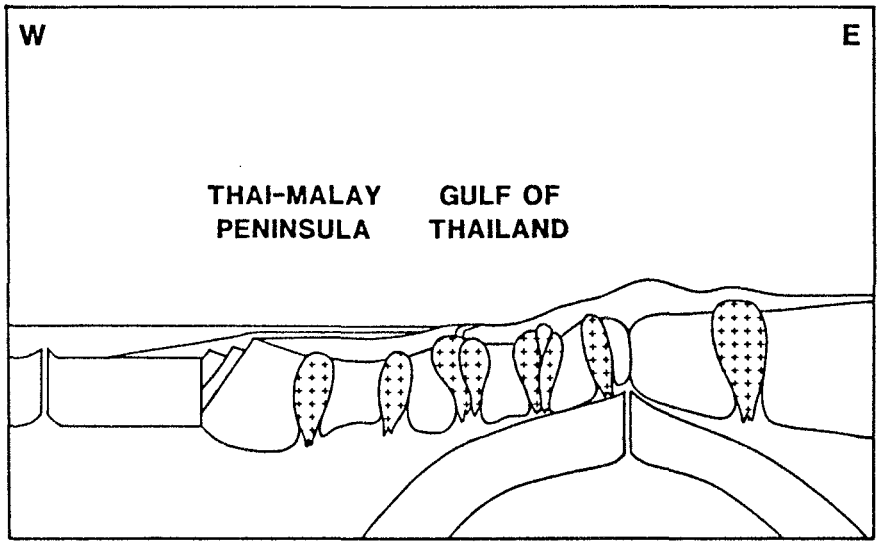


Figure 9. Middle to Late Triassic tectonic setting.

widespread granitic batholiths being intruded over most of the region (Figure 9). Molasse deposits began filling in the former forearc and backarc basins until the Early Cretaceous. At some time during the Jurassic, subduction was initiated from the west. This event led to the emplacement of small granitic bodies in the Late Jurassic to Early Cretaceous and larger batholiths in the Middle Cretaceous within the Thai-Malay Peninsula and western Gulf of Thailand (Figure 10). Initial subduction probably occured at an oblique angle causing large scale left-lateral faults to cut across the Thai-Malay Peninsula and out into the Gulf of Thailand. Movements along these faults continued until the early Tertiary. Evidence for this subduction zone to the west is confirmed by ophiolites which were emplaced during the Late Cretaceous. Hutchinson (1975) described this zone as the Mandalay belt of east Burma, which extends out into the present day Andaman Sea.

This subduction probably initiated backarc spreading within the Gulf of Thailand along older zones of weakness within the early Tertiary (Figure 11). Volcanic and intrusive activity associated with this spreading was noted by Paul and Lian (1975). They suggested that this igneous activity, found along the eastern margin and the floor of the Chao Phraya depression, was probably of late Miocene age.

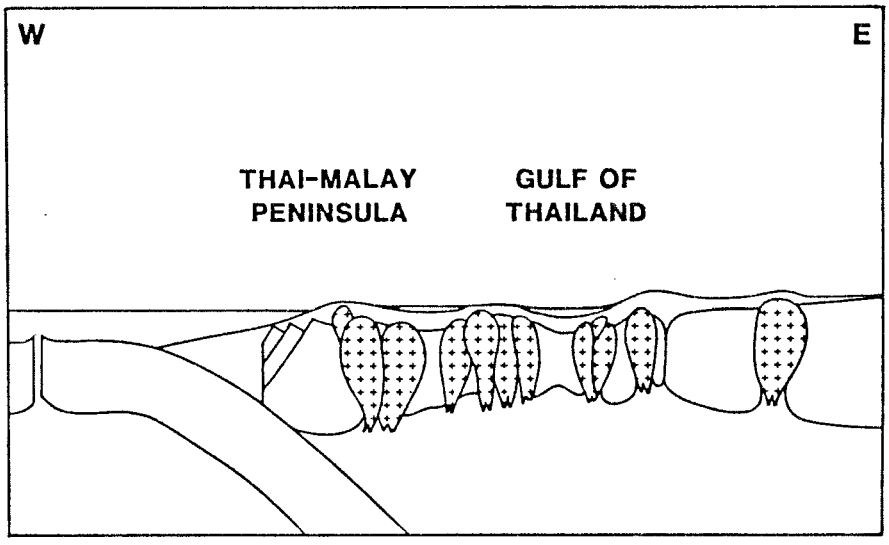


Figure 10. Late Jurassic to Middle Cretaceous tectonic setting.

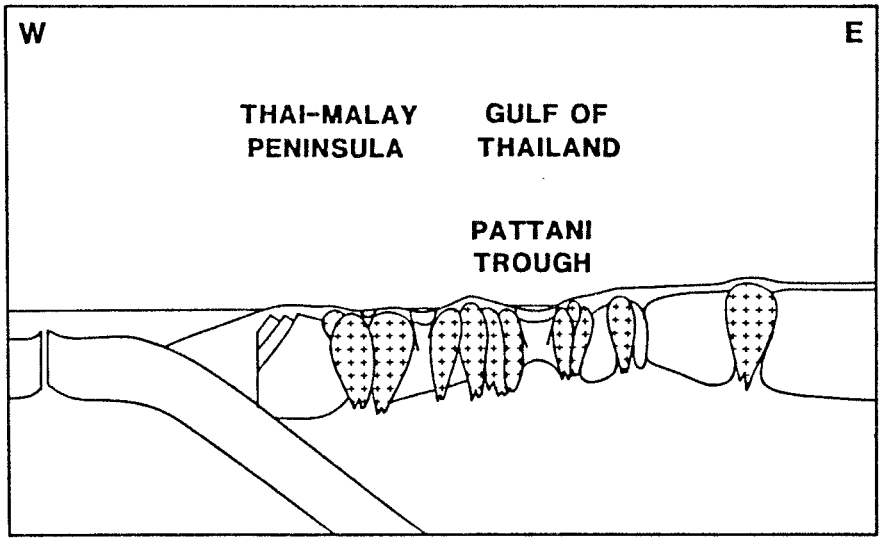


Figure 11. Early Tertiary tectonic setting.

At least once during the early Tertiary, the east-dipping subduction zone jumped back towards the west, possibly as the result of seamounts or a spreading ridge entering the subduction zone. During the middle Tertiary rifting west of the Thai-Malay Peninsula led to the formation of the Andaman Sea (Hamilton, 1979). Tertiary sediments began filling these newly formed basins, leading to the inception of the present day tectonic setting.

ROCK UNITS

General

The lowest rock units which underlie the Gulf of Thailand are probably equivalent to Paleozoic and Mesozoic rocks which crop out around the Gulf. These rocks onshore have a maximum thickness of 41,500 feet (12,600 meters) (Burton 1974), and are dominantly shallow water sandstones, shales, and carbonates which have been intruded by granites and consequently uplifted. These sediments are probably well preserved in the deeper parts of the Pattani trough, but there is such a thick section of overlying Tertiary sediments that they will probably never be reached by drilling. The Tertiary section consists of 29,500 feet (9,000 meters) of fluvial-deltaic sandstones and shales derived primarily from the uplift and erosion of the onshore Paleozoic and Mesozoic sequence. There are no exposed outcrops of the Tertiary section found in the Gulf of Thailand.

Description

Paleozoic Rock Units

Paleozoic rock units are most easily described if the area beneath and around the Gulf is divided into four zones as Burton described in 1974 (Figure 2). Formation

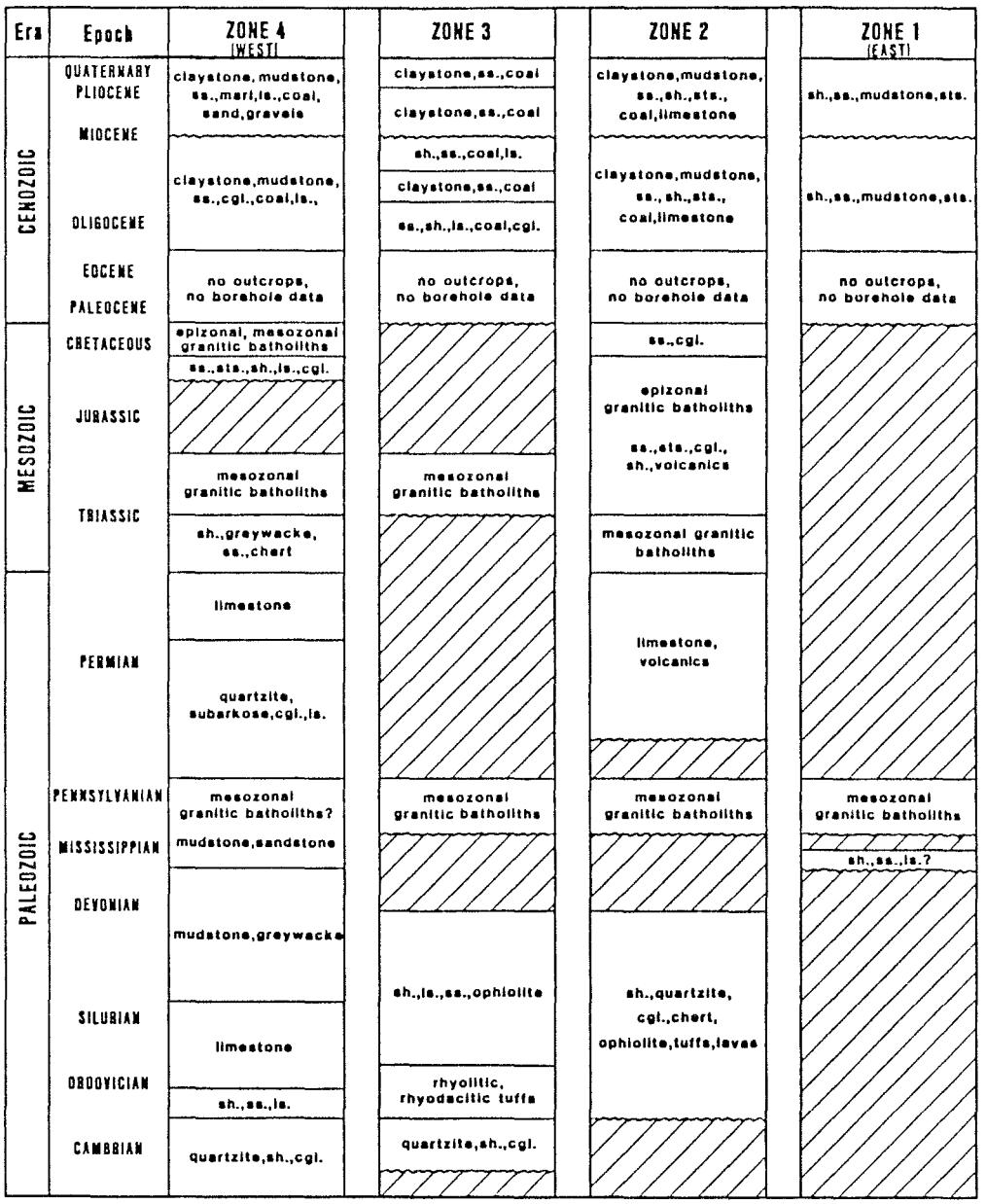
names in the description are those used by Burton and apply chiefly to the Thai-Malay Peninsula. A generalized stratigraphic section of the four zones is shown in Figure 12. Regional formation names have not been established for each zone, consequently they have been excluded from Figure 12.

The oldest known rocks are found in Zones 3 and 4, and are of Upper Cambrian age based on fossil evidence (Buravas, 1957). In Zone 4 these rocks are the lowest part of the Satun Group. The basal (Cambrian) member is the Taratao Quartzite. This unit contains pebbles of quartzite, quartz, siliceous slate, and biotite granite which may have been derived from Precambrian rocks. The approximate average thickness is 4,900 feet (1,500 meters). The equivalent unit in Zone 3 is the Papalut Quartzite which is the basal unit of the Bannang Sata Group. The average thickness is approximately 3,300 feet (1,000 meters).

In Zone 4 the next oldest member of the Satun Group is the Nai Tak Formation which is lowermost Ordovician in age. It is dominantly made up of calcareous argillite, sandstone, and impure limestone units ranging from 0 to 1,900 feet (570 meters) in thickness. In Zone 3 the next oldest member of the Bannang Sata Group is the Grik Tuffs of Ordovician age. These thick flows, 3,300 feet (1,000 meters) in average thickness, are rhyolitic and

GENERALIZED STRATIGRAPHIC SECTION

FIGURE 12



rhyo-dacitic in composition.

In Zone 2 the Tan Yong Mat Formation of Ordovician to Early Devonian age was deposited. An average thickness of 12,000 feet (3,650 meters) of argillite, quartzite, conglomerate, chert, and ophiolite was deposited along with some intercalations of tuffs and lavas. The ophiolites located in the western part of the zone are of Silurian to Early Devonian age. These rocks are equivalent to the upper member of the Bannang Sata Group, the Kroh Formation of Zone 3.

The Kroh Formation has an average thickness of 8,850 feet (2,700 meters) and is Late Ordovician to Lower Devonian in age. This age was based on graptolites found in black shale which is intercalated with dark limestone, arenite, and ophiolite. The ophiolites are found in the eastern part of this zone.

To the west in Zone 4, the upper member of the Satun Group, the Thung Song Limestone, was deposited with an average thickness of 5,250 feet (1,600 meters). This dark gray limestone was deposited from the Lower-Middle Ordovician to Upper Silurian, based on graptolites.

The Khlong Kaphong Formation of Early Devonian to Lower Mississippian age is dominantly mudstone and greywacke with an average thickness of 8,200 feet (2,500 meters). This formation is the lower member of the Phuket Group of Zone 4, and was described by Burton (1974) as a

flysch-like deposit.

The Pathiu Formation is the upper member of the Phuket Group. This formation is Upper Mississippian to Early Permian in age and is dominantly mudstone and sandstone with an average thickness of 5,400 feet (1,640 meters). Burton described this unit as a molasse-like deposit. No equivalent deposits have been found in Zones 2 and 3, although some remnants of Lower Mississippian argillites, arenites, and carbonate lenses have been found in Zone 1 (Fitch, 1952).

Late Mississippian and Pennsylvanian mesozonal granitic batholiths were intruded into all four zones with the largest amounts intruding Zones 1, 2, and 3. The granitic bodies of Zone 1 have a more silicic composition.

The Matsi Formation, the lower member of the Rat Buri Group, was deposited in the Early Permian. This formation is dominantly quartzite, subarkose, conglomerate, and limestone which ranges in thickness from 0 to 8,500 feet (2,600 meters) within Zone 4.

The Saraburi Limestone, the upper member of the Rat Buri Group, was deposited in Zones 2 and 4. In Zone 4 an average thickness of 2,800 feet (850 meters) of Early Permian to Late Permian pale limestone was deposited. In Zone 2 an average thickness of 8,200 feet (2,500 meters) of pale limestone with volcanics was deposited from Early Permian to Lower Triassic.

Mesozoic Rock Units

In the Early Triassic, mesozonal granitic bodies were intruded into Zone 2. Smaller epizonal granitic bodies were also intruded from Early Triassic to Late Jurassic or Early Cretaceous.

The Nathawi Formation was deposited in the Middle Triassic to Late-Upper Triassic with an average thickness of 3,300 feet (1,000 meters) in Zone 4. This formation is composed of black shale, greywacke, submature arenites, and bedded cherts. In the Late Triassic, mesozonal granitic batholiths intruded Zones 3 and 4.

The lower member of the Khorat Group was deposited in Zone 2 from Late Triassic to Late Jurassic with an average thickness of 9,850 feet (3,000 meters). The main lithologies are red sandstone, siltstone, conglomerate, shale, and minor volcanic intercalations, which are dominantly nonmarine.

In Zone 4, the Khorat Group is undivided and only averages 1,300 feet (400 meters) thick. These rocks were deposited from the Jurassic to the Cretaceous and are dominantly red sandstone, siltstone, and shale with minor amounts of limestone and conglomerate. The depositional environment was mainly nonmarine. During the Late Jurassic to Early Cretaceous, Zone 4 was intruded by small epizonal granitic bodies.

The Upper Khorat Group was deposited from Late Jurassic to Early Cretaceous in Zone 2. Coarsely cross-bedded mature sandstone and conglomerate of nonmarine origin was deposited with an average thickness ranging from 1,000 to 1,950 feet (300 to 600 meters). Middle Cretaceous mesozonal granitic batholiths intruded into Zone 4.

Cenozoic Rock Units

Onshore

Outcrops of Tertiary deposits are restricted to Zone 4. The Miocene to Pleistocene deposits are part of the Krabi Formation. These deposits consist of sand, clay, marl, limestone, and lignite which range in thickness from 0 to 575 feet (175 meters). They were deposited in a lacustrine and marginal marine environment. Quaternary deposits which crop out onshore include sands and gravels which range from 0 to 300 feet (90 meters) in thickness. They were deposited in a fluvial-estuarine environment.

Offshore

The Tertiary deposits of the Gulf of Thailand do not have any formalized names. Several authors have described these deposits in terms of cycles, chiefly Woollands and

Haw (1976) and Stump (1981). The cycles are represented by the general stratigraphy of Zone 3 in Figure 12.

The oldest Tertiary rocks that have been encountered by drilling are of Oligocene age. Paleocene and Eocene rocks may be present in the deeper parts of the Gulf but have not been reached by drilling. Rocks of this age are considered part of Cycle I. This cycle was the beginning of fluvial-deltaic progradation onto basement rocks.

Sediment type and color was highly dependent on the nature of the basement rocks. Plutonic basement yields much higher percentages of coarse sandstone along with shales which are normally red/brown or multicolored (Stump 1981). Metasediment basement rocks normally exhibit variable lithologies and colors. Cycle I can generally be described as alternating sandstones and shales with minor amounts of limestone, coal, and conglomerate present. The quantity of sandstone is controlled by its proximity to the source. There are extreme lateral variations of individual units within this cycle. Lithologies are very similar to those of the Krabi Formation onshore. The thickness of the cycle ranges from 0 to greater than 3,050 feet (930 meters) in the 12-1 well, located near the center of the Erawan field. Stump (1981) concluded that the dominant transport direction was from the east.

Detailed age correlation and dating within the Gulf is impossible due to the presence of large amounts of

nonmarine or marginal marine sediments. The marine fossils present (benthonic foraminifera) are not age diagnostic. These fossils are only useful as an indication for a marginal marine environment. Consequently, the only age correlations between rock units had to be done with palynology using the fossil spores which are present in both the marine and nonmarine sediments. Although spores and pollen are extremely resistant to destruction and are also light enough to be carried for considerable distances out into the sea, there are some problems with using palynology in the Gulf of Thailand deposits: (1) there are only six recognizable palynomorphs; (2) the presence of high heat flow causes thermal alteration; and (3) red beds make up a large portion of the section, which means palynomorphs have been oxidized. Nevertheless, Oligocene sediments can be distinguished by the palynomorph Florschuetzia trilobata. The environment of deposition associated with this palynomorph is normally littoral to inner sublittoral.

The progradation of Cycle I was followed by a transgressive sequence which Stump (1981) described as Cycle II. Woollands and Haw (1976) also recognized this transgressive marine sequence, but did not think it merited a cycle status. Stump describes this cycle as being uppermost Oligocene to middle-lower Miocene. This cycle can be recognized by either of the palynomorphs

Alnipollenites verus or Florshuetzia levipoli; the first palynomorph suggests an inner sublittoral, littoral, or a coastal plain environment while the second suggests a flood plain, coastal plain, or lagoonal environment. Sediments include gray/brown to varicolored carbonaceous claystone and sandstone with coal interbeds. These deposits appear to have been in close proximity to mangrove rich swamps (Stump, 1981; Woollands and Haw, 1976), and thus indicate the presence of brackish water. In the 12-1 well, a 1,960 feet (600 meter) interval containing marine calcareous benthonic foraminifera was identified by Robertson Research in 1973. Ammonia beccarii and Pseudorotalia yabei were described as being moderately abundant in this interval. The abundance of fossils could be explained by the existence of a few highly fossiliferous zones which may have contaminated the whole interval. The moderate abundance may also be the result of several thin marine units or a few thick units which contain an average amount of fossils.

Cycle III, which is equivalent to Woollands and Haws Cycle II, was deposited from uppermost Oligocene to upper middle Miocene. Stump divides this cycle into three sub-cycles. The lowermost Cycle IIIa, ranges in age from uppermost Oligocene to middle-lower Miocene. Lithologies consist of typically nonmarine limestones, with lignites which occur in multicolored mudstone or shale, which are

locally carbonaceous. Cycle IIIb commenced in lower-middle Miocene and continued to the upper-middle Miocene. The lithologies are similar to those of Cycle IIIa with the exception that they are red/brown to brick red in color and contain oxidized pollen. Cycle IIIc began overlapping Cycle IIIb between the lower-middle Miocene and upper-middle Miocene time. This cycle is characterized by abundant coals with some minor limestones, along with shale and interbedded sandstones which are varicolored. This is the last cycle which is predominantly varicolored. Cycle III is 2,200 feet (670 meters) thick in the 12-1 well.

Cycle IV of Stump (1981) or Cycle III of Woollands and Haw (1976) is separated from the previous cycle by the middle Miocene unconformity. This unconformity is probably the result of deposition overtaking subsidence rather than regional uplift and erosion. The palynomorph Florschuetzia meridionalis, which ranged in age from middle to upper Miocene, is found in the lower part of Cycle IV. This palynomorph is evidence for a coastal plain, lagoonal, or coastal swamp environment of deposition. Some marine influences are present as suggested by the brackish water foraminifera Miliammina in the lower part and by arenaceous calcareous benthonic foraminifera in the upper part of this portion of the cycle. This portion of Cycle IV is 2,920 feet (890

meters) in the 12-1 well and is dominantly gray/brown claystones with minor interbedded sandstone and some coals. The middle portion of Cycle IV is of Pliocene age, distinguished by the palynomorph Dacrydium, which suggests deposition in a coastal swamp, littoral, or sublittoral environment. An abundance of mangrove remains suggests a primarily coastal swamp environment. In the 12-1 well this portion of the cycle is 810 feet (250 meters) thick. The remainder of the deposits are Quaternary in age and are distinguished by the palynomorph Podocarpus. The environment of deposition is normally inner sublittoral. This portion of the cycle is dominantly light gray to gray/brown claystones with minor sandstone and lignite interbeds. In the 12-1 well this portion of Cycle IV is 610 feet (185 meters) thick. Units in this cycle appear to be slightly more laterally continuous. Mainly, Cycle IV represents a major marine transgression which is still occurring.

STRUCTURES

The principal structural features of the Gulf of Thailand are extensions of major structural features located onshore. Some of these features can be attributed to the emplacement of igneous bodies, but more generally to subduction. Large granitic ridges extend from the Thai-Malay Peninsula out into the Gulf with predominantly a north-south trend. These structures include the Narathiwat, Ko Kra, and Satun ridges. In between these ridges deep troughs formed. The main two are the Pattani trough and Malay basin (Figure 3).

Extending out into the Gulf and probably cutting some of these major features are large strike-slip faults. These include the Khlong Marui and Ranong faults which are both left-lateral, northeast-southwest trending faults. Another major fault is the Kanchanaburi, Kwae Noi, or the Three Pagoda-Ratburi fault which is a northwest-southeast trending left-lateral fault.

Locally within the Gulf, there are complex extensional features. Large scale normal faulting along the flanks of these deep troughs led to antithetic faulting as the axes of these troughs rapidly subsided. Figure 13 shows a proposed model for the formation of the Erawan structure. These graben structures are located all along the perimeters of these deep troughs. Rollover or folding

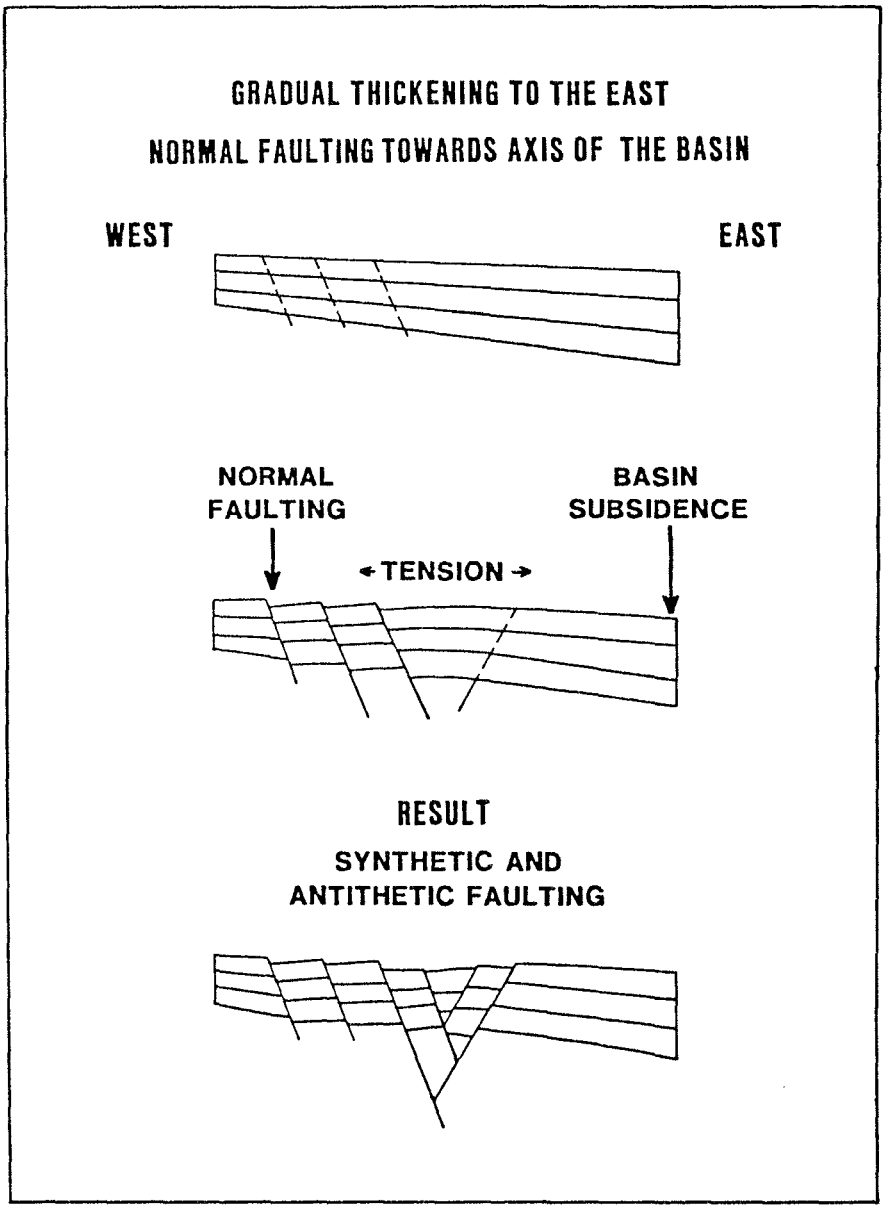


Figure 13. Formation of the Erawan structure.

commonly is found near the axis of the graben and occasionally within individual fault blocks. Normally this rollover is in an east-west direction, but seldom in a north-south direction. Breaks between structures are identified by major shifts in the position of the graben axis. These shifts are controlled by the orientation of the basement faults. Within the Gulf, all major folding appears to be fault controlled.

WELL DATA

General

Over one hundred exploration and development wells have been drilled in the Gulf of Thailand. Only nine wells encountered pre-Tertiary basement and at least six of the nine encountered some Paleozoic or Mesozoic metasediments. The other three encountered granite wash or granite in two wells and gneiss in the third. Probably a great deal of the initial Tertiary deposits in the Gulf of Thailand were derived from Paleozoic and Mesozoic sediments shed off adjacent structural highs.

Within the southern third of the Erawan field, the Tertiary rock units are typical of the previously described cycles. The 12-12 well, which is now the site of the "E" Platform, is on the western flank of the structure. The Tertiary section on this flank is considerably thinner, approximately 17,500 feet (5,335 meters) compared to 21,500 feet (6,555 meters) at the 12-7 or 13-5 wells. These two wells are on depositional strike with the 12-1 well whose cycle thicknesses were described earlier. The section continues to thicken eastward towards the axis of the basin, but in general the Erawan area was near the depocenter of the Pattani trough throughout most of the Tertiary.

The closest well to the Erawan field which encountered

pre-Tertiary basement was the Dara 3 well. Mesozoic or Paleozoic limestone, dolomite, and anhydrite from 7,400 feet (2,255 meters) to a total depth of 8,248 feet (2,515 meters) were encountered. The youngest carbonate sequence, that is greater in thickness than 850 feet (260 meters), which crops out onshore is the Saraburi Limestone which is the upper member of the Rat Buri Group. This unit was deposited from the Early Permian to Lower Triassic. Oligocene (Cycle I) sandstones and shales were deposited onto these limestones. The fact that most of these limestones have been dolomitized (possibly suggesting a period of groundwater circulation after deposition) and that the remainder of the Triassic to the Oligocene is missing, suggests a long period of erosion or non-deposition.

Source Directions

Overall source directions are difficult to determine because of the nature of sedimentation. Only a few wells have dipmeter and core data which are the main tools for determining source directions. In a dominantly fluvial-deltaic environment, well data can include information from meandering channels which migrate laterally, levees which deposit at nearly right angles to the channel direction, and from crevasse splays which also deposit at

nearly right angles to channel directions. Shallow marine deposits are normally influenced by longshore currents which can further complicate the determination of source directions.

Geothermal Gradient

Most of the drilling within the Gulf has been restricted to the uppermost 10,000 feet (3,050 meters) because of the extremely high geothermal gradient. Temperatures are normally higher over shallower basement suggesting that basement faulting present along the flanks of the basin has a greater influence in transmitting heat into the Tertiary sediments than does the heat formed by sediment loading. Heat coming up along these faults is probably related to backarc spreading. Areas where basement has little or no faulting or where basement is deep generally have lower geothermal gradients. In a study of wells drilled up to 1981, Elwood (1981) stated that geothermal gradients below the middle Miocene unconformity range from 2.15 degrees Fahrenheit (1.19 degrees Celsius) per hundred feet (33 meters) close to the center of the basin to 3.23 degrees Fahrenheit (1.79 degrees Celsius) per hundred feet along the flank of the basin. Bottom hole temperatures of up to 375 degrees Fahrenheit (191 degrees Celsius) at 9,000 feet (2,750

meters) have been recorded.

Source Rocks

A minor amount of geochemical work has been conducted for source rock analysis. Generally the source rock analysis conducted by Robertson Research (1974) suggests that the entire section contains potential source rocks. The best potential source rocks for oil and gas generation are of marine to marginal marine origin. These lithologies occur in Stump's (1981) Cycle II and also the lower part of Cycle IV. These stratigraphic intervals contain grayish-purple carbonaceous shales which have 1.77 to 2.18 percent organic carbon with 15.8 to 21.3 percent extractable hydrocarbons or 880 to 1,800 parts per million. Numerous coals which occur throughout the section were also described as having good potential for gas generation. Basically, the only stratigraphic section which Robertson Research determined to be poor source rocks are the upper and lower parts of Cycle I and Cycle III (Stump, 1981). These lithologies are dominantly nonmarine, delta plain and alluvial plain deposits that have experienced some degree of oxidation.

According to Turner (1980), most red beds were originally a drab color. In the Gulf, gray sediments were altered by the oxygenation of rich iron-bearing minerals

above the groundwater table. This transformation may have been aided by pedogenesis, the process of soil formation. Red beds are generally poor hydrocarbon sources because organic material is normally destroyed in this process.

Most of the stratigraphic section below the middle Miocene unconformity is considered mature enough for hydrocarbon generation, but deeper sediments of Cycle I and older probably have reached the stage of organic metamorphism. This stage is reached at temperatures greater than 350 degrees Fahrenheit (177 degrees Celsius), and subsequent hydrocarbon generation is only dry gas, with significant amounts of hydrogen sulfide and carbon dioxide. Some wells in the Gulf have high percentages of carbon dioxide, possibly due to the organic metamorphism of Tertiary sediments or migration along basement faults from Paleozoic or Mesozoic limestones.

Reservoir Rocks

Reservoir rocks range from claystone to conglomerate. Trevena (1981) described most reservoir rocks as sub-lithic and sub-feldspathic sandstones which are very fine to very coarse grained and moderately well to poorly sorted. The average composition of the sandstones is 67 percent quartz, 17 percent feldspar, and 16 percent rock fragments. Trevena (1981) classified them as lithic

arkoses to feldspathic litharenites. They contain sedimentary, metamorphic, and plutonic rock fragments with rare amounts of volcanic lithic fragments. Sedimentary rock fragments include shale, chert (with some radiolarian chert), siltstone, dolomite, calcite, and rare siderite. Metamorphic rock fragments include quartz-muscovite schist, phyllite, and metaquartzite. Plutonic fragments include granular sandstone, quartz, potassium feldspar, and plagioclase. Volcanic fragments are rarely found microporphoritic volcanic grains. Common accesory minerals include muscovite and biotite. Minor amounts of tourmaline and garnet are also present.

The degree of cementation and compaction is extremely important to the porosity of these reservoir rocks. An average total porosity at 4,000 feet (1,220 meters) from the density logs is 33 percent and at 8,800 feet (2,680 meters) is 16 percent. At these same depths from thin sections, the effective porosities are 15 and 2 percent (Trevena, 1981). The pore filling cements which help to decrease the porosity include kaolinite, secondary quartz, and illite with lesser amounts of calcite. Minor secondary cements include dolomite, authigenic chlorite, siderite, and pyrite. The abundance of cements at depth is primarily due to the break down of the detrital feldspars by hydrothermal alteration. Potassium feldspar is normally absent below 7,500 feet (2,285 meters).

Trevena (1981) recognized three types of porosity, including intergranular, secondary, and microporosity. Secondary porosity is due to the dissolution of detrital feldspars and calcite cement. Microporosity occurs between individual clay particles. Overpressuring is common below 6,200 feet (1,890 meters) which allows some reservoir rocks to maintain their porosity at greater depths. Permeabilities range from .02 to 402 millidarcies with most in the 2 to 200 millidarcies range.

Gamma ray and self potential log patterns from reservoir rocks can sometimes be very useful when trying to determine the environment of deposition. There are basically four main types of responses, fining upward, coarsening upward, flat topped or blocky, and interdigitate (Selley, 1978). The first three types are common on gamma ray logs run in the Gulf of Thailand. This observation would suggest that there has been more than one environment of deposition.

The first pattern, fining upward, was described by Selley (1978) as most likely being formed by the deposition of a fluvial or deltaic distributary channel. This pattern could be the result of a channel migrating across an alluvial or deltaic plain. Possible reservoir rocks from these two environments would include channel, point bar, levee, and crevasse splay sandstones.

The second pattern, coarsening upward, was described

by Selley to be formed by the deposition of a deltaic crevasse splay or a marine regressive bar. This pattern could be the result of progradation in an intertidal or delta front environment. Possible reservoir rocks from these two environments would include distributary mouth bar sandstones with bar finger sandstones and beach barrier sandstones which are all normally influenced by longshore currents. Also, sandstones described from the previous two environments may have been deposited subaqueously.

The third log pattern, flat topped or blocky, occurs in all of the environments stated earlier. Possible reservoir rocks with this type of pattern would include channel sandstones, distributary mouth bar sandstones, or beach barrier sandstones. Sometimes this pattern or a similar pattern with a rounded top can be suggestive of reworking of the sandstone units.

Most of the sandstones drilled in the area are relatively thin beds (0-100 feet; 0-30 meters). The distribution of sandstones within Cycles II and III from three of the vertical wells are shown in Table 3.

TABLE 3. DISTRIBUTION OF SANDSTONES WITHIN CYCLES II AND III FROM THE 12-12, 12-7, AND 13-5 WELLS

Sandstone Distribution

Thickness of unit	12-12 (E-1)	12-7	13-5
10'-19' (3m.-6m.)	21	23	15
20'-29' (6m.-9m.)	7	5	9
30'-39' (9m.-12m.)	2	5	3
40'-49' (12m.-15m.)	5	1	3
50'-59' (15m.-18m.)	2	4	2
>59' (18m.)	1	0	2

In all three wells the highest percentage of sandstones are those less than 20 feet (6 meters) thick. The highest percentage of total sandstone within these two cycles is in the 12-12 well which has 25 percent sandstone compared to 17 percent in the 12-7 well and 19 percent in th 13-5 well. No sandstones greater than 100 feet (30 meters) have been encountered in the study area. Most of these thicker sandstones are made up of several thinner sandstone units which were deposited on top of each other, possibly as nested channels.

Non-Reservoir Rocks

Generally, non-reservoir rocks form seals over the potential reservoir rocks. Non-reservoir rocks include: (1) flood plain or interchannel claystones and mudstones which were supplied by overbank flooding or by crevasse splays; (2) numerous thin coals deposited in interchannel areas; (3) claystones and mudstones deposited in lagoonal areas; and (4) thin limestones deposited in fresh water lakes or in shallow marine waters. Within Cycles II and III, claystones and mudstones usually make up more than 70 percent of the section.

The exact percentage of coal beds is difficult to determine because most of them don't have the classic log responses (a low gamma ray response, a high resistivity

reading, and a sharp sonic break) expected for coals. Many of the coals have a very high gamma ray response, very low resistivity reading, and a fairly high sonic break. The reason for this pattern is that most of the coals contain a fair amount of clay and some have an abundance of radioactive materials, which are often associated with organic matter. Most of the coal thicknesses are less than 10 feet (3 meters) and represent approximately 5 percent of Cycles II and III.

Limestone is present and comprises less than 1 percent of Cycles II and III. No fossils have been associated with these thin stringers which are less than 5 feet (1.5 meters) thick. These limestones are not as laterally extensive as the coals or shales making them difficult to correlate.

Overpressured shales are fairly common in Cycles I and II, but are uncommon in the oxidized Cycle III deposits or at depths less than 6,200 feet (1,890 meters).

Well Correlations

Actual well correlations are normally performed using overpressured shales and coal markers, rather than sandstones which in general are laterally discontinuous. Correlations are usually made on sonic logs because most of these markers have distinct sonic breaks. When

correlating sandstones, the character of the resistivity log is probably the most important. Sandstones, for the most part, are correlated by coincidence, that is, on the basis of similar position between correlatable shales or coals.

The middle Miocene unconformity can normally be recognized in the wells as: (1) a major color change from gray to red/brown or varicolored shales; (2) a change in regional dip on the dipmeter; (3) an increase in shale velocity on the sonic log; and (4) a marked increase in temperature. Picking an exact depth is sometimes difficult because of the reworking of pre-unconformity rocks. The subsea depths of the unconformity in the four vertical holes within the area are approximately 4,500 feet (1,370 meters) in the 12-7 well near the center of the graben, 4,300 feet (1,310 meters) in the 13-5 and C-1 wells just west of the center, and 3,900 feet (1,190 meters) in the 12-12 (E-1) well on the western flank. This pattern demonstrates the overall thickening of Cycle IV from west to east.

The best correlations below the unconformity are from the marine or marginal marine deposits of Cycle II. Fairly extensive coal and shale beds were deposited in lagoonal and/or interchannel environments. An example of this continuity is presented in Figure 14 which shows correlations between the 12-7 and 13-5 wells, which are

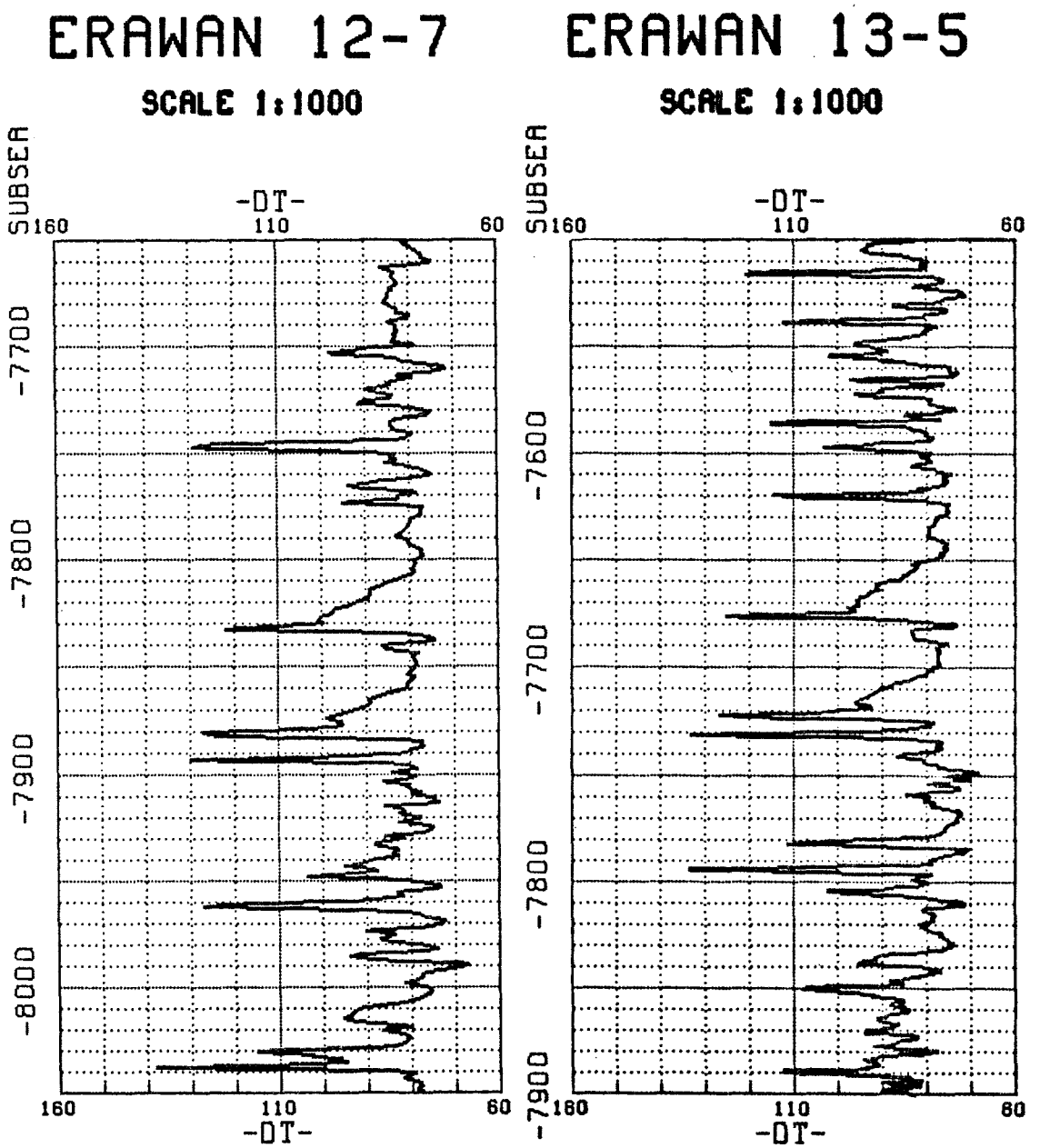


Figure 14. Well log correlations between the 12-7 and 13-5 wells.

2.75 miles (4.43 kilometers) apart. The process of correlation is complicated by marker beds being faulted out or cut out by rapidly changing stratigraphy.

Color changes can be used to give a general idea of cycle correlations. Most of Cycle III was oxidized during the hiatus of the middle Miocene unconformity, but the position of the groundwater table fluctuated and its former location does not correspond exactly with the base of the cycle. Also, the entire cycle did not respond the same way to oxidation. Generally this cycle is red/brown or multicolored and grades downward into gray/brown rocks which haven't been oxidized. Normally these gray/brown sediments can be associated with Cycle II marine or marginal marine deposits. Some oxidized sediments can be found within Cycle II, which may be the result of minor hiatuses caused by sea level fluctuations. The base of Cycle II is very difficult to determine because Cycle I sediments also are generally gray/brown. The base may be defined locally by an unconformity onto which transgressed a marine sandstone or possibly by the presence of oxidized sediments. Cycle tops and bottoms were best defined by paleontology and palynology studies which were conducted on early exploratory wells. When delineation and development drilling began, these studies ceased, with few exceptions.

SEISMIC DATA

General

Within the southern third of the Erawan field, the previously described cycles are seismically well defined. Four of the horizons selected for structural mapping correspond closely to cycle boundaries. The Red Horizon is the base of Cycle I and the top of Paleozoic or Mesozoic rocks. The Lower Yellow Horizon is approximately the base of Cycle II. The Blue Horizon is approximately the base of Cycle III. The Upper Yellow Horizon is the first continuous reflector above the middle Miocene unconformity and is near the base of Cycle IV. In addition, two other horizons were selected. The Orange Horizon is within Cycle II and was chosen for its continuity. The Green Horizon is within Cycle IV and was also selected for its continuity. The colors are used to define the horizons in this interpretation. Plate II is an interpreted section showing the six horizons and the position of three vertical wells, the 12-12 (E-1), the C-1, and the 12-7. Plate III is an interpreted section through the 13-5 well.

Over most of the area data quality is fairly good as shown by Plates II and III. Some areas are affected by shallow bright spots which have associated multiple trains. These multiple trains interfere with the primary

data. Shallow bright spots are probably caused by early generation of methane and/or from gas migrating up along faults from deeper in the section. Plate IV is a map showing the extent of major shallow bright spots.

Seismic Response

When trying to correlate a seismic reflection with a velocity and/or density contrast from a well, it is important to know how much acoustic impedance contrast is needed from an individual bed or a sequence of beds for the seismic method to resolve it. Based on synthetic modeling in the C-1 well, seismic responses may be caused by individual sandstone beds if they are thick enough, but normally they are composite responses from several closely spaced units. Unfortunately, not all responses are from sandstone units since other composite responses were observed from an interval of coals and overpressured shales. The synthetic seismogram was derived by: (1) extracting a source wavelet from the 3-D data volume; (2) taking the sonic and density logs and creating a reflectivity series; (3) taking the reflectivity series and convolving it with the source wavelet which yields a synthetic seismogram. Figure 15 is the seismogram along with the sonic log and reflectivity series. The six horizons were all initially picked along the zero crossing

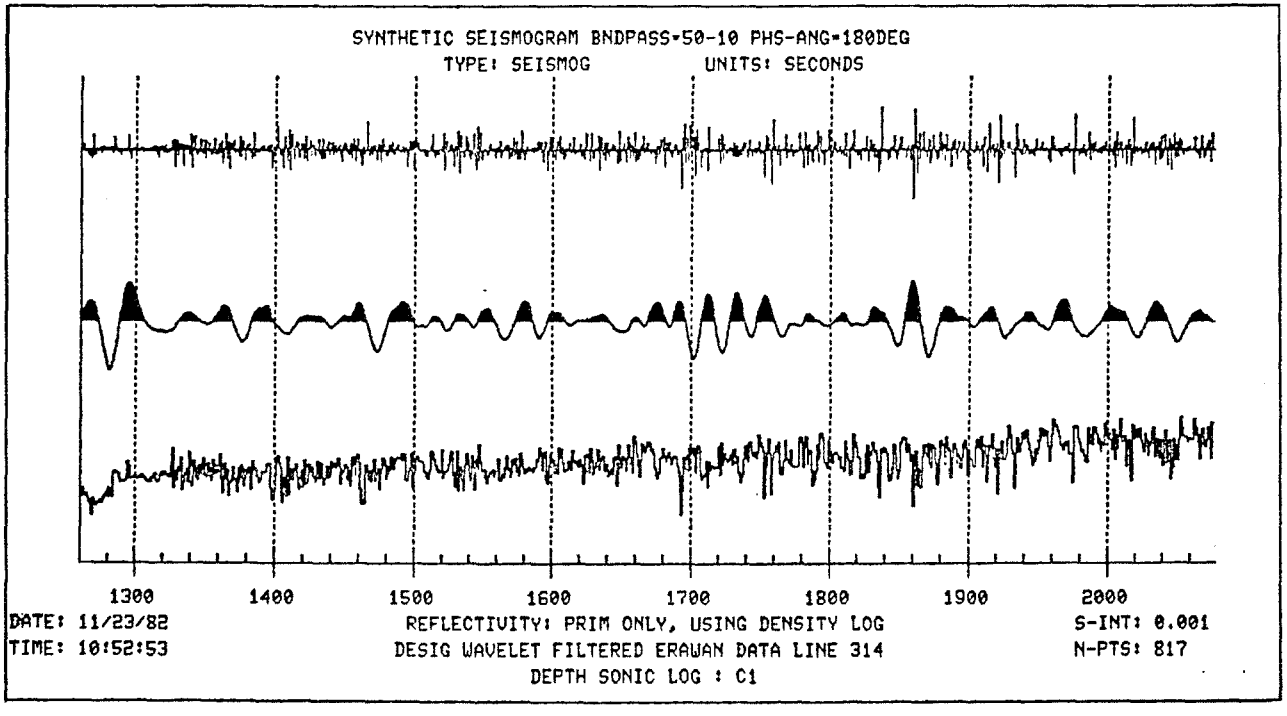


Figure 15. Synthetic seismogram from the C-1 well.

above a large peak which, by Society of Exploration Geophysicists format for normal polarity, would suggest the onset of a negative acoustic impedance contrast. The amplitude of the peak would normally suggest the size of the contrast. In this case, most of the contrasts are from thin beds. Based on modeling done by Union Oil personnel,it appears that the tops and bottoms of these thin beds cannot be resolved primarily due to the wavelength at depth. Shorter wavelengths of higher frequency are needed for resolution. Also based on their work, it appears that the actual seismic response is best seen in the trough, opposite of what was expected. Their work showed that the exact tie to the seismic response is dependent on the thickness of the unit. Thin units tied near the zero crossing of the trough and thicker units tied within the small peak. The upper five horizons are probably the results of thin bed responses so well ties can't be made at the onset of the large peak. Correlations must be made on the zero crossing of the trough or within the peak.

Tertiary Horizons

General Methods

The reason some horizons weren't picked along the zero crossing of the trough or within the peak is because

strong events must be used in order to get the maximum amount of information from the Seiscrops (Geophysical Service Incorporated term). Seiscrops are horizontal time slices taken through a 3-D data volume. They are normally displayed as though peaks are black, troughs are red, and zero crossings are white; they are also sometimes displayed without the white zero crossing. When the former display style is used, the 3-D data volume might yield any one of the three colors at each point when sliced. An actual Seiscrop display has bands of black and red separated by thin white lines. These lines represent the positions of contours in time. Abrupt termination of contours normally indicates the presence of a fault, although it may also be indicative of a stratigraphic change. Detailed techniques for the use of Seiscrops can be found in the Appendix. Seiscrop mapping was also used here for checking fault positions and for finding previously unrecognized faults. The approximate extent of a particular stratigraphic unit can be rapidly mapped, and amplitude variations within the unit can sometimes be observed. If you are required to use weak horizons, with low amplitude, most of the described capabilities are lost (Dahm and Graebner, 1982).

Red Horizon

The Red Horizon is the lowermost horizon and represents the base of the Oligocene Cycle I. The closest well reaching this horizon encountered dense Paleozoic or Mesozoic limestones which give a very good seismic response in contrast with Oligocene clastic sediments. The large high amplitude, low frequency reflection could readily correlated over the eastern half of the area. Correlation in the western portion is somewhat difficult because of the abundance and complexity of the faulting which causes a general deterioration of the data. For this reason the western portion of the Red Horizon is considered to be more of a form map rather than a true representation of a single horizon. Because many of the faults are oblique to the east-west lines, the basement configuration was almost entirely mapped from the Seiscrop sections.

Plate V is a time structure map to the Red Horizon. Time and depth values to the Red Horizon range from 2,880 milliseconds or 15,800 feet (4,816 meters) to 4,160 milliseconds or 25,000 feet (7,620 meters). This map is dominated by east-dipping normal faults, down towards the basin axis, which trend northwest-southeast. These faults are shown in red and represent the map projections of the

fault planes. In the northwest corner of the area the faults trend more north-south and the regional dip is generally north-south. West-dipping faults are shown in blue. The regional dip over the rest of the area is dominantly east-west. No evidence for faulting other than normal faulting is present along this horizon.

Lower Yellow Horizon

The Lower Yellow Horizon is near the base of Cycle II and is of lower Miocene age. Well correlations with this horizon are shown in Figure 16. This reflection appears to be the response from a fairly thick sandstone or sandstone package which may have been part of the initial marine transgression of Cycle II. This horizon is the most widespread Tertiary reflector, below the middle Miocene unconformity, in the area. Plate VI is a time structure map to the Lower Yellow Horizon. Time and depth values to the Lower Yellow Horizon range from 1,720 milliseconds or 6,600 feet (2,012 meters) to 2,320 milliseconds or 10,000 feet (3,050 meters). Faults cutting the Lower Yellow Horizon generally trend north-south, in contrast to basement faults generally trending northwest-southeast. Shifts in the graben axis at this depth may be the result of the change in orientation of the faulting.

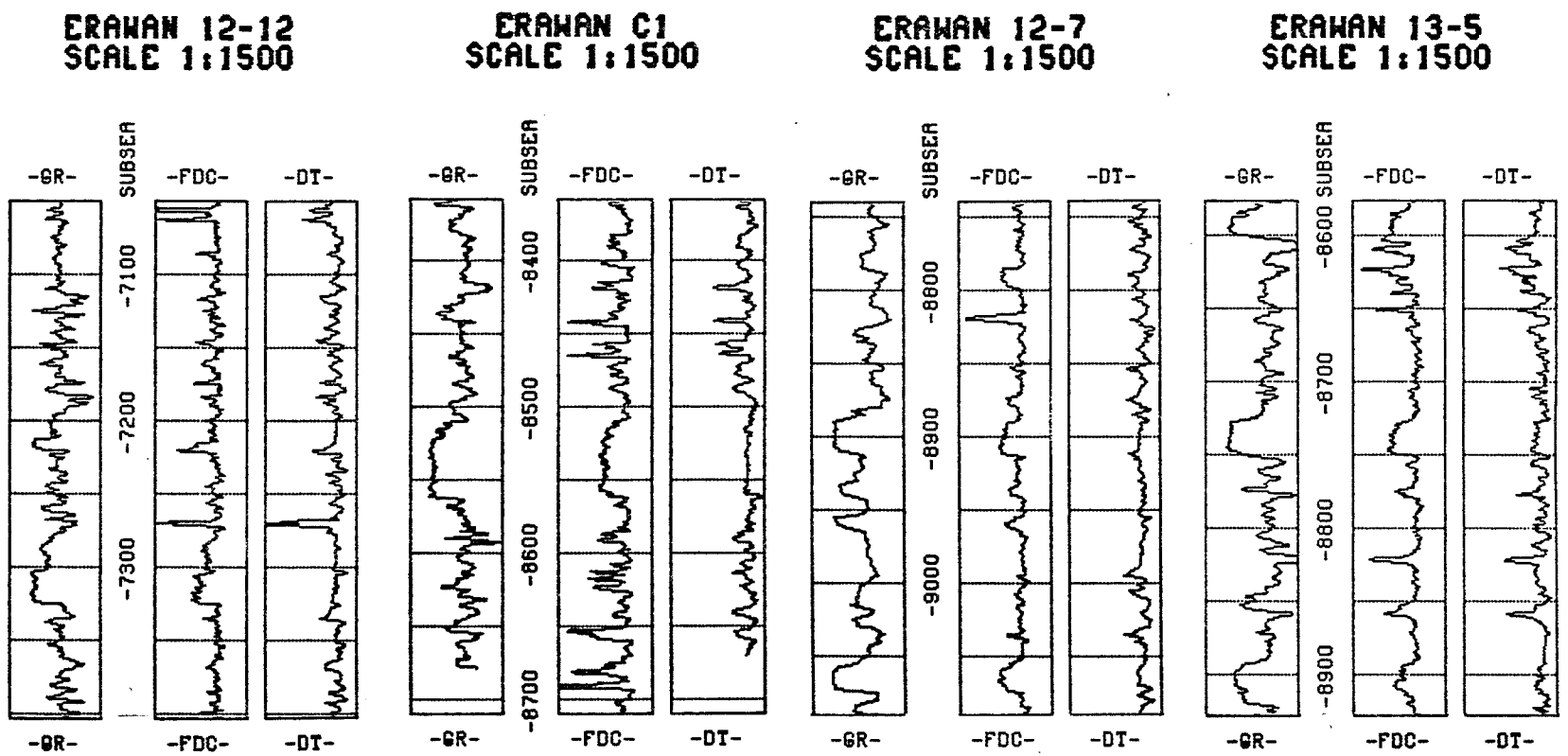


Figure 16. Well correlations with the Lower Yellow Horizon.

Dip reversals are present at this depth, representing the change from regional dip to the east to individual fault blocks dipping west. Such reversals may play a major role in the entrapment of hydrocarbons. Greater dip reversal within a portion of a fault block will give three-way structural closure, with the fourth side being a fault. The fault may act as a seal if movement along the fault causes a sandstone to be juxta-posed with a shale or if the fault gouge is impermeable. Faults may also act as a conduit for hydrothermal fluids which may contain gas or transmit heat. The fluids may also deposit precipitates in the fault zone creating permeability barriers.

Orange Horizon

The Orange Horizon is within Cycle II and is of lower Miocene age. Well correlations with this horizon are shown in Figure 17. This reflection appears to be a composite response from a series of thin sandstones, overpressured shales, and coals. This reflection is the strongest where it is buried deepest. This implies that overpressuring, which is more common at greater depths, plays a big part in the seismic response. Plate VII is a time structure map to the Orange Horizon. Time and depth values to the Orange Horizon range from 1,580 milliseconds or 5,800 feet (1,768 meters) to 2,040 millisconds or 8,400

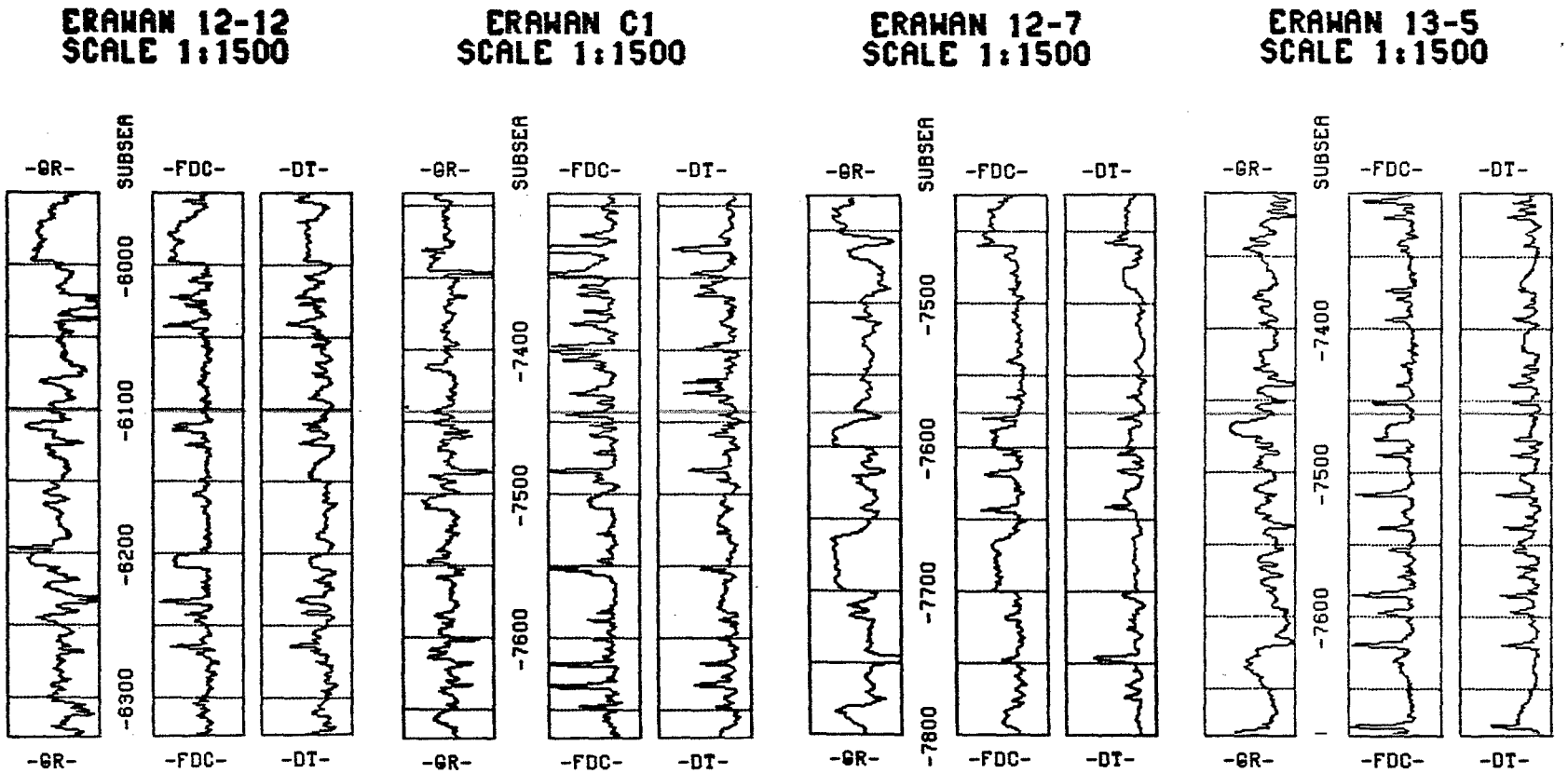


Figure 17. Well correlations with the Orange Horizon.

feet (2,560 meters). The general configuraton of this map is very similar to the Lower Yellow Horizon. Contouring on this horizon was difficult because of rapid changes in the character of the seismic response, especially on the western flank.

Blue Horizon

The Blue Horizon is near the base of Cycle III and is of lower Miocene age. Well correlations with this horizon are shown in Figure 18. This reflection appears to be a composite response normally associated with overpressured shales and coals, but in the 13-5 well a thick sandstone occurs at the top of this sequence. This horizon is faulted-out in the 12-12 well. Plate VIII is a time structure map to the Blue Horizon. Time and depth values to the Blue Horizon range from 1,500 milliseconds or 5,400 feet (1,646 meters) to 1,880 milliseconds or 7,500 feet (2,286 meters). This horizon is very similar to both the Lower Yellow and Orange Horizons. Major closures occur virtually in the same position on all three horizons. The reflector used for this horizon also displayed rapid character changes and was therefore difficult to contour.

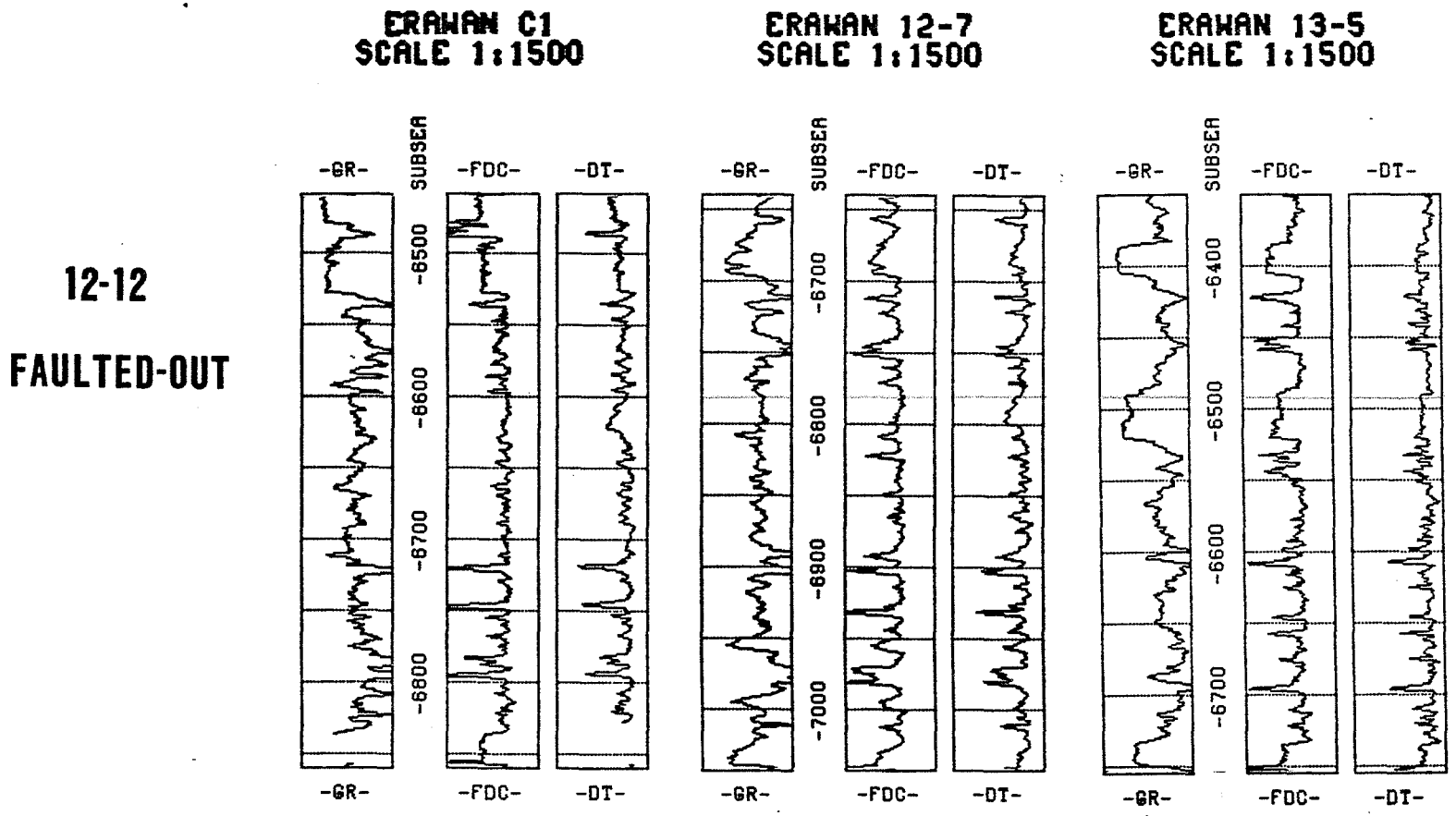


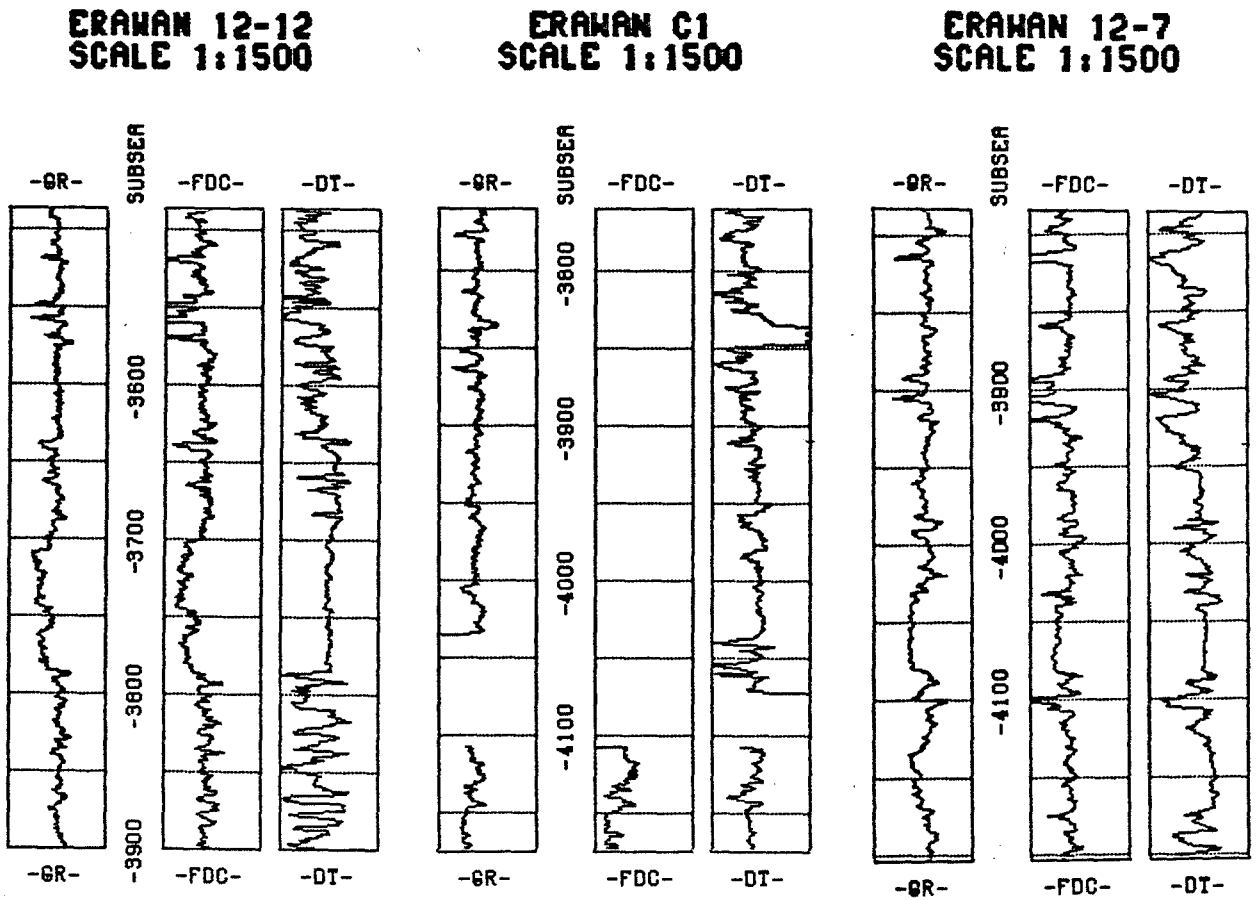
Figure 18. Well correlations with the Blue Horizon.

Upper Yellow Horizon

The Upper Yellow Horizon is near the base of Cycle IV which is upper Miocene in age. This horizon is just above the middle Miocene unconformity. Well correlations with this horizon are shown in Figure 19. This reflector does not appear to correlate with a lithologic contact which could give a negative acoustic impedance contrast. It is then proposed that this regional reflector is the response of a positive contrast associated with the middle Miocene unconformity. Plate IX is a time structure map to the Upper Yellow Horizon. Time and depth values to the Upper Yellow Horizon range from 1,120 milliseconds or 3,600 feet (1,097 meters) to 1,300 milliseconds or 4,400 feet (1,341 meters). The complexity of the structure is still apparent along this horizon, with most of the major faults and many of the closures still present. This horizon is near the top of the productive hydrocarbon interval. Shallower gas zones are present, but normally not enough pressure exists within the reservoirs to make them economically producible.

Green Horizon

The Green Horizon is located within Cycle IV and is of upper Miocene age. Only one well in the area has been



13-5

FAULTED-OUT

Figure 19. Well correlations with the Upper Yellow Horizon.

logged from this interval, and it appears that this regional reflector is a composite response from a sequence of coal beds. One thin sandstone may also be included in the response. Plate X is a time structure map to the Green Horizon. Time and depth values to the Green Horizon range from 840 milliseconds or 2,500 feet (762 meters) to 960 milliseconds or 3,000 feet (914 meters). This horizon is only slightly faulted in comparison with the deeper horizons. It is above the productive hydrocarbon interval and basically shows only the regional dip towards the east. The shallow bright spots seem to affect this horizon the most; they appear to be directly responsible for causing closed-lows (depressions in the seismic data) which are not associated with faulting. These lows are probably the result of velocity pulldowns beneath these low velocity zones.

Seismic Stratigraphy

Normal seismic stratigraphy techniques were not very useful because of the lack of good regional unconformities to define sequence boundaries and the complexity of the faulting. In some places onlap onto basement seems apparent, but there is a significant deterioration of data quality within the sediments overlying basement.

The Tertiary section can still be broken down into

four general seismic sequences which correspond fairly well with the four cycles described earlier. Plate XI is a line showing these four sequences. The lowermost sequence on basement has fairly discontinuous reflectors, and contains only a few partially correlatable horizons. The next sequence contains numerous correlatable horizons. The third sequence is similar to the first and contains some correlations, but never across the whole section. The uppermost sequence contains several good correlatable horizons at the base and another very good reflector in the middle. These transitions from correlatable to non-correlatable sequences probably correspond to transitions from nonmarine to marginal marine environments of deposition.

Rapid lateral changes in seismic character over most of the Tertiary section suggest that most of the sandstones are not blanket type deposits, but are smaller more discontinuous units.

Shallow Seiscrop Sections

Shallow Seiscrop sections are defined here as those time records down to a few hundred milliseconds which are basically unfaulted. These Seiscrops essentially parallel stratigraphic surfaces. This orientation is very important because it allows stratigraphic features to be

seen in their lateral extent. As an example, Figure 20 is a Seiscrop at 104 milliseconds which shows a meandering channel. This channel can be recognized because of the difference between the lithologies that filled the channel and those which encased the channel. This difference is represented on the Seiscrop as a change in polarity which corresponds to a change in color.

Stratigraphic Mapping within the Productive Hydrocarbon Interval

The importance of recognizing stratigraphic features on shallow Seiscrops is that similar features may be present at depth within the productive hydrocarbon interval. Geologically sensible stratigraphic patterns can be developed from specific reflections deeper in the Tertiary section after palinspastic reconstructions. Detailed techniques for stratigraphic mapping using three-dimensional seismic methods can be found in the Appendix.

Some examples of stratigraphic features recognizable on amplitude maps generated on an interactive computer system are shown in Figures 21 and 22. Similar stratigraphic features on amplitude maps were recognized by Dahm and Graebner (1982). A feature in Figure 21 is interpreted as a channel which meanders from the north

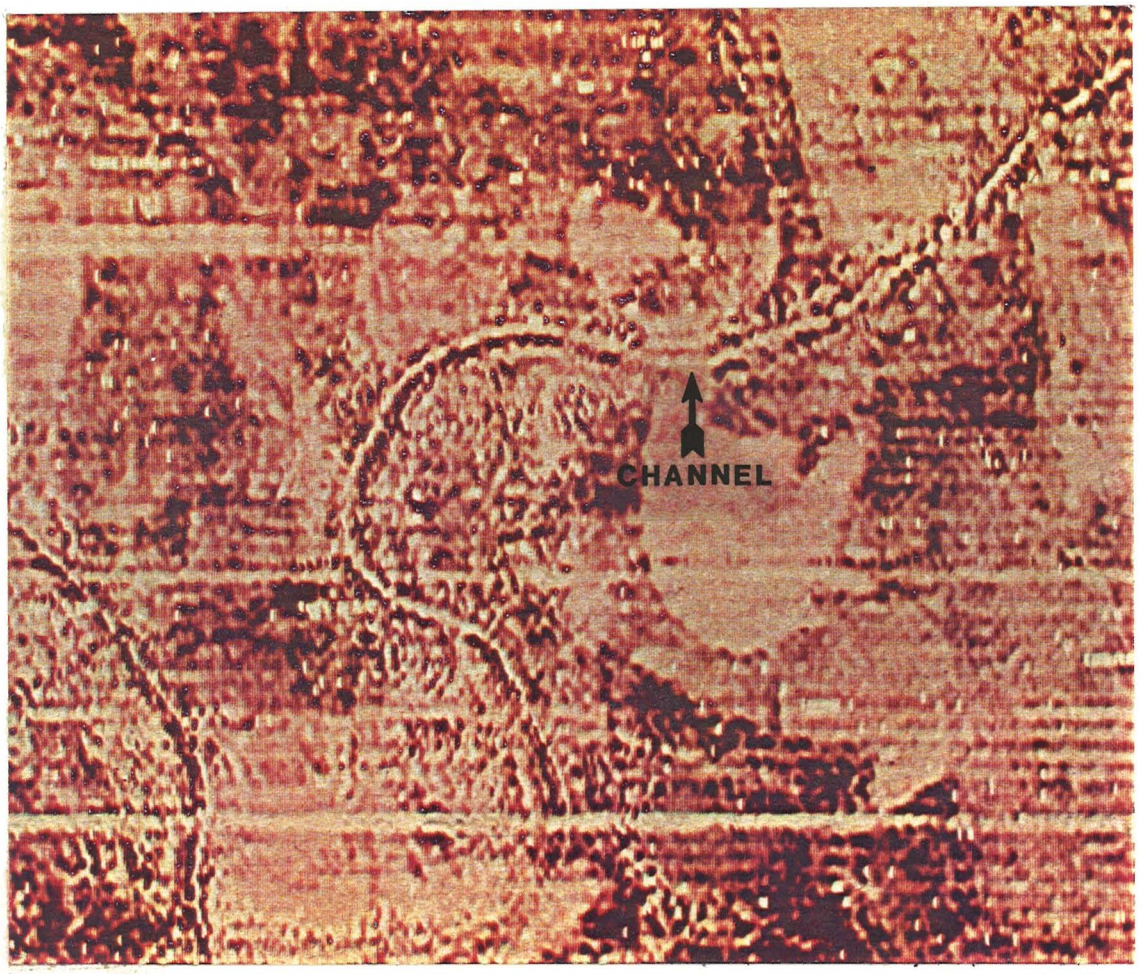


Figure 20. Shallow Seiscrop section showing a meandering channel.

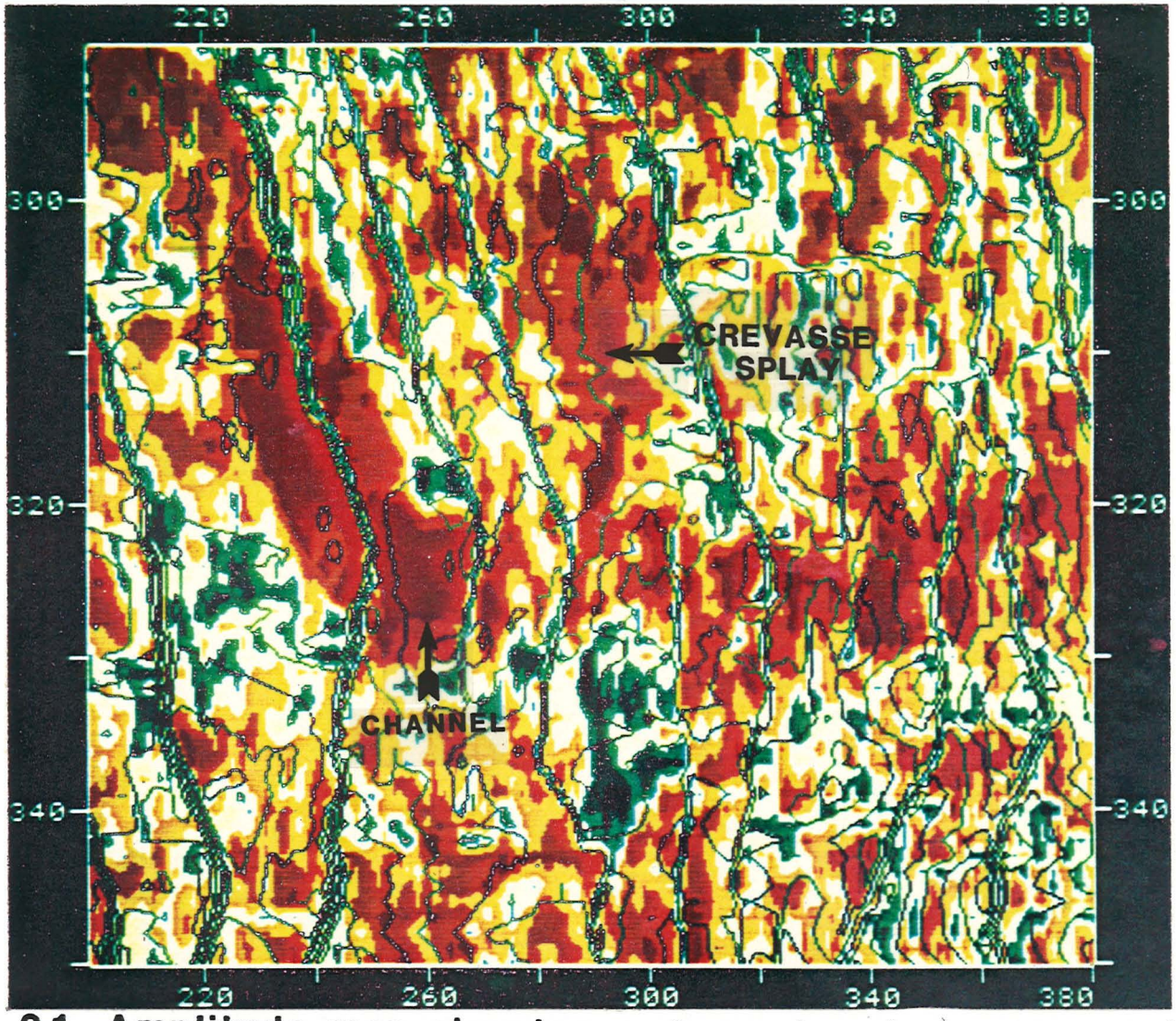


Figure 21. Amplitude map showing a channel and crevasse splay.

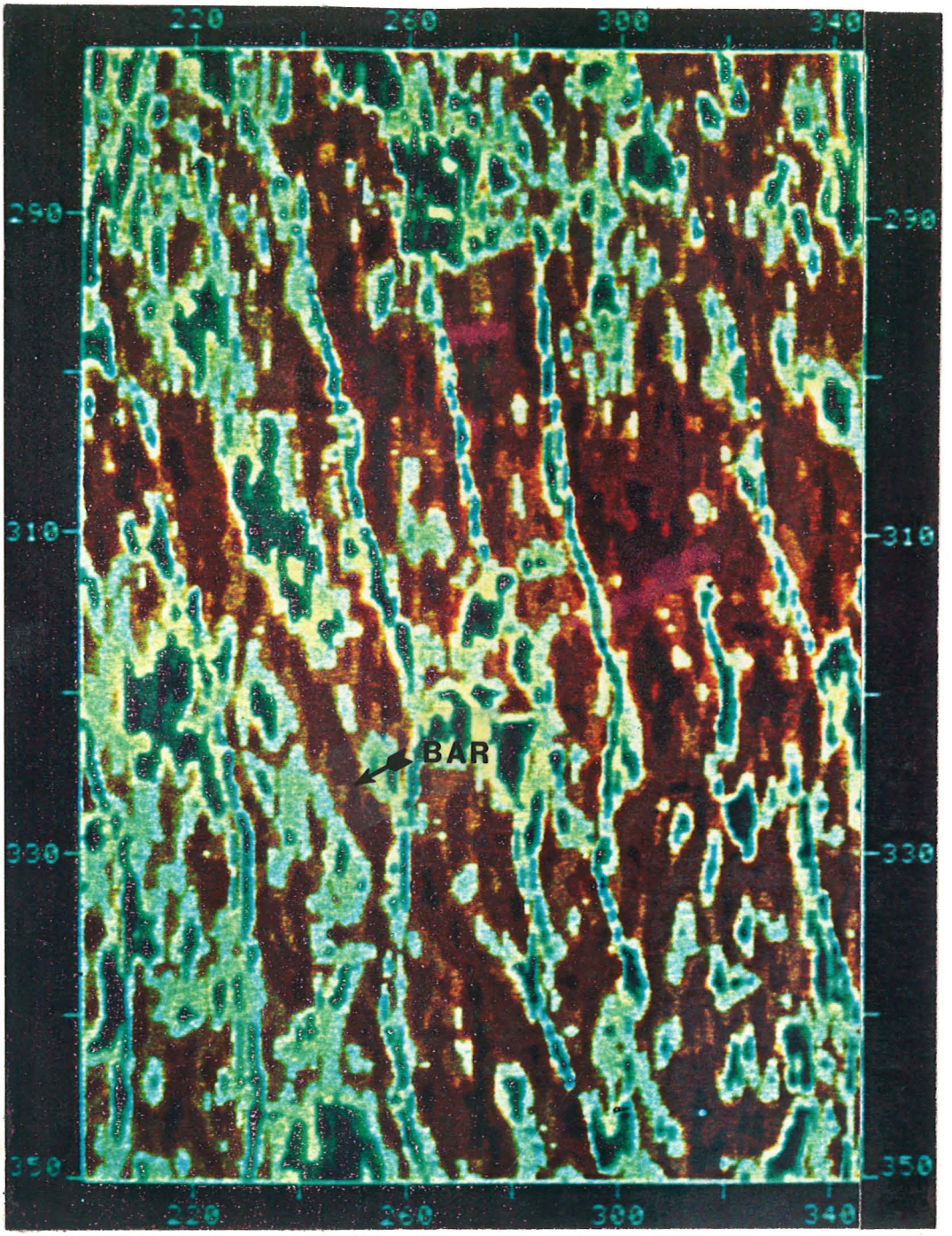


Figure 22. Amplitude map showing a bar.

then to the east as seen on an amplitude map. This channel location ranges from 1,320 milliseconds or 4,500 feet (1,372 meters) to 1,450 milliseconds or 5,200 feet (1,585 meters) and falls within Cycle III. Before faulting, the channel was approximately 2,050 feet (625 meters) at its widest point. This feature was encountered in a structurally low position, with relatively low amplitude, in the C-3 well where it was water saturated and 44 feet (13.4 meters) thick. Another feature might be recognizable in this figure. A crevasse splay may extend northward from the channel just east of where the channel trends north-south.

In Figure 22, a long narrow linear bar is interpreted to trend northwest-southeast. This bar location ranges from 1,670 milliseconds or 6,300 feet (1,920 meters) to 1,720 milliseconds or 6,600 feet (2,012 meters) and falls within Cycle II. Before faulting, the bar was approximately 900 feet (275 meters) at its widest point. The bar (which had fairly good amplitude and structural position) was encountered by the C-3 well, but the zone was water saturated. The well penetrated the edge of the bar which was 23 feet (7 meters) thick.

Numerous stratigraphic features, such as bars and channels, are recognizable throughout the section. The stratigraphic evaluation in this interpretation was concentrated in the platform areas where observed features

could be correlated with existing wells. When stratigraphic features are observed, they can be used to help determine the environment of deposition. A meandering channel normally indicates deposition on an alluvial or delta plain. A long linear bar may suggest deposition in a marginal marine environment. When 3-D seismic methods are used in evaluating a horizon, stratigraphic features associated with a particular environment might become easier to recognize. The most important aspect before evaluating any horizon is to determine what environments may be present, and how the stratigraphic features associated with these environments would appear preserved in the subsurface.

SUMMARY AND CONCLUSIONS

The southern third of the Erawan field lies along the western edge of the Tertiary Pattani trough. The basement rocks underlying the Pattani Trough were subjected to a complex geologic history prior to its Tertiary inception. Within the study area the depth to basement ranges from 15,800 feet (4,816 meters) to 25,000 feet (7,620 meters). A large basement reflection is present over most of the area. The presence of this reflection is due to Tertiary clastic sediments lying unconformably on Paleozoic and Mesozoic limestones generating a major acoustic impedance contrast. These rocks were part of a thick sequence of dominantly shallow marine deposits which were laid down in a large Paleozoic and Mesozoic basin. This basin was then subjected to several stages of deformation. Subduction from the east commenced in the Silurian to Lower Devonian and continued until continental collision occurred in the Triassic. Subduction from the west commenced in the Jurassic and has continued to the present. Associated with the subduction was the emplacement of large granitic batholiths. In between these batholiths, zones of structural weakness developed which, during the Tertiary, formed into deep troughs. A large portion of the Mesozoic section which was present at the time of intrusion was probably eroded off and incorporated into the initial

deposits within these troughs.

The Tertiary history within the study area began with the deposition of Oligocene (Cycle I) sediments onto pre-Tertiary basement. Cycle I was dominated by nonmarine processes, with deposition being confined to a fluvial-lacustrine environment. Deposition was initially onto a fairly rugged topography which later developed into a broad alluvial plain. Some potential hydrocarbon source rocks are present within this cycle, but most of the reservoir rocks are so deep that they have lost nearly all of their effective porosity.

During the lower Miocene (Cycle II), the first marine influences within the study area occured. Most of the deposition during this cycle took place on a rapidly subsiding delta plain, but some marine deposits have been identified. Faults in basement which generally trend northwest-southeast start to trend more north-south within Cycle II. Many of the sediments within this cycle are overpressured, and many of the reflections within this cycle are attributed to composite responses from sequences of overpressured shales and coals. Many potential source and reservoir beds exist within this cycle. Stratigraphic features from within this cycle include meandering channels and linear bars which are recognizable when using three-dimensional seismic methods.

The lower Miocene (Cycle III) marked the resumption of

dominantly nonmarine fluvial-lacustrine deposits. This environmental change was probably the result of the sediment supply overtaking the rate of subsidence. Most of the reflections in this cycle are from sand bodies. Only a very limited amount of overpressuring within Cycle III has taken place. Stratigraphic features are therefore easier to isolate. Recognizable features from three-dimensional seismic methods include meandering channels, linear bars, and crevasse splays.

The top of Cycle III is identified as the middle Miocene unconformity. This unconformity was the result of basin infill rather than of uplift and erosion. A hiatus occured which allowed most of the Cycle III sediments to be oxidized before the deposition of Cycle IV. Potential hydrocarbon source rocks may have existed prior to oxidation, but after oxidation these deposits must be considered poor potential source rocks.

The upper Miocene to Recent (Cycle IV) began the second stage of marine influences. Once again deposition occurred mainly on a delta plain until the advent of modern marine conditions in the late Tertiary or early Quaternary. Potential hydrocarbon source and reservoir rocks are present within this cycle, but source rocks are dominantly immature.

The Erawan structure is a complexly faulted graben which probably began developing, with down towards the

basin axis faulting, possibly as early as Cycle I. The main episode of synthetic and antithetic faulting probably occurred in the latter half of Cycle III. Some faulting has continued through Recent times. The fact that normal faults in basement have a very different trend than the same faults at shallower depths explains why there are such rapid graben shifts within the area. Mapping at various levels has defined numerous structural closures which may trap hydrocarbons even if definite stratigraphic features cannot be defined within them. These features are sometimes difficult to recognize because of the interference which can take place between closely spaced reflectors. Interference is most common within Cycle II, where overpressuring has affected much of the section.

The use of three-dimensional seismic methods have greatly aided in the subsurface interpretaion of the study area. Primarily, the technique has helped to accurately define the structure at various depths, and has helped in unraveling the complex stratigraphy which is present throughout the Tertiary section.

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APPENDIX

3-D SEISMIC METHODS

Seiscrop Sections

This section describes the techniques used in the interpretation of Seiscrop sections. The actual process of contouring must be done with a series of horizontal time slices (Brown and McBeath, 1980). With changing time, the contour lines will move a distance which is dependent on the sample rate and the amount of dip present. Seiscrops are best used by preparing a fault map made along a particular horizon of interest. This map should be made on vellum or some type of transparent paper at the scale of the data volume for best use on the Seiscrop machine. Minor scale changes can be perfomed by the machine. The Seiscrop machine is a display device which projects the Seiscrop film images through a series of mirrors onto a screen. The user can move up or down in time rapidly or display one slice at a time. After the fault map is prepared, hand picked times at the contour interval chosen should be put onto the map with the exact location of the zero crossing for calibration. This approach can be done on as many lines as data would merit. It is especially crucial in areas of rollover or where faults die or come together. A general rule might be to do this on the first and last lines, and then pick a

few other lines in between where problems might occur. Contouring with this method is not only fast, but it takes away the artistic license used by many interpreters.

Stratigraphic Mapping

This section describes how stratigraphic mapping can be done with the aid of an interactive computer system. Stratigraphic mapping can be done manually on the Seiscrop machine by mapping the extent of individual stratigraphic features within each fault block, along a correlatable horizon. Stratigraphic mapping can also be done on an interactive computer system which allows the user to access the 3-D data volume in several displays. These displays include vertical sections which can be presented in any direction. The interactive computer system can also display horizontal Seiscrop sections. Correlatable reflectors can be digitized or tracked on vertical sections displayed on the screen. When tracking, the computer records the time and the amplitude from each peak and trough. When a series of sections are tracked, maps can be displayed in the form of time contours and/or amplitude. Generally, when using an east-west line, good correlations can only be made when the stratigraphic feature parallels the line. Meandering channels make correlating features more difficult. When a meandering

channel is recognized, a line can be generated along the axis of the channel by the computer to confirm correlations. In addition, by using a combination of the time and amplitude maps, amplitude anomalies which may represent stratigraphic features can be found in their best structural position at their highest amplitude. This is very significant when trying to do direct detection of hydrocarbons using amplitude. Amplitude changes within an individual unit can represent lithologic or fluid content changes. First and most important is increased amplitude due to an increased acoustic impedance contrast. This pattern may suggest that either: (1) the lithology of the rock unit has changed, for example, a dirty sandstone grades into a clean sandstone; and/or (2) there is a change in what is contained in the pore space, for example, water changes to hydrocarbons. This model is the basis for direct detection of hydrocarbons, especially gas. Changes in amplitude may also indicate a thickening or thinning of the rock unit. Amplitude is also controlled by how ray paths must travel down and back to the unit. Ray paths may be obstructed by numerous faults or be interfered with by multiple wave trains causing a deterioration of amplitude.

Various horizons may be generated by flattening the tracked horizon simultaneously with portions of the section above and below the horizon. This flattened data

volume can then be displayed as Horizon Seiscrops (Geophysical Service Incorporated term), which are essentially stratigraphic surfaces which have been palinspastically reconstructed.