E & P Notes

Subsalt Play, Gulf of Mexico: A Review

Scott L. Montgomery[1] and Dwight "Clint" Moore[2]

ABSTRACT

Exploration for deep-water sandstone reservoirs beneath allochthonous salt in the Gulf of Mexico represents a major new frontier play in North America. More than 30 wells thus far have been drilled with subsalt targets, resulting in 8 discoveries, at least 3 of which are commercial and 3 that have reserves of 100 million bbl oil equivalent or more. Reservoirs consist of Miocene–Pleistocene sandstones deposited in submarine fan channel system environments on the paleoslope, where salt deformation has a complex late Cenozoic history. Salt sheets exist at various stratigraphic levels and have overridden sandstone fairways on the present-day outer continental shelf and upper slope, where water depths are moderate and where pipeline and other infrastructure facilities already exist. Potential reserves for the subsalt play have been estimated at 1.2 billion bbl of oil and 15 Tcf* gas from 25 or more significant fields

Recent success in the subsalt play has depended upon (1) advances in 3-D (three-dimensional) seismic acquisition and processing (in particular, 3-D prestack depth imaging) and (2) improved geologic modeling of salt deformation and depositional systems. In addition, better understanding of the drilling risks frequently encountered in penetrating salt sheets has been important. Progress in all these areas is certain to continue and will result in significant new tools and techniques for exploration as a whole.

[1]Petroleum Consultant, 1511 18th Avenue East, Seattle, Washington 98112.

[2]Anadarko Petroleum, 17001 Northchase Drive, Houston, Texas 77060.

Grateful acknowledgment is made to Anadarko Petroleum, Phillips Petroleum, TGS-Calibre Geophysical Company and Geco-Prakla for permission to use data included in this report. Appreciation is also extended to Holly Harrison for helpful comments, to Anadarko Petroleum for preparation of figures, to Floyd Bardsley for additional artwork, and to Robert O. Brooks, Clint Moore's coauthor.

Send reprint requests to AAPG Publications Manager, P.O. Box 979, Tulsa, Oklahoma 74101-0979.

*Tcf = trillion cubic feet; Gcf = billion cubic feet; Mcf = million cubic feet.

INTRODUCTION

Exploration for hydrocarbons trapped in late Tertiary deep-water sandstones beneath allochthonous salt has achieved impressive success in the northern Gulf of Mexico. The main area of the play is the South Louisiana Shelf, regionally situated between a series of interior salt basins (East Texas, North Louisiana, and Mississippi salt basins) and the more offshore Texas-Louisiana Slope (Figure 1). As of December 1996, more than 30 wells had been drilled with subsalt targets (Figure 2a, Table 1), resulting in 7 announced discoveries (Figure 2b), 3 of which had been deemed commercial and 3 with reserves of 100 million bbl or more. Six of these discoveries, including all three commercial fields, were made between 1993 and 1996 (see Table 2). Increased success in this complex and challenging play has been attributed to progress in two main areas of analysis: (1) improvements in subsalt seismic acquisition and imaging, related to longer offset capabilities and to three-dimensional (3-D) prestack and poststack depth migration (Ratcliff and Weber, 1995); and (2) significant advances in geologic modeling of allochthonous salt development, depositional history, and reservoir occurrence (see, for example, McGuinness and Hossack, 1993; Diegel et al., 1995; Jackson, 1995; Moore and Brooks, 1995; Moore et al., 1995a; Rowan, 1995; Schuster, 1995). The progress achieved reflects the large investment in technological and scientific effort required for subsalt exploration. Such effort promises substantial benefits for

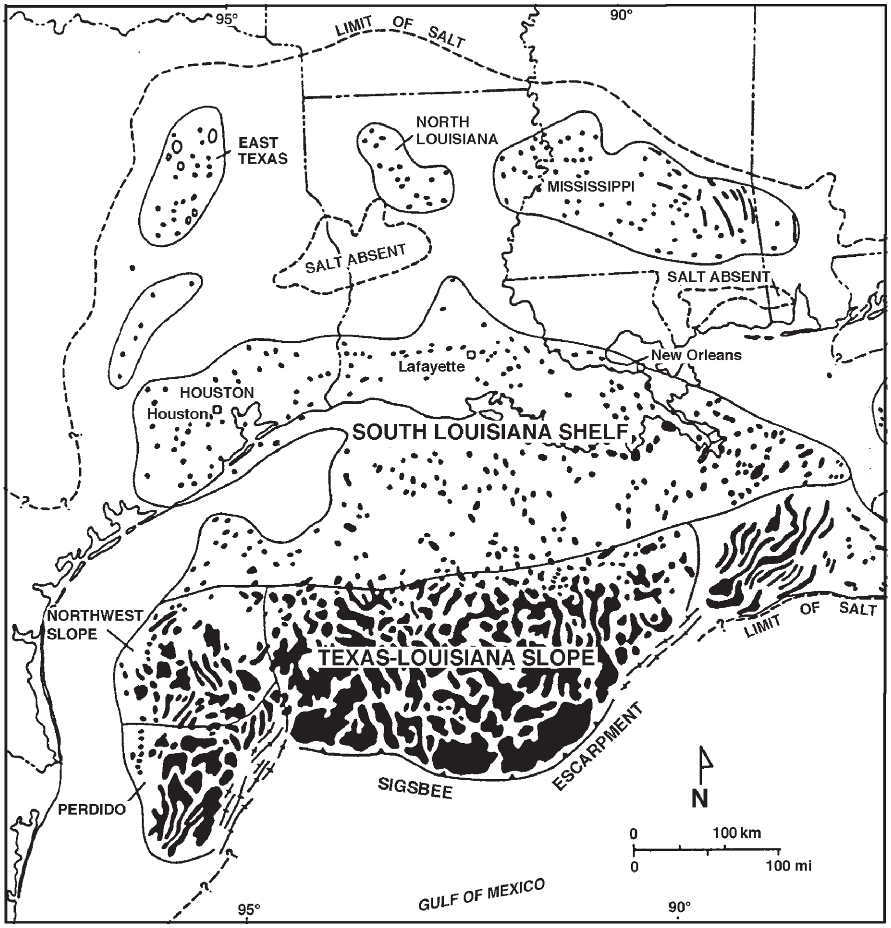

Figure 1—Salt provinces of the northern Gulf of Mexico. (After Ewing, 1991.)

exploration in other settings worldwide, both offshore and onshore.

The following report presents a basic introduction to the subsalt play, focusing on its general character, petroleum geology, and history. As a whole, the play has been active since the early 1980s. Wells drilled during the past decade-and-a-half added enormously to industry understanding of the geology of the outer continental shelf and upper slope. Every success to date stands upon the knowledge gained from a dozen dry holes.

BASIC CHARACTER OF THE PLAY

The Gulf of Mexico subsalt play has been concentrated in water depths of 200–600 ft (60–182 m) along the outer part of the South Louisiana Shelf (see Figure 2a, b, Table 1), with two significant discoveries on the slope in the Mississippi Canyon area (Exxon Mississippi Canyon 211 #1 and Texaco Mississippi Canyon 292 #1). The outer part of the present-day shelf corresponds to the position of the ancestral Pliocene–Miocene slope, whose general characteristics can be approximated by comparison with the present-day slope configuration, indicated on the sidescan sonar mosaic of Figure 3. A complex pattern of minibasins, intervening salt ridges, and downdip salt sill "platforms" is evident from Figure 3. The general southward progression between deeper and elongated to more shallow and circular basin morphologies, and finally to the nonbasinal, lobate, overthrust margin (Sigsbee Scarp), reflects a corresponding decrease in sediment thickness above salt. Such observations support the general conclusion that depositional load has been the driving force behind salt movement in the Gulf since the Cenozoic (Diegel et al., 1995).

Slope depositional patterns are predominantly controlled by (1) sediment supply from the shelf, (2) interbasinal fairways and salt-related blockages, and (3) intrabasinal lows and salt-inflated highs. Thinned and condensed sections exist on highs; thickened and more sand-rich sequences characterize basinal lows. Sand-rich sequences typically correspond either to episodes of increased influx to the continental shelf or to shifts in the loci of sediment input.

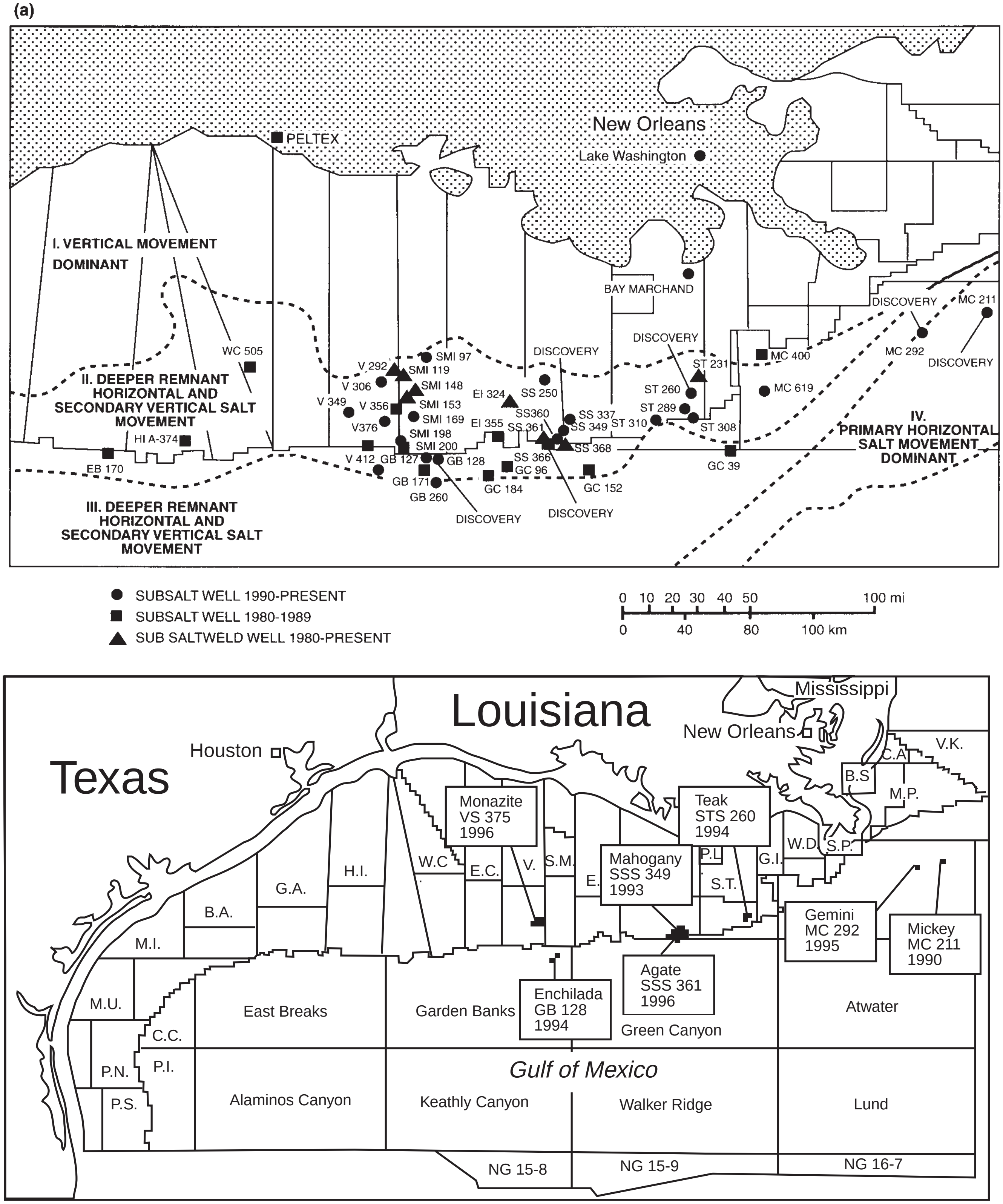

Figure 2—(a) Subsalt drilling in the northern Gulf of Mexico, offshore Louisiana and Texas. Well numbers refer to Table 1. EB = Ewing Bank, HI = High Island, GC = Green Canyon. (b) Map showing subsalt discoveries. See Table 2 for data on discovery wells.

Table 1. Significant Subsalt Wells in the Offshore Gulf of Mexico*

Well Name	Date Cmpltd.	Water Depth (ft)	Spud Date	Date Reached Total Depth	Status	Top of Salt (ft)	Base of Salt (ft)	TVD Thickness of Salt (ft)	Drld. MD Well (TD) (ft)	Drld. TVD Sediment Thickness Below Salt (ft)
Eugene Island 324 #1, Gulf	05/84	253	10/05/83	02/25/84	P&A	Salt weld	Salt weld	Salt weld	15,492	Salt weld
West Cameron 505 #2, Gulf	09/84	138	12/25/83	09/13/84	P&A	-13,900	-15,590	1690	18,500	2820
Garden Banks 171, Marathon	05/84	670	02/09/84	04/18/84	P&A	-8400	-9510	1110	10,597	997
S. Marsh Island 200 #1, Diamond Shamrock	02/86	475	11/14/85	01/29/86	P&A	-8730	-9720	990	13,500	3700
Vermilion 356 #1, Amoco (Pooh)	12/87	265	08/22/87	12/18/87	P&A	-8400	-10,500	2100	17,000	6360
South Marsh Island 148 #1, Chevron	12/88	227	10/01/88	12/02/88	P&A	Salt weld	Salt weld	Salt weld	19,500	Salt weld
Missssissippi Canyon 211 #1, Exxon (Mickey)	06/90	4356	02/08/90	05/25/90	DISC	-5750	-8780	3030	14,670	5820
Lake Washington #1, Amoco (onshore)	05/91	Land	02/20/91	05/28/91	P&A	-9350	-13,410	4075	21,241	7781
Bay Marchand 4 #1, Amoco	05/91	36	02/20/91	04/22/91	P&A	-9820	-14,160	4340	18,277	4260
Garden Banks 165 #1, Chevron	04/92	724	11/09/91	03/22/92	P&A	-5765	-12,715	6950	18,000	5200
Ship Shoal 349#1, Phillips (Mahogany 1)	10/93	372	06/19/93	09/06/93	DISC	-7603	-11,428	3825	16,500	4990
South Marsh Island 169 #1, Amoco (Mattaponi)	12/93	288	07/01/93	11/17/93	P&A	-11,222	-12,392	1170	18,020	5520
South Timbalier 260 #1, Phillip (Teak)	05/94	295	10/06/93	03/05/94	DISC	-9740	-11,600	1860	16,610	4920
Ship Shoal 349 #2, Phillips (Mahogany 2)	08/94	372	01/23/94	06/21/94	DISC	7660	-11,280	3620	18,603	7243
Vermilion 349 1, Anadarko (Mesquite)	06/94	237	02/17/94	05/25/94	P&A	-9550	-12,010	2460	16,146	4046
Garden Banks 128 #1, Shell (Enchilada 1)	07/94	718	03/16/94	06/20/94	DISC	Salt weld	Salt weld	Salt weld	17,477 TVD	Salt weld
Ship Shoal 360 #2, Unocal (Rhino)	08/94	397	05/07/94	08/07/94	P&A	-8335	-10,745	2410	19,000	8180
Ship Shoal 250 #1, Japex	09/94	184	05/26/94	08/27/94	P&A	-12,246	-13,202	956	17,750	4447
South Timbalier 289 #1, CNG (Cypress)	11/94	397	07/10/94	10/06/94	P&A	-12,078	-13,003	925	18,034	4934
Ship Shoal 359 #2, Phillips (Mahogany 3)	04/95	372	09/23/94	04/14/95	DISC	Conf.**	Conf.	Conf.	18,308 TVD	Conf.
Vermilion 308 #1, Amoco (South Anna)	07/95	205	10/25/94	07/01/95	P&A	Conf.	Conf.	Conf.	20,399	Conf.
Ship Shoal 368 #1, Amerada (Citation)	02/95	454	11/03/94	02/04/95	P&A	Conf.	Conf.	Conf.	15,774 TVD	Conf.
Garden Banks 127 #1, Shell (Chimichanga)	05/95	622	02/09/95	05/12/95	DISC	Conf.	Conf.	Conf.	14,730	Conf.
Ship Shoal 359 #3, Phillips (Mahogany 4)	05/96	372	05/02/95	04/23/96	DISC	Conf.	Conf.	Conf.	17,924 TVD	Conf.
Mississippi Canyon 292 #1, Texaco (Gemini 1)	08/95	3393	06/06/95	07/10/95	DISC	Conf.	Conf.	Conf.	17,976	Conf.
South Timbalier 308 #2STH1, Marathon (North Lobster)	04/96	554	10/30/95	04/04/96	SUSP	Conf.	Conf.	Conf.	18,199 TVD	Conf.
Ship Shoal 337 #1, Phillips (Alexandrite)	04/96	295	11/20/95	03/18/96	P&A	Conf.	Conf.	Conf.	17,851	Conf.
Ship Shoal 361 #1, Phillips (Agate)	03/96	405	12/10/95	02/16/96	DISC	Conf.	Conf.	Conf.	16,163	Conf.
Vermilion 375 #1, Anadarko (Monazite)	11/96	318	12/21/95	08/28/96	DISC	Conf.	Conf.	Conf.	14,386 TVD	Conf.
South Timbalier 231 #3, LL&E (Golden Eagle)	08/96	235	03/23/96	08/29/96	P&A	Conf.	Conf.	Conf.	19,609 TVD	Conf.
South Timbalier 310 #1, Marathon (Siskin)	08/96	447	04/28/96	08/22/96	P&A	Conf.	Conf.	Conf.	16,570 TVD	Conf.
Mississippi Canyon 619 #1, Chevron (Keweenaw)	08/96	1334	04/29/96	08/08/96	P&A	Conf.	Conf.	Conf.	21,000	Conf.
South Marsh Island 198 #1, Amerada (Donatello)	07/96	380	05/05/96	07/02/96	P&A	Conf.	Conf.	Conf.	13,439	Conf.
Ship Shoal 350 #1, Vastar (Kingfisher)	10/96	311	07/19/96	10/30/96	P&A	Conf.	Conf.	Conf.	16,422	Conf.
Garden Banks 128 #2, Shell (Enchilada 2)	11/96	633	05/20/96	11/14/96	DISC	Conf.	Conf.	Conf.	12,211 TVD	Conf.
Ship Shoal 357 #3, LL&E (Pelican)	02/97	420	09/08/96	11/30/96	P&A	Conf.	Conf.	Conf.	20,611	Conf.
Mississippi Canyon 627 #1, Chevron (Vince)	02/97	2559	10/16/96	02/13/97	P&A	Conf.	Conf.	Conf.	20,076	Conf.
Mississippi Canyon 292 #2 OH, Texaco (Gemini 2)	02/97	4151	09/05/96	02/3/97	DISC	Conf.	Conf.	Conf.	19,500	Conf.
South Marsh Island 97 #4, Pennzoil	Spud 06/96	180	06/23/96		DRLG	Conf.	Conf.	Conf.	21,000 PTD	Conf.
Garden Banks 215 #4, Amerada Hess (CongerR)	Spud 10/96	1451	10/25/96		DRLG	Conf.	Conf.	Conf.	22,000 PTD	Conf.
South Timbalier 299 #1, BHP (Lion)	Spud 01/97	290	01/06/97		DRLG	Conf.	Conf.	Conf.	20,000	Conf.

*Includes wells that penetrated salt sheet, salt withdrawal remnants, and salt welds.
**Conf. = confidential.

Table 2. Subsalt Discoveries, Gulf of Mexico

Well	Operator	Total Depth (ft) (Year)	Gross/Net Pay (ft)	Initial Production	Estimated Reserves*
Mississippi Canyon 211 #1 (Mickey)	Exxon Conoco	14,670 (1990)	Gross ~175	Not available	100–200 Mbbl
Ship Shoal 349 #1 (Mahogany)**	Phillips Anadarko Amoco	16,500 (1993)	Gross = 180	7256 bbl 9.9 Mcf	>100 Mbbl
South Timbalier 260 #1 (Teak)	Phillips Anadarko	16,610 (1994)	Gross = 100	4431 bbl 7.7 Mcf	Under evaluation
Garden Banks 127 #1 (Enchilada/ Chimichanga)**	Shell Amerada Hess Penzoil	14,730 (1995)	Gross ~ 170	20 Mcf 900 bbl cond.	400 Gcf 25 Mbbl cond.
Mississippi Canyon 292 #1 (Gemini)**	Texaco Chevron	17,976 (1996)	Gross > 150	54 Mcf 4405 bbl cond.	Not available
Ship Shoal 361 #1 (Agate)	Phillips Anadarko	16,163 (1996)	Gross = 105	4126 bbl 24 Mcf	Not available
Vermilion South Addition 375 #1 (Monazite)	Anadarko Phillips BHP	14,368 (1996)	Not available	Not available	Not available

*M = million; G = billion.
**Commercial discovery.
Note: This table is the corrected version published in the AAPG Bulletin, V. 81, No. 9 (September 1997), P. 1435-1436.

Drilling has been targeted for Pliocene–Miocene turbiditic sandstones deposited in fairways on the paleoslope. These fairways were subsequently overridden by mobile sheets of salt that developed in complex fashion as a result of sediment loading and salt withdrawal. As indicated by discoveries at Mahogany (see Harrison et al., 1995) and Teak (see Snyder and Nugent, 1995) (see Figure 2b), reservoir sandstones range in thickness from about 50 to 150 ft (15–45 m), are generally fine to very fine grained, and possess excellent reservoir quality, including porosities above 23% and permeabilities in the range of 0.2–2.5 d. Log characteristics include low resistivities and relatively high gamma-ray values caused by laminated or finely interbedded channel, channel-levee, or sheet-flow sandstones with siltstone and shale. Much understanding of these deposits has come from analysis of reservoirs in the deep-water Gulf trend.

Subsalt wells present several challenges with respect to drilling and completion. Salt supersaturated drilling fluid systems are used primarily to inhibit dissolution (and thus hole widening) during penetration of salt. In addition, sedimentary inclusions up to 80 ft (24 m) thick trapped within salt sheets and tongues (see Moore et al., 1995a) can be highly pressured and even yield hydrocarbons in core samples. The sedimentary section immediately below the base of salt is typically characterized by noncompetent shale zones (frequently referred to as "gumbo" zones) as much as 1000 ft (303 m) or more thick. In some cases, these zones are significantly overpressured; in other cases, however, lost circulation has occurred within them. Due to insufficient sampling, such zones are not well understood at the present, but may result from a combination of factors related to the sealing capacity of salt. Finally, heavy-walled intermediate casing is employed to resist hole deformation caused by salt flowage at depths of up to 18,000 ft (5450 m).

PLAY HISTORY

Initial subsalt wells in the Gulf of Mexico were drilled in the early 1980s (Table 1). These wells were deeper than most previous exploratory attempts on the shelf and resulted in several unintentional penetrations of salt sheets, withdrawal remnants (zones from which salt has been almost completely withdrawn), and salt welds (zones of complete withdrawal). Data from these wells helped overturn earlier concepts of massive, rooted salt on the outer

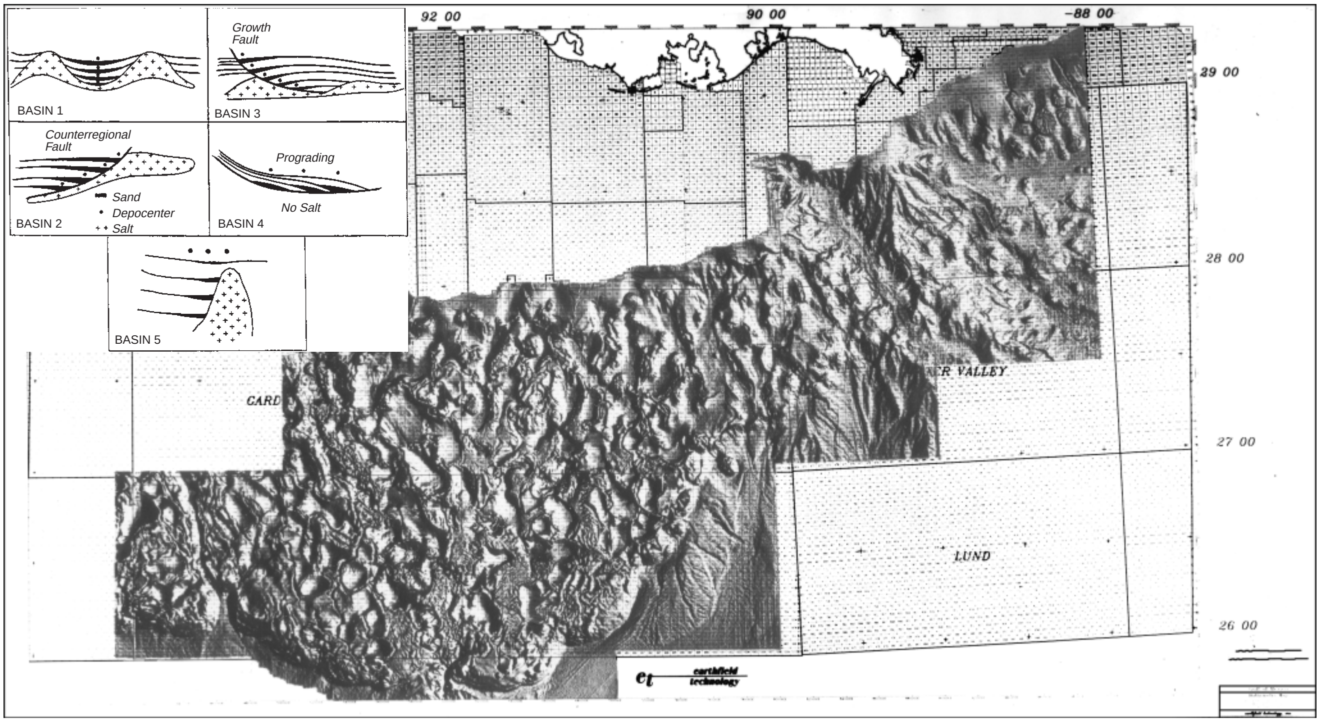

Figure 3—National Oceanographic Atmospheric Administration data multibeam sidescan sonar image of the present-day slope along the northern Gulf of Mexico, showing minibasins, intervening salt ridges, and broader salt-supported "platforms" toward the slope base. Inset indicates five slope basin types. (Courtesy Earthfield Technology; basin types modified from Montgomery, 1995.)

continental shelf and slope in favor of ideas proposing the existence of tabular bodies that were either entirely allochthonous sheets or else tongue-like bodies attached to "feeder" stocks. The advent of such ideas highlighted significant new regional potential on the present-day outer shelf and upper slope. To a degree, a vast new portion of the Gulf Basin had been "discovered" and opened for exploration.

Such potential was further confirmed by several "milestone" wells. In 1986, Diamond Shamrock Corp. drilled the South Marsh Island 200 #1, penetrating 1000 ft (330 m) of salt and encountering a massive 990-ft (300-m) wet sandstone interval of Pleistocene age (*Lenticulina* biozone). Still more significantly, in 1990 Exxon announced the first subsalt discovery in the Gulf at its "Mickey" prospect, the Mississippi Canyon 211 #1, drilled in 4356 ft (1330 m) of water. This well penetrated 3030 ft (918 m) of shallow salt and an underlying productive section consisting of 5 sandstone zones between 10,000 and 13,000 ft (3030 and 3940 m) straight-hole depth. Core analysis and log data indicate good reservoir quality for these zones, and Exxon has reported estimates of 100–200 million bbl of reserves. Due to water depth, the discovery has not been developed to date. In 1991–1992, the Chevron Garden Banks 165 #2 well was drilled through 6950 ft (2106 m) of salt and logged a significant thickness (250 ft; 76 m) of high porosity/permeability sandstone in the subsalt section, between 15,200 and 15,900 ft (4600 and 4820 m) measured depth. Though a commercial failure (the sandstones were wet), the well is considered to have major historical significance, as it demonstrated that unprecedented thicknesses of salt could be successfully drilled with continued penetration of a highly prospective underlying clastic section.

The 3 wells just noted, along with more than 12 others, provided data essential for a new phase of exploration that led to the first round of discoveries in 1993–1994. The first such discovery, and the most developed to date, was the Ship Shoal 349 #1, otherwise known as the Mahogany prospect, drilled by partners Phillips Petroleum, Anadarko Petroleum, and Amoco in 372 ft (113 m) of water to a total depth of 16,500 ft (5000 m). Several sandstone pay sections tested at a combined flow rate of 7256 bbl oil and 9.9 Mcf gas per day. Three field delineation wells have been successfully completed; total reserves are estimated at more than 100 million bbl (Montgomery, 1995). Subsequent to Mahogany, hydrocarbon discoveries were made at the Teak (Phillips/Anadarko) and Enchilada (Shell Offshore/Amerada Hess/Pennzoil) prospects in 1994–1995, and during 1996

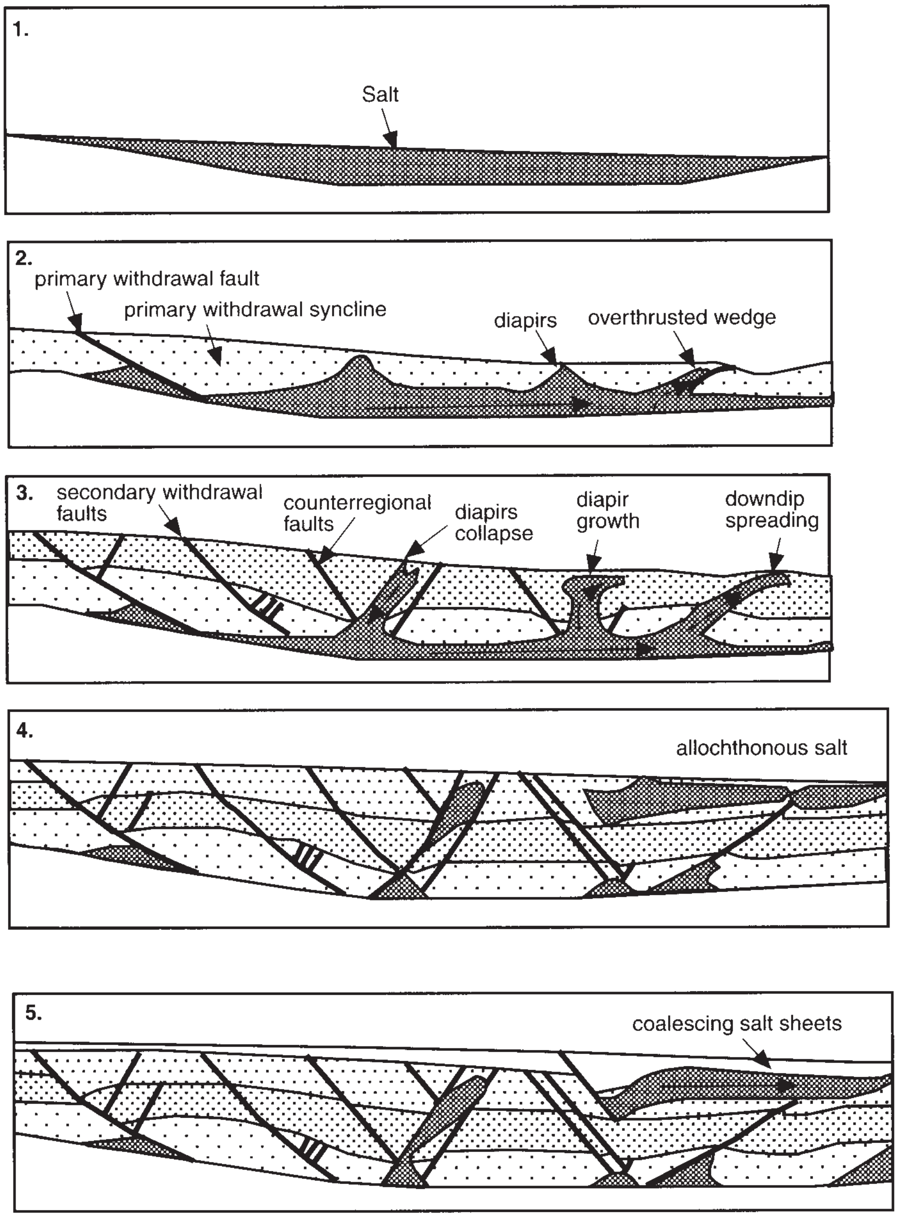

Figure 4—Simplified evolutionary model for creation of allochthonous salt sheets, Gulf of Mexico. Sedimentary loading of an original salt mass produces piercement diapirs that undergo downdip gravitational spreading at shallow subsurface levels, where density differences between salt and enveloping water-saturated sediment are low. (Modified from Bradshaw and Watkins, 1994.)

alone, at Agate (Phillips/Anadarko), Gemini (Texaco/Chevron), and Monazite (Anadarko/Phillips/ BHP) (see Table 2). As of December 1996, Mahogany, Enchilada, and Gemini have been deemed commercial, with other discoveries under appraisal.

SALT DEFORMATION

Current understanding of allochthonous salt bodies in the Gulf of Mexico is based, in part, on a proposed evolution involving two major stages: (1) initial sedimentary loading of a Jurassic salt mass, resulting in salt withdrawal and diapir formation, followed by downdip gravitational spreading into sheets and tongues, and (2) a later phase (or phases) of suprasalt sediment loading, causing complex growth-fault-type sedimentary relationships associated with both regional and counterregional faults (Wu et al., 1990; Diegel et al., 1995; Rowan, 1995). These stages are shown, in simplified fashion, in Figures 4 and 5.

In particular, downdip gravitational spreading of salt is assumed to take place at shallow subsurface levels, where density differences are low between the salt itself and enveloping water-saturated sediment. Spreading results in salt sheets and tongues

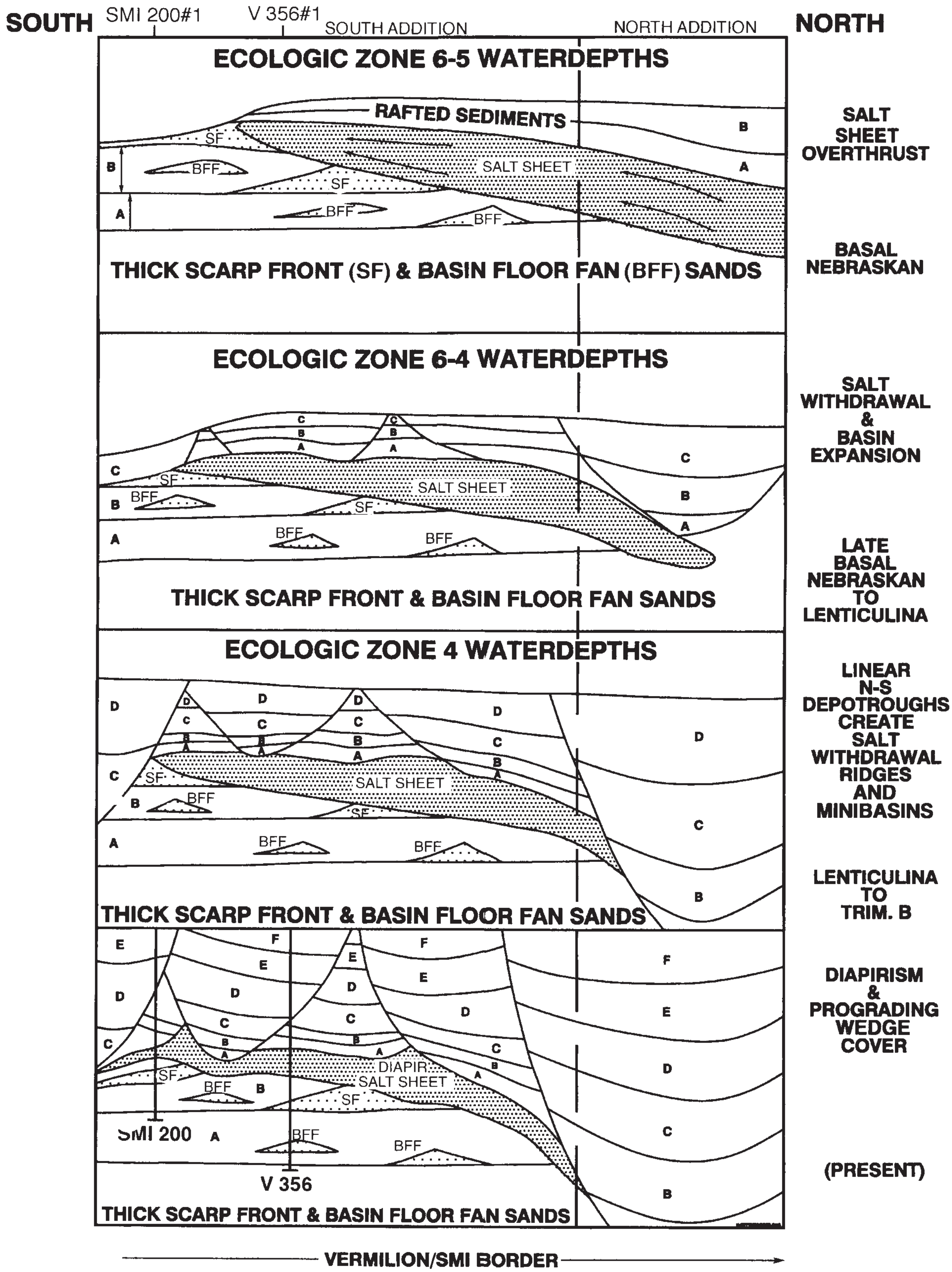

Figure 5—Model illustrating evolution of allochthonous salt sheet subsequent to formation. Progressive sedimentary loading produces complex growth-fault-type geometries and relationships in the suprasalt section.

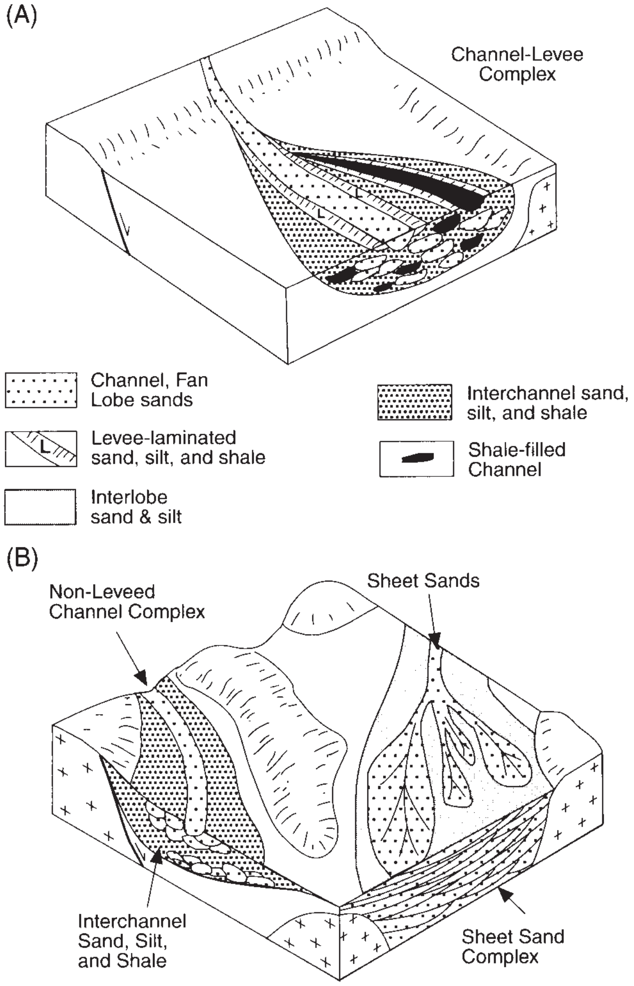

Figure 6—Depositional models illustrating (A) submarine channel-levee setting; and (B) non-leveed channel and sheet sand setting.

that override existing minibasins and depositional fairways. Continued gulfward and lateral spreading can result in suturing of individual sheets and tongues into large salt canopies, with thrusting along their southern edge (Huber, 1989; Diegel et al., 1995; Harrison et al., 1995; Rowan, 1995). In addition, shear along the base of tabular salt bodies may result in significant deformation of underlying sediments. The upper surface of the spreading salt body becomes progressively more rugose as a result of continued sediment loading. With time, secondary diapirs become common. Resulting withdrawal within the allochthon leads to dramatic changes in salt thickness, in both the strike and dip directions. Eventually, withdrawal remnant and salt-weld zones are produced as the sheet becomes dismembered, with "gap" areas acting as local minibasin depocenters.

Multiple episodes of sheet formation appear to have occurred. This is revealed, for example, by seismic data showing two or more levels of salt sheet emplacement within the overall sedimentary column (Diegel et al., 1995; Harrison et al., 1995; Peel et al., 1995). It is also suggested by the widespread occurrence of late Eocene–Oligocene sedimentary inclusions found in allochthonous salt bodies that override deposits of mainly Pliocene–Pleistocene age (Moore et al., 1995a). A higher concentration of thicker inclusions (or "anomalous zones," as they are sometimes called) in the lower 1000 ft (330 m) of salt at Mahogany has been interpreted as evidence for a basal shear mechanism (Harrison and Patton, 1995) operating during the early phases of salt movement. However, the occurrence of thinner inclusions throughout the overlying 2000+ ft (660+ m) of salt suggests a more complex origin, possibly related to intrasalt flowage patterns over time.

DEPOSITIONAL MODELS

Information essential to building depositional models with the potential to help predict subsalt reservoir fairways has been derived from two main sources: (1) study of present-day slope sediments and (2) analysis of productive Pliocene–Miocene sandstones of the deep-water Gulf trend. Data from these sources have suggested the importance of two main depositional settings, the slope fan and basin-floor fan systems.

Slope fan systems develop in interbasinal lows and along basin margins. They consist of channel, channel-levee, and subsidiary sheet (fan lobe) deposits (Figure 6A, B). Slope fan systems may prograde over basin-floor deposits, dominated by sheet sand sediments. The development and distribution of these depositional systems are closely related to paleobathymetry produced by salt movements. Over time, such movements resulted in changing basinal and intrabasinal configurations, which in turn produced complex vertical successions in specific sediment type (see, for example, Weimer et al., 1994).

Techniques of sequence stratigraphy, which make integrated use of seismic, well log, and biostratigraphic data, have proved of enormous benefit in delineating specific sandstone fairways. In general, sea level highstands have been correlated with reservoir-poor intervals consisting of shale, siltstone, and thin interbeds of marl representing condensed sections (Moore et al., 1995b). Sea level lowstands and subsequent initial transgressive phases were characterized by maximum sand input to the shelf, and thus the slope as well. Sequence boundaries correlated with sea level lowstands are commonly marked by a basal unconformity or onlap surface, above which a slope fan or basin-floor system may have

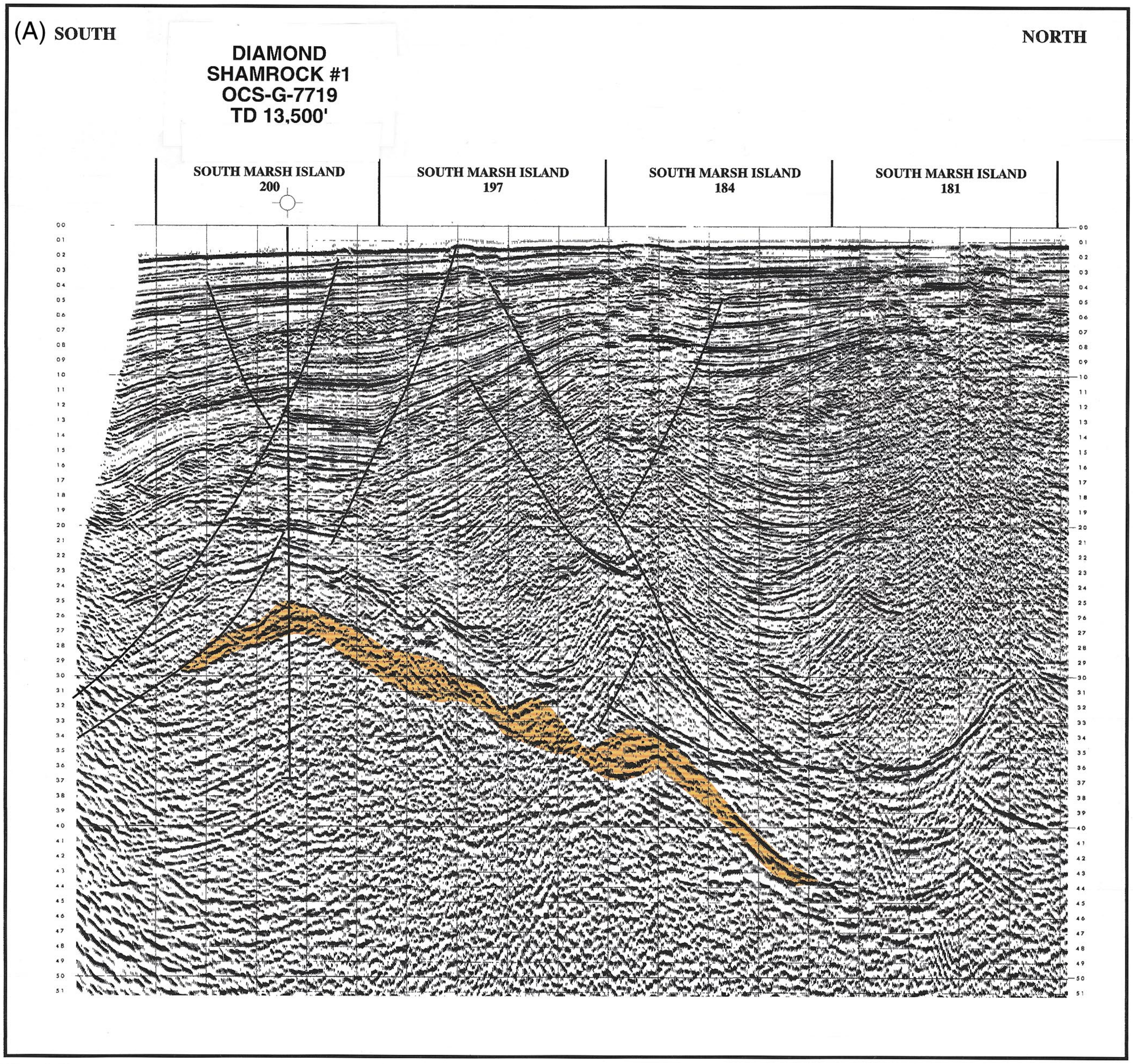

Figure 7—(A) Seismic profile and (B) well log from the Diamond Shamrock South Marsh Island 200 #1 well, which encountered a massive, high-permeability sandstone below salt. (Data courtesy TGS and Geco-Prakla.)

developed. An age-limited exploratory approach using sequence stratigraphy has been used to identify specific sand-rich sequences in the deep-water Gulf trend and trace these northward, as sandstone fairways, beneath allochthonous salt.

RESERVOIRS

Although detailed data on reservoir sandstones in subsalt discovery wells are not yet available, some important information has been released, particularly regarding the Mahogany field. Productive sandstones at Mahogany are interpreted as slope fan channel and levee deposits, reworked in part by contourite currents. The main reservoir interval, known as the "P" sand, displays an overall fining-upward texture, with coarser grained and thicker bedded individual sandstones in its lower portion and an extensively rippled, highly laminated sandstone and siltstone section above (Harrison et al., 1995). Gross pay is approximately 180 ft (55 m).

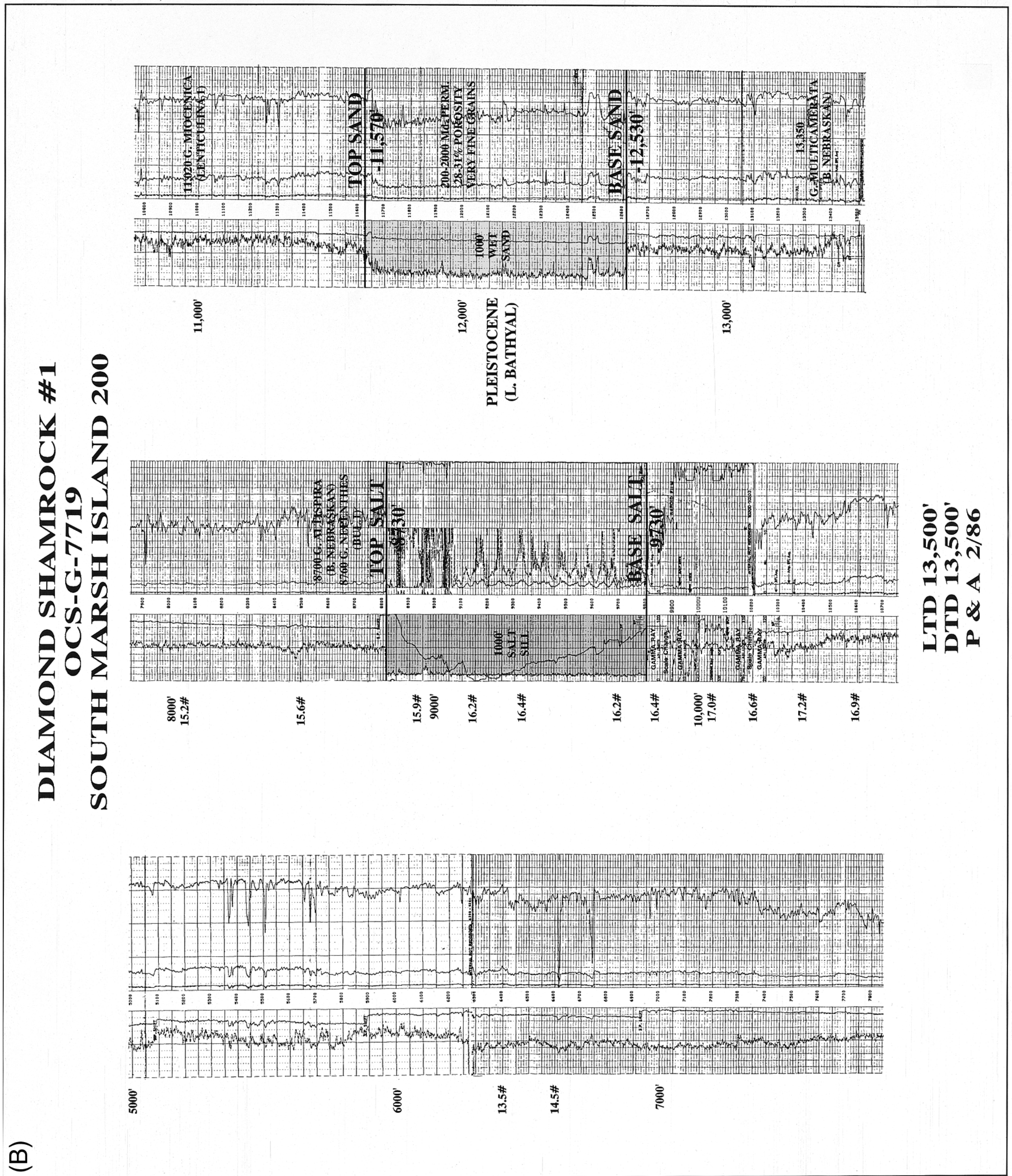

Figure 7—Continued.

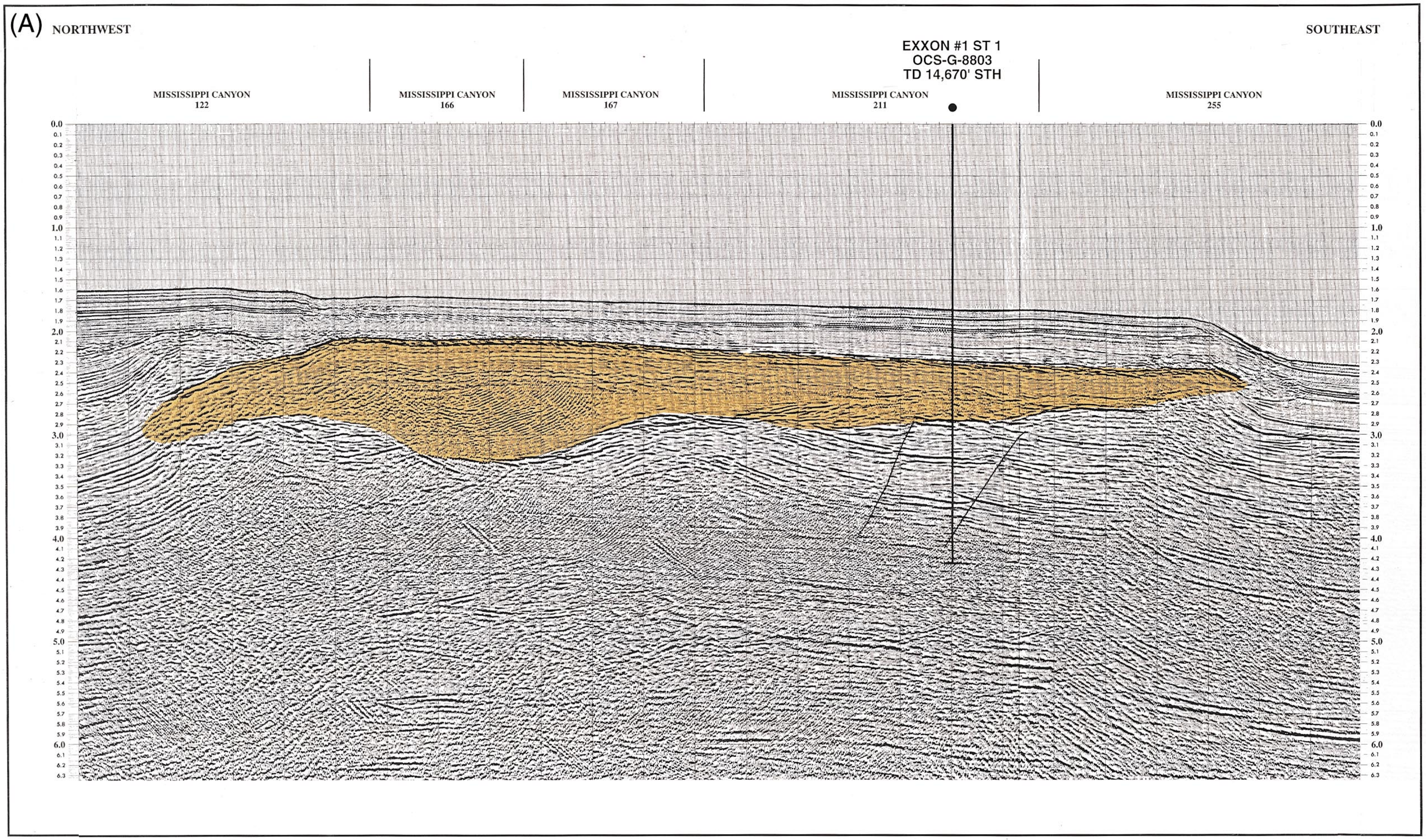

Figure 8—(A) Seismic profile and (B) well log from the Exxon Mississippi Canyon 211 #1 (Mickey), the first announced discovery in the Gulf subsalt play. (Data courtesy Geco-Prakla.)

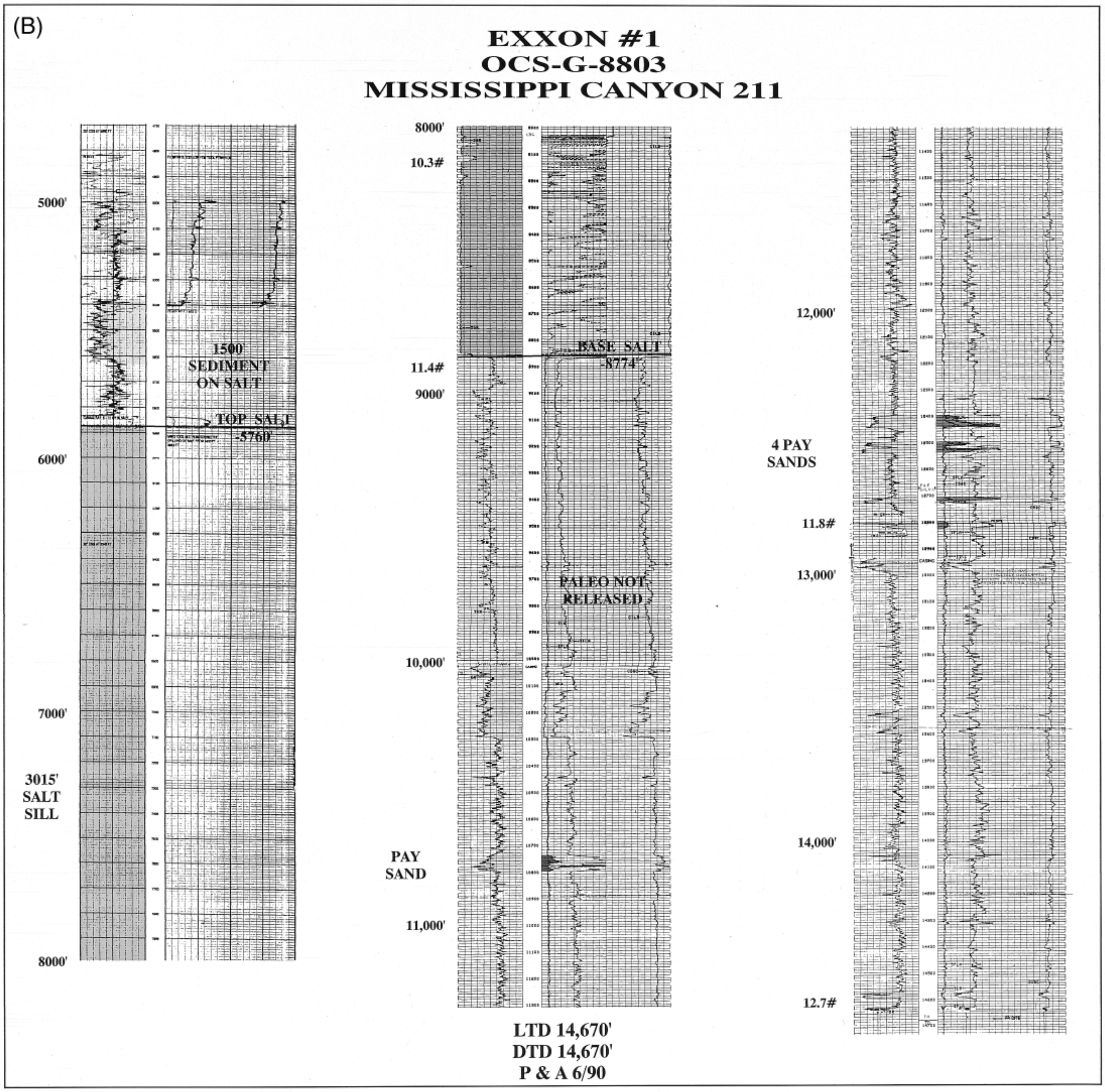

Figure 8—Continued.

The lower, high-resistivity (2.0 ohms) part of the "P" sand has better overall reservoir quality, with porosities and permeabilities of up to 33% and 2.5 d, respectively. The upper, laminated reservoir section is characterized by low resistivities (0.4–0.6 ohms) and has porosity and permeability of 18–28% and 100–500 md, respectively.

Such low-resistivity intervals are considered prospective reservoirs in many parts of the subsalt play and require specialized well logs and cores to be properly evaluated. Despite the high degree of interlamination between individual sandstone layers (as thin as .25 in. [.05 cm] or less) and shale layers, overall intervals of this type are capable of significant flow rates. In the Mahogany discovery well, for example, a total of 28 ft (8.5 m) of perforated low-resistivity "P" sand (0.45 ohms) produced at rates up to 3700 bbl oil per day.

In Mahogany field, where three confirmation wells now exist, reservoir continuity is good to

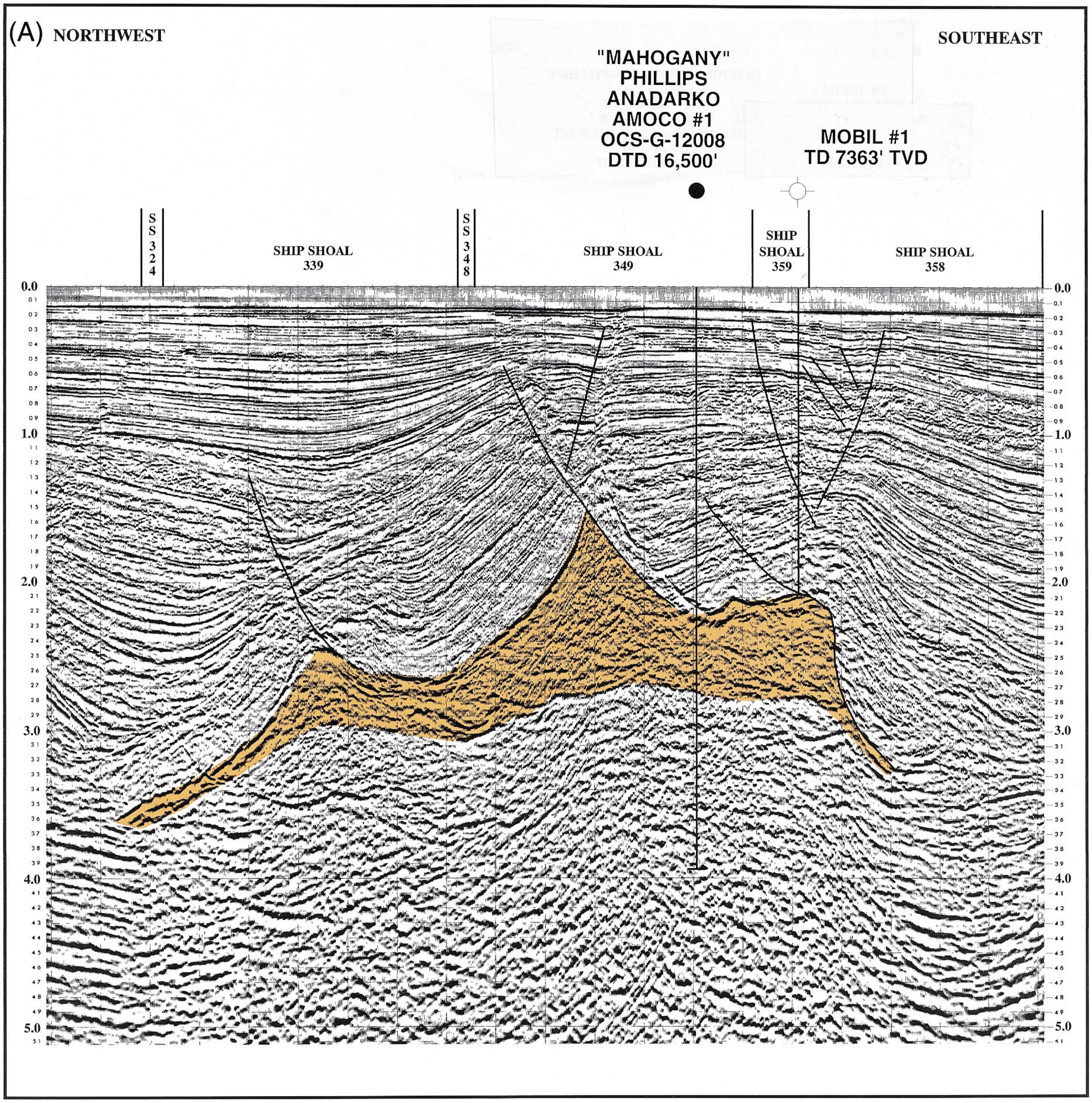

Figure 9—(A) Seismic profile and (B) well log from the Phillips/Anadarko/Amoco Ship Shoal 349 #1 well (Mahogany), the first commercial discovery in the subsalt play. (Data courtesy TGS and Geco-Prakla.)

excellent across a structure roughly 4 mi^2 (10.4 km^2) in size. Sandstone zones, such as the "O" sand, untested in the discovery well, have been proven productive in later wells in more favorable structural positions, leading to higher estimates of field productive capacity and ultimate reserves. The "O" sand, for example, yielded a rate of 4366 bbl oil and 5.3 Mcf gas in the Mahogany #2 and may have contributed to a total net pay section of 180 ft (54.5 m) in the Mahogany #4. These data confirm the existence of a productive sandstone fairway up to several miles in width in this area.

Tested rates and hydrocarbon characteristics have varied considerably among subsalt discovery wells. In general, discoveries to date have been in either oil or gas-condensate reservoirs. Oil reservoirs exist at

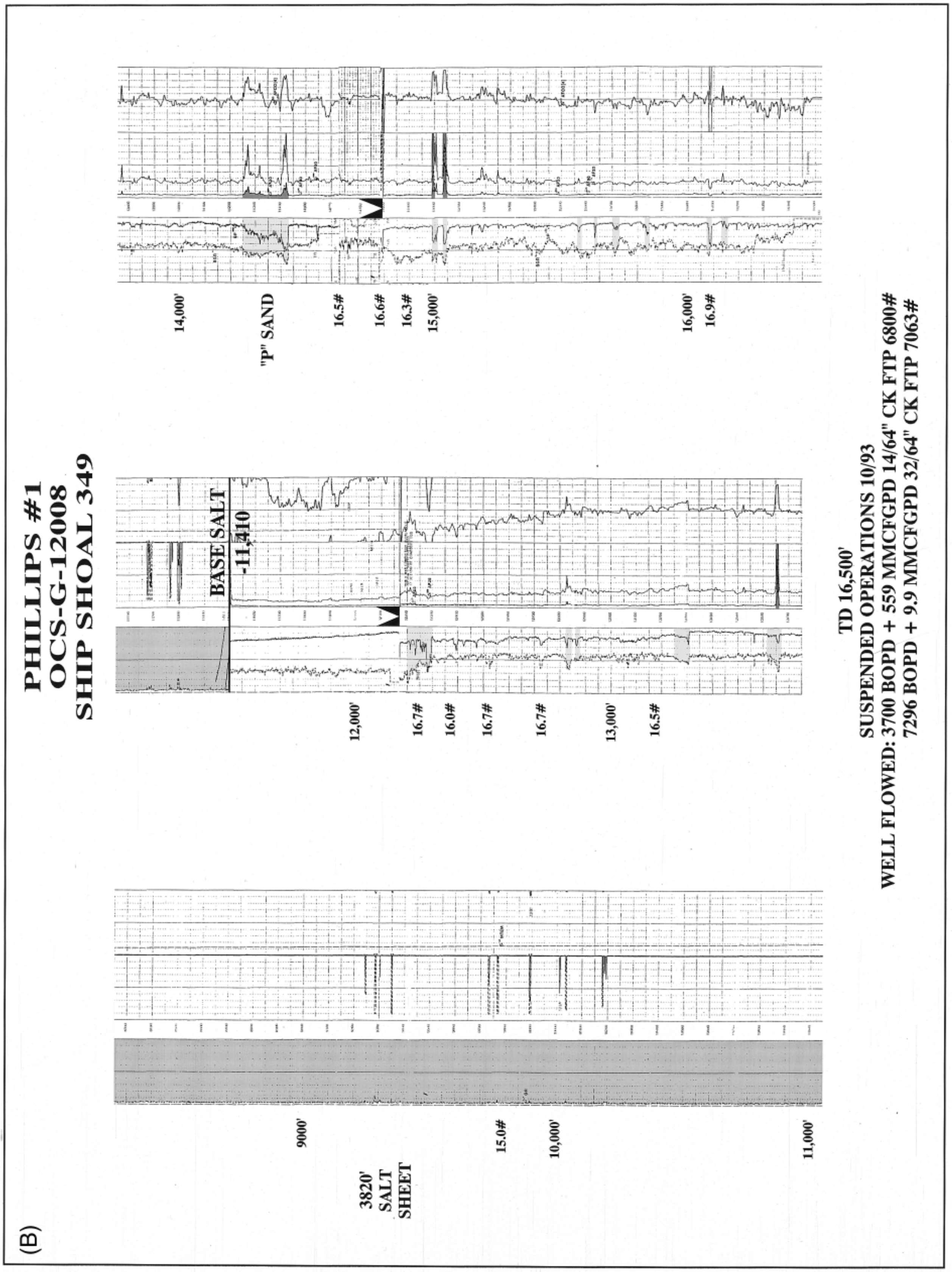

Figure 9—Continued.

Mahogany, Teak, Agate, Mickey, and possibly Monazite, with gas-condensate reservoirs reported at Gemini and Enchilada. At Mahogany #1, the total commingled daily flow rate from the "P" sand was 7256 bbl oil and 9.9 Mcf gas. In the Teak discovery well, three zones tested at rates between 413 bbl/0.673 Mcf and 3742 bbl/5.98 Mcf per day. The oil at Mahogany has an API gravity of 22° and a GOR (gas-to-oil ratio) of 1300 scf/bbl. By contrast, the Gemini discovery well reported two productive sandstone intervals with tested rates of 22.0 Mcf gas/3778 bbl of 46.5° gravity condensate and 32.0 Mcf gas/627 bbl of 52.6° gravity condensate per day.

SEISMIC AND WELL LOG CHARACTER: EXAMPLES

Figures 7–12 present a series of examples of seismic profiles and well logs from significant subsalt wells and discoveries drilled during the past decade. These data are meant to provide a brief visual overview of the complexity and variety that characterize the subsalt play. Subsalt prospects have been located beneath salt sheets lying at 2.0–3.2 s (two-way traveltime) on seismic lines. Good-quality data below 7.0–8.0 s (>25,000 ft) suggest a deeper level of allochthonous salt. Remobilization due to sediment loading of this earlier (Eocene–Paleocene?) intruded material may be responsible for a large part of the shallower salt features currently being explored.

The Diamond Shamrock South Marsh Island 200 #1 is considered both a landmark well in the play and a unique penetration. As shown on Figure 7A, the well penetrated a 1000-ft thick salt sheet and encountered more than 990 ft (300 m) of reservoir-quality, water-bearing sandstone having porosities and permeabilities in the range of 28–31% and 200–2000 md, respectively (Figure 7B). No other well to date has penetrated such a massive sandstone interval. The age of the sandstone is early Pleistocene and correlates with a period of increased sedimentation in this area.

SUBSALT DISCOVERIES

1990–1995

The first subsalt discovery, at the Exxon Mississippi Canyon 211 #1 well drilled in late 1989–early 1990, penetrated 3000 ft (990 m) of salt overlain by a thin 1500 ft (455 m) covering of Pleistocene(?)–Holocene sediments (Figure 8A). The well encountered a productive fault block, with five thin pay sandstones between 10,900 and 12,900 ft (Figure 8A). The age of these sandstones has not been released. The thickest and uppermost pay sandstone is apparently within the "gumbo" zone (Montgomery, 1995). Maximum potential exists in the lower four pay zones, described as very fine to fine grained, unconsolidated, and interbedded with siltstone and shale. Total reserves reported by Exxon are 100 million bbl or greater. No plans have been announced as yet to develop the prospect, which exists in 4400 ft (1300 ft) of water.

The second subsalt discovery, at Mahogany in 1993, had good structural position beneath a salt sheet displaying highly variable thickness and geometry (Figure 9A). The discovery well penetrated 3825 ft (1160 m) of salt and logged as many as 14 individual sandstone zones between depths of 12,300 and 16,300 ft (3750 and 5000 m) (Figure 9B). As shown by 3-D prestack depth-migrated seismic data over the discovery (Figure 10), the well went through an noncompetent zone approximately 1000 ft (300 m) thick (on Figure 10, the zone of reduced seismic amplitudes immediately below salt) before entering the flank of a structure described as an anticline with three-way dip closure and bounded on its northwest flank by a counterregional (northerly dipping) fault.

Following Mahogany, the next subsalt discovery took place at Teak in 1994. The Phillips South Timbalier 260 #1 was drilled through 1860 ft (564 m) of salt and tested three sandstone zones at a combined flow rate of 4431 bbl oil and 7.7 Mcf gas per day. The salt sheet at this location displays a high degree of irregularity along its upper and lower boundaries (Figure 11A). Productive sandstones are thin (<50 ft [15 m] thick; see Figure 11B), laminated, and include both low resistivity and high resistivity parts. The commerciality of the Teak discovery has not been determined.

In May 1995, the second discovery deemed commercial occurred on the Enchilada prospect, drilled by partners Shell Offshore, Amerada Hess, and Pennzoil, in Garden Banks 127 #1 (Figure 12A). This was a follow-up well to the Garden Banks 128 #1, drilled the year before outboard of salt. The Garden Banks 127 #1 well reported 20 Mcf gas and 900 bbl condensate per day. Net pay ranges from 114 to 150 ft (35–45 m) in thickness (Figure 12B), and reservoir quality is reported to be excellent. Estimated recoverable reserves are more than 400 Gcf and 25 million bbl condensate. A potentially significant aspect to the discovery is the reported lack of a noncompetent zone immediately below salt.

1996

During 1996, three new subsalt discoveries occurred, expanding the play considerably. The

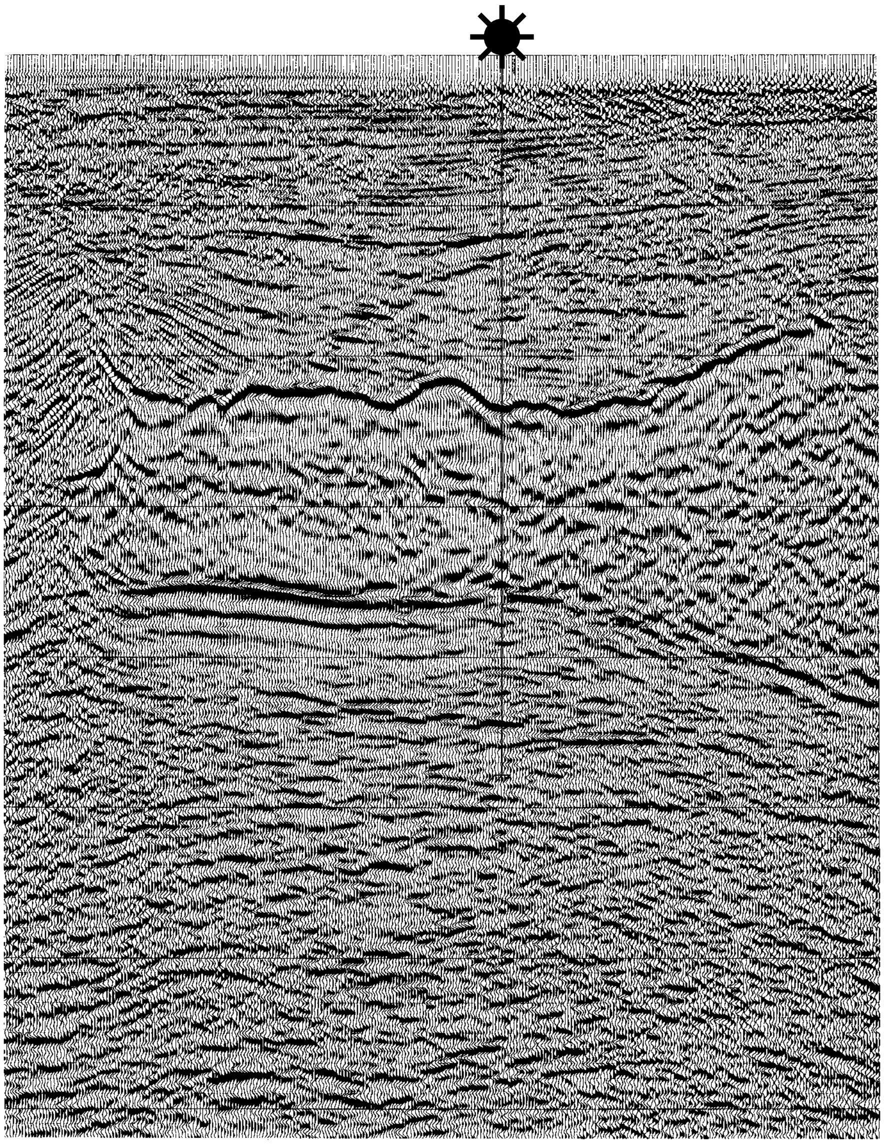

Figure 10—Seismic profile showing 3-D prestack depth-migrated data over the Mahogany subsalt discovery. (Data courtesy Diamond Geophysical.) (From Ratcliff and Weber, 1997.)

first of these wells, and the third commercial discovery in the history of the play, was drilled by Texaco and Chevron on the Gemini prospect, Mississippi Canyon Block 292, in 3393 ft (1028 m) of water. As shown in Figure 13, this well penetrated 2908 ft (880 m) of salt near the margin of an allochthonous sheet, with apparent steeply dipping, faulted beds beneath. The sheet overrides the northern part of a slope basin and has major thicknesses of probable Pliocene–Miocene sediments. Texaco has reported that the reservoir intervals encountered are capable of producing at rates of 50 Mcf gas with 7700 bbl condensate per day in one case, and 80 Mcf with 1500 bbl condensate in the other.

The second discovery during 1996 occurred in March at the Phillips/Anadarko Agate prospect, located approximately 5 mi (8 km) west of Mahogany, beneath the edge of a separate salt sheet on Ship Shoal 361 (Figure 14). The well tested two separate porosity zones within a single sandstone interval (gross pay of 105 ft [32 m]), at a combined rate of 4126 bbl oil and 24 Mcf gas per day. No log data are currently available for this well or its successor discovery, the Monazite prospect, drilled by Anadarko/Phillips/BHP at the Vermilion South Addition 375 #1. This well encountered multiple hydrocarbon-bearing sandstones, but was plagued by mechanical problems, including excessive sand production, that led to its being plugged and abandoned. Future appraisal drilling will evaluate the commerciality of the Monazite discovery.

The complexity of the subsalt play is highlighted by a dry hole drilled on the Alexandrite prospect. As is evident on Figure 15, this prospect was located

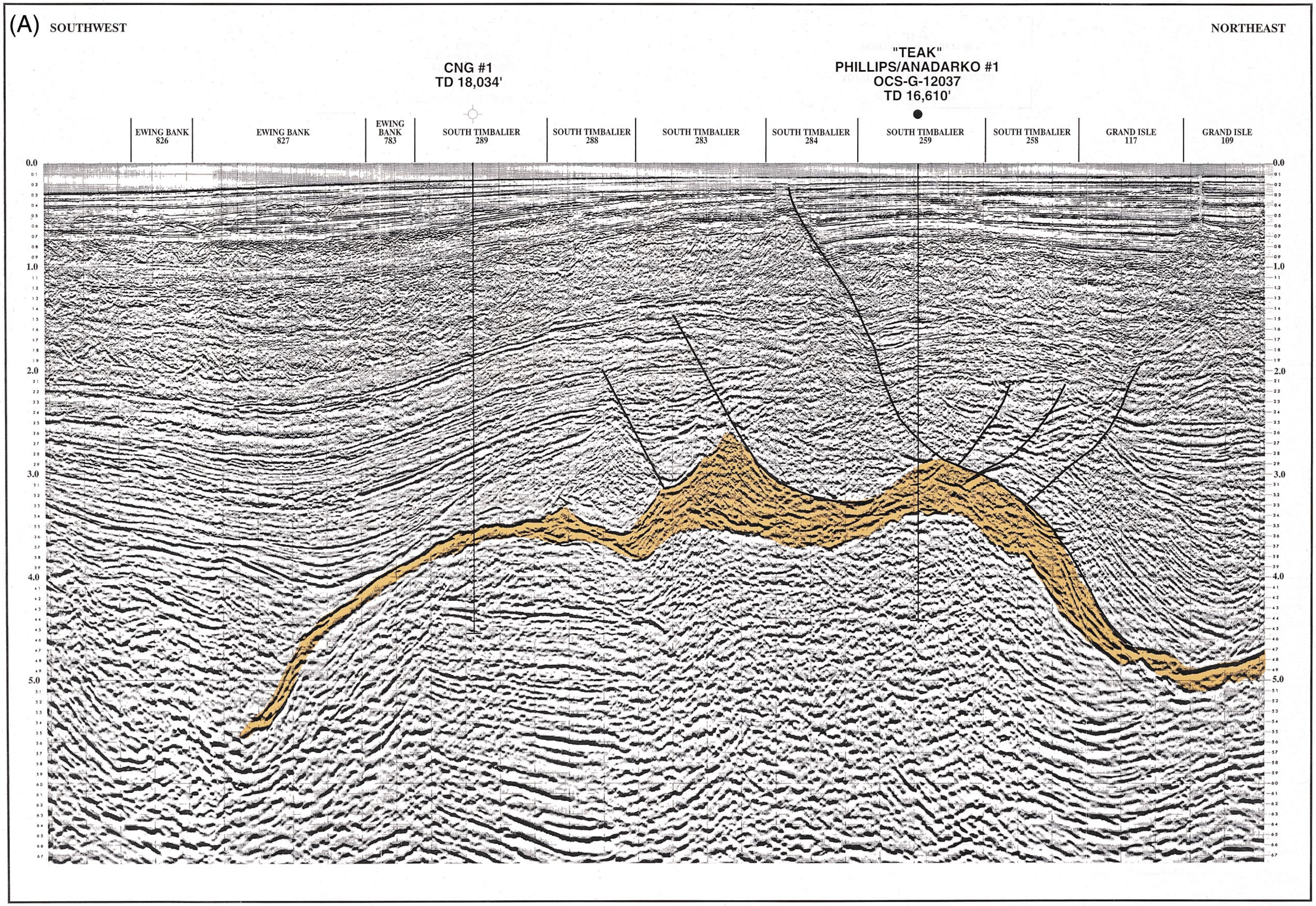

Figure 11—(A) Seismic profile and (B) well log from the Phillips/Anadarko South Timbalier 260 #1 (Teak) subsalt discovery. (Data courtesy TGS and Geco-Prakla .)

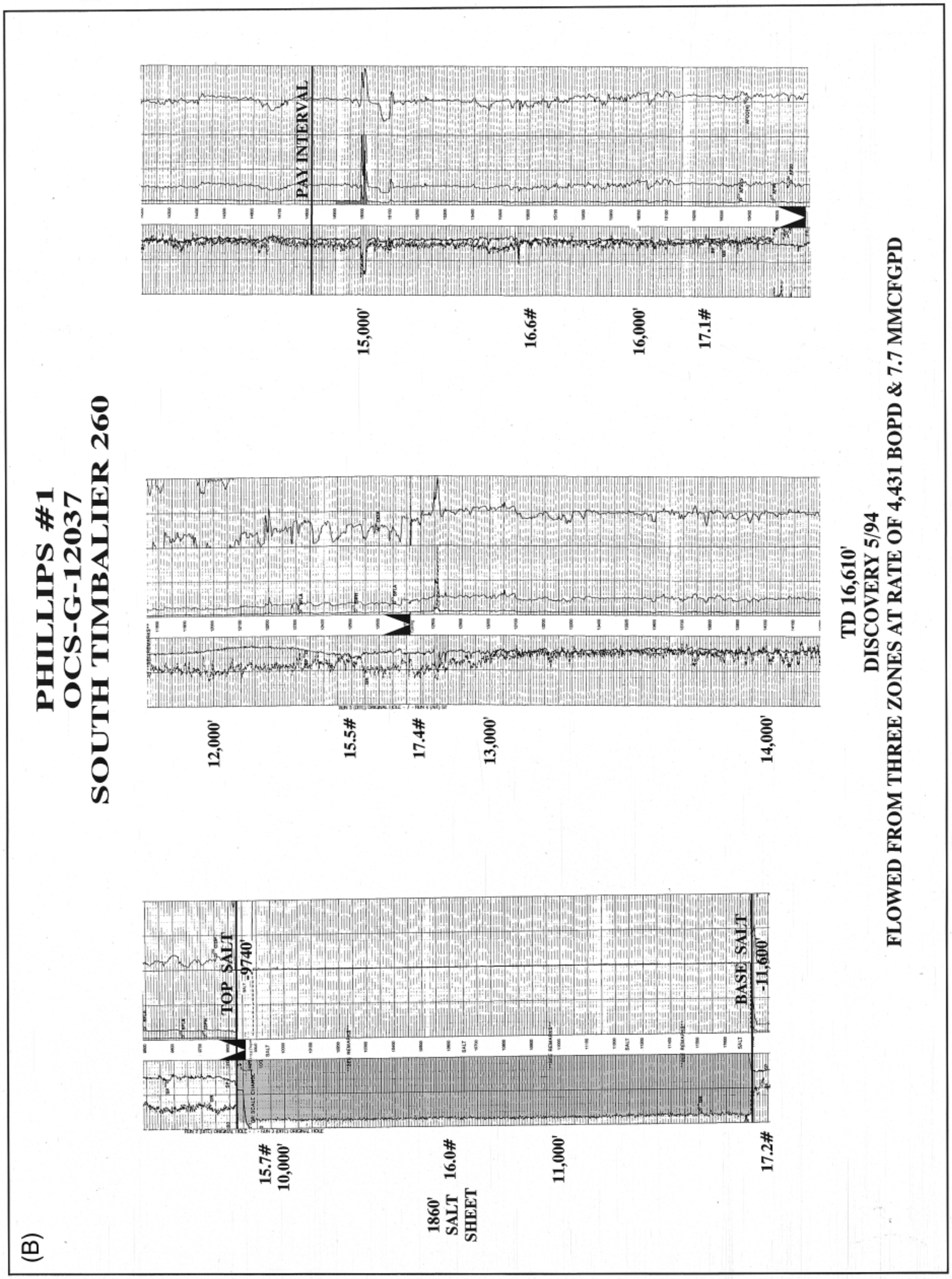

Figure 11—Continued.

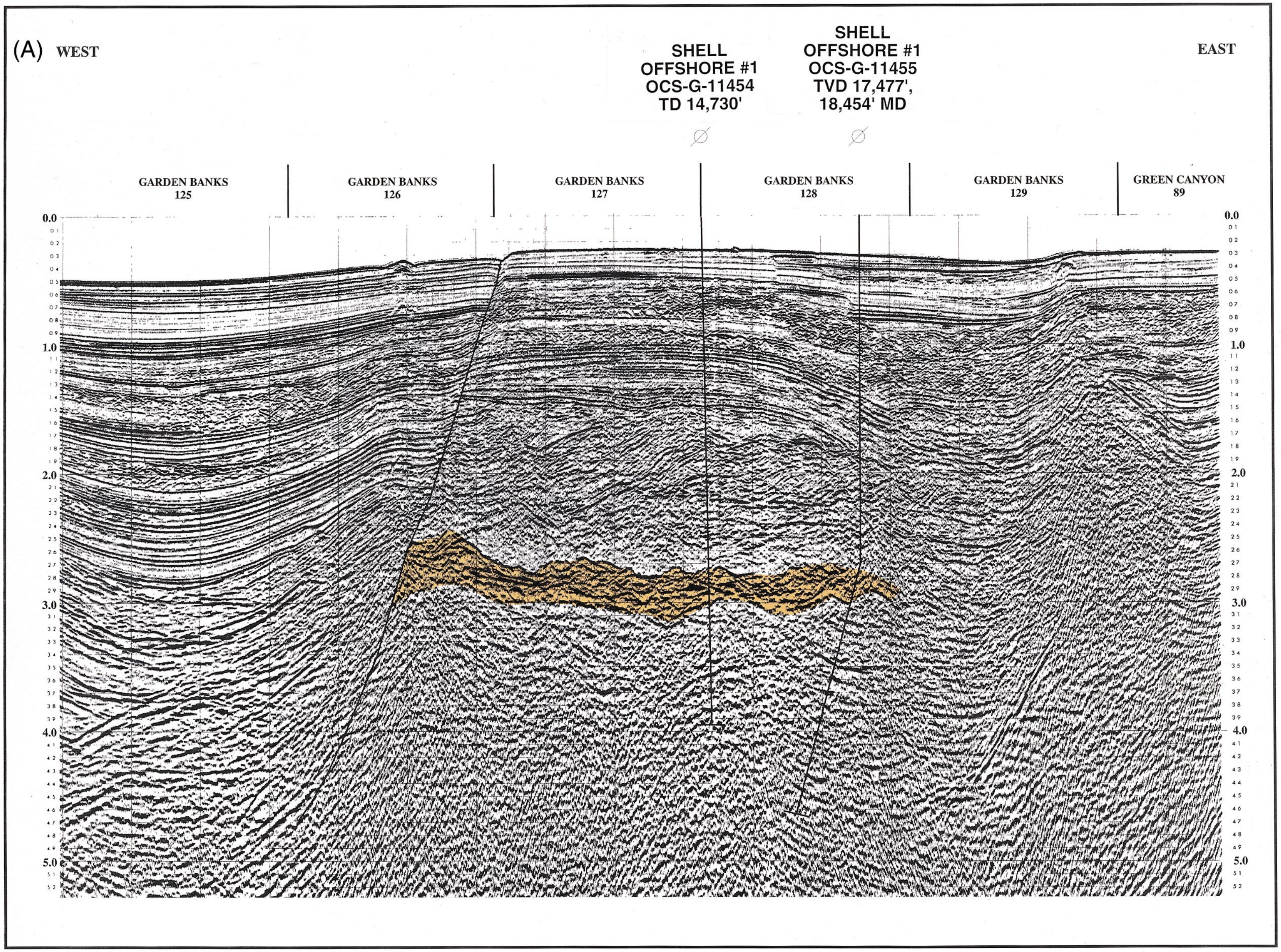

Figure 12—(A) Seismic profile and (B) well log from the Shell/Amerada Hess/Pennzoil Garden Banks #1 (Enchilada) subsalt discovery. (Data courtesy TGS and Geco-Prakla.)

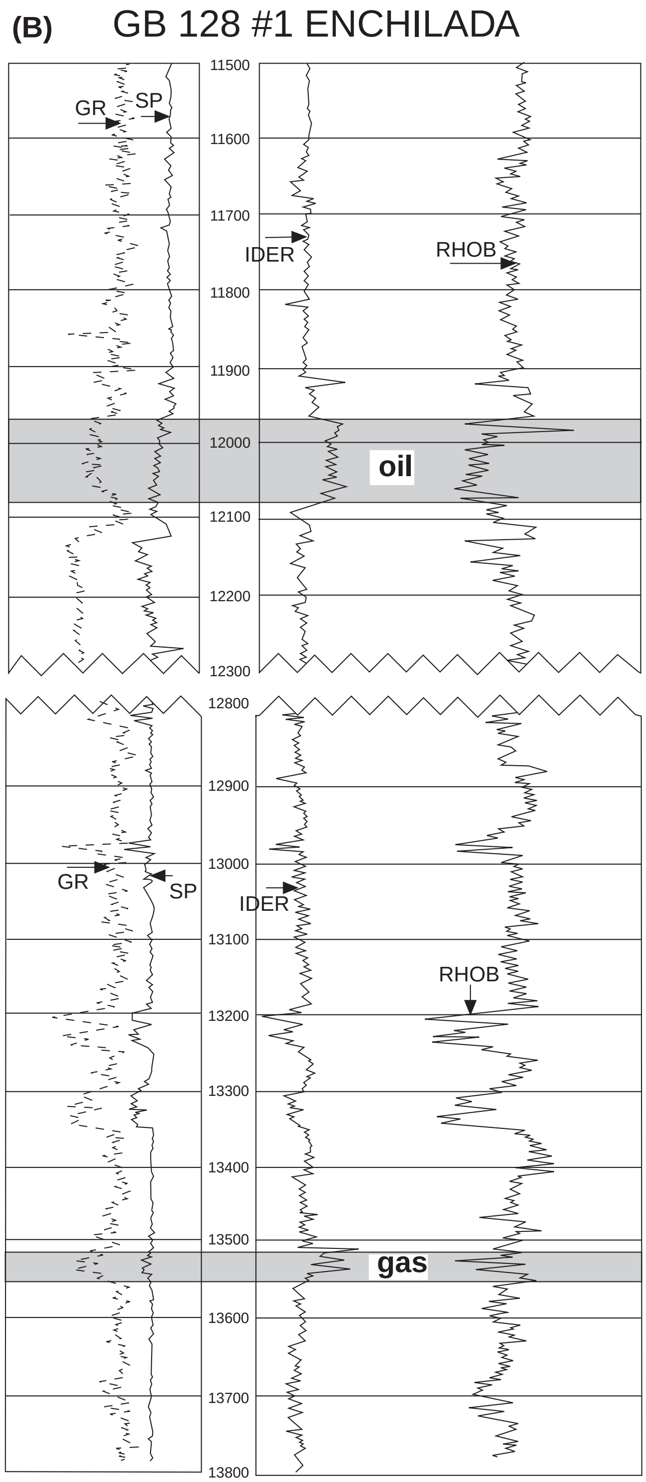

Figure 12—Continued.

updip from the Mahogany discovery, with excellent structural position beneath the same salt sheet. Such data were instrumental to the $40 million bid—a historical high for the play—offered for the relevant block at the April 1994 lease sale. Data from the Ship Shoal 337 #1 well remain confidential; the well was plugged and abandoned in mid-1996. Phillips and its partners will evaluate all data to determine if a second test should be drilled.

OUTLOOK

Any evaluation of the current and future status of the Gulf of Mexico subsalt play must take into account the following factors:

(1) As much as 60% of the outer continental shelf and upper slope in the northern Gulf of Mexico is covered by allochthonous salt, most of which occurs in sheets, tongues, and canopies less than 3000 ft (910 m) in thickness and in moderate water depths ranging from 250 to 2000 ft (75–660 m).

(2) Reservoir quality in sandstone fairways has been repeatedly determined to be good to excellent among more than 30 wells drilled with subsalt targets to date.

(3) Substantial infrastructure for hydrocarbon production already exists in this part of the Gulf, due to existing Pliocene–Pleistocene suprasalt and deep-water plays.

(4) Prospecting beneath salt bodies has been advanced in recent years due to technological advances in 3-D seismic acquisition processing and to continued improvement in geologic models (confirmed by recent drilling results), allowing for reservoir prediction.

(5) Experience in drilling deep, subsalt wells has led to considerable progress in the ability to manage common problems associated with penetrating salt and subsalt "gumbo" sections, thus promising continued decrease in overall well costs.

(6) Out of seven discoveries made to date, three have been deemed commercial and three have estimated ultimate reserves of more than 100 million bbl oil equivalent each.

Together, these factors argue that strong potential exists for the discovery of large petroleum resources from the outer continental shelf and upper slope. Current estimates by Phillips propose recovery of 1.2 billion bbl oil and 15 Tcf gas from 25 possible major fields located within the total prospect area of Figure 16. The feasibility for such level of discovery and development requires that significant challenges be met. Current indications are that these challenges will be successfully overcome and that the results will provide new tools and expertise for exploration generally. The subsalt play is thus a major new frontier that highlights the value of reexamining "known" provinces in the light of new techniques.

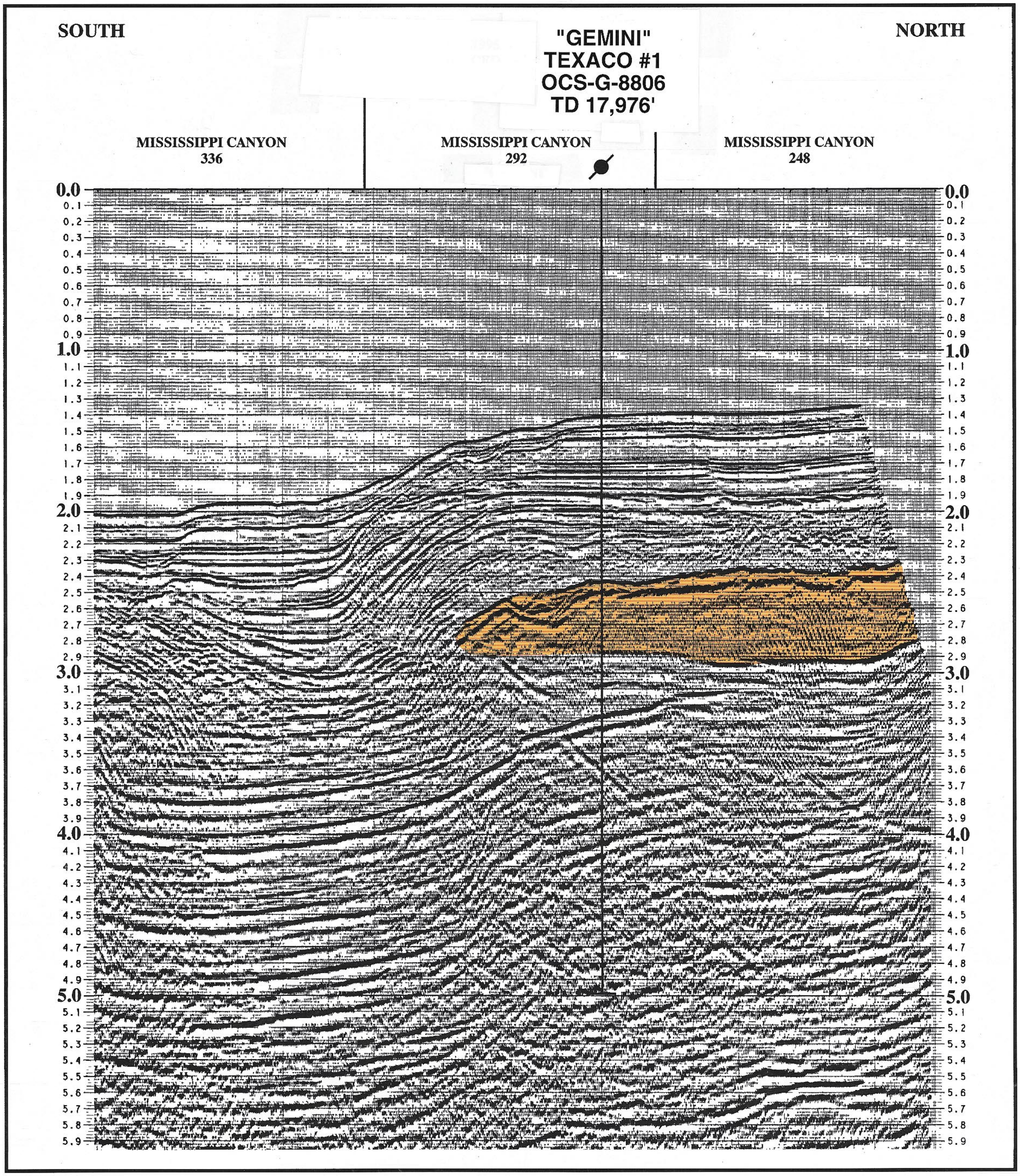

Figure 13—Seismic profile over the Texaco Mississippi Canyon 292 #1 (Gemini) subsalt discovery.

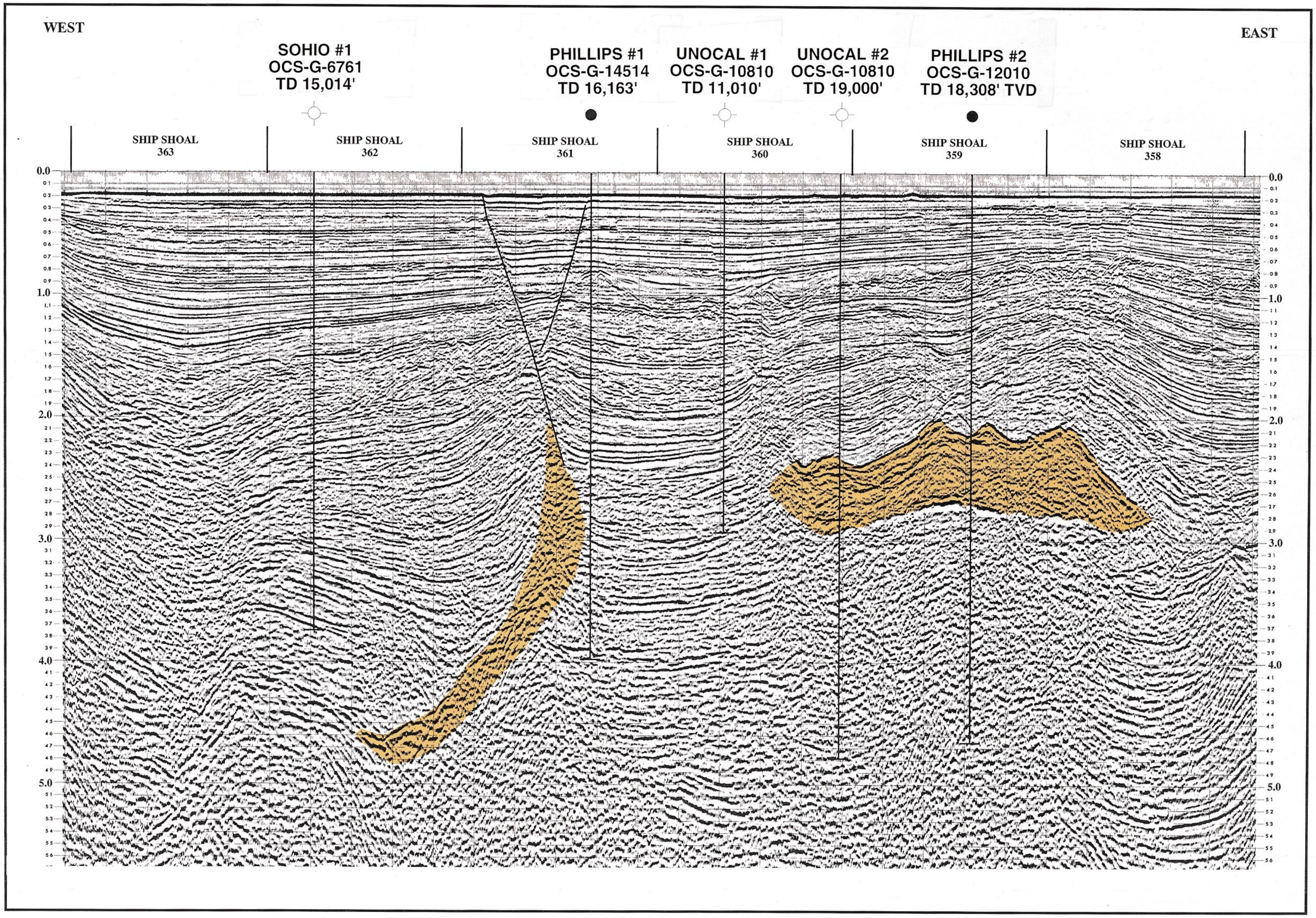

Figure 14—Seismic profile over the Phillips Ship Shoal 361 #1 (Agate) subsalt discovery. Also shown on this profile is the Mahogany discovery to the east. (Data courtesy TGS and Geco-Prakla.)

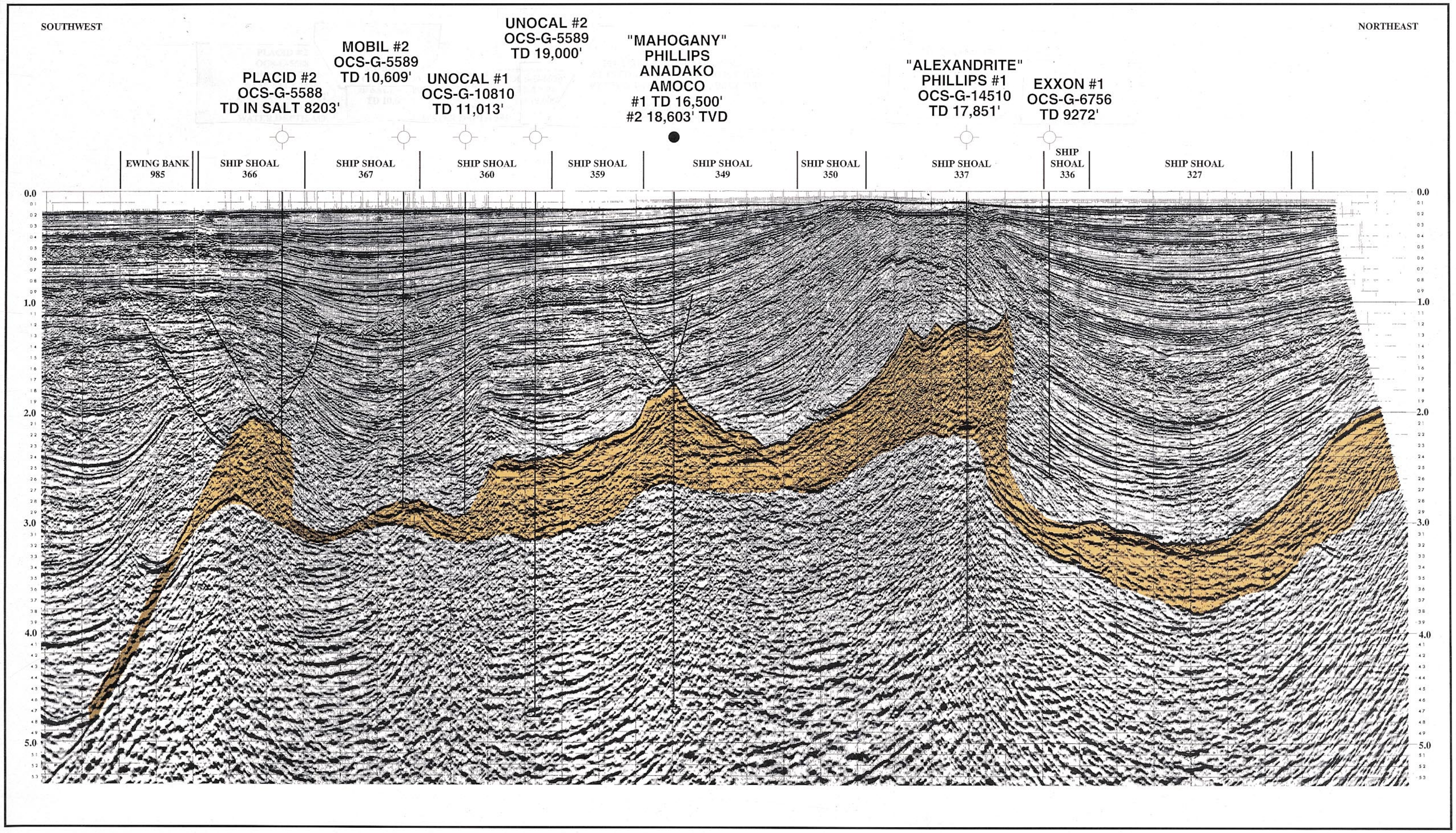

Figure 15—Seismic profile showing position of the Alexandrite prospect updip to the Mahogany discovery. (Data courtesy TGS and Geco-Prakla.)

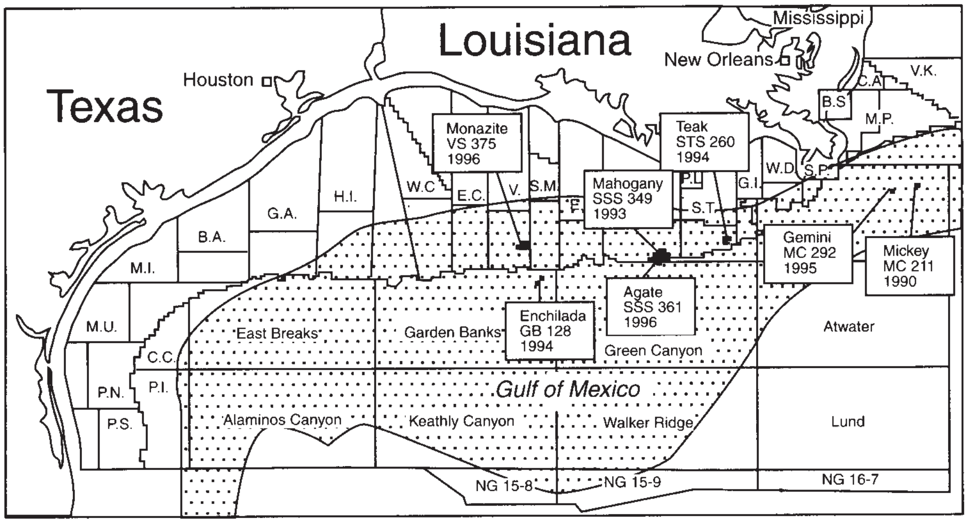

Figure 16—Map showing total estimated prospective area (stippled) for subsalt drilling, outer continental shelf and upper slope, offshore Texas and Louisiana, northern Gulf of Mexico. (After Moore and Brooks, 1997.)

REFERENCES CITED

Bradshaw, B. E., and J. W. Watkins, 1994, Growth fault evolution in offshore Texas: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 103–110.

Diegel, F. A., J. F. Karlo, D. C. Schuster, R. C. Shoup, and P. R. Tauvers, 1995, Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: a global perspective: AAPG Memoir 65, p. 109–151.

Ewing, T. E., 1991, Structural framework, *in* A. Salvador, ed., Gulf of Mexico Basin: Geological Society of America, Geology of North America, v. J. p. 31–52.

Harrison, H., and B. Patton, 1995, Translation of salt sheets with a basal shear model, *in* Salt, sediment, and hydrocarbons: Gulf Coast Section SEPM, 15th Annual Research Conference, p. 99–107.

Harrison, H., D. C. Moore, and P. Hodgkins, 1995, The Mahogany subsalt discovery: a unique hydrocarbon play, offshore Louisiana, *in* Salt, sediment, and hydrocarbons: Gulf Coast Section SEPM, 15th Annual Research Conference, p. 95–97.

Huber, W. F., 1989, Ewing Bank thrust fault zone, Gulf of Mexico, and its relationship to salt sill emplacement: Gulf Coast Association of Geological Societies Transactions, v. 39, p. 60–64.

Jackson, M. P. A., 1995, Retrospective salt tectonics, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: a global perspective: AAPG Memoir 65, p. 1–78.

McGuinness, D. J., and J. R. Hossack, 1993, The development of allochthonous salt sheets as controlled by the rates of extension, sedimentation, and salt supply, *in* Rates of geologic processes: Gulf Coast Section SEPM, 14th Annual Research Conference, p. 127–139.

Montgomery, S. L., 1995, Gulf of Mexico subsalt play: Petroleum Frontiers, v. 12, no. 1, 97 p.

Moore, D. C., and R. O. Brooks, 1995, The evolving exploration of the subsalt play in the offshore Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 45, p. 7–12.

Moore, D. C., and R. O. Brooks, 1997, U.S. Gulf subsalt evolves into successful play: Offshore Magazine, v. 57, no. 1, p. 30–36.

Moore, D. C., H. Harrison, and F. C. Snyder, 1995a, Sedimentary inclusions and internal salt stratigraphy within allochthonous salt sheets, offshore Gulf of Mexico: Gulf Coast Section SEPM, 15th Annual Research Conference, p. 193–194.

Moore, D. C., F. C. Synder, and S. S. Rutkowski, 1995b, Supra-salt stacked condensed sections (SCS): potential indicators of subsalt stratigraphy, *in* Salt, sediment, and hydrocarbons: Gulf Coast Section SEPM, 15th Annual Research Conference, p. 195.

Peel, F. J., J. R. Hossack, and C. J. Travis, 1995, Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: a preliminary analysis, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: a global perspective: AAPG Memoir 65, p. 153–175.

Ratcliff, D., and D. J. Weber, 1995, 3-D PreSDM reduces risk for subsalt exploration: American Oil and Gas Reporter, February 1995, p. 47–55.

Ratcliff, D. W., and D. J. Weber, 1997, Geophysical imaging of subsalt geology: Leading Edge, February 1997, p. 115–142.

Rowan, M. G., 1995, Structural styles and evolution of allochthonous salt, central Louisiana outer shelf and upper slope, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: a global perspective: AAPG Memoir 65, p. 199–228.

Schuster, D. C., 1995, Deformation of allochthonous salt and evolution of related salt-structural systems, eastern Louisiana Gulf Coast, *in* M. P. A. Jackson, D. G. Roberts, and S. Snelson, eds., Salt tectonics: a global perspective: AAPG Memoir 65, p. 177–198.

Snyder, F. C., and J. Nugent, 1995, Teak-testing a subsalt hydrocarbon trap geometry, South Timbalier Block 260, Gulf of Mexico, *in* Salt, sediment, and hydrocarbons: Gulf Coast Section SEPM, 15th Annual Research Conference, p. 257–267.

Weimer, P., P. Varnai, Z. M. Acosta, F. M. Budhijanto, R. E. Martinez, A. F. Navarro, M. G. Rowan, B. C. McBride, and T. Villamil, 1994, Sequence stratigraphy of Neogene turbidite systems, northern Green Canyon and Ewing Bank, northern Gulf of Mexico, *in* P. Weimer, A. H. Bouma, and B. F. Perkins, eds., Submarine fans and turbidite systems: Gulf Coast Section SEPM, 14th Annual Research Conference, p. 383–399.

Wu, S., A. W. Bally, and C. Cramez, 1990, Allochthonous salt, structure and stratigraphy of the northeastern Gulf of Mexico, part II: structure: Marine and Petroleum Geology, v. 7, p. 334–370.

ABOUT THE AUTHORS

Scott L. Montgomery

Scott L. Montgomery is a geologist, author, and translator residing in Seattle, Washington. He received his B.A. degree in English from Knox College in 1973 and his M.S. degree in geological sciences from Cornell University in 1978. He is the author of the quarterly monograph series *Petroleum Frontiers*, published by Petroleum Information Corporation, and of books and articles on the history of science. His current research interests include frontier plays and technologies and various topics in the history of geology and astronomy.

Dwight "Clint" Moore

Dwight "Clint" Moore is Offshore Exploration Geological Supervisor for Anadarko Petroleum Corporation in Houston, Texas, and grew up as a son of late Mississippi wildcatter, Alfred C. Moore. He received his B.A. degree in geology, and his B.B.A. degree in finance (both cum laude) with a minor in economics from Southern Methodist University in 1978. He has chosen to work the offshore Gulf of Mexico nearly all of his 19-year geological career, for the first 10 years with Diamond Shamrock (Maxus), and with Anadarko Petroleum since 1988. He was also senior business analyst for Maxus and was involved with the 1987 reorganization of Diamond Shamrock that resulted in the creation of Maxus. He has been the 1994–1995 president of the Houston Geological Society, and editor-in-chief of the Houston Geological Society/New Orleans Geological Society guidebook entitled *Productive Low Resistivity Well Logs of the Offshore Gulf of Mexico*. His scientific interests involve salt emplacement models, deep-water sedimentation systems, and low-resistivity petrophysical analysis. He has published several articles on subsalt topics, and has spoken to many scientific organizations on the subject as well.