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# Depositional Systems and Structural Controls of Hackberry Sandstone Reservoirs in Southeast Texas

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# DEPOSITIONAL SYSTEMS AND STRUCTURAL CONTROLS OF HACKBERRY SANDSTONE RESERVOIRS IN SOUTHEAST TEXAS


by

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## ABSTRACT

Deep-water sandstones of the Oligocene-age Hackberry unit of the Frio Formation contain significant quantities of oil and gas and remain potentially one of the most productive exploration targets in southeast Texas. The Hackberry is a wedge of sandstone and shale containing bathyal fauna that separates upper Frio barrier-bar - strandplain sandstones from lower Frio neritic shale and sand. Major Hackberry sandstones lie atop a channeled unconformity that forms the base of the unit. Sandstones in a typical sand-rich channel at Port Arthur field grade upward from a basal, confined channel-fill sandstone to more widespread, broad, fan-channel deposits. Topmost are proximal to medial fan deposits and overbank turbidite deposits. The sequence suggests that Hackberry sandstones were laid down by an onlapping submarine canyon - fan complex deposited in canyons that eroded headward into the contemporaneous Frio barrier system. Regional maps and seismic interpretations outline a network of sand-filled channels extending from the barrier toward the southeast.

The earliest structural activity of the Port Arthur area is lower Oligocene (Vicksburg) faulting associated with continental-slope sedimentation. Small growth faults of late Oligocene (Frio) age displace the Hackberry section less than 500 ft and extend upward into Miocene strata. Isopach and isolith maps indicate that the Orange, Port Neches, and Fannett salt domes were active uplifts during Frio and Anahuac (lower Miocene) deposition. Near Spindletop dome, however, only a north-south-trending salt-cored ridge is present. The Hackberry channels are in part located in salt-withdrawal basins, but major channel axes extend across the uplifts.

Time versus depth plots of water depth and sediment thickness indicate that most of the Hackberry Embayment in Texas could have been formed by normal subsidence during the later Oligocene if the embayment were cut off from its supply of muddy sediment. Thick, sandy, lower Hackberry deposits filled deep canyons eroded into the retreating shelf margin.

**Keywords: Frio Formation, growth faults, Gulf Coast, Jefferson County, oil and gas fields, Orange County, reservoir rocks, salt tectonics, Texas, turbidites.**

The Hackberry contains two hydrocarbon plays. The updip play is relatively shallow and oil-rich and lies near the updip limit of deep-water deposition. Some of the fields in this play produce from barrier-bar - strandplain Frio sandstones erroneously correlated with the Hackberry. The downdip play is gas-rich and generally geopressured. The reservoirs lie either within or on the flanks of the major channel systems and are commonly bounded updip by small growth faults. Understanding the component depositional environments represented by the discontinuous and complex lithofacies of these sandstones will improve hydrocarbon exploration and production.

## INTRODUCTION

The Frio Formation is one of the major clastic progradational units of the Texas Gulf Coast Basin (Galloway and others, 1982). Two large delta systems, the Norias in South Texas and the Houston in East Texas, prograded more than 60 mi basinward of the previous continental margin and in the process created large growth-fault systems and stimulated salt tectonics. Barrier-bar - strandplain systems extended between the main deltas (forming the Greta/Carancahua system) and east of the Houston delta into Louisiana (forming the Buna system) (fig. 1). Both of these barrier-bar - strandplain systems prograded the shelf margin seaward and are also associated with regional growth faults.

Shale and sandstone of the Hackberry Member form a seaward-thickening wedge (the Hackberry Embayment) in southeast Texas and southwest Louisiana that lies within the Frio marine succession (fig. 2). The wedge pinches out to the north along a zone that Bornhauser (1960) termed the "Hartburg flexure." The term "Hackberry" was first used for the bathyal (deep-water) foraminiferal assemblage at Hackberry salt dome in Louisiana by Garrett (1939) but was later generalized as a member or facies of the Frio by Bornhauser (1960) and Paine (1968).

Over most of the embayment, the lower Hackberry is a sand-rich unit that fills channels eroded as much as 800 ft into pre-Hackberry sediments (fig. 3). Previous studies have indicated

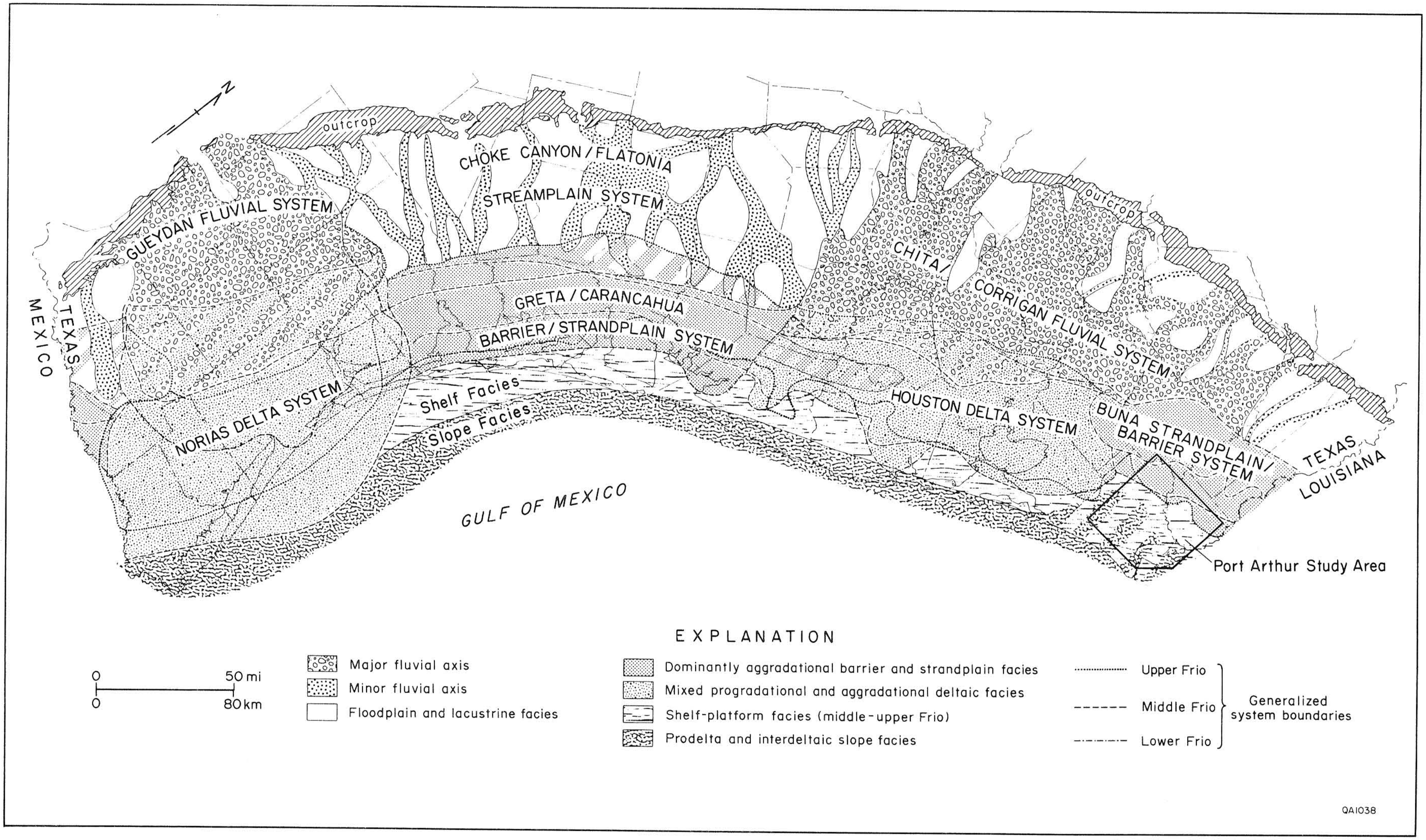


Figure 1. Depositional systems of the Frio Formation (from Galloway and others, 1982) and location of the Port Arthur study area.

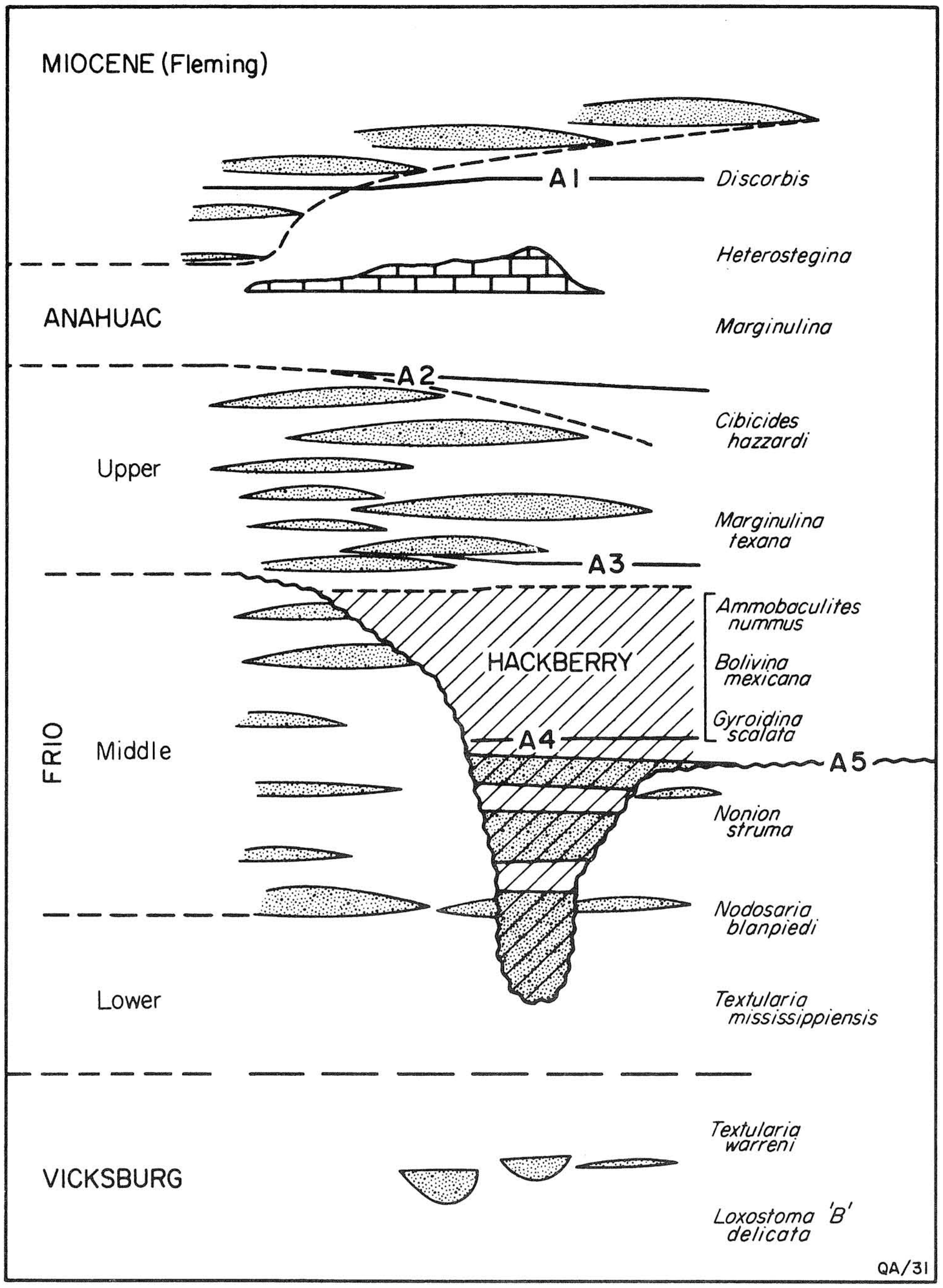


Figure 2. Stratigraphic diagram of Frio and related strata, Jefferson County area, and diagnostic foraminifers, sand-body distribution (shaded), and marker horizons used for this study (A1 through A5).

that these sands were deposited in a submarine canyon-fan environment (Paine, 1968; Brown and Fisher, 1977; Berg and Powers, 1980). A more uniformly distributed, seaward-thickening wedge of shale overlies the lower Hackberry sands; it grades upward into upper Frio sediments of shallow-water origin. The lower Hackberry sands are productive oil and gas reservoirs; exploration for deeper geopressured gas fields is continuing.

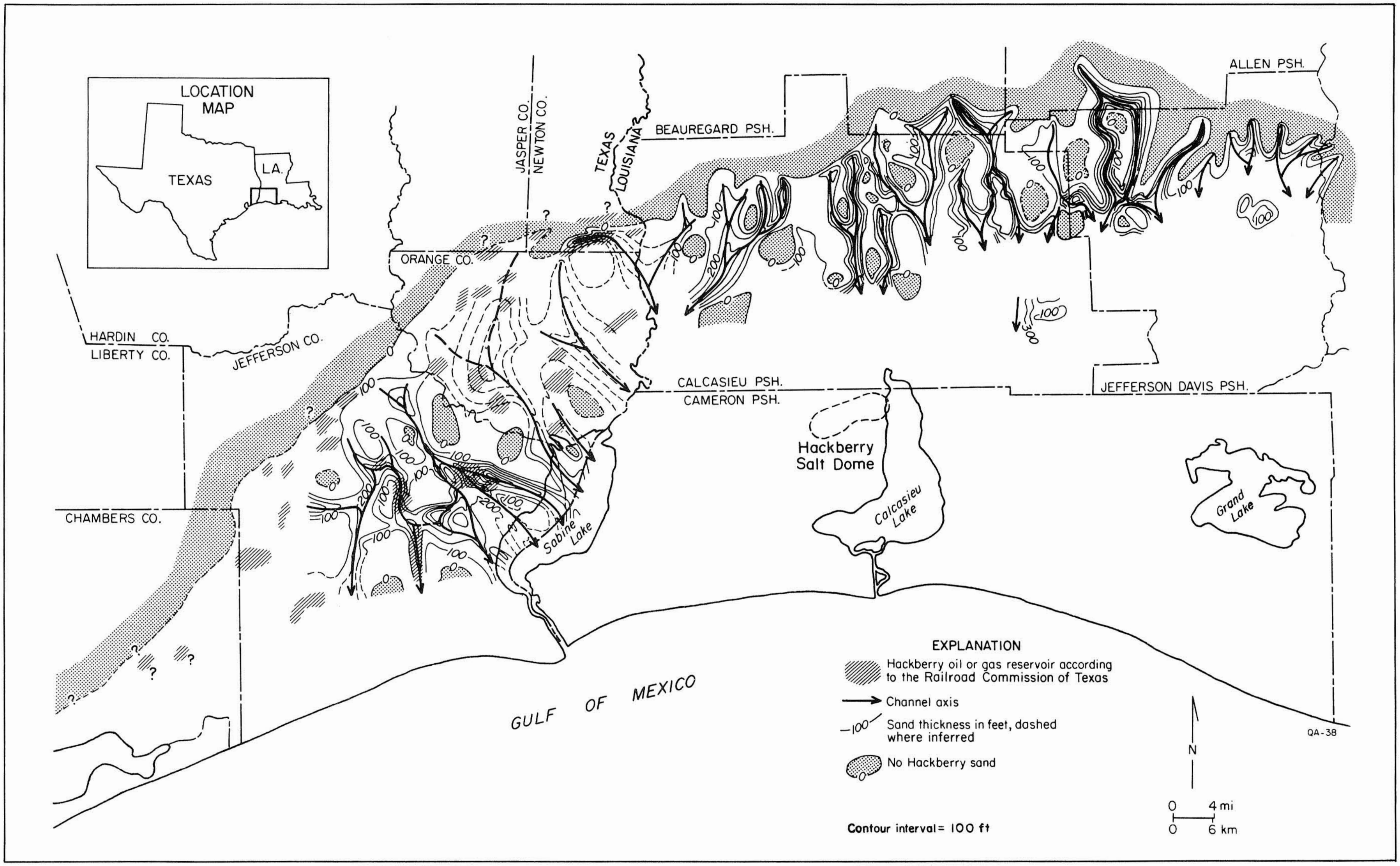


Figure 3. Regional distribution of sand-bearing lower Hackberry channels in the Hackberry Embayment. Louisiana data from Paine (1968); Texas data from Bornhauser (1960) and this study. The type locality of the Hackberry at Hackberry salt dome is also shown.

No adequate regional structural and stratigraphic study of the Hackberry of southeast Texas has previously been published. Thus, the location of the major submarine channels, the geometries of the sandstone bodies, and the evolution of the Hackberry depositional system are poorly known. Reedy (1949) published a regional study of the Frio Formation in southeast Texas. Berg and Powers (1980) described cores from two wells in Jefferson County. The Port Arthur field, which produced gas and condensate from Hackberry sandstone reservoirs from its discovery in 1959 until its abandonment in 1980, has been described by Halbouty and Barber (1961) and Weise and others (1981). The field has also been studied by researchers at the Bureau of Economic Geology as a candidate for enhanced gas recovery (Gregory and others, 1983).

To understand the geologic setting and the characteristics of the reservoirs, we selected a study area centered on the Port Arthur field. The area extends from the updip limit of the Hackberry wedge to the downdip limit of well control in Jefferson County, Orange County, and adjacent parts of Louisiana (fig. 4). We correlated more than 220 logs of deep wells, and we used paleontological data to pick the sub-Hackberry unconformity and to define the lower Frio and Vicksburg units. Six seismic sections were used to determine the structure and distribution of channels downdip from the Port Arthur field. Information from seismic sections and well logs was merged to produce structure and sand maps. In addition, we studied the geophysical logs of wells in Port Arthur field to analyze sandstone facies.

## FRIO FORMATION STRATIGRAPHY, PORT ARTHUR AREA

The Frio Formation (upper Oligocene) in the Port Arthur area ranges from about 2,000 ft to more than 6,000 ft thick, increasing basinward. The updip part of the area consists of stacked barrier-bar and strandplain sandstones of the Buna barrier system. Downdip the sandstone content decreases, and sandstones and shales of deep-water origin become dominant.

The Frio can be divided into three units (fig. 2). The lower unit (between the top of the Vicksburg at the Textularia warreni horizon and the Nodosaria blanpiedi horizon) is thin and sandstone poor and is lithologically similar to the underlying Vicksburg. The middle unit (from

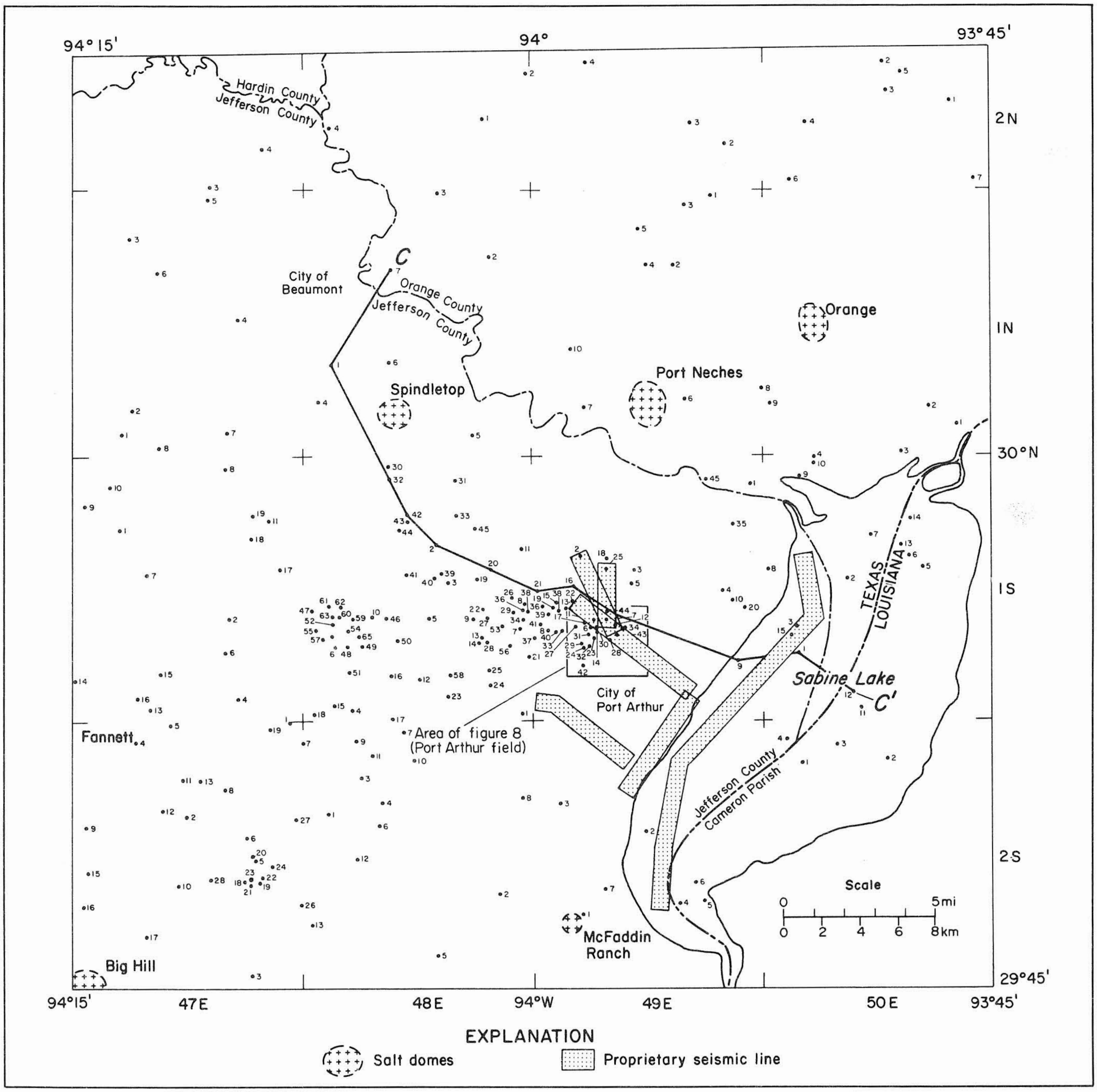


Figure 4. Location map of the Port Arthur area showing wells used for correlation and general locations of seismic lines and line of cross section C-C' (fig. 5).

the Nodosaria blanpiedi to about the Marginulina texana horizon) contains abundant sandstone updip but only a few discontinuous sandstones of indeterminate origin downdip. This unit is extensively eroded at the sub-Hackberry unconformity, so that its original thickness is difficult to determine. The Hackberry wedge lies between the Nonion struma horizon and the Marginulina texana horizon, that is, in the upper middle Frio. The upper Frio consists of sandstone updip and alternating sandstone and shale downdip. These sandstones contain upward-coarsening cycles and are continuous along strike, but they shale out fairly abruptly downdip and are inferred to be barrier-bar or strandplain sand bodies, or both. The upper Frio sand system prograded with time, capping the deep-water Hackberry shale (fig. 5). It is overlain by lowermost Miocene, shallow marine shales of the Anahuac Formation that contain neritic fauna. A limestone member known informally as Heterostegina exists locally within the Anahuac Formation. Undifferentiated Miocene sandstone and shale overlie the Anahuac Formation.

The underlying Vicksburg Formation of early Oligocene age consists largely of shale. The resistivity of the shale is commonly higher than that of the lithologically similar lower Frio. Within the Vicksburg are discontinuous sand bodies with log characteristics similar to those of Hackberry sands; this suggests that some of the Vicksburg sediments are also deeper water (slope?) deposits.

Correlation markers A1 through A5 were established on the basis of distinctive resistivity signatures on well logs. They range from the top of the Anahuac to the pre-Hackberry unconformity (fig. 2). Progradation of upper Frio and lower Miocene sand bodies indicated that the A3 and A1 markers pass downdip from sand to shale sequences. Markers A1 through A3 occur in shallow-water deposits, whereas A4 and A5 occur in deep-water strata of the Hackberry Member. In downdip parts of the study area, the quality of seismic data is poor, and no intervals below the pre-Hackberry unconformity (A5) can be correlated in enough wells to permit reliable determination of the deep structure.

East and southeast of Spindletop, the top of geopressure occurs near A3, the base of the upper Frio sandstones (fig. 5); the Hackberry and lower sandstones are geopressured. Northwest of Spindletop, the top of geopressure lies below the base of the Frio Formation (Morton and others, 1983). In extreme downdip wells where the upper Frio lacks sandstones, the top of geopressure rises to the base of the Miocene strata. In the Port Arthur - Sabine Lake area, the

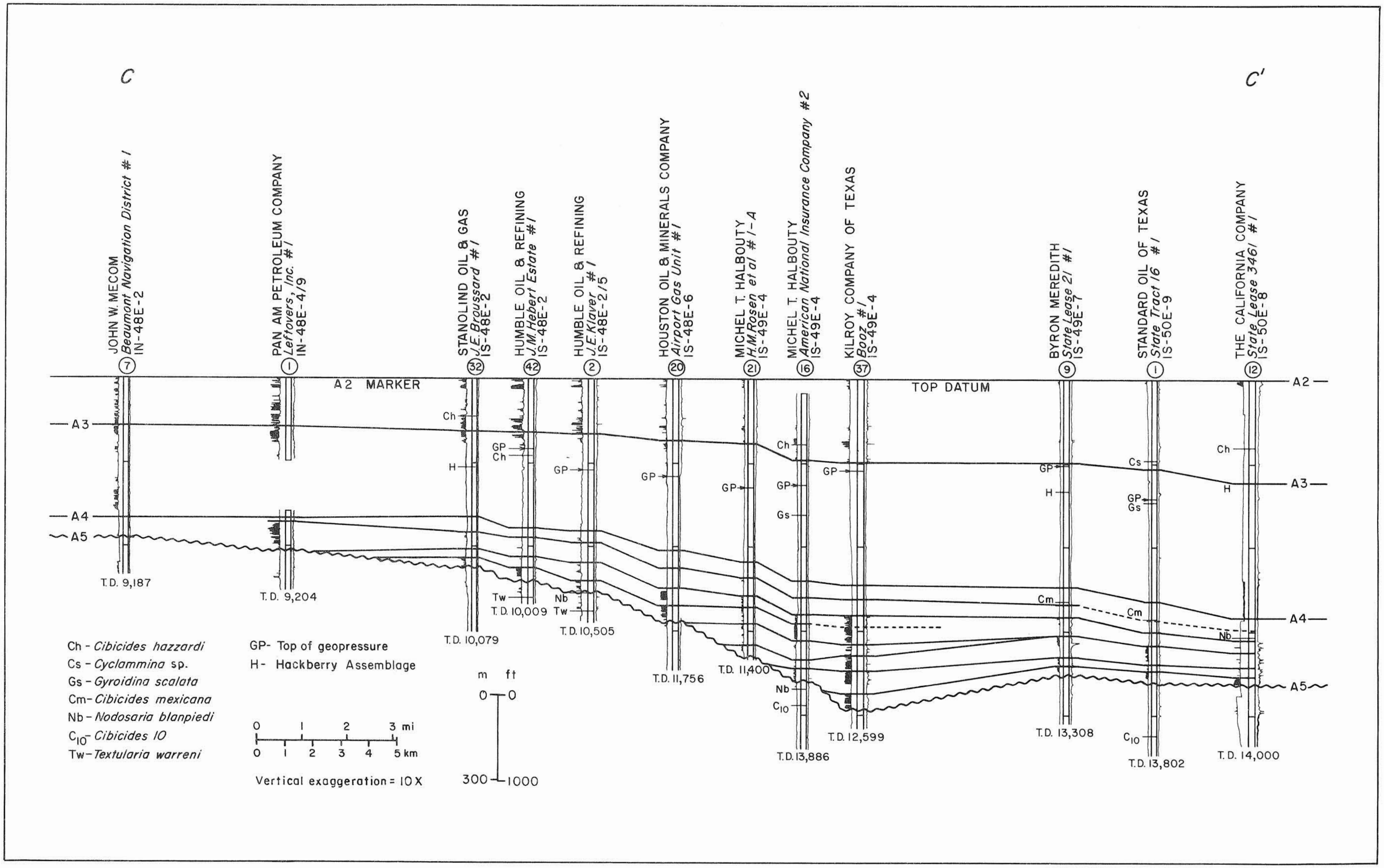


Figure 5. Stratigraphic section C-C' of Hackberry and upper Frio sands along the major channel near Port Arthur field. A possible sand-package correlation is shown, suggesting progressive onlap of the deep-water sandstones against the pre-Hackberry unconformity. Several of the wells used are marginal to the main channel. Also note the seaward progradation of the upper Frio sandstones. Line of section is shown in figure 4.

top of geopressure at A3 coincides with a sharp drop in seismic velocity, as determined by two velocity surveys (fig. 6). However, the effects of geopressure at A3 are coincident with the lithologic transition from a sandstone- to a shale-dominated sequence; hence, the top of geopressure cannot be defined with assurance using velocity data alone. The lower Hackberry sandstones have higher velocities than does the Hackberry shale, although the velocities are lower than a simple extrapolation from shallower sands would indicate.

## Sandstone Distribution, Port Arthur Area

In the Port Arthur field area, as in most of the Hackberry Embayment, only the lower Hackberry unit contains sandstone. However, to the west and the east, additional deep-water sandstones occur near the middle of the upper Hackberry units. These are probably recurrences of the lower Hackberry depositional style. As they are local and do not affect the Port Arthur field area, they will not be discussed further.

The lower Hackberry was deposited on a highly channeled surface (fig. 7). Relief on the unconformity locally exceeds 1,200 ft southeast of Port Arthur field. The channels form a complex, anastomosing pattern, especially south and southeast of Port Arthur field. Six main channel axes can be defined from west to east (fig. 7): (1) The narrow Fannett channel passes near Fannett dome, then south past Big Hill. (2) The Gum Island channel system contains the producing Hackberry reservoirs at Lovells Lake, Hildebrandt Bayou, and Gum Island fields. It has an eastward branch that joins Salt Bayou channel. (3) The broad Salt Bayou channel extends southeast from the junction of minor crossover channels leading from the Gum Island and Port Arthur axes. (4) The Port Arthur channel is the thickest of the six. It extends from Spindletop salt dome south and southeast through Port Acres and Port Arthur fields to Sabine Lake. Subsidiary channels trend southeastward through Port Arthur field to merge into the minor South Port Arthur channel. (5) The Port Neches channel extends from northern Orange County south and southeast to Sabine Lake; the Hackberry reservoirs at Port Neches dome fill part of this channel. The depocenter in 1N-49E is probably a salt-withdrawal basin formed by the

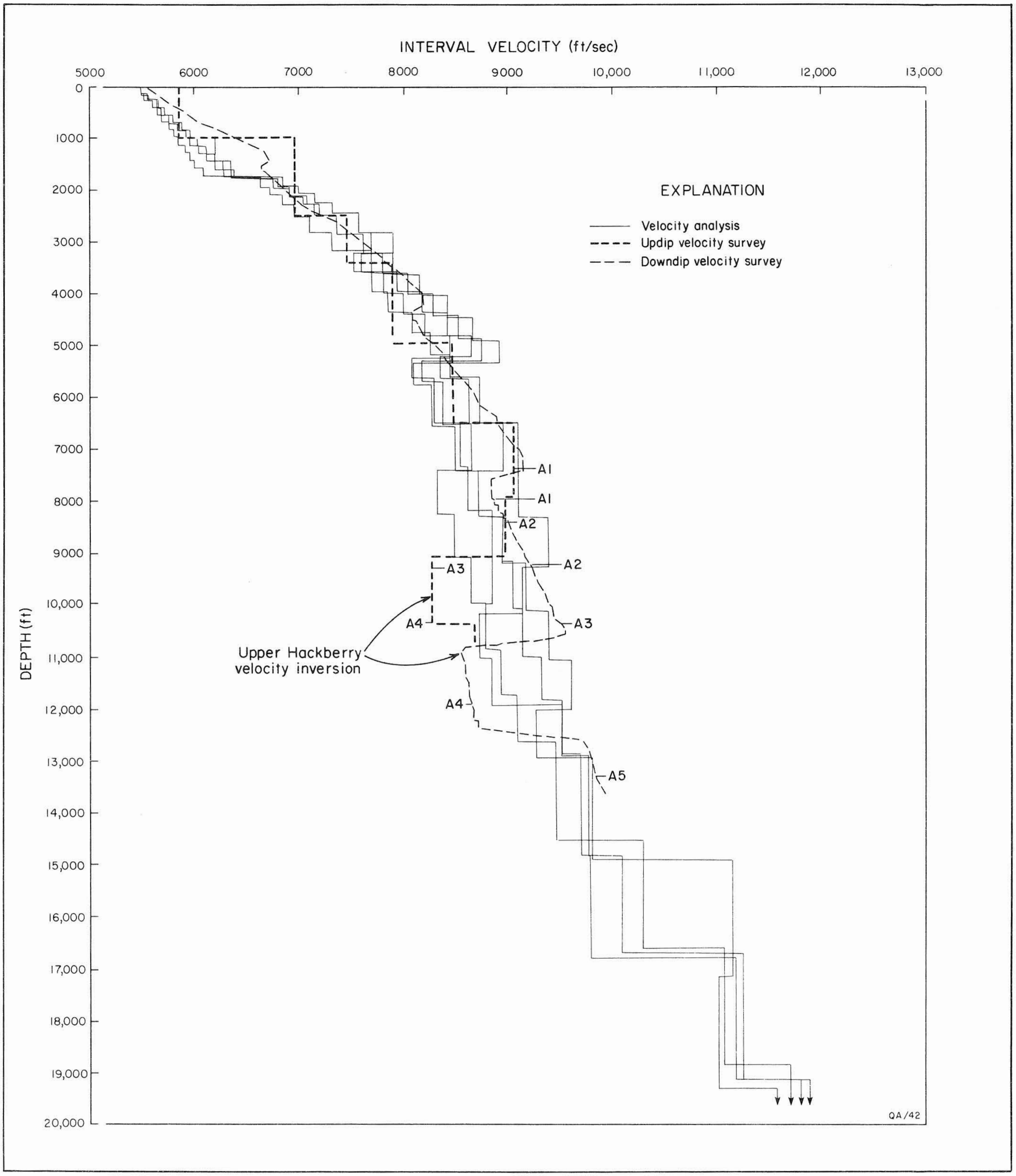


Figure 6. Interval velocity versus depth for two velocity surveys and velocity analyses from seismic data. Stratigraphic horizons are shown for the two well surveys. The surveys show a velocity inversion between A3 and A4.

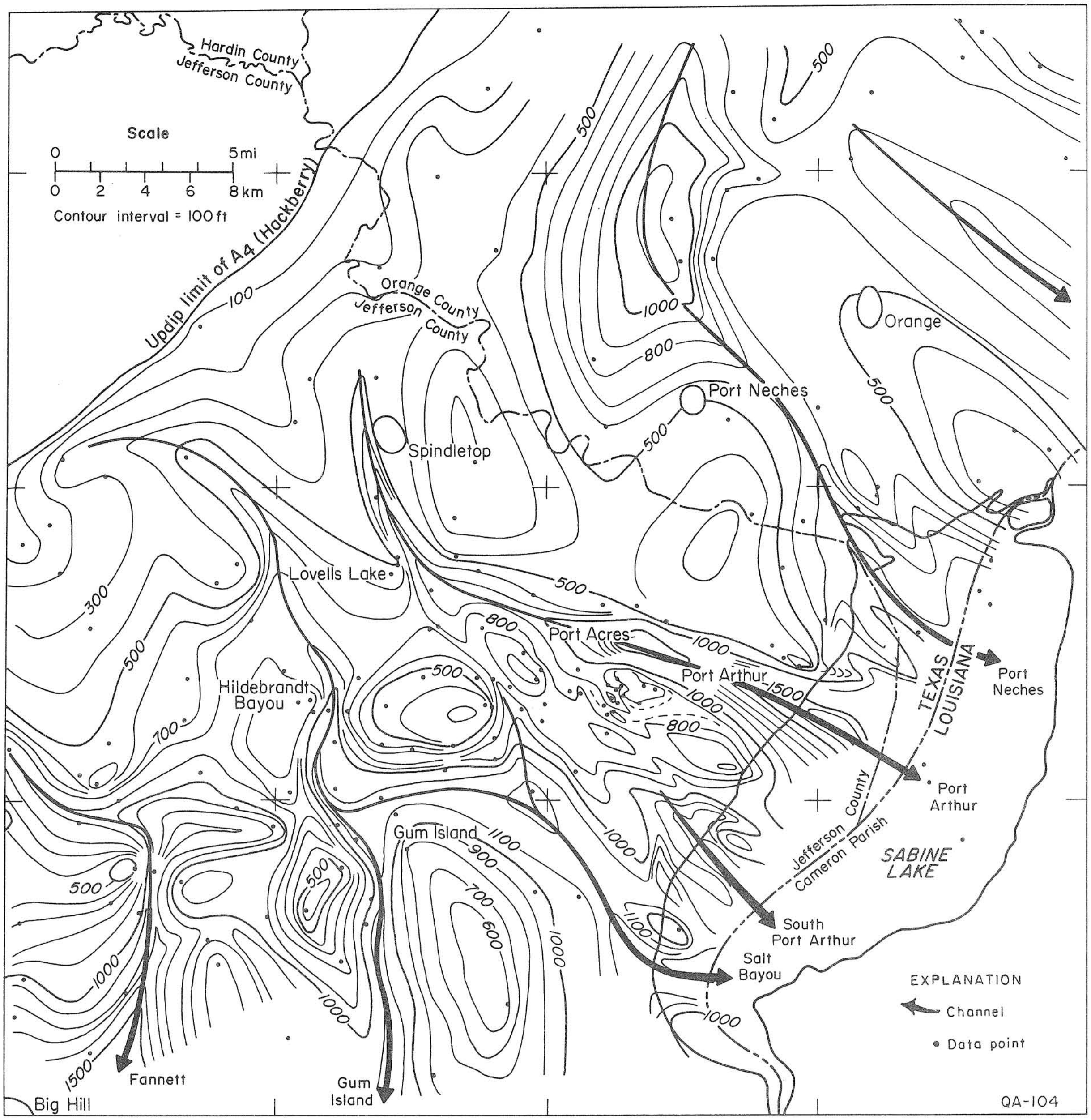


Figure 7. Isopach map of the A4 through A5 interval (lower Hackberry), Port Arthur area. Several large channel axes are woven together by minor channels that surround isolated high areas on the pre-Hackberry unconformity.

growth of Port Neches and Orange domes, as noted by Reedy (1949). (6) The poorly defined Orange channel passes northeast of Orange salt dome.

In general, the axes of maximum sand and maximum percent sand closely follow the channels (figs. 8 and 9), but locally the sand maxima follow somewhat divergent courses. This

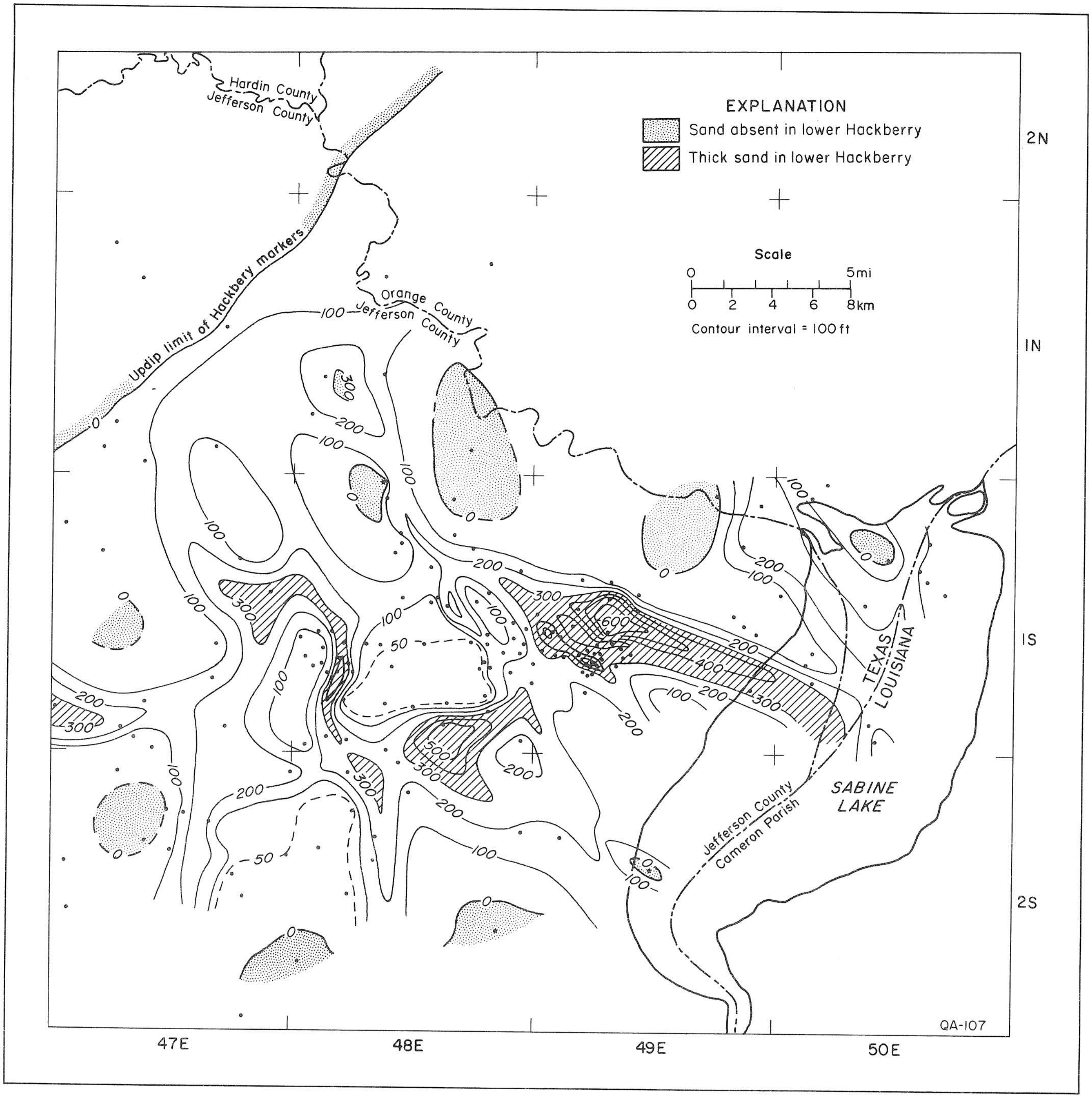


Figure 8. Sandstone isolith map of the lower Hackberry, Jefferson County. Thick sand bodies follow the major channels.

may be caused either by slight meandering of the sand-filled channel toward the outside of curves in the channel system or by differing times of channel cutting and filling.

The sand-percent map (fig. 9) shows two areas of high sand content separated by an area of confined channels. The updip area, which has more than 70 percent sand, lies in an area of

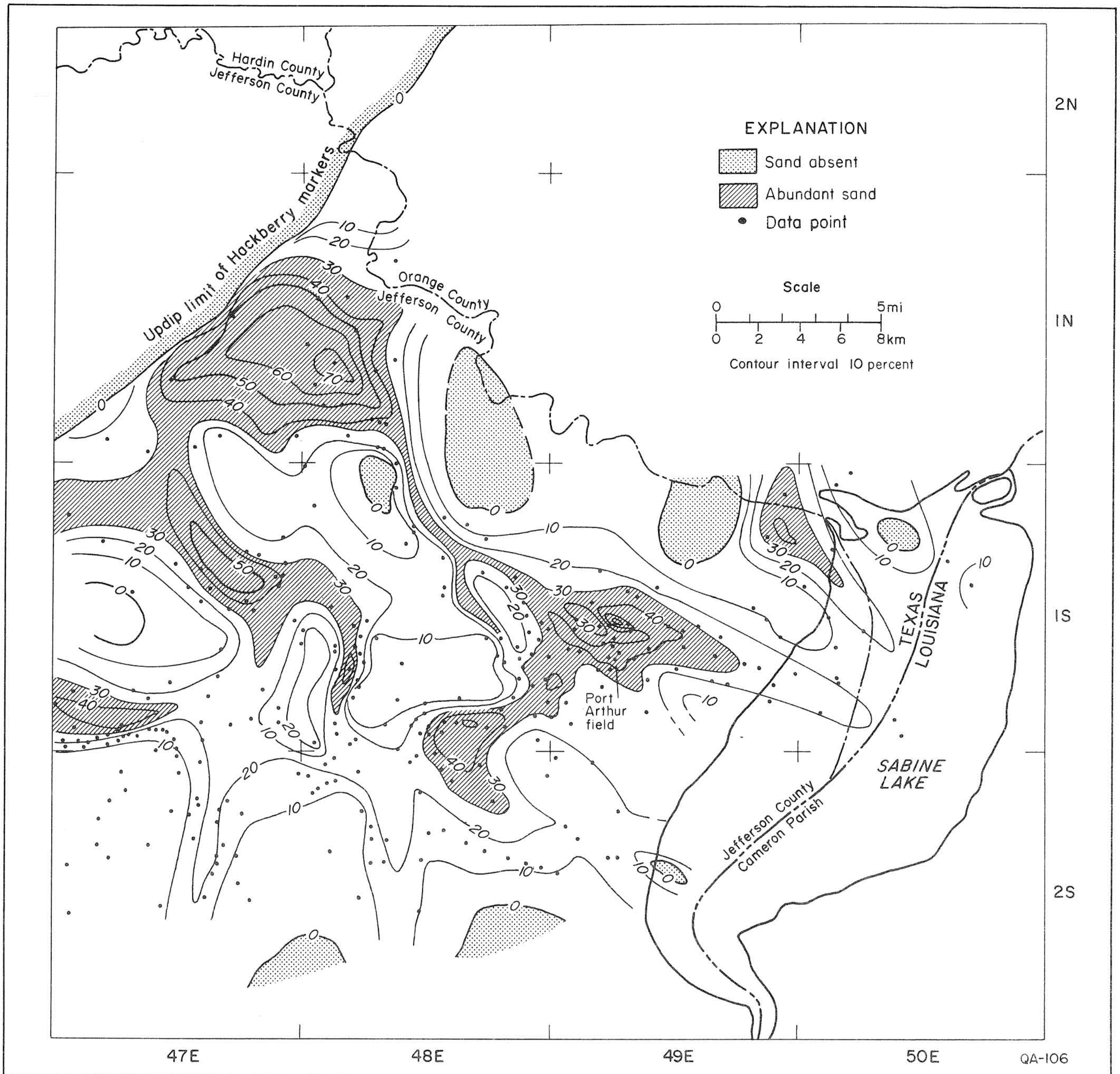


Figure 9. Percent-sandstone map of the lower Hackberry, Jefferson County. Maximum sand percentages occur in downdip, lower-channel positions and locally in the far updip reaches.

thin lower Hackberry strata. The sandstones here have not been studied in detail, but may represent local slumped sands or sandstone resedimented by grain flow from coeval strandplain sand bodies to the northwest. The downdip area, having up to 40 percent sand, occurs at the transition between the local confined channels and a laterally more continuous sandstone geometry; it is inferred to mark the head of the submarine fan system.

## Sandstone Facies and Sand-Body Geometry, Port Arthur Field

The lower Hackberry sandstones are lenticular and range from a few feet to more than 150 ft thick. Individual sandstones were correlated with some difficulty in the field and cannot be correlated for any distance beyond the field area. However, groups of sandstones occur throughout the Port Arthur channel (fig. 5). Maximum thickness and best development of the interval occur in relatively narrow, dip-aligned bands (fig. 10).

Both Port Arthur and Port Acres gas/condensate fields are within and on the southern flanks of the Port Arthur channel (fig. 10). The main Port Acres reservoir is a stratigraphic trap within the uppermost lower Hackberry sandstone (Halbouty and Barber, 1961), whereas the Port Arthur field contains 14 reservoirs within an anticline downdip of a regional growth fault (fig. 11). The individual reservoirs are thicker and generally more persistent in Port Arthur field (the downthrown side of the fault) than in the Port Acres field (the upthrown side of the fault). Maximum interval thickness is along the axis of the Port Arthur channel and its secondary channels, which contain massive sandstone bodies exhibiting blocky SP responses. In the absence of whole-core data, the geophysical log patterns of six of the major reservoirs ("C" through "H") in Port Arthur field have been studied to determine the component depositional facies in the units.

Geophysical responses of Hackberry sandstones (in this case, spontaneous potential [SP] response) can be related to the submarine-fan model by Walker (1979) (fig. 12). The lower fan deposits, consisting of widespread classic turbidite deposits, are not recognized in the Hackberry in Texas. Intermediate suprafan deposits commonly show progradational sequences (Walker, 1979, p. 99) in which the cleanest, coarsest sandstones are at the top; several cycles of progradation may be stacked, as shown by irregularly increasing SP deflections. The proximal suprafan contains generally coarser grained, channel-filling sandstones having upward-fining sequences, also in several cycles: the SP responds with upward-decreasing deflections. Proximal suprafan facies merge updip into braided fan-channel deposits (Normark, 1978) that

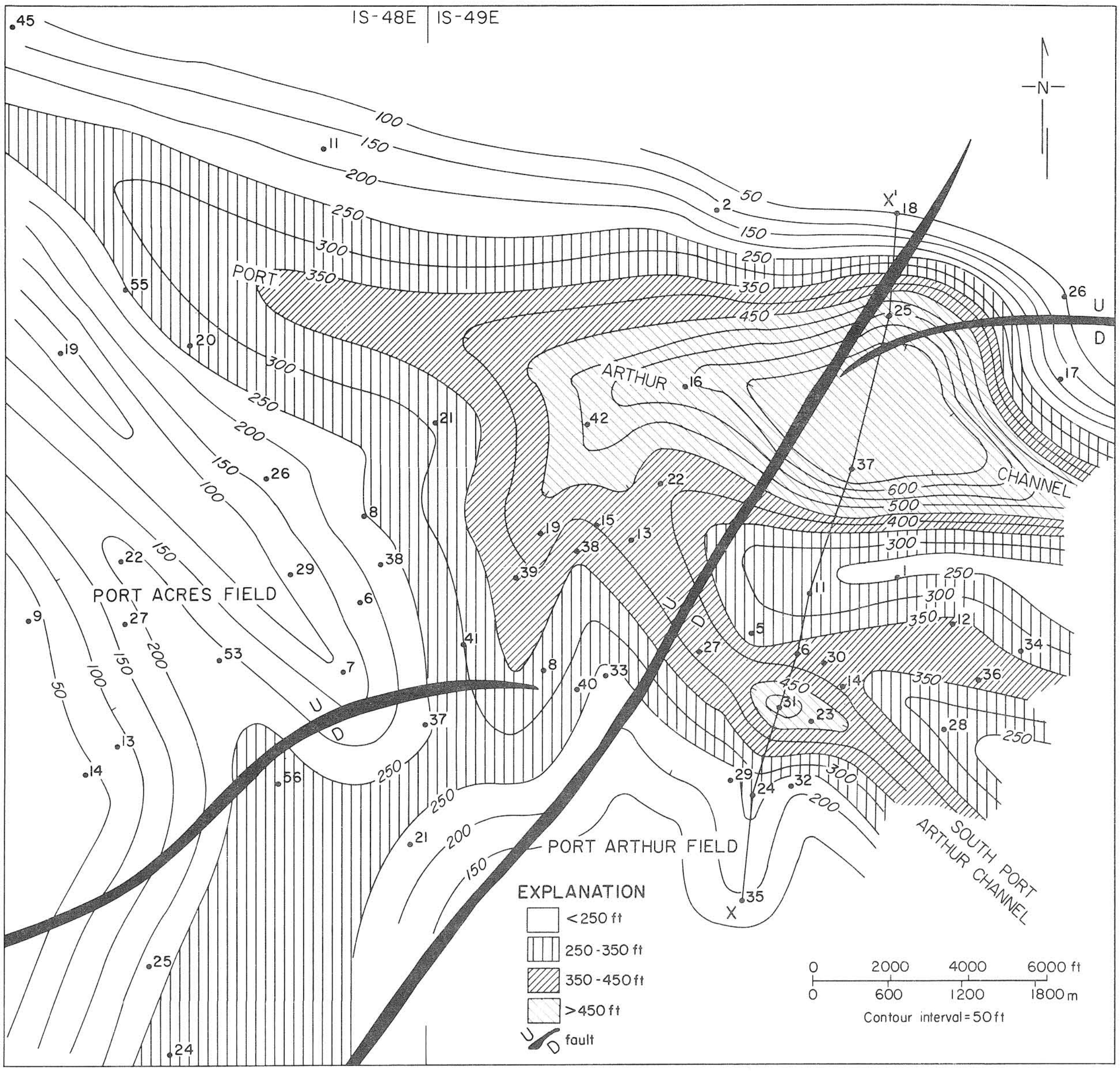


Figure 10. Net-sandstone map of the lower Hackberry, Port Arthur - Port Acres area. For cross section X-X', see figure 11.

have a higher massive sandstone and pebbly sandstone content. The SP shows an increase in blocky patterns and a loss of clean, upward-fining sequences.

Channels may be incised into the proximal suprafan to feed new suprafan lobes downslope. These channels are filled by massive sandstones and pebbly sandstones that do not fine upward. The SP response is inferred to be blocky and to have a sharp base and top. Near the head of the fan, the major feeder channel is filled with coarse sandstone (conglomerate, if the sediment is available), slump and debris-flow deposits, and massive sandstones. No clear upward-fining

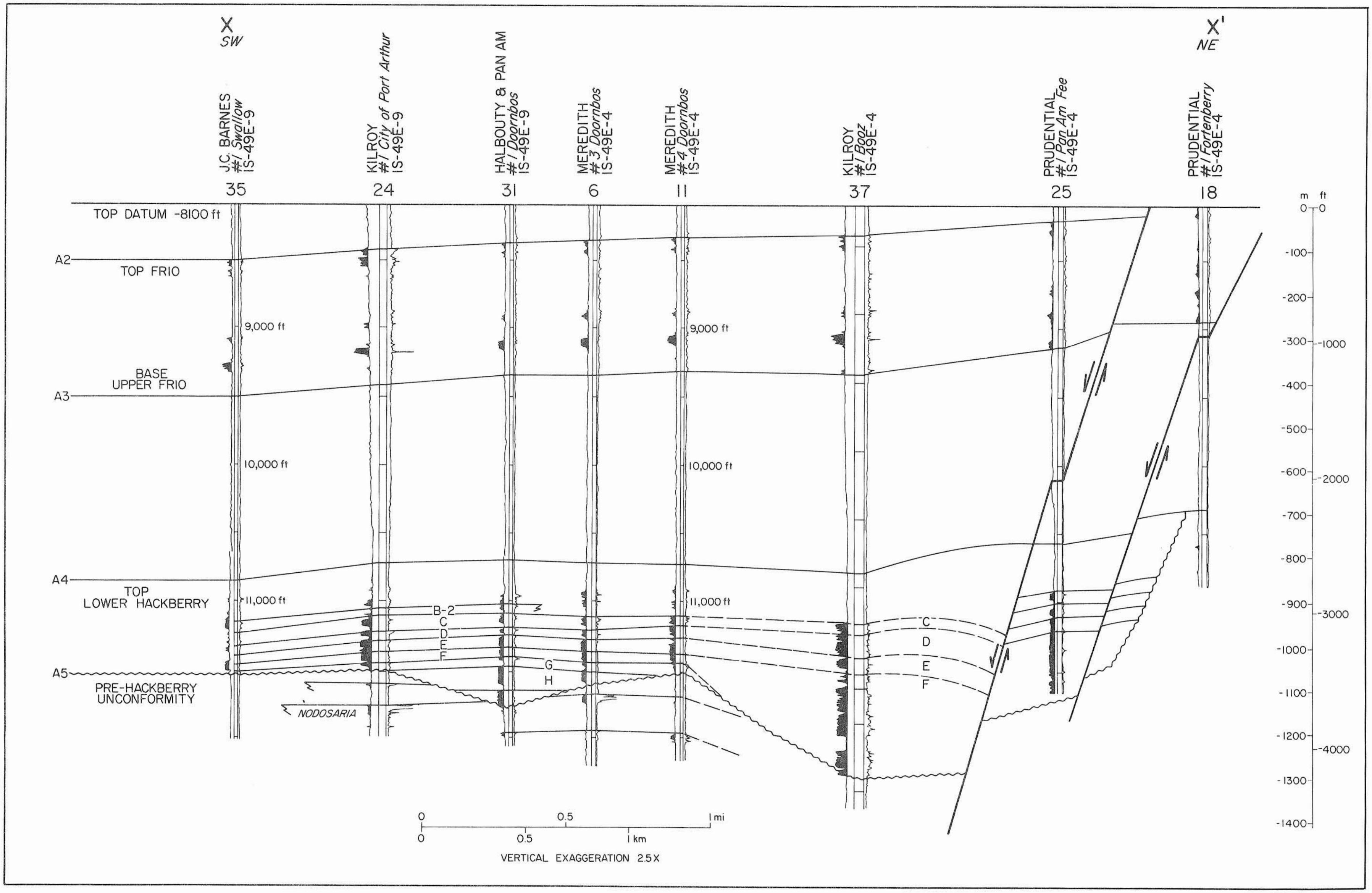


Figure 11. Structural section X-X' across Port Arthur field showing named sand units within the lower Hackberry, the relation of the main field to the large channel and growth fault, and the log characteristics of the sands. Line of section is shown in figure 10.

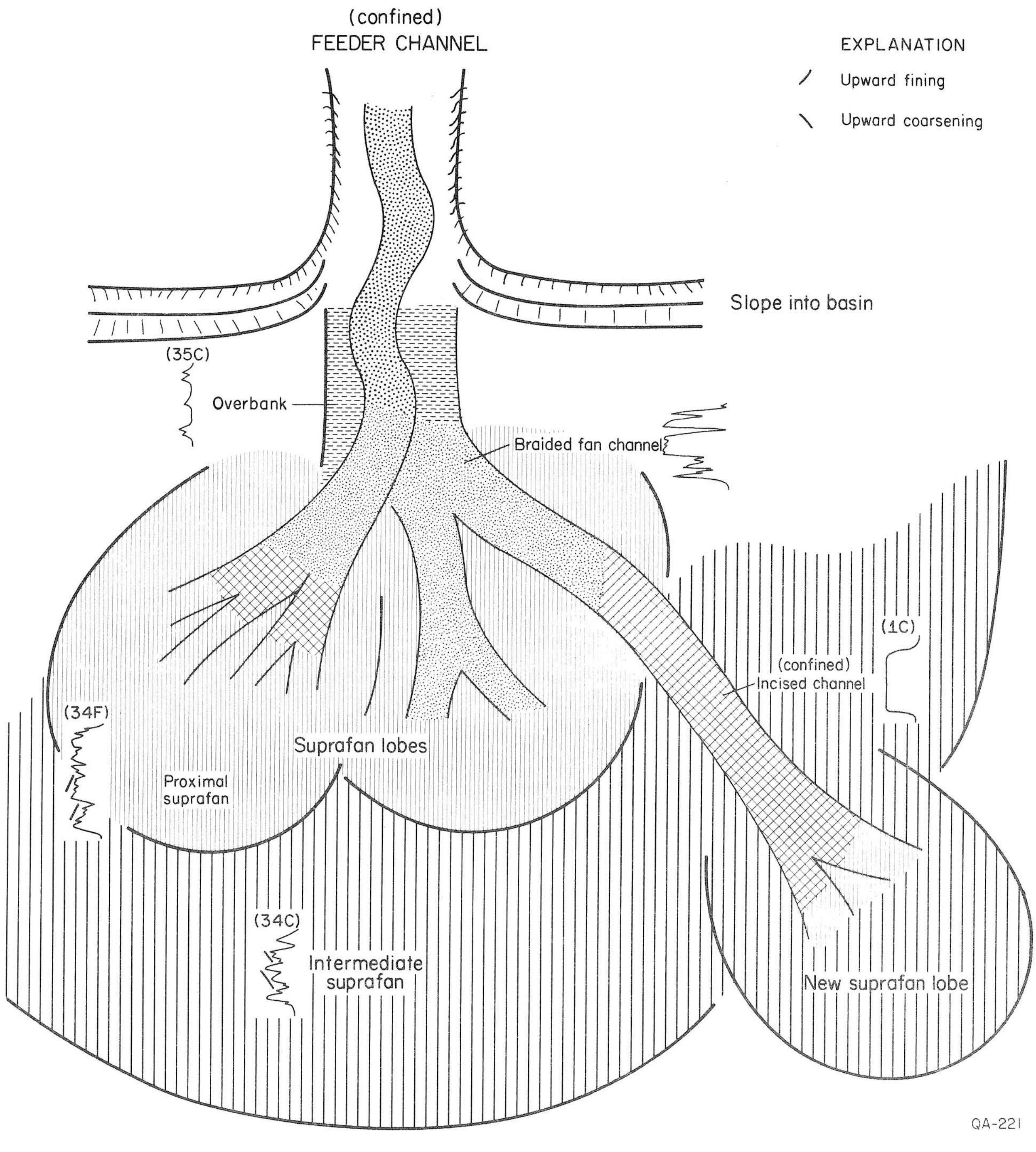


Figure 12. Submarine fan facies model (Walker, 1979) and SP curves from the "C" sandstone at Port Arthur field.

trends are evident, and the SP responds in blocky patterns. Flanking the major channel at the head of the fan are levee or overbank deposits. These consist of thin, turbidite-deposited sands formed by the spillover from large channeled flows and are the facies poorest in sand of the entire upper fan assemblage. The SP response reflects the predominance of shale, and thin sandstone or siltstone beds produce erratic spikes.

The "H" sandstone displays a blocky SP pattern formed by massive sandstones with few shale partings, a characteristic of confined channel-fill or feeder-channel deposits (fig. 13a). The "H" sandstone appears in only six wells and rests directly on the sub-Hackberry unconformity; the walls of the channel are formed by lower and middle Frio rocks. The maximum width of this channel is 6,000 ft.

Spontaneous potential curves for the "G" sandstone indicate braided fan-channel-fill deposits and adjacent overbank deposits (fig. 13b). Wells 12, 28, and 36 have generally blocky SP patterns and more abundant shale partings than does the confined-channel "H" sand. Curves for wells 11, 23, and 29 suggest overbank deposition containing 2- to 10-ft-thick turbidite sandstones and interbedded shales.

The SP curve for the "F" sandstone in most of the wells is a serrate blocky pattern containing some upward-fining cycles (fig. 13c). This pattern is most evident in wells 1, 12, 34, and 36. Wells 24, 29, and 32 have SP curves indicative of braided fan-channel-fill deposits, whereas the SP curve for well 35 suggests that a confined channel has developed at the south end of the field.

The "E" sandstone shows serrate blocky patterns characteristic of broad fan-channel-fill deposits (fig. 13d). On the northeast side of the field, SP curves for wells 1, 12, and 36 suggest that a confined fan channel was eroded there.

The "C" and "D" sandstones appear to represent all parts of the submarine fan model shown in figure 12. The "D" sandstone (fig. 13e) yields a SP response in most wells that is consistent with a braided fan-channel complex and related proximal and intermediate suprafan deposits. Wells 24, 29, and 32 penetrate incised-channel sands having blocky patterns. Three wells penetrate thin sands that may have been deposited on levees or on local highs on the

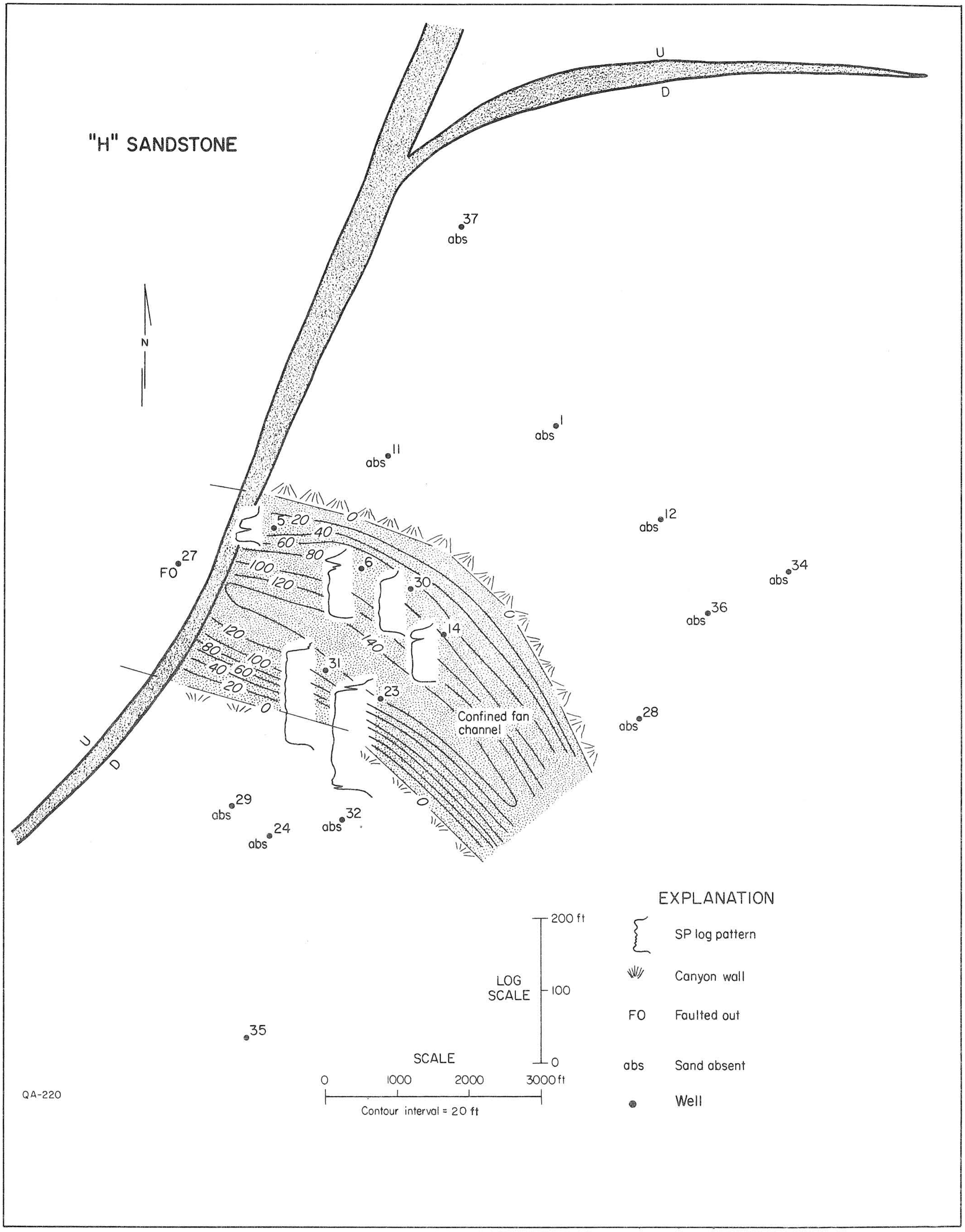


Figure 13a. Distribution and log character of "H" sandstone, Port Arthur field.

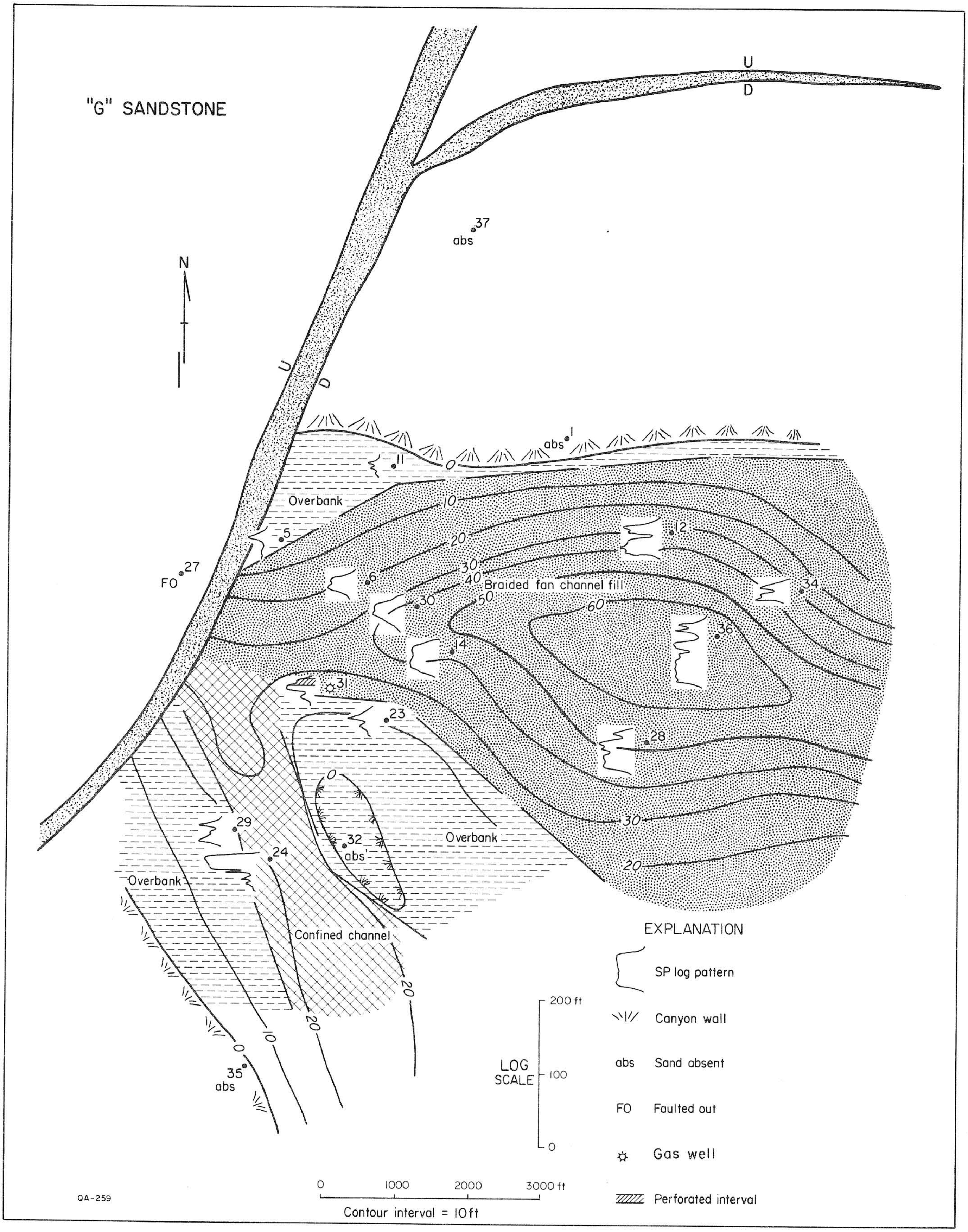


Figure 13b. Distribution and log character of "G" sandstone, Port Arthur field.

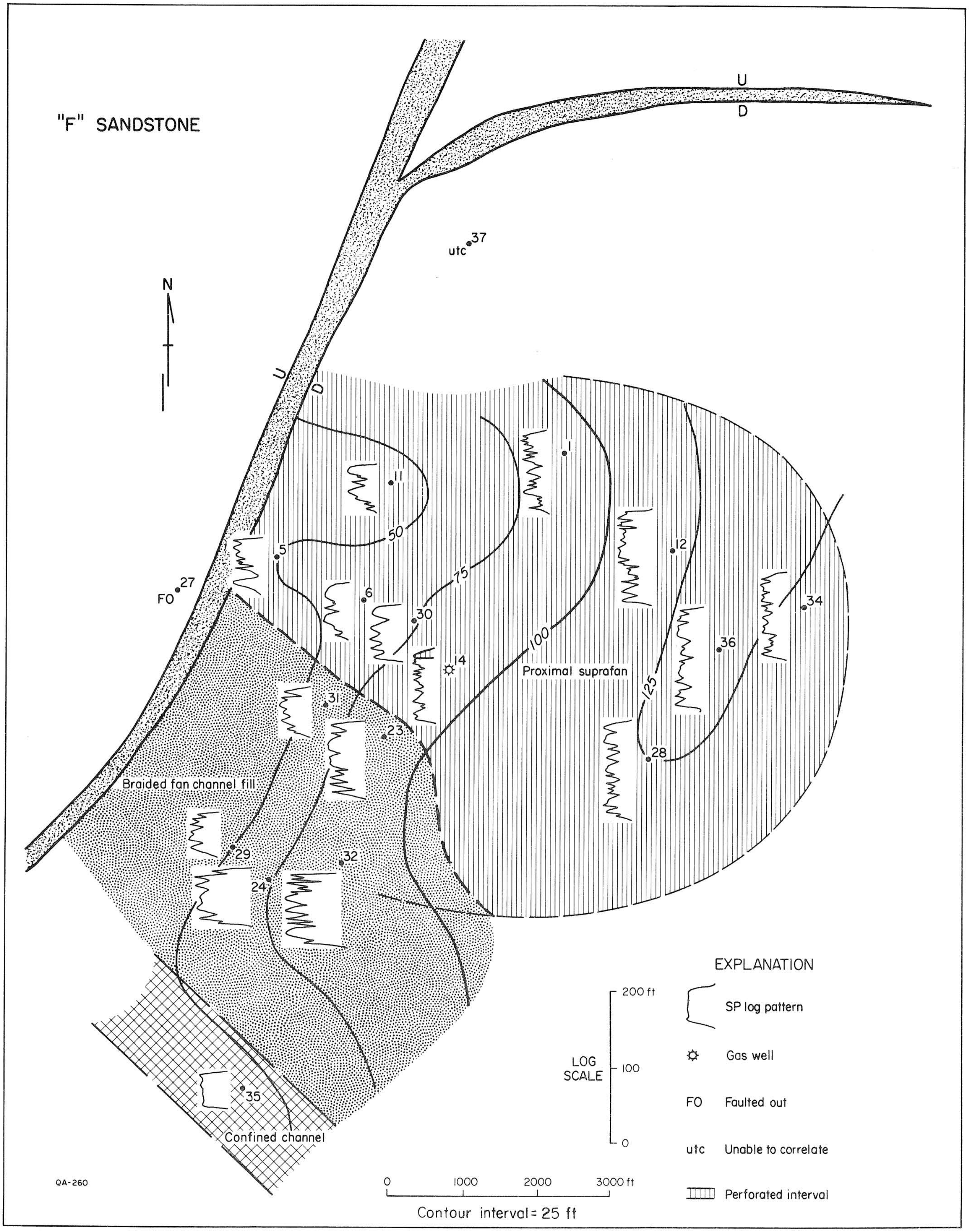


Figure 13c. Distribution and log character of "F" sandstone, Port Arthur field.

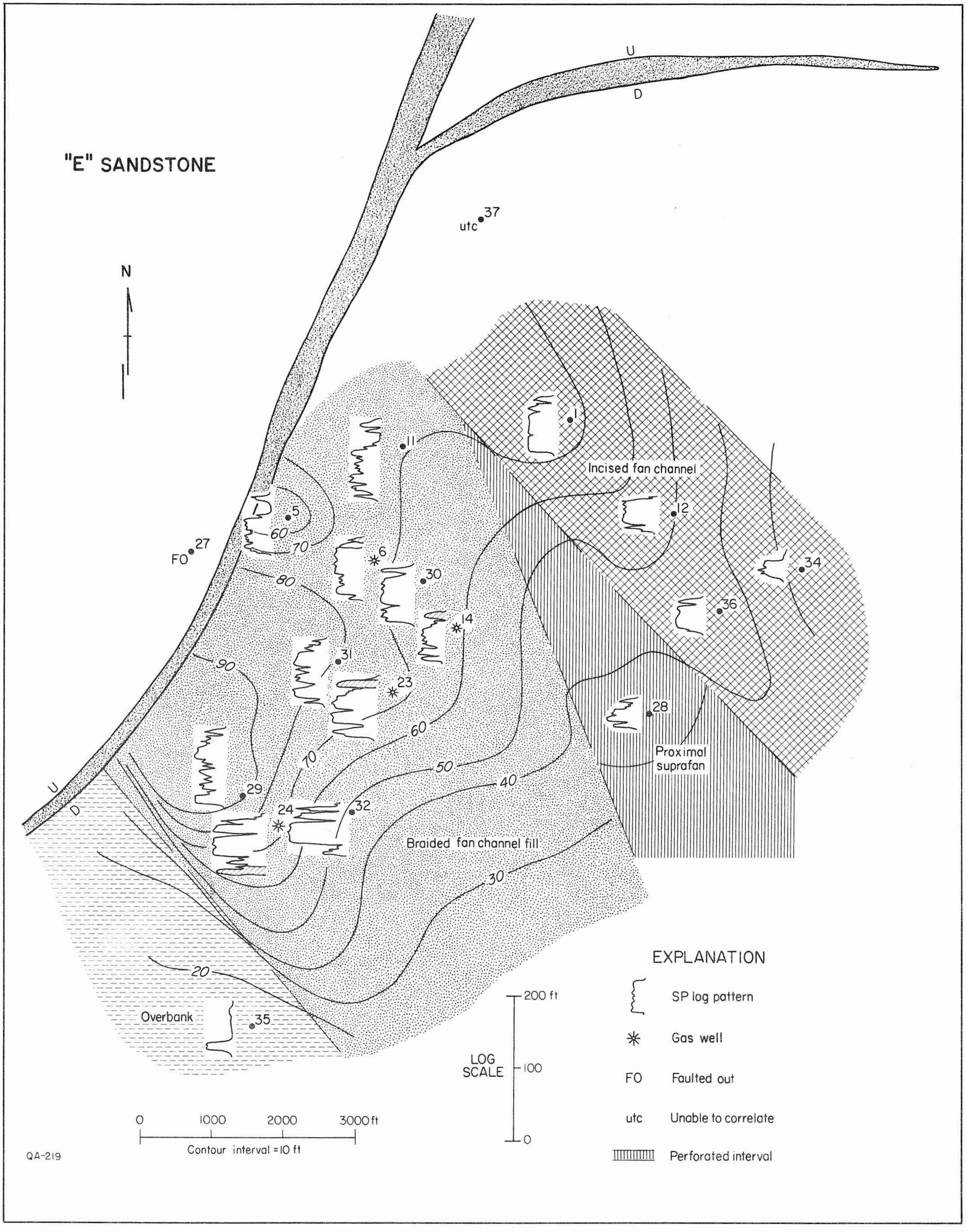


Figure 13d. Distribution and log character of "E" sandstone, Port Arthur field.

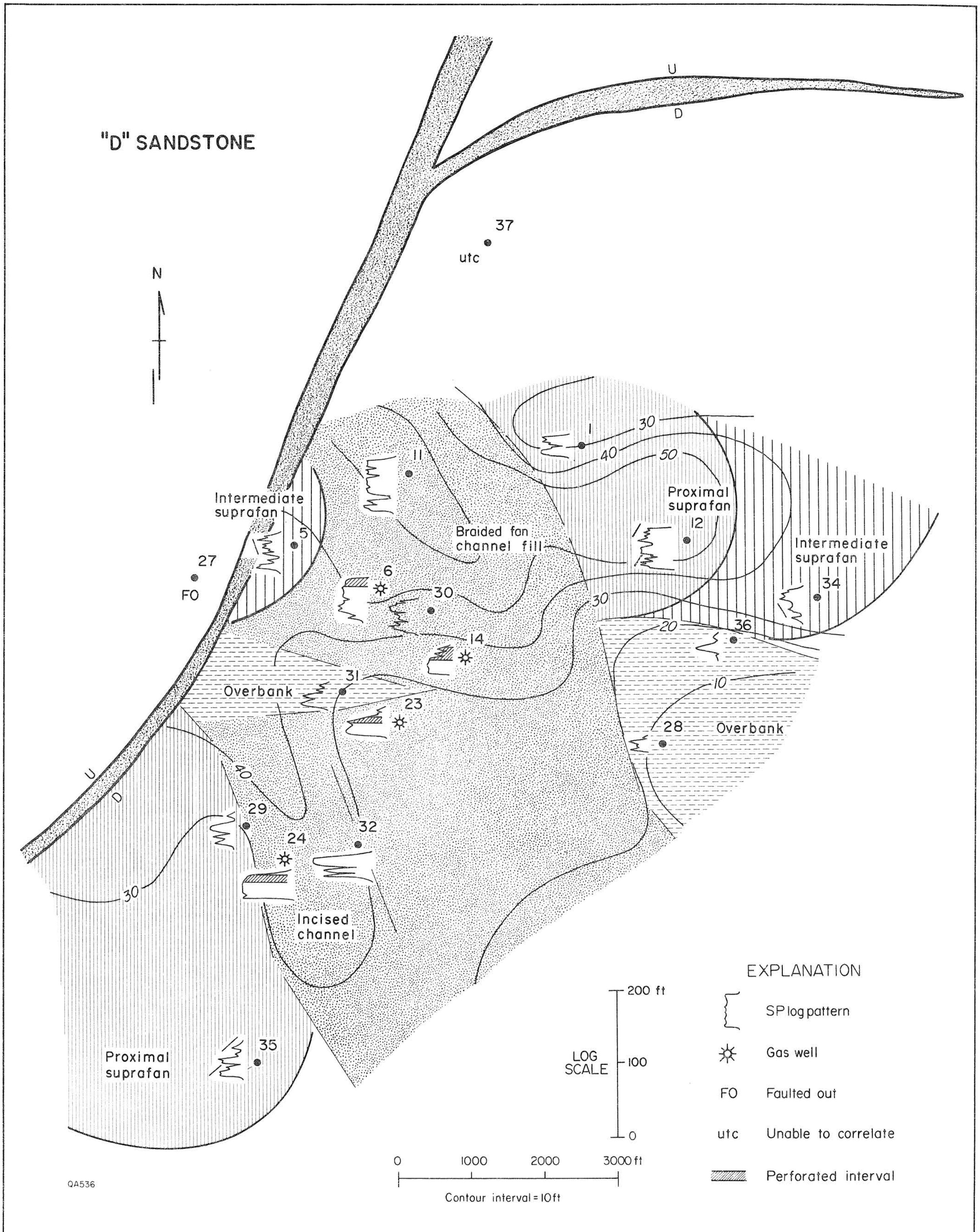


Figure 13e. Distribution and log character of "D" sandstone, Port Arthur field.

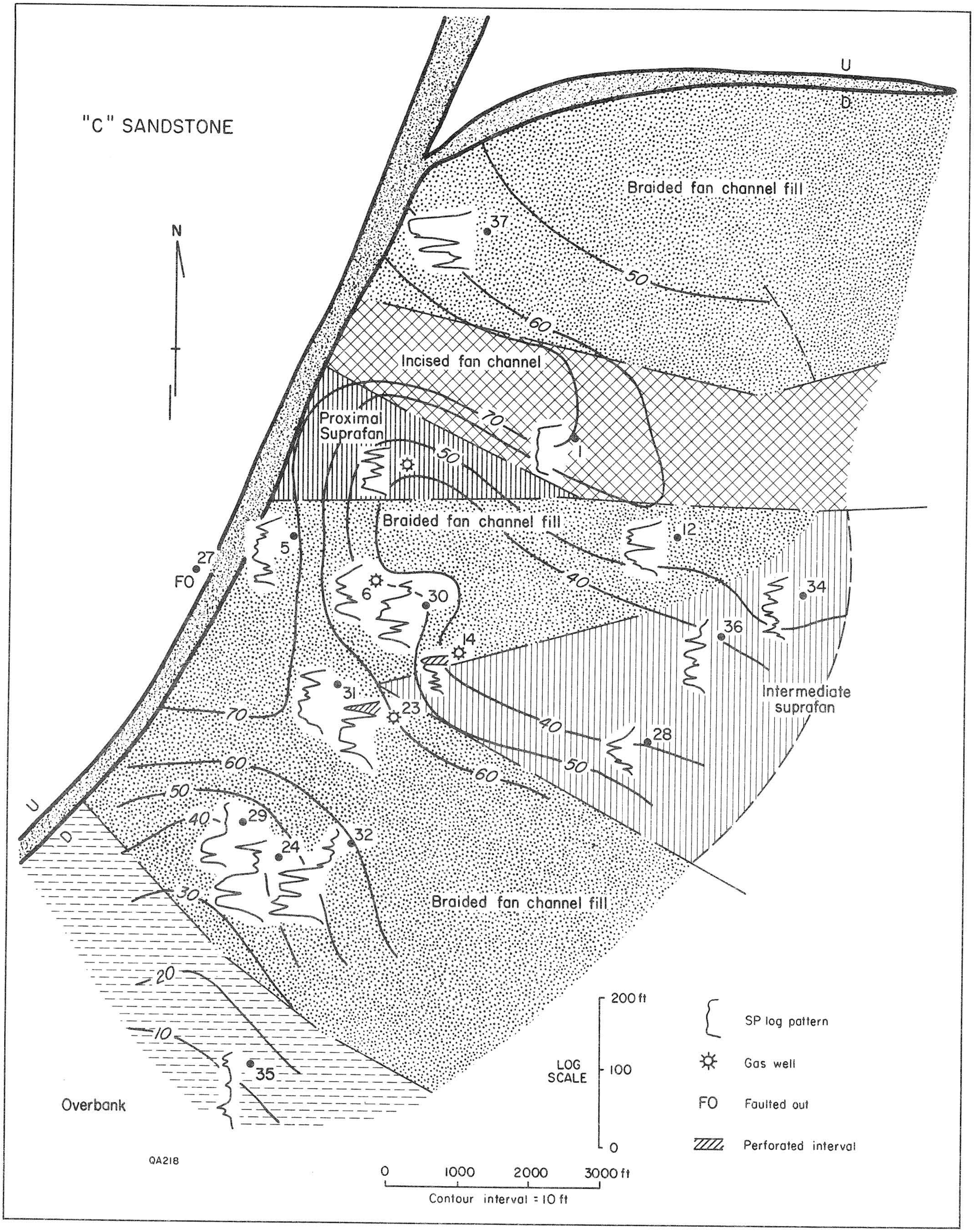


Figure 13f. Distribution and log character of "C" sandstone, Port Arthur field.

suprafan. The "C" sandstone (fig. 13f) has a broad area of braided fan-channel deposits marked by erratic, blocky to serrate SP patterns passing laterally and downdip into intermediate suprafan deposits with upward-coarsening cycles. Well 1 displays a blocky pattern suggesting a deeper, incised channel. Overbank deposition is inferred to have occurred at the southwest end of the field (well 35).

The overlying "A-1," "A-2," "B," "B-1," and "B-2" reservoirs all appear to be thin turbidite sandstones (intermediate suprafan?) with a few very thin scattered channel deposits. The lower "C," upper "D," and lower "E" stringers are similar in nature and may have been formed after temporary abandonment of the suprafan lobe.

The SP log patterns of the lower Hackberry sandstones indicate deposition within a highly channeled submarine fan system. Up-section the average thickness of the channel sandstones decreases. The depth of scour appears to have decreased with time. In addition, the lateral continuity across the channel complex is greatest at the "C" sandstone level, decreasing downward. The "C" sandstone is the only sand that is easily correlatable to well 37 north of the field.

The geometry of the submarine channels and the succession of facies in the Port Arthur field suggest that the lower Hackberry unit formed as an onlapping, retrogradational, submarine channel-fan sequence (fig. 14). Initially, deep canyons were cut during headward erosion of the channels into the shelf flanking the Buna barrier/strandplain system. Port Arthur channels were first filled by a thick, coarse, confined channel sand ("H" sand) deposited at the head of a fan complex. If it is analogous to exposed or modern examples (Walker, 1979), this sand may include grain-flow and laminar-flow deposits as well as deposits of proximal turbidity currents. As the fan accumulated, these deposits were overlain by proximal channeled fan deposits ("D," "E," and "F" sands), which occupied a broader valley in which channel, proximal suprafan, and overbank deposits are preserved. At this stage, scouring of the major Port Arthur channel north of the field occurred. Further growth of the fan led to the deposition of thinner, complex sand bodies ("B" and "C" sands), which include thin channel and suprafan deposits. Final deposition

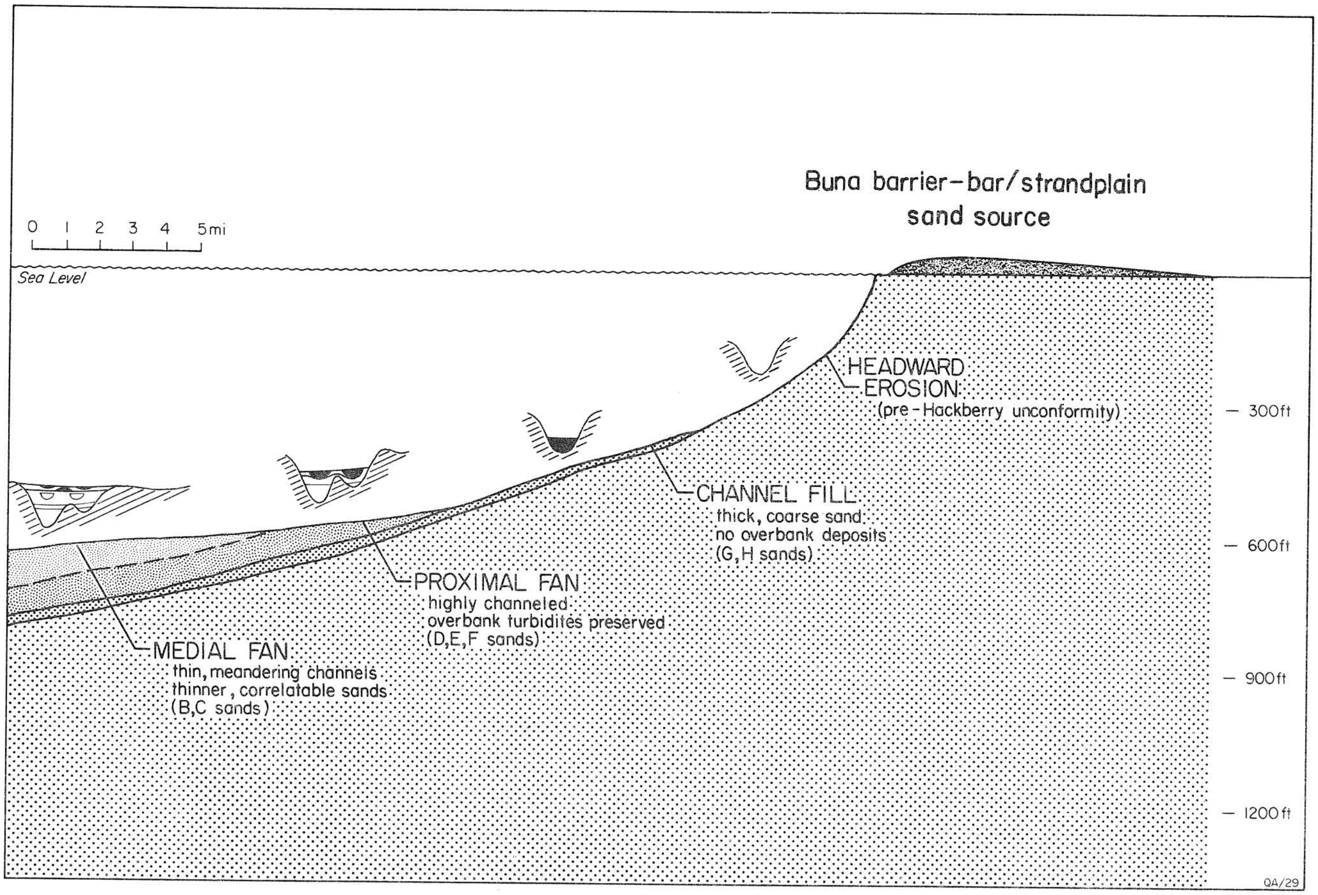


Figure 14. Onlapping submarine fan depositional model of lower Hackberry sand in the Port Arthur field. Channel sandstones are shown in black on the channel cross sections.

was either from low-density turbidity currents of the distal fan or from suspension; these sediments form the upper Hackberry shale sequence.

Fan growth of this type should have produced onlap within the major channels updip. A stratigraphic section of sands along the Port Arthur channel (fig. 5) shows both apparent onlap and the landward migration of the sand-bearing depositional system. The poor quality of the available seismic dip lines does not permit detection of onlap.

Seismic sections show much poorer reflection coherence on dip lines as compared with a strike line shot in the same survey (fig. 15). This may be due in part to the marked lateral facies variations in the Hackberry system. Whereas strike-oriented lines crosscut features such as sand pinch-outs and channel margins at a high angle (enabling these features to be satisfactorily migrated), the dip-oriented lines receive off-line diffractions from these linear features, thus destroying the continuity of reflectors.

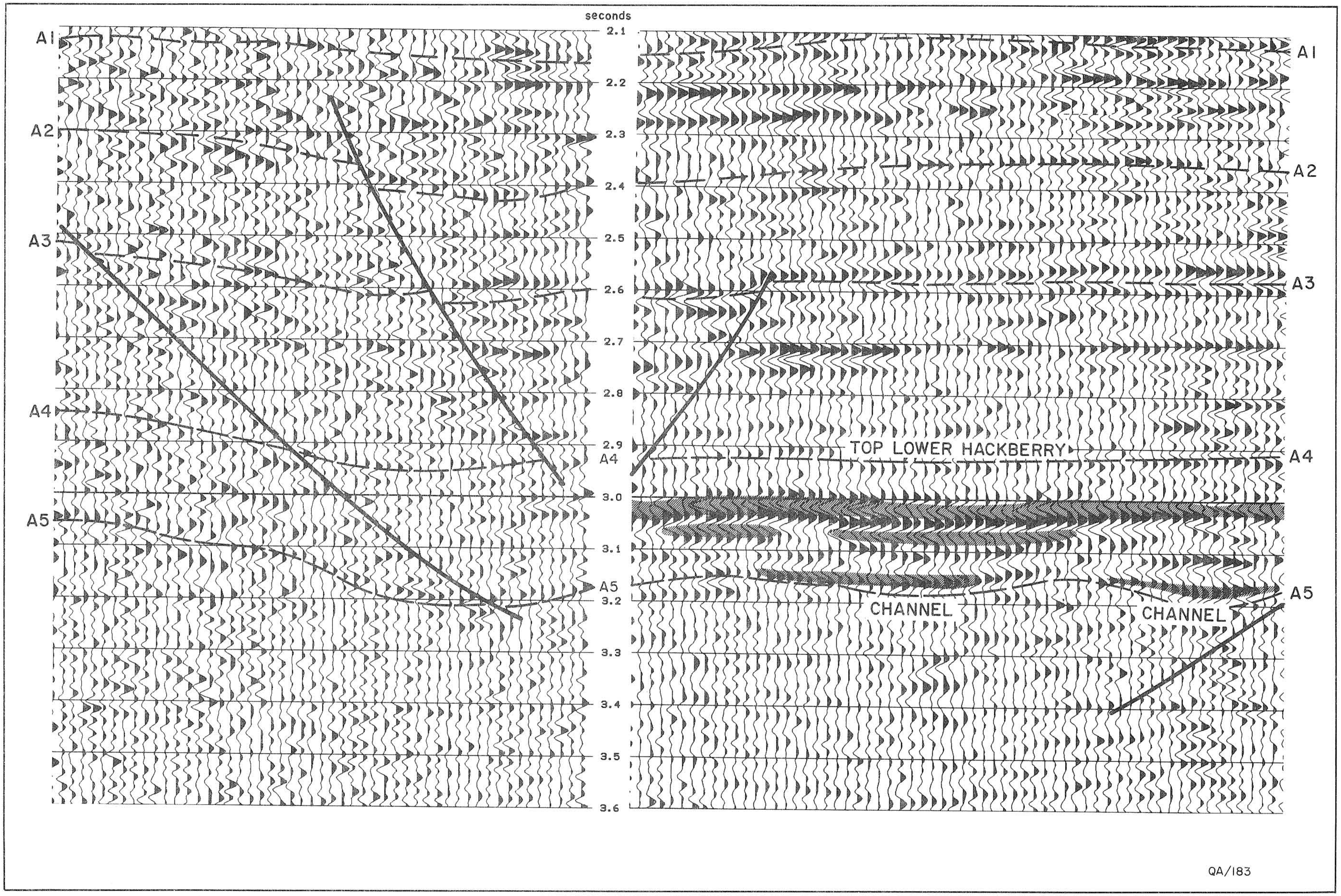


Figure 15. Seismic reflection character of the Hackberry in wavelet-processed, migrated dip (left) and strike (right) lines. Note the extremely poor reflector quality in the dip-oriented data and the submarine channels shown in the strike-oriented data.

The strike-oriented section also shows a channeled lower surface and increased reflector continuity upward; the reflector at 3.03 s (possibly "C" sand equivalent) exhibits good continuity and amplitude. This upward increase in reflector continuity suggests that more continuous sandstone and shale beds occur near the top, much like the "C" and "D" sandstones in Port Arthur field.

## STRUCTURAL CONTROLS ON HACKBERRY SEDIMENTATION

### Structural Development and Shelf Margins

Well penetrations below the Hackberry sand sequence are sparse, and the top of Vicksburg is difficult to pick using the available logs. However, using paleontological information and limited well-log correlations, we sketched an isopach map of A3 to the top of Vicksburg (fig. 16). Two broad uplifts (or areas of thinner sediments, not sites of absolute uplift), inferred to be salt cored, underlay the present-day Orange and Port Neches domes and the area west of Spindletop dome. A withdrawal basin north of the uplifts and a sag to the south suggest that salt was moving into the uplifts. The large, irregular changes in thickness near Gum Island field may reflect growth faulting or salt-related subsidence. One shale diapir has placed pre-Vicksburg (upper Eocene) shale immediately below the Hackberry.

The position of the early Frio and Vicksburg shelf margins is unclear. Sands found within the Vicksburg in the study area near Gum Island field appear to be similar to Hackberry sands and were probably deposited in deep water on the continental slope. Fauna in lower Frio mudstones indicate shallow-water (neritic) deposition, as documented in Chambers County (Gernant and Kesling, 1966). If so, the shelf margin prograded across the study area during upper Vicksburg and Frio time. However, virtually no sand marked this progradation; this may be one instance of progradation of a mud-dominated shelf margin. Other examples on the Texas Gulf Coast include the Yegua-Jackson-Vicksburg progradation immediately northwest of the

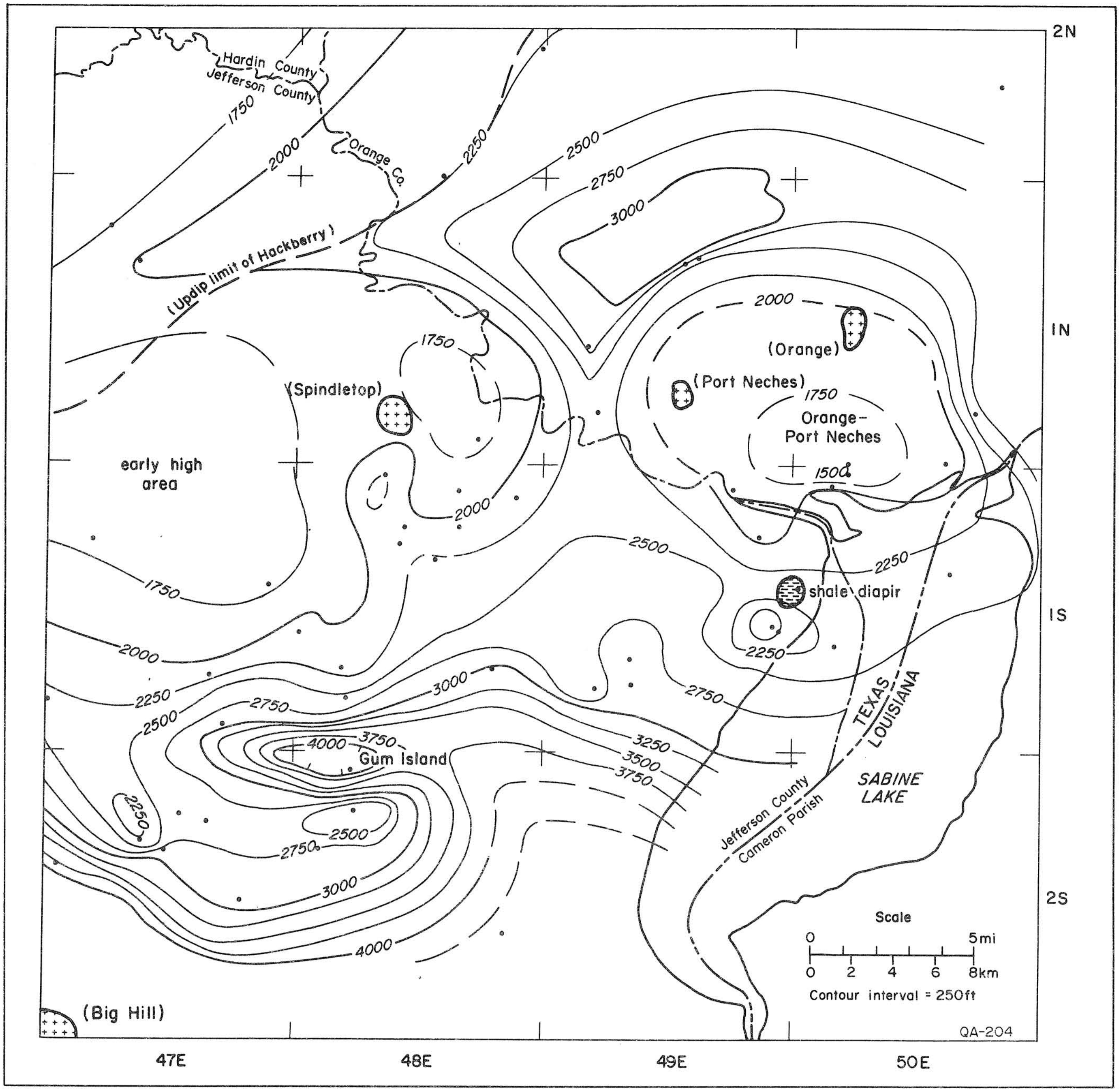


Figure 16. Isopach map of the A3 through Vicksburg interval, Port Arthur area, showing broad uplifts and depressions during lower Frio deposition.

Port Arthur area (Morton and others, 1983), the muddy shelf seaward of the Greta - Carancahua (Frio bar/strandplain) system (Galloway and others, 1982), and the Claiborne progradation from Victoria to Starr Counties in Central and South Texas.

After early Frio deposition, the deep-water Hackberry Embayment formed and was filled by deep-water shales and channel sands (fig. 17). A pre-Hackberry unconformity (A5) developed

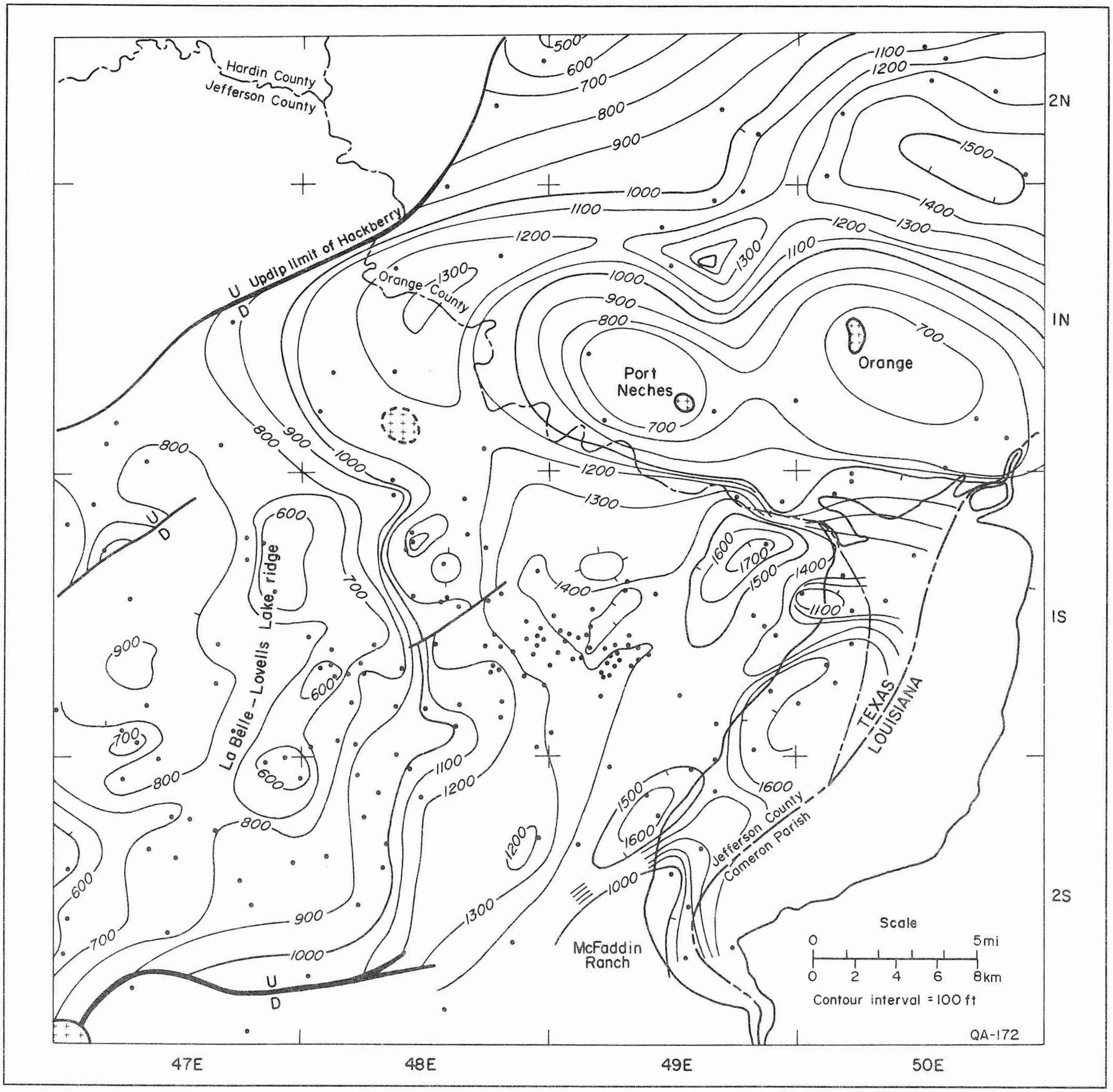


Figure 17. Isopach map of the A3 through A4 interval, Port Arthur area, showing salt uplifts and major growth faults influencing Hackberry deposition.

over the entire area downdip of the Hartburg flexure, an area marked by a growth-fault zone. This unconformity reflects subsea erosion of variable intensity related to channel cutting and submarine fan deposition downdip.

An isopach map of the A3 through A4 interval (fig. 17) depicts the structural elements active during Hackberry time. The large uplift in Orange County has split into two broad

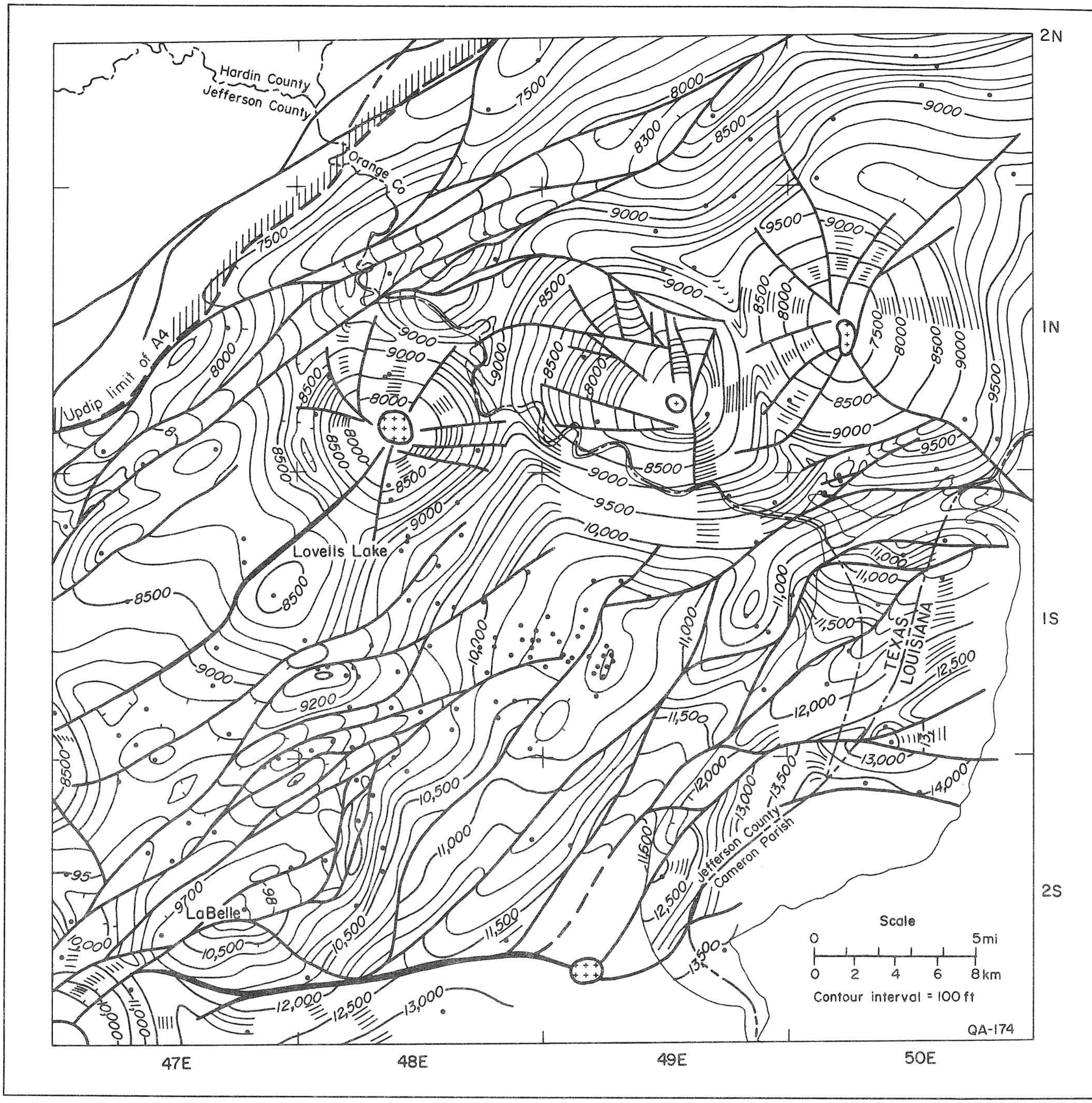


Figure 18. Structure map of the Port Arthur area contoured on the A4 horizon.

uplifts centered on Orange and Port Neches domes. The previous uplift in Jefferson County now appears as an elongate high extending from Lovells Lake south to La Belle field. An uplift around the McFaddin Ranch dome to the south is possible but unproven. The eastern margin of the north-south high is sharp and may be faulted; however, no fault can be proven on a structure map of the lower Hackberry marker (fig. 18). The courses of the sand-filled Hackberry channels cut across all the salt highs, but the highs influence the channels; channels tend to be oriented down the paleoslope. Movement on the numerous small growth faults shown in figure 18 probably occurred throughout Frio time, but total displacements are small.

After the slope erosion ceased, the muddy shelf margin of the upper Frio prograded to the McFaddin Ranch area and was capped by barrier-bar or strandplain sandstones. During and after this progradation, present-day salt domes and withdrawal basins were formed (Ewing, 1983).

## Subsidence and Water Depth

Additional insight into the geologic history of the western Hackberry Embayment can be obtained by plotting sediment thicknesses and inferred water depths against geologic time. For this reconstruction, we assume that water depths in the upper Frio (A3 through A2) and Neogene (A1 to the present) are essentially zero. Water depth in the pre-Hackberry Frio is poorly determined; however, the presence of neritic foraminifers such as Nodosaria suggests water depths of less than 400 ft, as discussed previously. The maximum depth of water in the Anahuac transgression can be estimated given the occurrence of a 350-ft pinnacle reef at the Heterostegina horizon in the Hildebrandt Bayou field. The Heterostegina horizon is thought to mark the time of maximum Anahuac transgression. Water depths of 200 to 350 ft are inferred for the middle part of the Hackberry Embayment in Texas during Anahuac time. Updip of the embayment, sandstones of Anahuac age are present, indicating that water depths were probably less than 100 ft. Water depth during Hackberry erosion and deposition is not directly determinable from this study. However, close constraints can be put on the depth-time curve because the rate of subsidence of the Nodosaria horizon during middle and late Frio time is roughly constant (as noted in several wells; see figure 19b). Assuming constant subsidence, the positions of the A5 unconformity and the A4 marker can be estimated at the inferred times of A5 erosion and A4 deposition. The time scale used is a composite scale for the Gulf Coast Tertiary (Ewing, in preparation), which includes planktonic foraminiferal identifications presented by Echols and Curtis (1982). Relative ages may be in error by 0.5 to 1.0 m.y. in some

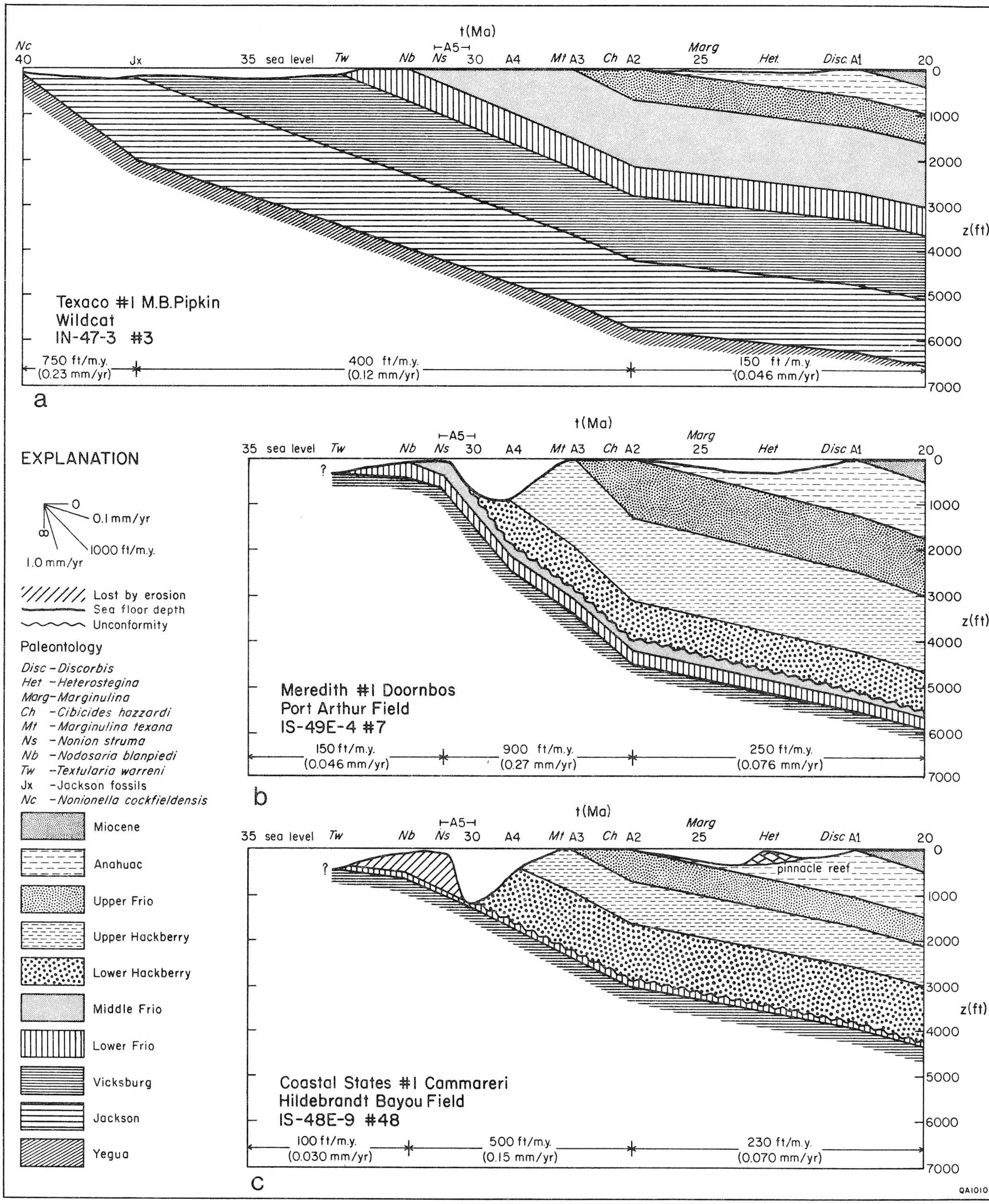


Figure 19. Time-depth curves for three wells in Jefferson County showing reconstructed water depths and subsidence and sedimentation history for (a) a well updip of the embayment, (b) a well in Port Arthur field (interchannel), and (c) a well in the Gum Island channel. Location of wells is shown in figure 4.

instances, whereas absolute ages have a greater error (1 to 3 m.y.). The resulting figure (fig. 19) therefore is not numerically accurate, but the general form of the diagrams should remain the same, whatever the true age scale may be. Eustatic sea-level fluctuations are not shown, as their magnitude and timing are not well determined; their inclusion would not greatly alter the form of the diagrams.

Figure 19 shows the subsidence rates of a well updip of the embayment, a well in Port Arthur field, and a well in the Gum Island channel. Subsidence rates within the embayment show three distinct periods: (1) slow subsidence and sedimentation perhaps filling a deep-water basin by the time of the Nodosaria blanpiedi horizon; (2) fast subsidence at a nearly constant rate through Frio time; and (3) slower subsidence from A2 to the present. Subsidence rates during Frio time were nearly twice as fast in the Port Arthur area as at Hildebrandt Bayou, which confirms the interpretation shown in figure 17 (Coastal States #1 Cammareri lies on the La Belle - Lovells Lake ridge, whereas Meredith #1 Doornbos lies in the basin to the east). Subsidence at Hildebrandt Bayou was not much greater than that updip of the embayment. As noted earlier, subsidence rates were not affected by the development of the Hackberry Embayment. By extrapolation, the entire upper Hackberry shale interval can be accounted for by the deep-water embayment being filled and undergoing normal subsidence after the embayment developed.

Erosion and filling of lower Hackberry channels occur in varying degrees throughout the area. The Meredith #1 Doornbos well lies in an interchannel section of the Port Arthur field; the depth of erosion on the A5 unconformity is slight. As shown in figure 17, development of the Hackberry Embayment at this location could be due wholly to normal subsidence coupled with sediment starvation. In contrast, at the Coastal States #1 Cammareri well about 900 ft of pre-Hackberry erosion has eliminated most of the lower and middle Frio strata. This channel was then filled with lower Hackberry sandstones and shales. The inferred maximum water depth is similar in both areas--about 1,000 to 1,200 ft.

It appears then that most of the Hackberry deposition resulted from the filling of a basin created by subsidence under conditions of sediment bypassing. When bypassing took place, local sand-filled channels were carved into the subsiding shelf margin, creating a retreating shelf-slope boundary and feeding into an onlapping submarine fan complex. Restoring the supply of muddy sediment led to basin filling, which was capped by progradation of the barrier-bar - strandplain system.

The question then arises: What could have led to the shunting of the muddy sediment that built the lower to middle Frio shelf margin? Some sediment was undoubtedly carried down the channel system onto the submarine fan complex. Although the sediment preserved in the channels is mostly sand, the finer sediments were probably transported farther into the Hackberry Embayment. It is possible (but unproven) that the Hackberry Embayment began with a few active channels offshore of major sediment sources such as the delta front of the Houston delta system. These channels may have been similar to the Pleistocene Mississippi canyon (Coleman and others, 1982). These offshore channels captured most of the fine-grained sediment supply, preventing maintenance of the shelf margin and allowing lesser canyons to be cut into the retreating shelf/slope boundary. Whatever the cause, the starvation and erosion of the embayment was a short-lived phenomenon, probably lasting no longer than 1 to 2 m.y. It was followed by a similar period of basin filling before the upper Frio member was deposited.

## Distribution of Hydrocarbons in Hackberry Sandstones

Sandstone reservoirs deposited by the Hackberry depositional system have yielded large amounts of oil and gas in southeast Texas. Forty-five Hackberry oil reservoirs had been designated by the Railroad Commission of Texas (1982) in Jefferson, Orange, and Newton Counties. By the end of 1981 (table 1), these reservoirs had produced more than 23 million barrels of oil. Of this total, Port Neches and Rose City fields in Orange County account for more than 18 million barrels (fig. 20). Some 92 gas reservoirs, including sizeable gas fields such as Port Acres and Port Arthur, occur in the same counties.

Two hydrocarbon plays, play I and play II, can be distinguished within the Hackberry depositional system (table 2). Play I is relatively shallow (7,000 to 8,000 ft) and oil-prone. It extends from the Hartburg group of fields in Newton County to the Marrs McLean field in

Table 1. **Oil and gas fields producing from Hackberry reservoirs according to Railroad Commission of Texas files (Railroad Commission of Texas, 1982).**

| Field | Reservoir | Discovery date | Depth (ft) | Cumulative bbl to 1/82 | Status |
|---|---|---|---|---|---|
| | | **Oil Fields** | | | |
| **Jefferson County:** | | | | | |
| Amelia | Hackberry #1 | 1960 | 7,349 | 327,855 | abd. |
| | Hackberry #2 | 1961 | 7,438 | 370,314 | abd. |
| | Hackberry 7,414 | 1966 | 7,422 | 13,838 | abd. |
| Big Hill | Hackberry Sand | 1953 | 9,666 | 27,968 | abd. |
| Big Hill West | Hackberry "A" | 1954 | 10,462 | | abd. |
| China | Upper Hackberry | 1957 | 7,494 | 214,947 | |
| China South | Hackberry A-1 | 1960 | 7,426 | 280,765 | |
| Gilbert Woods | Hackberry | 1961 | 9,908 | 10,452 | abd. |
| Hildebrandt Bayou | Hackberry 9,660 | 1969 | 9,668 | 249,095 | abd. |
| Hildebrandt Bayou SE | Hackberry #2 | 1979 | 9,646 | 15,291 | |
| Marrs McLean | Hackberry FB-6 | 1968 | 11,127 | 64,385 | |
| Oak Island | Lower Hackberry | 1976 | 11,260 | 17,400 | abd. |
| Phelan | Hackberry | 1954 | 7,832 | 906,958 | |
| | Hackberry 7,420 | 1966 | 7,428 | 3,041 | abd. |
| | Hackberry 7,450 | 1965 | 7,450 | 21,449 | abd. |
| Port Acres | Hackberry 10,000 | 1965 | 10,003 | 781 | abd. |
| Port Acres SW | Lower Hackberry | 1961 | 10,637 | 979 | abd. |
| Weed | Lower Hackberry | 1957 | 8,004 | 171,836 | abd. |
| Weed East | Hackberry | 1966 | 8,029 | 60,104 | abd. |
| Nome South* | Hackberry | 1956 | 8,076 | 507,734 | |
| | Hackberry 8,150 | 1979 | 8,148 | 26,833 | |
| | TOTAL: | Definite | | 2,575,458 | |
| | | Questionable | | 534,567 | |
| **Orange County:** | | | | | |
| Bridge City | Hackberry 8,830 | 1966 | 8,842 | 7,688 | abd. |
| Doty East | Lower Hackberry | 1953 | 8,095 | 12,062 | abd. |
| Doty South | Hackberry Sand | 1956 | 8,082 | 3,241 | abd. |
| Doty Southwest | Hackberry Stringer | 1965 | 7,368 | 7,899 | abd. |
| Echo | Hackberry | 1964 | 10,203 | 72,507 | abd. |
| Orange | Hackberry | 1947 | 7,590 | 132,209 | abd. |
| | Lower Hackberry | 1953 | 8,468 | 281,725 | |
| Pine Forest | Hackberry 6,900 | 1981 | 6,908 | 12,573 | |
| | Block Hackberry | 1980 | 7,065 | 7,234 | |
| Port Neches North | (Hackberry) | 1946 | 8,744 | 4,756,042 | abd. |
| Rose City | Hackberry C | 1963 | 8,132 | 161,420 | abd. |
| Rose City North | (Hackberry 2 and 3) | 1950 | 8,126 | 884,701 | |
| Rose City South | (Hackberry 1 and 2) | 1950 | 8,102 | 12,662,776 | |
| Shannon | Hackberry | 1981 | 8,172 | 3,025 | |
| Vidor North | (Hackberry) | 1955 | 7,573 | 75,731 | abd. |
| | Second Hackberry | 1962 | 7,333 | 127,524 | |
| | | TOTAL | | 19,028,357 | |
| **Newton County:** | | | | | |
| Hartburg North | Segment A Hackberry | 1957 | 7,355 | 225,772 | |
| | Segment B Hackberry | 1958 | 7,243 | 911 | abd. |
| Hartburg Northwest | First Hackberry | 1967 | 6,945 | 170,560 | abd. |
| Hartburg South | Hackberry | 1954 | 8,234 | 75,787 | abd. |
| | Hackberry C | 1956 | 8,236 | 203,150 | abd. |
| | Hackberry Segment B | 1956 | 8,155 | 7,182 | abd. |

Table 1. (cont.)

| Field | Reservoir | Discovery date | Depth (ft) | Cumulative bbl to 1/82 | Status |
|---|---|---|---|---|---|
| **Newton County (cont.)** | | | | | |
| | First Hackberry | 1967 | 7,921 | 92,957 | abd. |
| | Third Hackberry | 1967 | 8,319 | 96 | abd. |
| Hartburg West | Hackberry | 1952 | 7,238 | 2,962 | abd. |
| | | TOTAL | | 779,377 | |
| | | **Gas Fields** | | | |
| **Jefferson County:** | | | | | |
| Amelia | Lower Hackberry | 1959 | 7,803 | 14,071 | abd. |
| | Hackberry 1A | 1960 | 7,403 | 1,167 | abd. |
| Amelia South | Hackberry | 1960 | 7,734 | 1,202 | |
| Big Hill | Lower Hackberry 7,700 | 1955 | 7,721 | 1,372 | abd. |
| | Hackberry 8,400 | 1955 | 8,369 | 10,017 | abd. |
| | Hackberry 9,400 | 1955 | 9,414 | 16,421 | abd. |
| | Northwest Lower Hackberry | 1961 | 10,132 | 257 | abd. |
| | Hackberry 10,300 | 1972 | 11,282 | 2,608 | |
| Big Hill West | Upper Hackberry 9,000 | 1955 | 8,932 | 14,275 | abd. |
| | Hackberry 9,600 | 1954 | 9,648 | 9,670 | abd. |
| China South | Hackberry A-1 | 1960 | 7,428 | 958 | abd. |
| | Upper Hackberry Sand | 1959 | 8,155 | 274 | abd. |
| French Island | Hackberry 3 | 1979 | 10,268 | 177 | |
| | Hackberry 4 | 1980 | 10,239 | 32 | |
| Gilbert Ranch | Hackberry 2 | 1962 | 8,337 | 587 | abd. |
| Golden Triangle | Hackberry 1 | 1970 | 10,956 | 1,877 | abd. |
| | Hackberry | 1960 | 11,356 | 384 | abd. |
| Gulf Refinery | Hackberry | 1962 | 12,006 | 465 | abd. |
| Gum Island North | Hackberry | 1971 | 10,230 | 3 | abd. |
| | Hackberry C-1 | 1977 | 10,787 | 964 | |
| | Hackberry 2 | 1974 | 10,493 | 3,332 | |
| | Hackberry C-3 | 1979 | 10,753 | 740 | |
| | Hackberry 4 | 1977 | 10,973 | 18,245 | |
| | Hackberry 10,800(?) | | | | |
| Hildebrandt Bayou | Hackberry | 1966 | 9,534 | 17,999 | |
| Hildebrandt Bayou SE | Hackberry 2 | 1979 | 9,643 | 207 | |
| Lovells Lake | Frio Hackberry 9,000 | 1949 | 9,004 | 61,891 | abd. |
| Marrs McLean | Hackberry FB-3 | 1962 | 10,224 | 55,960 | |
| | Hackberry FB-4 | 1963 | 9,897 | 1,257 | |
| | Hackberry FB-5 | 1962 | 10,910 | 979 | abd. |
| | Hackberry FB-6 | 1956 | 11,094 | 1,262 | abd. |
| | Hackberry FB-7 | 1959 | 10,824 | 6,350 | |
| | Hackberry 10,200 | 1956 | 10,195 | 38 | abd. |
| | Hackberry 10,700 | 1968 | 10,764 | 1,132 | |
| | Hackberry 10,800 | 1957 | 10,950 | 1,501 | abd. |
| | Hackberry 10,900 | | | | |
| | Hackberry 11,100 | | | | |
| | Hackberry | 1959 | 10,991 | 2,230 | abd. |
| Marrs McLean North | Hackberry | 1961 | 8,731 | 55 | abd. |
| Oak Island | Massive Hackberry | 1971 | 10,439 | 16 | abd. |
| | Hackberry 10,300 | 1972 | 10,295 | 45 | abd. |
| Phelan | Hackberry 7,600 | | | | |
| | Hackberry 7,800 | 1956 | 7,873 | 5,860 | abd. |
| Port Acres | Lower Hackberry | 1957 | 10,526 | 305,081 | abd. |
| | Lower Hackberry 10,450 | 1970 | 10,475 | 196 | abd. |
| | Hackberry 10,000 | 1961 | 10,000 | 383 | abd. |
| | Hackberry 10,600 | 1972 | 10,605 | 719 | |

Table 1. (cont.)

| Field | Reservoir | Discovery date | Depth (ft) | Cumulative MMcf to 10/80 | Status |
|---|---|---|---|---|---|
| **Jefferson County (cont.)** | | | | | |
| Port Acres North | Hackberry 10,500 | 1975 | 10,781 | 328 | abd. |
| Port Acres South | Lower Hackberry | 1961 | 10,973 | 672 | abd. |
| | Hackberry 10,700 | 1966 | 10,712 | 1,576 | abd. |
| | Hackberry 10,800 | 1967 | 10,731 | 187 | abd. |
| Port Arthur | Hackberry A-1 | 1959 | 10,946 | 1,127 | abd. |
| | Hackberry A-2 | 1959 | 10,925 | 8,482 | abd. |
| | Upper Hackberry B Stringer | 1967 | 10,994 | 90 | abd. |
| | Hackberry B | 1966 | 10,986 | 200 | abd. |
| | Hackberry B-1 | 1962 | 11,021 | 3,326 | abd. |
| | Hackberry B-2 | 1959 | 11,077 | 13,343 | abd. |
| | Hackberry C | 1959 | 11,128 | 13,752 | abd. |
| | Upper Hackberry D Stringer | 1960 | 11,218 | 6,834 | abd. |
| | Hackberry D | 1975 | 11,204 | 616 | abd. |
| | Hackberry E | 1959 | 11,276 | 2,470 | abd. |
| | Lower Hackberry E | 1967 | 11,387 | 34 | abd. |
| | Hackberry F | 1961 | 11,350 | 6,212 | abd. |
| | Hackberry G | 1966 | 11,458 | 449 | abd. |
| | Hackberry H | 1975 | 11,782 | 1 | abd. |
| Spindletop North | Hackberry 8,300 | 1952 | 8,341 | 3,405 | abd. |
| | Hackberry 8,000 | 1960 | 8,030 | 610 | abd. |
| Stowell | Hackberry 10,000 | 1949 | 9,990 | 7,063 | abd. |
| | Hackberry 10,100 | 1954 | 10,113 | 96 | abd. |
| | Hackberry 10,300 | 1949 | 10,301 | 12,015 | abd. |
| | Hackberry 10,500 | 1951 | 10,496 | 6,812 | abd. |
| | Hackberry 10,600 | 1945 | 10,674 | 6,633 | abd. |
| | Hackberry 10,900 | | 10,911 | 322 | |
| Weed | Lower Hackberry | 1972 | 8,007 | 2,250 | |
| Weed South | Hackberry | 1962 | 8,199 | | abd. |
| | | TOTAL | | 665,155 | |
| **Orange County:** | | | | | |
| Orange North | Hackberry | 1956 | 7,123 | 2,344 | abd. |
| Pine Forest | Hackberry 6,900 | 1980 | 6,906 | 47 | |
| Port Neches | Hackberry 8,000 | 1950 | 7,933 | 10,950 | abd. |
| Port Neches North | Hackberry 7,700 | 1951 | 7,790 | 52 | abd. |
| | Frio Hackberry | 1949 | 8,524 | 364,038 | act. |
| Vidor North | Hackberry | 1956 | 7,227 | 3,658 | abd. |
| | | TOTAL | | 381,089 | |
| **Newton County:*** | | | | | |
| Camptown | Hackberry 6,700 | 1952 | 6,712 | 6,751 | abd. |
| | Hackberry 7,100 | 1952 | 7,075 | 4,411 | |
| Camptown South | Morgan Hackberry | 1960 | 6,817 | 35 | abd. |
| Deweyville | Hackberry | 1964 | 6,775 | 340 | abd. |
| Gist | Hackberry 7,100 | 1979 | 7,080 | 192 | |
| Hartburg | First Hackberry | 1956 | 7,490 | 1,442 | |
| Lemonville | First Hackberry | 1963 | 7,235 | 171 | abd. |
| | TOTAL: | Questionable | | 13,342 | |
| **Jasper County:*** | | | | | |
| Adams Ranch | First Hackberry | 1960 | 6,450 | 3,257 | abd. |
| | First Hackberry Stringer | 1968 | 6,426 | 903 | abd. |
| | Second Hackberry | 1961 | 6,550 | 3,466 | abd. |

Table 1. (cont.)

| Field | Reservoir | Discovery date | Depth (ft) | Cumulative MMcf to 10/80 | Status |
|---|---|---|---|---|---|
| **Jasper County (cont.)** | | | | | |
| Adams Ranch (cont.) | Second Hackberry Stringer | 1969 | 6,538 | 409 | abd. |
| | Third Hackberry | 1955 | 6,775 | 9,125 | abd. |
| | Third Hackberry Stringer | 1969 | 6,861 | 230 | abd. |
| | TOTAL: | Questionable | | 17,390 | |
| **Chambers County:*** | | | | | |
| Mayes South | Hackberry 15 | 1960 | 11,361 | 38 | abd. |
| | Hackberry 16 | 1960 | 11,463 | 31 | abd. |
| Oyster Bayou | Hackberry A | 1964 | 9,269 | 1,970 | abd. |
| Willow Slough | FB-B, Hackberry A | 1972 | 9,465 | 693 | abd. |
| | FB-B, Hackberry B | 1968 | 9,653 | 372+ | abd. |
| | FB-B, Hackberry C | 1963 | 10,066 | 1,182 | abd. |
| | TOTAL: | Questionable | | 4,286 | |
| **Liberty County:*** | | | | | |
| Cottonwood North | Hackberry 7,900 | 1950 | 7,913 | 9,702 | abd. |
| | TOTAL: | Questionable | | 9,702 | |

*Correlations questionable

Table 2. Hackberry oil and gas production by plays.

| | PLAY I | | PLAY II | |
|---|---|---|---|---|
| | Oil (bbl) | Gas (MMcf) | Oil (bbl) | Gas (MMcf) |
| **Definite** | 17,184,507 | 133,799 | 5,561,685 | 912,465 |
| **Questionable** | 534,567 | 44,720 | none | none |

Jefferson County (fig. 20). Play I lies along the updip margin of deep-water Hackberry facies--the "Hartburg flexure" (Bornhauser, 1960)--which is marked by a line of growth faults. Much of the gas and some of the oil produced in this play comes from sandstone reservoirs of the Buna barrier-bar - strandplain system rather than from true Hackberry sandstones; this production is labeled "questionable" in the tables. The Rose City South field contributed over 12.6 million

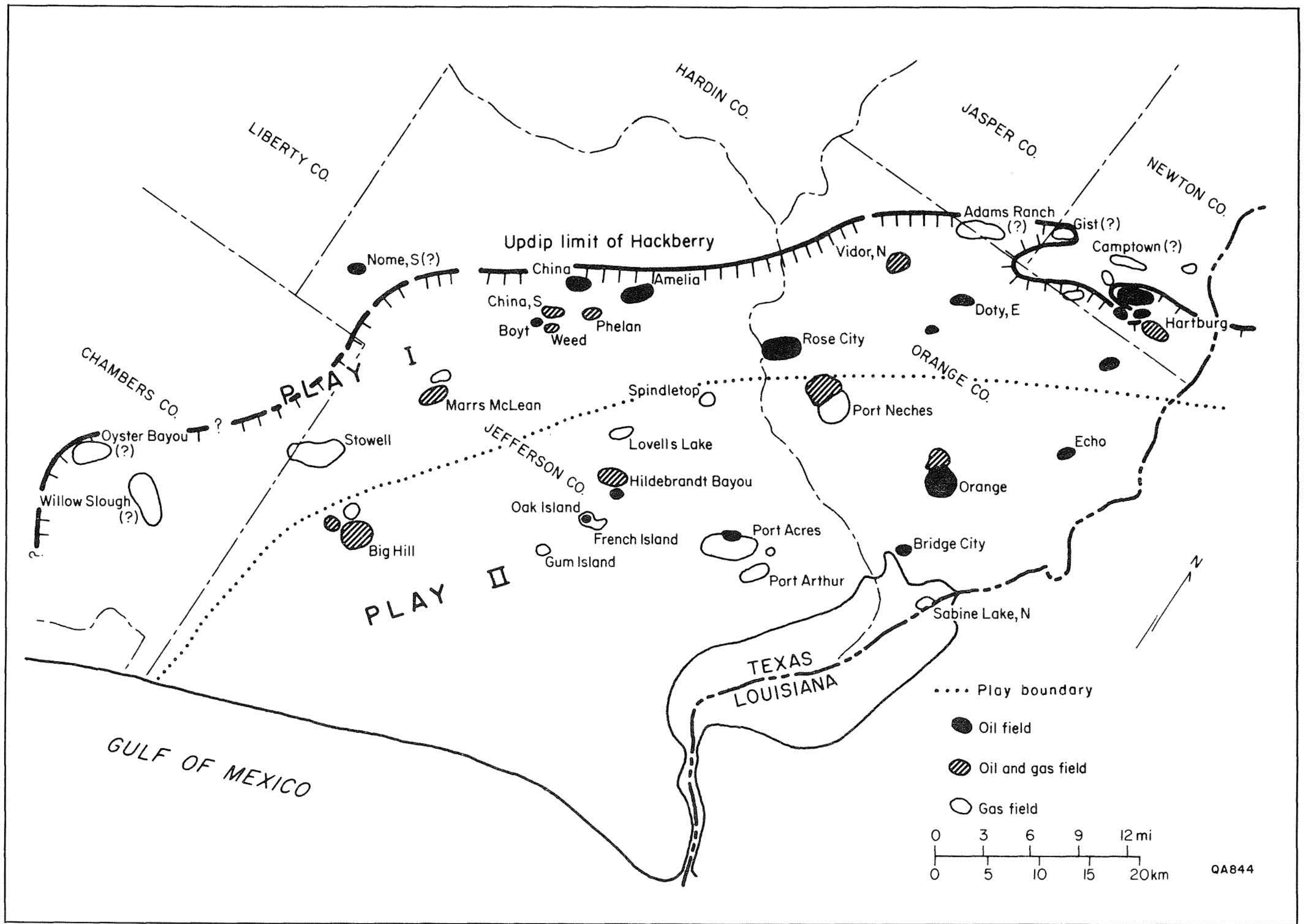


Figure 20. Oil and gas fields producing from the Hackberry sandstones in southeast Texas, according to the Railroad Commission of Texas (1982). Fields with question marks probably produce from shallow-water Hackberry sandstones.

barrels of the 17.2 million barrels of oil produced to date (table 2). Sandstones of deep-water origin along the Hartburg flexure are stacked sand bodies (fig. 5), which yield a very high sand percentage in the lower Hackberry interval, as shown on figure 9. The most productive reservoirs are those higher in the sand section that have the greatest continuity and the best seals; these include the "C" sand at Port Arthur and the producing sand (equivalent to "B-2") at Port Acres. Trapping mechanisms range from structural (normal faults and rollover, as at Port Arthur) to stratigraphic (updip pinch-out, as at Port Acres). The reservoir zones generally consist of complex assemblies of individual sand bodies, as documented for the Port Arthur sandstones and noted in general by LeBlanc (1977). Because of this complexity, porosity and permeability may vary greatly across a field, and reliable reserve estimates are difficult to calculate. The best gas fields appear to exist in eastern Jefferson County in the embayment formed between the La Belle - Lovells Lake ridge and the Port Neches - Orange salt uplift (fig. 17).

Exploration within the two plays is relatively advanced. The Hackberry production of Play I and of the salt domes was established in the 1950's, so the development of the play is fairly mature. New fields, such as Shannon field in 1981, are still being found in Play I, however. Gas production at Play II was also established in the 1950's by the discovery of the large Port Acres stratigraphic trap; however, exploration for the smaller fault-related traps awaited the greater price incentives of the 1970's. New discoveries, such as the Gum Island - French Island area, are still being made in the channel-fan complex along major channel axes.

Future exploration for oil and gas reserves should employ many strategies. Additional fault-stratigraphic prospects in the channel complex of Play II are likely to be found. A new play may be established still farther downdip in southeast Jefferson County if the intermediate suprafan or outer fan facies tracts corresponding to the channels of central Jefferson County can be found; such a play would probably yield geopressured gas from large, low-permeability reservoirs. Finally, a thorough understanding of the complexities of both overall channel geometry and the internal heterogeneity of Hackberry sandstones should facilitate the discovery of stratigraphic reservoirs in the areas of Plays I and II. Channel geometries may be mapped using modern, high-quality seismic data, but internal sandstone geometries and fluid contacts will not generally be resolvable because of their complexity and depth. Determining internal geometries and fluid contacts will require enlightened and persevering study of deep-water sandstone depositional processes and the influences of syndepositional salt mobility.

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## REFERENCES

Berg, R. R., and Powers, B. K., 1980, Morphology of turbidite-channel reservoirs, lower Hackberry (Oligocene), southeast Texas: Gulf Coast Association of Geological Societies Transactions, v. 30, p. 41-48.

Bornhauser, Max, 1960, Depositional and structural history of Northeast Hartburg field, Newton County, Texas: American Association of Petroleum Geologists, v. 44, no. 4, p. 458-470.

Brown, L. F., Jr., and Fisher, W. L., 1977, Seismic-stratigraphic interpretation of depositional systems: examples from Brazilian rift and pull-apart basins, in Payton, C. E., ed., Seismic stratigraphy--applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 213-248.

Coleman, J. M., Prior, D. B., and Lindsay, J. F., 1982, Formation of the Mississippi Canyon (abs.): Gulf Coast Association of Geological Societies Transactions, v. 32, p. 519.

Echols, D. J., and Curtis, D. M., 1982, Calibration of Gulf Coast Tertiary marker benthic foraminiferas to world-wide planktonic zones (abs.): Geological Society of America, Abstracts with Programs, v. 14, no. 7, p. 481.

Ewing, T. E., in preparation, Correlation of stratigraphic units in the Texas Gulf Coast.

_________ 1983, Growth faults and salt tectonics in the Houston diapir province--relative timing and exploration significance: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 83-90.

Galloway, W. E., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of the Texas Gulf Coastal Plain--depositional systems, structural framework, and hydrocarbon origin, migration, distribution, and exploration potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 122, 78 p.

Garrett, J. B., 1939, The Hackberry assemblage--an interesting foraminiferal fauna of post-Vicksburg age from deep wells in the Gulf Coast: Journal of Paleontology, v. 12, p. 309-317.

Gernant, R. E., and Kesling, R. V., 1966, Foraminiferal paleoecology and paleoenvironmental reconstruction of the Oligocene middle Frio in Chambers County, Texas: Gulf Coast Association of Geological Societies Transactions, v. 16, p. 131-158.

Gregory, A. R., Lin, Z. S., Reed, R. S., Morton, R. A., and Rogers, E. A., 1983, Watered-out gas reservoirs profitable via enhanced recovery: Oil and Gas Journal, v. 81, no. 11, p. 55-60.

Halbouty, M. T., and Barber, T. D., 1961, Port Acres and Port Arthur fields, Jefferson County, Texas: Gulf Coast Association of Geological Societies Transactions, v. 11, p. 225-234.

LeBlanc, R. J., Sr., 1977, Distribution and continuity of sandstone reservoirs--part I: Journal of Petroleum Technology, v. 29, p. 777, 791-792.

Morton, R. A., Ewing, T. E., and Tyler, Noel, 1983, Continuity and internal properties of Gulf Coast sandstones and their implications for geopressured fluid production: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 132, 70 p.

Normark, W. R., 1978, Fan valleys, channels, and depositional lobes on modern submarine fans--characters for recognition of sandy turbidite environments: American Association of Petroleum Geologists Bulletin, v. 62, no. 6, p. 912-931.

Paine, W. R., 1968, Stratigraphy and sedimentation of subsurface Hackberry wedge and associated beds of southwestern Louisiana: American Association of Petroleum Geologists Bulletin, v. 52, no. 2, p. 322-342.

Railroad Commission of Texas, 1982, Annual report of the oil and gas division for 1981, 700 p.

Reedy, F., Jr., 1949, Stratigraphy of Frio Formation, Orange and Jefferson Counties, Texas: American Association of Petroleum Geologists Bulletin, v. 33, no. 11, p. 1830-1858.

Walker, R. G., 1979, Facies models 8, turbidites and associated coarse clastic deposits, in Walker, R. G., ed., Facies models: Geological Association of Canada, Geoscience Canada Reprint Series 1, p. 91-103.

Weise, B. R., Jirik, L. A., Hamlin, H. S., Hallam, S. L., Edwards, M. B., Schatzinger, R. A., Tyler, Noel, and Morton, R. A., 1981, Geologic studies of geopressured and hydropressured zones in Texas: supplementary tasks: The University of Texas at Austin, Bureau of Economic Geology, final report to Gas Research Institute, contract no. 5011-321-0125, p. 56-57.

## APPENDIX

### Wells Used for Correlation

| Location | Well no. | Well name | Well depth (ft) |
|---|---|---|---|
| 2N-47E-8 | 3 | Amoco #4 Caswell Trust | 7,618 |
| -7 | 4 | Sun #1 B. E. Quinn | 8,293 |
| 2N-48E-7 | 1 | Hemingway & Bartell #1 Arco | 8,170 |
| -6 | 2 | Gulf #3 M. Vidor Land Co. Unit 2 | 13,601 |
| -9 | 4 | Sun #1 E. Beaumont Townsite | 8,527 |
| 2N-49E-7 | 2 | Brewster et al. #1 P. Lacy et al. Unit | 9,502 |
| -7 | 3 | Kelly-Brock #1 Arco Fee | 9,329 |
| 2N-50E-7 | 1 | McCarthy #1 Lutcher-Moore Lumber Co. | 10,515 |
| -5 | 2 | Sun et al. #1 "A" Lutcher-Moore Lumber Co. | 8,927 |
| -5/7 | 3 | Texas Pacific #1 Lutcher-Moore Lumber Co. | 9,704 |
| -9 | 4 | Coastal States #1 H. J. L. Stark | 10,500 |
| -5/7 | 5 | Texas Gulf et al. #1 Lutcher-Moore Lumber Co. | 9,550 |
| -9 | 6 | Midwest #2 Starks | 10,082 |
| -7 | 7 | Tenneco #1-A H. L. Stark | 10,341 |
| -1 | 9 | Penton & Penton et al. #6 Powell | 8,574 |
| 1N-47E-9 | 1 | Crown Central #1 M. Guiterman "A" | 8,315 |
| -9 | 2 | Meredith et al. #1 B. Quinn | 7,586 |
| -3 | 3 | Texaco #1 M. B. Pipkin | 14,500 |
| -6 | 4 | Humble #B-1 Broussard | 8,261 |
| -2 | 5 | Stanolind #1 Caswell Trust | 7,698 |
| -2 | 6 | Amerada #1 Lanman Co. | 8,780 |
| -7 | 7 | Sun #1 Tyrell | 8,751 |
| -8 | 8 | Magnolia #1 Funchess | 8,842 |
| 1N-48E-4/9 | 1 | Pan American #1 Leftovers, Inc. | 9,200 |
| -1 | 2 | Mecom #1 N. N. Adcock | 10,043 |
| -2 | 3 | Atlantic #1 M. Vidor | 9,121 |
| -9 | 4 | K&M & Halbouty #1 Weiss | 9,431 |
| -7 | 5 | Stanolind #A-2 McFaddin Trust | 9,928 |
| -5 | 6 | Stanolind #1 Lamar College | 9,441 |
| -2 | 7 | Mecom #1 Beaumont Navigation District | 9,494 |
| 1N-49E-1 | 1 | Phillips #1 Boise "A" | 10,066 |
| -5 | 2 | Tenneco #1 Lutcher-Moore Lumber Co. | 10,515 |
| -1/2 | 3 | W. L. Sinclair et al. #1 Lutcher-Moore Lumber Co. | 10,015 |
| -5 | 4 | Oil Development Texas #1 Boise Southern | 11,830 |
| -2 | 5 | Anderson et al. #1 Lutcher-Moore Lumber Co. | 10,817 |
| -7/8 | 6 | Texaco #34 Kuhn | 9,254 |
| -9 | 7 | Gulf #A-1 Caswell Trust | 10,197 |
| -7 | 8 | Tennessee Gas #1 Pan American Fee | 10,302 |
| -7 | 9 | Texas Crude #1 N. Stark | 9,012 |
| -4 | 10 | Gulf #1 W. W. Kyle | 8,801 |
| 1N-50E-7 | 1 | Mecom #2 N. L. Brown | 10,023 |
| -7 | 2 | Mecom #1 E. W. Brown ST | 12,998 |
| -8 | 3 | Mecom #2 E. W. Brown | 14,003 |
| 1S-47E-3 | 1 | Revel #1 Ward State Tract #1 | 10,026 |
| -6 | 2 | Gulf #1 Rake | 10,013 |
| -7 | 4 | Prudential #1 F. C. Smith | 12,271 |
| -5 | 5 | Macpet & Dow #1 G. D. Clubb et al. | 10,429 |
| -7/8 | 6 | Coastal States #1 M. T. Schlicher et al. | 10,515 |
| -4 | 7 | Hunt #1 G. O'Brien | 8,914 |
| -2 | 8 | Pelto #1 First Security Bank et al. | 8,042 |
| -3 | 9 | Meredith #1 Boyt | 8,353 |
| -3 | 10 | Meredith #1 Weed | 8,152 |

## Appendix (cont.)

| Location | Well no. | Well name | Well depth (ft) |
|---|---|---|---|
| -6 | 11 | Humble #C-1 Jefferson Land Co. | 9,968 |
| -8/9 | 13 | Kilroy #1 Wingate | 9,905 |
| -9 | 14 | Gulf #1 Lindsey | 13,132 |
| -8 | 15 | Gulf #1 E. Wingate et al. | 10,518 |
| -9 | 16 | Kilroy #1-B Wingate | 10,474 |
| -6 | 17 | Humble #40 Jefferson Land Co. | 9,856 |
| -1 | 18 | Humble #42 Jefferson Land Co. | 8,849 |
| -1 | 19 | Humble #44 Jefferson Land Co. | 8,539 |
| 1S-48E-7 | 1 | Shell #1 Tyrrell-Combest Realty | 12,496 |
| -2/5 | 2 | Humble #1 J. E. Klaver | 10,506 |
| -5 | 3 | Owen #2 F. Hebert | 10,479 |
| -9 | 4 | Harrison et al. #1 State Gaulding Gas Unit | 11,511 |
| -5 | 5 | Shell (Meredith) #1 E. B. Hebert | 10,824 |
| -4/9 | 6 | Coastal States et al. #1 R. Parr | 10,025 |
| -6 | 7 | Halbouty & Pan American #4 H. M. Rosen et al. | 10,800 |
| -6 | 8 | Halbouty #2-A H. M. Rosen | 11,405 |
| -6 | 9 | Pan American #2 D. M. Cordts | 10,999 |
| -4 | 10 | Texaco #B-1 Bordages | 10,507 |
| -6 | 11 | Rebel et al. #1 L. Callaway | 10,981 |
| -8 | 12 | Pan American #1 F. M. Hebert | 11,070 |
| -7 | 13 | Martin #1 L. W. Snell | 10,888 |
| -7 | 14 | Martin #1 Griffin Unit | 10,876 |
| -9 | 15 | Harrison #1-A L. B. Broussard | 11,456 |
| -8 | 16 | Pan American #1 W. C. Burrell | 10,595 |
| -8 | 17 | C. H. Sands #1 McFaddin Trust | 11,762 |
| -9 | 18 | Harrison #2-A L. B. Broussard | 10,562 |
| -6 | 19 | Gulf #1 W. Doornbos et al. | 11,017 |
| -6 | 20 | Houston Oil & Minerals #1 Jefferson Co. Airport Gas Unit | 11,017 |
| -7 | 21 | Halbouty et al. #8 H. M. Rosen et al. Gas Unit | 13,750 |
| -6 | 22 | Henderson #2 Doornbos | 10,650 |
| -8 | 23 | Owen #1 Rosen | 11,629 |
| -7 | 24 | Pan American #1 Tyrrell-Combest Realty | 11,625 |
| -7 | 25 | Pan American #1 E. P. Starcke Unit | 11,280 |
| -6 | 26 | Humble #1 M. E. Young | 11,801 |
| -7 | 27 | Pan American #1 D. I. Vernon Mcf. Cordts | 11,201 |
| -7 | 28 | Henderson #1-A L. E. Penalec | 10,711 |
| -6 | 29 | Humble #1 L. C. Edwards et al. | 10,735 |
| -2 | 30 | Gulf #1 Lucas Tank Farm | 11,019 |
| -2 | 31 | U.S. Oil of Texas #2-A McFaddin | 10,180 |
| -2 | 32 | Stanolind #1 J. B. Broussard #1 State Tract | 10,084 |
| -2 | 33 | Kirby et al. #1 Garth Brothers | 10,627 |
| -6 | 34 | Meredith (Amoco) #1 Edwards Unit 2 | 11,173 |
| -6 | 35 | Humble #2 L. C. Edwards et al. | 10,761 |
| -6 | 36 | Sunset International #3 Edwards et al. Unit | 10,603 |
| -6 | 37 | Halbouty et al. #3 H. M. Rosen et al. | 11,406 |
| -6 | 38 | Pan American #4 Edwards-Shelby Gas Unit | 10,606 |
| -5 | 39 | Owen #1 F. M. Hebert | 10,728 |
| -5 | 40 | Owen #3 F. M. Hebert et al. | 10,308 |
| -5 | 41 | Owen #4 F. M. Hebert | 10,052 |
| -2 | 42 | Humble #1 J. M. Hebert Estate | 10,015 |
| -3 | 43 | Phillips #A-1 Hebert | 9,910 |
| -2 | 44 | Midwest #1 H. R. Hunsucker | 10,200 |
| -1 | 45 | Kirby #1 Wedgeworth et al. | 10,718 |
| -4 | 47 | Humble #1-B J. E. Broussard Trust | 10,306 |
| -9 | 48 | Coastal States #1 Cammareri | 10,346 |
| -9 | 49 | Coastal States #1 DiStefano Jr. | 10,210 |
| -8 | 50 | Texaco #1 H. E. Dishman | 10,200 |
| -9 | 51 | Halbouty & Sohio #1 Sun-Aubey | 11,153 |
| -9 | 52 | Coastal States et al. #1 Broussard | 10,024 |
| -6 | 53 | Henderson #1 Sassine | 10,691 |
| -4 | 54 | Signal #1 Broussard | 8,501 |
| -4 | 55 | Central Southern #1 Broussard Trust | 8,565 |

Appendix (cont.)

| Location | Well no. | Well name | Well depth (ft) |
|---|---|---|---|
| -7 | 56 | Halbouty et al. #6 Rosen | 11,386 |
| -9 | 57 | Union Sulphur #1 Galloway | 9,867 |
| -8 | 58 | Owen #1 Ritchey Unit | 10,846 |
| -4 | 59 | Meredith et al. #1 Broussard | 8,265 |
| -4 | 60 | Sun #1 Broussard Trust | 8,265 |
| -4 | 61 | Sun #A-1 Broussard Trust | 8,251 |
| -4 | 62 | Sun #A-2 Broussard Trust | 8,000 |
| -4 | 63 | Morse #1 Morse-Sun Jordan Unit 1 | 8,251 |
| -4 | 64 | Morse #1 J. Talbot | 9,511 |
| -4 | 65 | Coastal States #1 M. L. Welch | 9,743 |
| 1S-49E-1 | 1(2) | Sun #1 Howth Fee | 11,010 |
| -4 | 2 | Trice #1 L. C. Edwards | 11,494 |
| -5 | 3 | Meredith #1 American Cyanamid | 11,697 |
| -6 | 4 | Halbouty #1 Flanagan | 11,596 |
| -5 | 5(17) | Meredith #1 P. Doornbos | 9,379 |
| -4 | 6 | Meredith #3 Doornbos | 12,212 |
| -4 | 7(1) | Meredith #1 Doornbos | 12,299 |
| -4 | 8 | Meredith et al. #1 Edwards-Shelby Gas Unit 1 | 11,497 |
| -7 | 9 | Byron et al. #1 State Lease 21 | 13,328 |
| -6 | 10 | Meredith #1 B. Foster | 11,433 |
| -4 | 11 | Meredith #4 Doornbos | 12,191 |
| -4 | 12 | Meredith #5 Doornbos | 12,352 |
| -4 | 13 | Pan American #1 H. W. Gilbert Fee | 10,806 |
| -4 | 14 | Meredith et al. #2 W. Doornbos et al. | 12,199 |
| -4 | 15 | McCarthy #1 Shelby | 10,585 |
| -4 | 16 | Halbouty #2 American National Insurance Co. | 13,888 |
| -4 | 17(5) | Meredith #6 Doornbos | 12,687 |
| -4 | 18 | Prudential #1 T. J. Fortenberry et al. Unit | 10,886 |
| -4 | 19 | Halbouty et al. #1 H. M. Rosen | 11,462 |
| -6 | 20 | Meredith et al. #1 Texas Education Association | 12,308 |
| -4 | 21 | Halbouty #A-1 H. M. Rosen et al. | 11,403 |
| -4 | 22 | Halbouty #1 American National Insurance Co. | 11,008 |
| -9 | 23 | Kilroy et al. #1 Doornbos | 12,168 |
| -9 | 24 | Kilroy #1 City of Port Arthur | 12,004 |
| -4 | 25 | Prudential #1 Pan American Fee | 11,692 |
| -4 | 27 | Pan American #3 H. W. Gilbert Fee | 12,747 |
| -8 | 28 | Texaco #1 Port Arthur Refinery Fee | 14,202 |
| -8 | 29 | Halbouty et al. #2 Doornbos | 12,202 |
| -8 | 30 | Prudential #1-A Doornbos | 11,781 |
| -8 | 31 | Halbouty et al. #1 Doornbos | 12,103 |
| -8 | 32 | Kilroy et al. #2 W. Doornbos | 12,209 |
| -4 | 33 | Pan American #4 H. W. Gilbert | 12,997 |
| -5 | 34 | Meredith et al. #1 Port Arthur Vicksburg Gas Unit | 14,125 |
| -1 | 35 | Meredith et al. #3 Grinnell-Texas | 11,281 |
| -4 | 36 | Halbouty #2 H. M. Rosen et al. | 11,454 |
| -4 | 37 | Halbouty #5 H. M. Rosen | 10,805 |
| -4 | 38 | Halbouty et al. #1 J. T. Shelby | 11,468 |
| -4 | 39 | Meredith #1 J. T. Shelby | 10,750 |
| -4 | 40 | Pan American #2 H. W. Gilbert Fee | 10,803 |
| -4 | 41 | Meredith #1 Edwards | 10,812 |
| -8 | 42(35) | Barnes et al. #1 Swallow | 12,001 |
| -8 | 43(36) | Texaco #1 Park Place Gas Unit | 13,478 |
| -4 | 44(37) | Kilroy #1 Booz | 12,600 |
| -1 | 45 | Halbouty #1 E. W. Brown, Jr. | 9,859 |
| 1S-50E-9 | 1 | Standard of Texas #1 State Tract 16 | 13,808 |
| -5 | 2 | Humble #1 Sabine Lake State Tract 8 | 13,008 |
| -5 | 3 | Standard of Texas #1 State Tract 12 | 12,631 |
| -3 | 4 | Scoggins et al. #1 Donner Properties | 10,300 |
| -6 | 5 | Shell #3 State Lease 3460 | 12,011 |
| -5 | 6 | Shell #2 State Lease 3460 | 12,503 |
| -2 | 7 | Texaco #1 State Tract 3 | 11,515 |
| -4 | 8 | Meredith et al. #1 Grinnell-Texas Co. | 12,784 |

## Appendix (cont.)

| Location | Well no. | Well name | Well depth (ft) |
|---|---|---|---|
| -3 | 9 | Texaco #1 H. J. L. Stark "B" NCT-1 | 11,065 |
| -3 | 10 | Texaco #2 H. J. L. Stark "B" NCT-1 | 10,300 |
| -8 | 11 | California #2 State Lease 3461 | 14,001 |
| -8 | 12 | California #1 State Lease 3461 | 13,500 |
| -2 | 13 | Shell #1 State Lease 3459 | 12,092 |
| -1 | 14 | Houston Oil & Minerals #1 State Lease 7555 | 11,445 |
| -4/9 | 15 | Standard #1 State Tract 15 | 13,130 |
| 2S-47E-1 | 1 | Sohio #1 B. C. Hebert Heirs | 9,712 |
| -5 | 2 | Tenneco et al. #1 M. McFaddin Ward | 14,022 |
| -7 | 3 | Amoco #1 "A" McFaddin Ranch | 12,663 |
| -3 | 4 | Magnolia #B-1 B. E. Quinn | 10,712 |
| -6 | 5 | Sun #25 Broussard-Hebert | 13,005 |
| -6 | 6 | Sun #26 Broussard-Hebert | 11,015 |
| -1 | 7 | Union of California #1 B. C. Hebert Heirs | 11,941 |
| -2 | 8 | Superior et al. #1 La Belle Ranch "DD" | 12,745 |
| -4 | 9 | Mobil #1 Gill Estate | 14,422 |
| -5 | 10 | Coline #1 Sun-Broussard Trust | 10,656 |
| -2 | 11 | Pure #1 C. E. Ward | 10,505 |
| -2 | 12 | Tenneco #1 J. Wilfert | 14,500 |
| -2 | 13 | Hunt & Hebert Trust #1 C. E. Ward et al. | 12,881 |
| -1 | 14 | Sohio #1 H. C. Broussard Estate 1 | 10,950 |
| -4 | 15 | McCarthy #1 J. J. Craigen | 10,895 |
| -9 | 16 | McCarthy #B-1 W. B. Davidson Estate | 11,416 |
| -9 | 17 | General Crude #1 Nold | 12,872 |
| -9 | 19 | Sun #4 Broussard-Hebert | 7,535 |
| -9 | 20 | Sun #6 Broussard | 8,224 |
| -9 | 23 | Sun #35 Broussard-Hebert | 7,700 |
| -9 | 24 | Sun #37 Broussard-Hebert | 7,704 |
| -9 | 25 | Sun #1 W. N. Folts | 8,661 |
| -6 | 27 | Dow #2-A Hebert-Broussard | 11,089 |
| -5 | 28 | Sun #1 Carroll Ward | 8,919 |
| 2S-48E-4 | 1 | Houston Natural Gas #1 Broussard Heirs | 13,458 |
| -6 | 2 | Magnolia #B-1 McFaddin | 14,611 |
| -3 | 3 | Shell #B-1 Hebert-Broussard | 15,450 |
| -2 | 4 | Dow #1 D. B. Lavin | 11,405 |
| -8 | 5 | Amoco #B-1 McFaddin Ranch | 14,990 |
| -4 | 6 | Shell #1 McFaddin Cee Cross | 12,004 |
| -2 | 7 | NorAm #1 McFaddin Ranch | 11,935 |
| -1 | 8 | Rutherford et al. #1 McFaddin Trust | 12,537 |
| -3 | 9 | Houston Natural Gas #1 Cee Cross | 14,795 |
| -2 | 10 | Shell #1-C Hebert Ranch | 12,507 |
| -2 | 11 | Magnolia #1 B. C. Hebert Trust | 12,704 |
| -4 | 12 | Dow #7 Hebert-Broussard | 11,159 |
| -9 | 13 | Sun #38 Broussard-Hebert | 13,000 |
| 2S-49E-9 | 1 | Shell #3 McFaddin Ranch | 8,504 |
| -5 | 2 | Humble #1 State Tract 38 | 13,906 |
| -3 | 3 | Gulf #1 Port Arthur Refinery Fee | 13,448 |
| -7 | 4 | California #3 State Lease 3565 | 8,400 |
| -7 | 5 | California #1 State Lease 3565 | 14,500 |
| -6 | 6 | California #2 State Lease 3565 | 8,737 |
| -4/9 | 7 | Shell #7 McFaddin Ranch | 8,420 |
| -7 | 8 | Associated #1 Doornbos | 8,714 |
| 2S-50E-2 | 2 | Shell #1 State Lease 3464 | 16,000 |
| -3 | 3 | California #1 State Lease 3463 | 14,094 |
| -3 | 4 | Amoco #1 State Lease 6935 | 8,595 |