Geologic Model and Reservoir Description of the Deepwater "P Sand" at Subsalt Mahogany Field, Gulf of Mexico

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Abstract

An integrated conceptual geologic model has been developed to aid exploitation strategies for the deepwater, thin-bedded P sand reservoir at Mahogany field. The oil pay occurs primarily within the upper member of the P sand that is interpreted as submarine channel-levee deposit. Reservoir quality is primarily a function of grain size and clay content, and is facies dependent. Proximal levee, distal levee, basal levee and channel-fill facies are described. Maximizing production rates and ultimate recovery requires an understanding of the distribution of the various facies types that is predicted by the geologic model. Applications of this model may extend beyond Mahogany field, providing an analog for exploration and development of other subsalt and deepwater projects in the Gulf of Mexico.

Introduction

Geologic models have wide applications that affect many decisions throughout the life of a project, ranging from initial exploration through field development and enhanced recovery. Successful geologic models integrate geologic, geophysical and engineering disciplines; are adaptable to various scale requirements; and are flexible to incorporate new information. The predictive capabilities of geologic models make them useful not only for the specific locations from which they were developed, but also as instructive analogs for other areas.

This paper describes a conceptual geologic model that was developed to guide exploitation decisions for the P sand reservoir at Mahogany field. The geologic model has evolved with time and integrates the latest information available from six wells, 3-D seismic and production data. Reservoir descriptions, and interpreted depositional facies units, were based on conventional and sidewall cores that were described and used to calibrate well log data. Three-dimensional pre-stack depth migrated seismic was used to map facies units beyond the existing well control. Seismic modeling, including 3-D ray tracing, helped to constrain seismic interpretations. Bottom hole pressure measurements and production logs provide additional information and were used to corroborate predicted

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reservoir flow characteristics and lateral reservoir connectivity.

Geologic Setting

The subsalt play, as defined by drilling through 1998, extends over 480 km (300 mi) in length, from the outer continental shelf to the upper slope, in water depths ranging from 55 to 1340 m (180-4400 ft) (Figure 1). The current play area, however, represents only a fraction of the potential play area that is defined by tabular salt bodies extending up to 240 km (150 mi) south of the present-day shelf margin to the Sigsbee Escarpment in water depths exceeding 2100 m (7000 ft). Primary objectives include deepwater Miocene to Pleistocene sandstone reservoirs in a variety of structural and stratigraphic traps below allochthonous salt sheets of probable Jurassic age. Mahogany field is located in 115 m (375 ft) of water on the outer continental shelf in Ship Shoal South Addition Blocks 349 and 359 (Figure 2).

Several deepwater sandstone oil reservoirs occur entirely below a laterally extensive salt sheet that is approximately 1160 m (3800 ft) thick at Mahogany field. Current production occurs from three main reservoirs, informally named in descending order, the O, P and Q sands. The P sand is currently the primary development drilling objective and focus of this paper. Deeper R, S and T sands that have been penetrated to date are water bearing and remain as important exploratory objectives.

Field and Play History

Mahogany field was discovered in 1993 and is the first producing field in the subsalt play of the Gulf of Mexico. Through September 1998, six wells have been drilled and completed. First production was in December 1996 following installation of a 20-slot, conventional fixed platform in August 1996. Daily production reached 19,900 BO and 33 MMCFG with the completion of the fifth well in February 1998. A seventh development well has begun drilling and additional exploitation wells, and recompletions and workovers of existing wells are being evaluated.

The success at Mahogany field proved the viability of a new play that was largely the result of applying new and emerging technologies to a frontier play in a mature drilling province (Camp and McGuire, 1997). The Mahogany discovery demonstrated the potential for high flow rates in the subsalt play and helped to turn around declining exploration trends in the Gulf of Mexico. Only seven wells were drilled in the subsalt play during the ten-year period prior to the Mahogany discovery. Since the Mahogany discovery, 37 new field wildcat wells have been drilled in the play by 16 different operators, resulting in 13 new discoveries through 1998 (Figure 2).

Three subsalt fields are currently producing: Mahogany (Ship Shoal 349), Agate (Ship Shoal 361) and Enchilada (Garden Banks 128). Gemini field (Mississippi Canyon 292) is anticipated to commence production in mid-1999 (Figure 2). Exploration activity in the subsalt play remains high with six exploratory wells drilled during 1998 resulting in three new discoveries: Atlantis (Green Canyon 699), Tanzanite (Eugene Island 346) and Hickory (Grand Isle 116). Delineation drilling has begun at Tanzanite and Hickory fields, and the remaining discoveries await further evaluation.

Reservoir Description

Upper P Sand Member

Gross thickness of the P sand at Mahogany field ranges from 30 to 107 m (100 to 350 ft) and it is informally divided into upper and lower members. The oil pay occurs mainly within the upper member that is composed primarily of thin-bedded, very fine-grained, ripple- and parallel-laminated sand interbedded with laminated silty claystone. A thick-bedded, massive, fine- to medium-grained sand, with rare rounded mudstone clasts, occurs at the base of the upper member in most wells, forming a sharp basal contact with the underlying mudstones. This unit is referred to as the basal levee sand and defines the base of the upper P sand unit (Figure 3).

Levee-Overbank Facies

The thin-bedded rippled and laminated units of the upper P sand are interpreted as levee and overbank deposits flanking a submarine channel. Although the individual sand beds of the levee deposits are very thin, they exhibit very good reservoir quality. Average core porosity of the levee sands is 25% (range 18 to 30%) and average core permeability is 136 md (range 1.3 to 560 md). The levees are further divided into proximal and distal facies with distinct reservoir characteristics. Proximal levee deposits are thicker, have higher net-to-gross sand ratios, and generally contain less shale matrix than the distal levee deposits, and thus exhibit greater reservoir quality. For example, the proximal levee facies in the A-1 well has a net-to-gross sand ratio of 0.69 and average core permeability of 160 md, compared to 0.47 net-to-gross sand and average core permeability of 81 md from the distal levee facies in the A-5 well.

Basal Levee Facies

The ungraded, homogeneous bedding of the basal levee sand is probably due to very rapid sedimentation. This basal sand unit attains a maximum thickness of about 10 m (30 ft) and is interpreted as a submarine crevasse splay deposited by unconfined, high-density turbidity flows. The lens-shape sand geometry and presence of levee deposits directly overlying the massive sand is inconsistent with a channel sand interpretation for the basal levee unit based on aggradational deepwater channel models.

Core from the basal levee sand is similar to massive sands that occur at the base of other interpreted fining-upward levee deposits in the Gulf of Mexico, e.g. the J sand at Ram/Powell field (Clemenceau, 1995). Although the basal levee sand comprises only a small portion of the total P sand reservoir volume, it represents the best quality sand, with up to 1.0 net-to-gross sand, and average core porosity and permeability measurements of 33% and 4,952 md, respectively.

Lower P Sand Member

The lower P sand is composed of three to four discrete sand bodies, 6 to 21 m (20-70 ft) thick, separated by intervening mudstones (Figure 3). The sandstone bodies are typical thin-bedded turbidites, composed of very fine- to fine-grained, unconsolidated sand interbedded with silty mudstone. Sedimentary structures include parallel laminations, ripple cross laminations and climbing ripple stratification. Log analysis indicates cleaner, thicker bedded intervals 3 to 5 m (10 to 15 ft) thick are locally present, particularly towards the base of the lower P sand member (Figure 3).

The lower P sands pinch out to the southwest (Figure 3), and appear to form tabular or sheet-like sandstone bodies based on log correlations that indicate continuous sand bodies extending into the basin over 3 km (2 mi) to the northeast. The lower P sands are interpreted as depositional lobe deposits and are similar to the layered sheet sands described by Chapin et al. (1994).

Geologic Model

Development Strategies

The upper P sand body forms two wedge-shaped units that thin away from the A-2 well. The A-2 well is interpreted to have penetrated a predominately shale-filled channel (Figure 3). The orientation of this channel is critical to the geologic model as it has several implications for development drilling. These include: (1) the channel facies is predominately shale and thus non-productive, (2) the shale-filled channel may form a permeability barrier isolating the western and eastern levees into separate reservoir units, and (3) thicker, better quality reservoir sands are associated with the proximal levee deposits that parallel the channel margins.

The P sand channel is interpreted to be oriented northeast-southwest based on a trend of low seismic amplitude values extracted from the P sand horizon such as at the A-2 well (gray to yellow, Figure 4). Higher amplitude values (red to pink) located west and east of the channel, such as at the A-1 and A-6 wells, are associated with thicker upper P sands and are interpreted as proximal levee deposits. Lower amplitude values at the A-5 well (yellow to orange) are related to a thinner upper P sand interval and are interpreted as distal levee or overbank deposits. The orientation of the channel to the south becomes problematic based solely upon seismic amplitude interpretations. The channel is mapped west of the A-4 and A-6 wells as pressure data indicates that these two wells are in pressure communication. It is therefore unlikely that the impermeable, shale-filled channel exists between these two wells.

Another important aspect to developing the P sand is predicting the distribution of the basal levee sand. Understanding the distribution of this high flow capacity unit is critical to selecting development well locations and completion strategies to maximize production rates and recovery, and to reduce potential premature water breakthrough.

The massive, basal levee sand is mapped as a continuous sand unit connecting the eastern and western levees below the shale-filled channel (Figure 3). Reservoir connectivity between the east and west levees is supported by common original oil/water contacts. The basal levee sand is interpreted to pinch out to the west below distal levee deposits, however the eastern limits have yet to be defined by drilling.

Depositional History

Lower Lobe (Sheet) Sands

P sand deposition at Mahogany field began with the unconfined lobe or sheet-like deposits of the lower member presumably deposited at the mouths of upstream submarine channels (Figure 5a). The lower P sands are only present in a few wells in the northeast portion of the field and are thought to be concentrated in a paleodepocenter associated with salt withdrawal east of the field. A paleobathymetric high may have been present to the north related to early movement of the Mahogany salt sheet. Continued southward movement of the Mahogany salt sheet resulted in salt completely covering the P sand and younger deposits.

Channel-levee deposits of the upper P sand member overlie the lower P sand lobe deposits. Deposition of the upper P sand channel-levee complex is thought to be a result of a channel bifurcation process as described for the Amazon fan by Flood et al. (1995) and Pirmez et al. (1997), and is divided into three stages: (1) early channel-levee, (2) channel avulsion, and (3) late channel-levee (Figure 5b-5d).

Early Channel-Levee

The location of the early channel-levee system is poorly constrained, but it is thought to have been deposited in the northwest portion of the field based on a relatively thick interval of thin-bedded, levee-overbank sands penetrated in the Unocal Ship Shoal 360 #2 well (Figure 5b). The correlative P sands in the 360 #2 well are water bearing and occur below the Mahogany field oil-water contact. They may also be separated stratigraphically from the productive P sand levee deposits. The gross P sand interval in the 360 #2 well is thicker than what would be predicted by westward thinning trends established by the levee-overbank deposits between the A-1 to the A-5 wells, indicating separate levee deposits.

Basal Levee Sand

The early leveed channel was later breached by high-density turbidity currents resulting in the deposition of the basal levee sand in the inter-channel low east of the early channel-levee system (Figure 5c). The massive character of this sand is indicative of very rapid deposition, and the rounded mudstone pebbles are probably clasts derived from levee and overbank deposits by erosive turbidity currents during channel avulsion.

Late Channel-Levee

A new, active channel prograded basinward from the bifurcation point at the breach in the early levee. Levee and overbank sands were deposits over the basal levee sand and earlier deposits associated with the abandoned channel (Figure 5d). Schematic well locations are shown with reference to the interpreted upper P sand facies: proximal levee (A-1 and A-6 wells), distal levee (A-5 well) and channel-fill facies (A-2 well).

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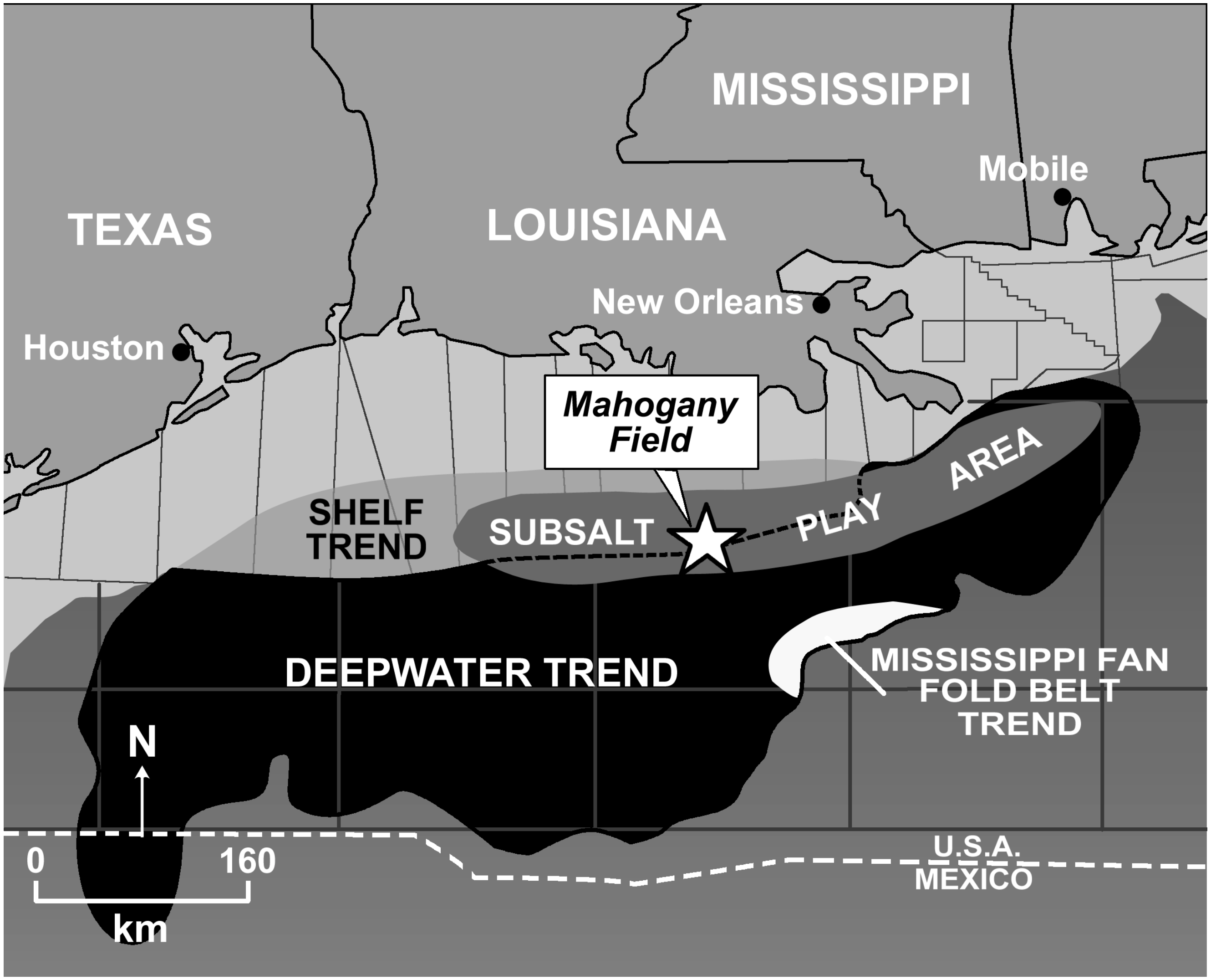

Figure 1 Location of Mahogany field and subsalt play area defined by drilling through 1998, offshore Gulf of Mexico. Larger potential play area divided into shelf, deepwater and Mississippi Fan fold belt trends.

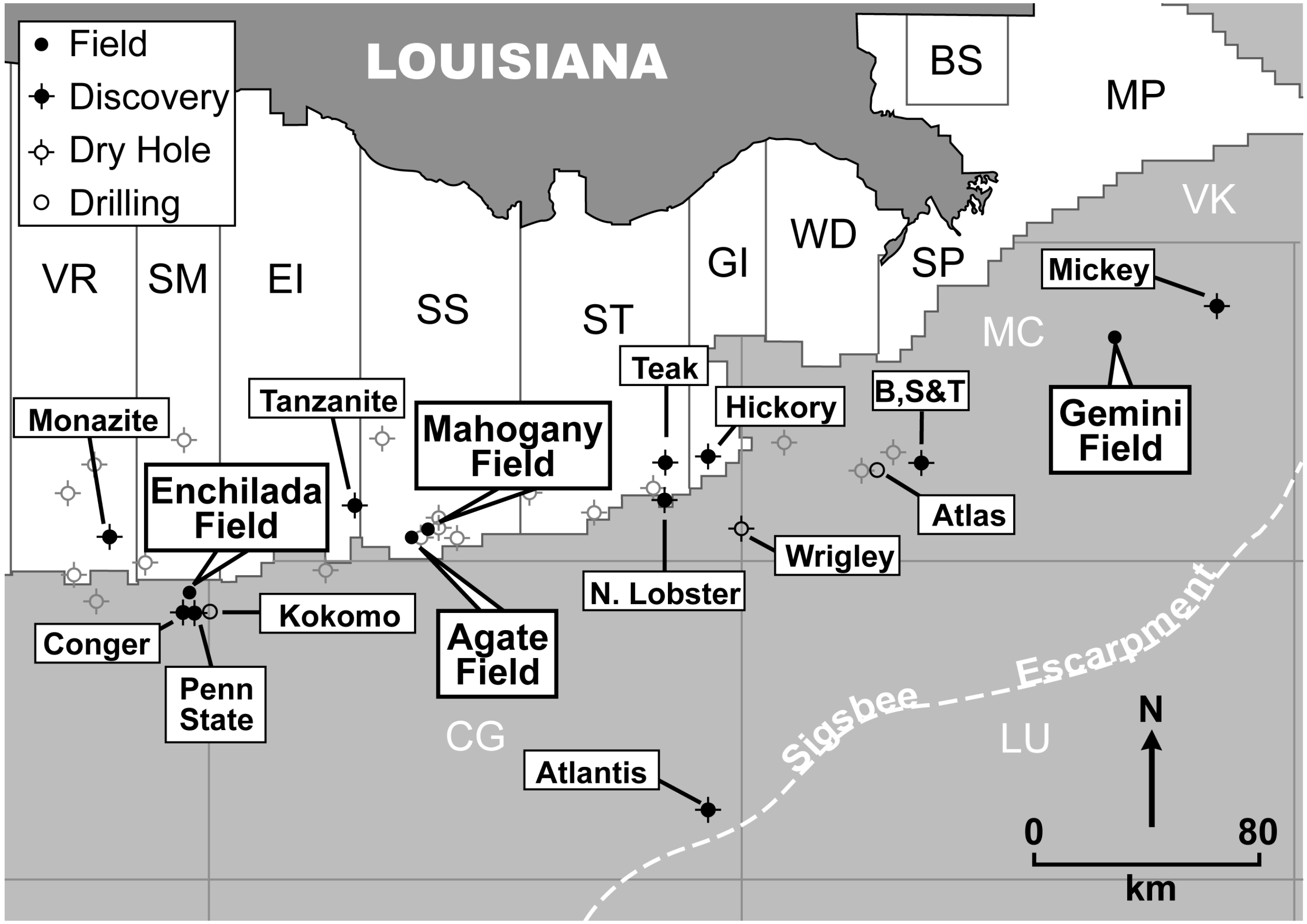

Figure 2 Subsalt drilling activity 1990-1998, offshore Louisiana. VR=Vermilion, SM=South Marsh Island, EI=Eugene Island, SS=Ship Shoal, ST=South Timbalier, GI=Grand Isle, GC=Green Canyon and MC=Mississippi Canyon Federal Offshore Protraction Areas.

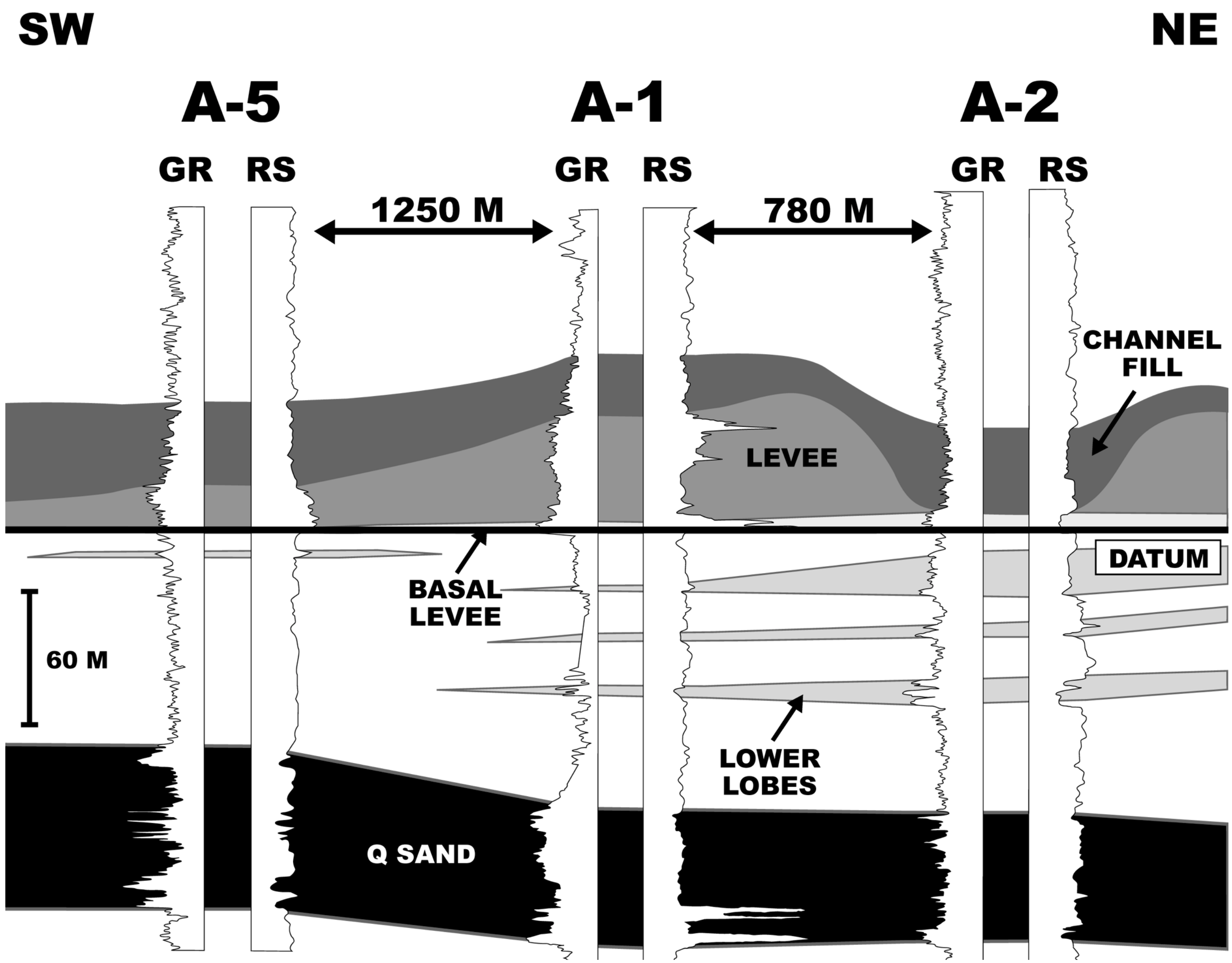

Figure 3 SW-NW stratigraphic cross section, datum base upper P sand member. Upper P sand divided into levee, channel fill and basal levee facies. Lower P sand lobes pinch out to the southwest. See Figure 4 for location of wells. GR=gamma ray and RS=shallow resistivity log curves.

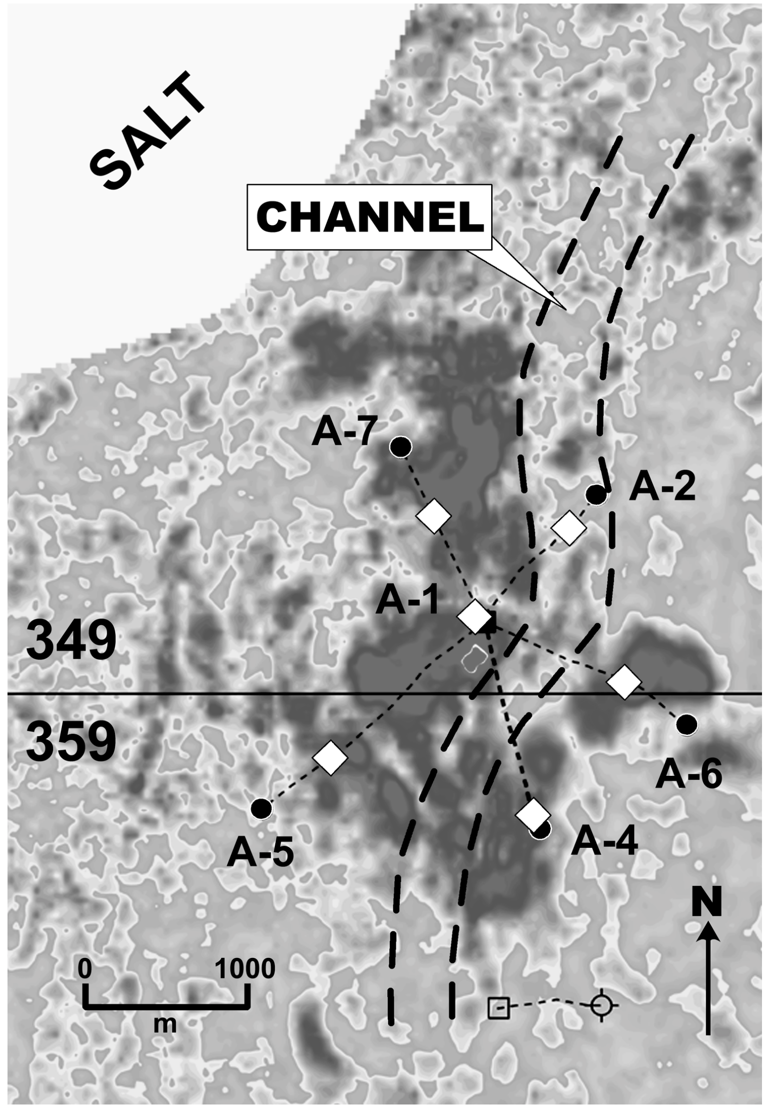

Figure 4 Three-dimensional seismic amplitude map of P sand horizon at Mahogany field. Interpreted shale-filled channel (dashed lines) follows trend of low seismic amplitude values (yellow to orange) as penetrated by A-2 well. High seismic amplitude areas (red to pink) are associated with levee deposits. P sand penetration points indicated by white diamond shapes.

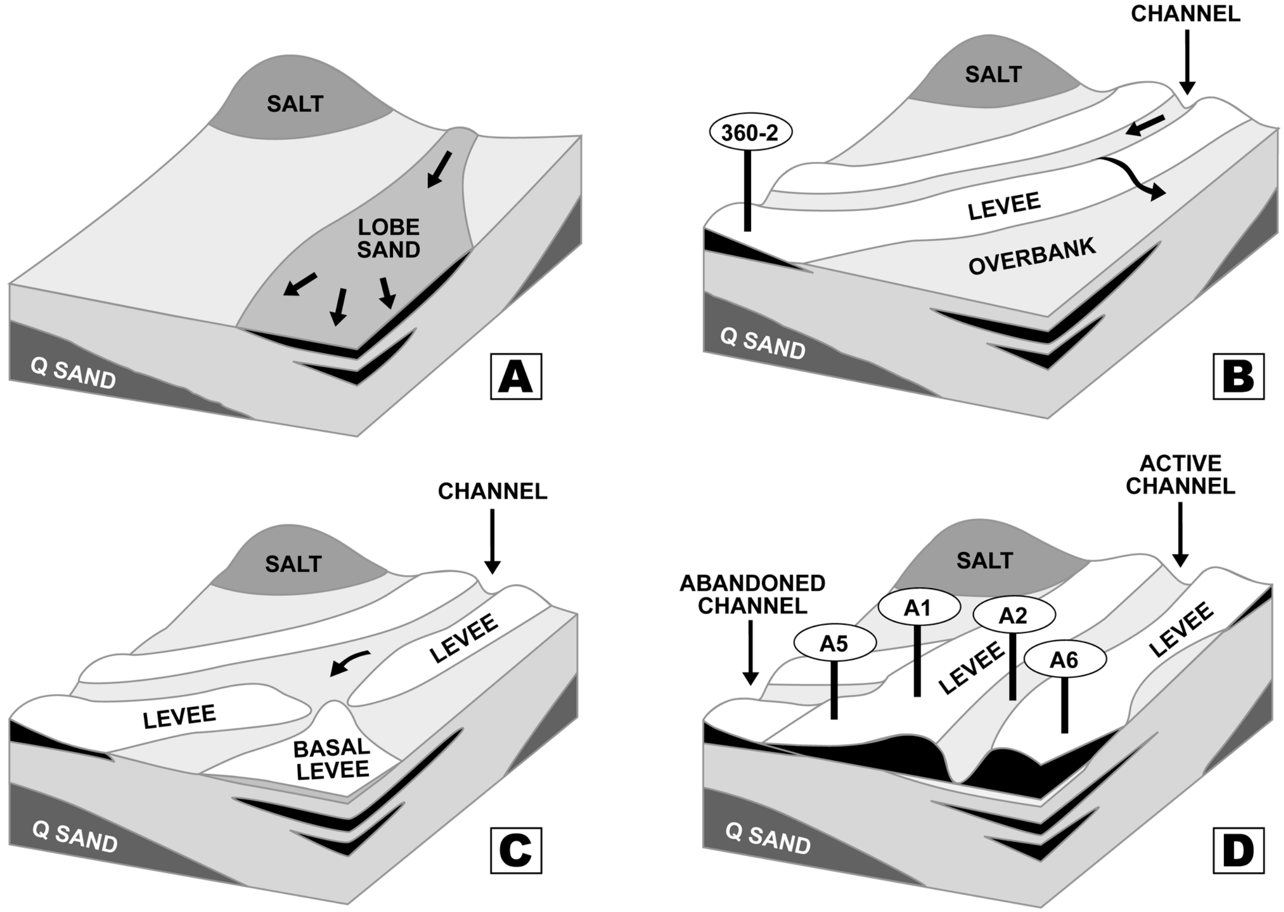

Figure 5 Depositional model of the P sand at Mahogany field (north to the top of the block diagrams). (A) Lower P sands deposited as unconfined lobe or sheet-like deposits in eastern salt-withdrawal basin. (B) Early channel-levee system of the upper P sand as penetrated by the 360 #2 well. (C) Basal levee sand deposited as a crevasse splay deposit due to breaching of the early leveed channel. (D) Late channel-levee deposited over basal levee sand and levee-overbank deposits associated with the early, abandoned channel. Schematic locations of A-1, A-2, A-5 and A-6 wells are shown with reference to interpreted proximal levee, distal levee and channel-fill facies.