CONSOLIDATION OF GEOLOGIC STUDIES OF GEOPRESSURED-GEOTHERMAL RESOURCES IN TEXAS

1988 Annual Report

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ABSTRACT

The Pleasant Bayou C zone geopressured-geothermal reservoir is currently undergoing long-term production testing. Using all available deep-well data and building on broad-based previous work, we constructed a detailed geologic characterization of the C zone reservoir, including sandstone geometry and continuity, porosity distribution, depositional facies interpretation, and structural configuration. This characterization formed the basis for calculating total sandstone volume and effective pore volume of the reservoir and for constructing models for use in numerical simulations. Total effective pore volume of the C zone reservoir is estimated to be between 6.2 and 6.6 billion barrels. With respect to the test well, one-third of this volume is proximal (within about 3 mi) and two-thirds is remote. Geologically-based reservoir volume and models will be useful in predicting long-term well performance and interpreting pressure and production trends during the testing program.

We are monitoring pressures in deep gas wells in Chocolate Bayou field to detect possible changes that can be related to production at the Pleasant Bayou test well. No wells produce gas directly from the C zone reservoir, but several do produce from thin, overlying sandstones, which may be in contact with the perforated interval. Gas-well pressure data are reported semiannually and must be monitored for several years to obtain meaningful trends.

At a depth of 20,200 ft, the DOE Hulin No. 1 well in southwestern Louisiana penetrates a 550-ft-thick sandstone, which is the deepest known Gulf Coast geopressured-geothermal reservoir. Although the lack of deep well control has precluded detailed mapping, regional stratigraphic context and log response suggest that the Hulin reservoir was deposited in a submarine canyon or proximal submarine fan on the lower Miocene continental slope. Testing the Hulin reservoir will offer a unique opportunity for research and resource evaluation.

PLEASANT BAYOU C ZONE RESERVOIR

Introduction

The Pleasant Bayou No. 2 geopressured-geothermal test well was completed in 1979 in Brazoria County, Texas, about 40 mi south of Houston (fig. 1). The well site was selected on the basis of regional geologic analysis conducted at the Bureau of Economic Geology during the 1970's. Initial production testing took place in the early 1980's and, along with logging and sampling operations, provided a wealth of data for ongoing research. The geology of deep geopressured reservoirs in the Pleasant Bayou area was extensively investigated, including the structural configuration, stratigraphic framework, sandstone composition and diagenesis, depositional setting and sandstone continuity, fluid compositions, flow patterns, and development of geopressure. In preparation for the new phase of long-term production testing that began this year, we reviewed results of these earlier studies and extended the research by focusing on the C zone reservoir.

During FY 1988 the geometry, dimensions, boundary conditions, internal heterogeneities, and producible pore volume of the Pleasant Bayou C-zone reservoir were determined. Well log correlations traced the continuity and interconnectedness of individual sandstone and mudstone beds, which are illustrated in a series of cross sections (fig. 2). Sandstone thickness was contoured, and total reservoir volume was measured. Sandstone geometries, distinctive log patterns, and core analysis formed a basis for extending earlier depositional facies interpretations. Porosities measured in core samples from the test well were by analogy assigned to similar sandstone facies throughout the reservoir, and total effective pore volume was calculated. Models were constructed that approximate reservoir volume, dimensions, and pore-space distribution but that are simple enough to be used in two-dimensional numerical simulations. Distribution of faults within the main Pleasant Bayou fault block was mapped, and potential effects of these internal faults as barriers or conduits to flow were analyzed. Finally, production and development activity in the nearby Chocolate

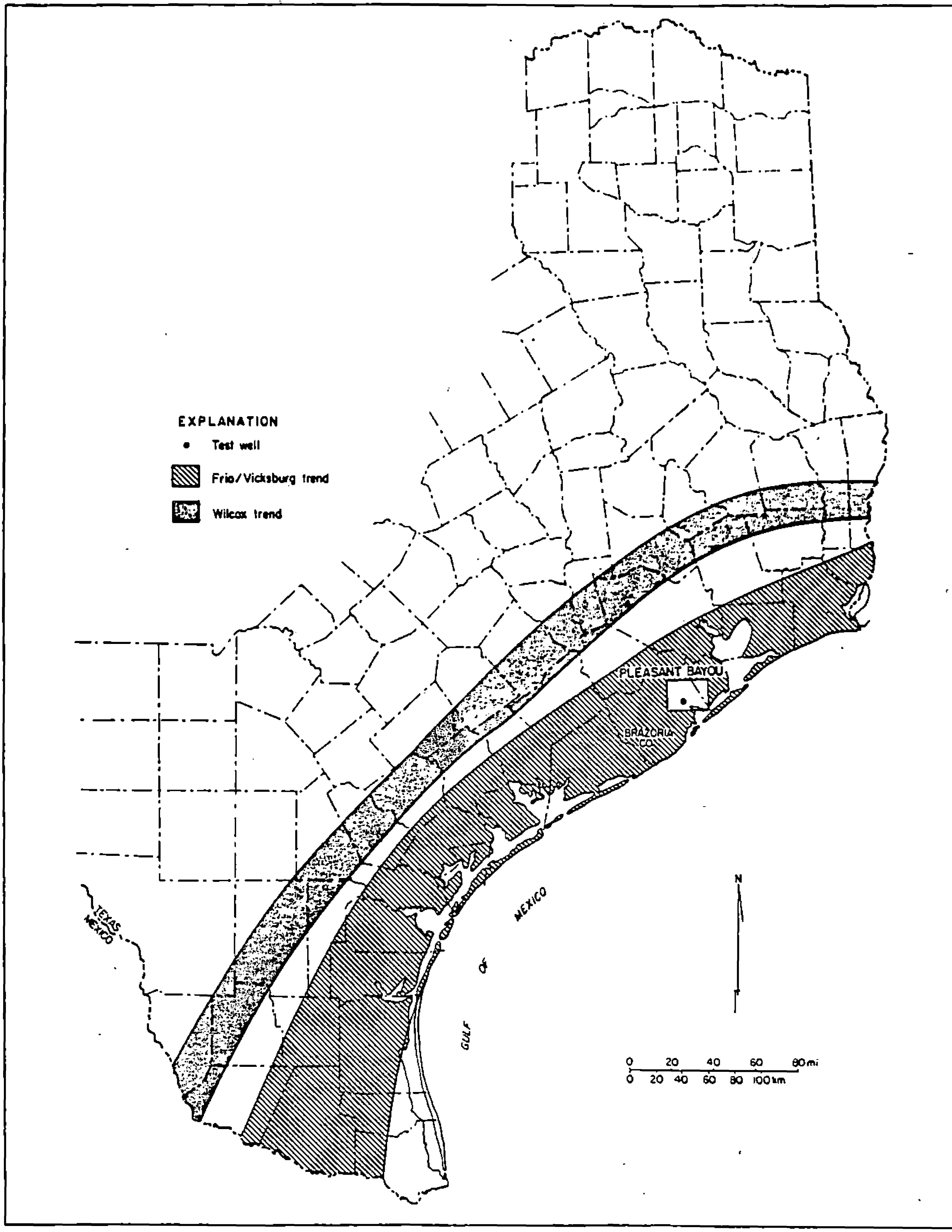

Figure 1. Location map of the Pleasant Bayou No. 2 test well and the major geothermal exploration trends, Texas Gulf Coast. Modified from Winker and others (1983).

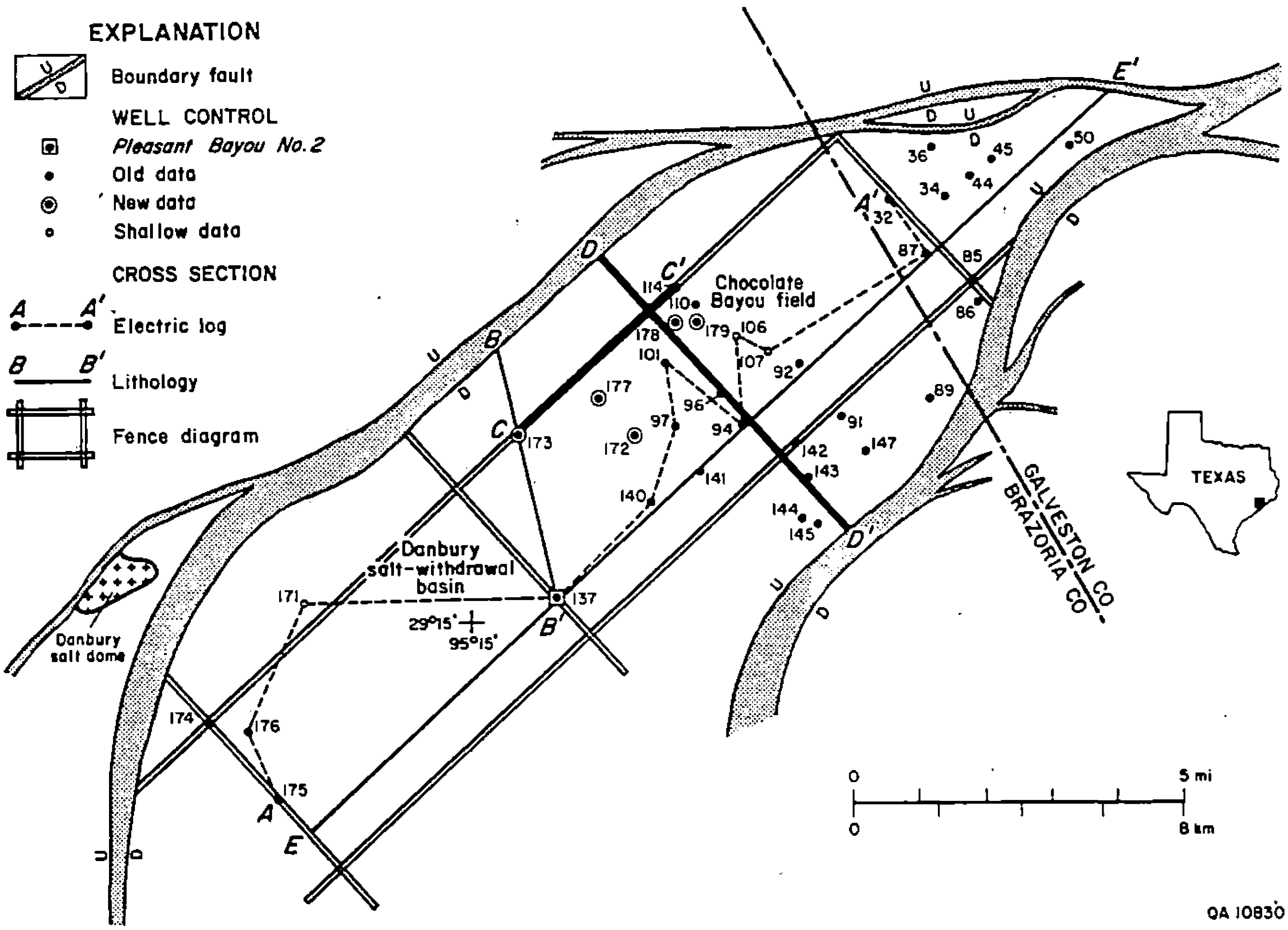

Figure 2. Index map of the Pleasant Bayou fault block showing well control and cross section lines.

Bayou oil and gas field was reviewed as a potential source of pressure data that could be related to production at the test well.

Summary of Results

1. The lower Frio Formation C zone contains a good quality reservoir that is continuous throughout the Pleasant Bayou fault block.

2. The C zone reservoir includes not only the 60-ft perforated interval in the test well but also several other interconnected sandstones; total reservoir sandstone thickness reaches 200 ft locally.

3. Within the Pleasant Bayou fault block, the main area of vertical porosity interconnection is Chocolate Bayou field, where the reservoir is a single thick sandstone with only isolated thin mudstone interbeds.

4. The major C zone sandstones were deposited primarily in deltaic distributary channels and channel-mouth bars, thus accounting for their relatively coarse grain size and high porosity and permeability.

5. Total effective pore volume in the C zone reservoir is 6.2 to 6.6 billion barrels, one-third of which is proximal volume and two-thirds is remote volume.

6. The C zone has been sufficiently documented by well-data analysis that geologic models of varying degrees of complexity can be designed for use in numerical simulations.

7. Several discontinuous faults occur within the main Pleasant Bayou fault block, forming partial barriers to flow. Reservoir volume may be increased, however, where the C zone is juxtaposed against other thick sandstones.

8. In Chocolate Bayou field, deep gas wells may provide important pressure data that could be related to long-term production at the test well.

Reservoir Properties

The Pleasant Bayou No. 2 test well is perforated across 60 ft between 14,644 and 14,704 ft, which is the main sandstone reservoir in the "C" correlation interval (C zone) (fig. 3). This is the same reservoir that was tested soon after the well was completed (Morton, 1981) (table 1) and that is currently undergoing long-term production testing. On the basis of analysis of core samples from the Pleasant Bayou No. 2 well, the C zone contains the highest quality geopressured reservoir at that site (Loucks and others, 1980; Morton and others, 1983). This reservoir has been called the "Andrau sandstone," although in Chocolate Bayou field, "Andrau" refers to a larger interval that includes both the B and C zones (fig. 3). Porosity averages 19 percent; permeability averages 200 md (table 1). The medium- to coarse-grained framework sand grains are 50 to 85 percent quartz, the remainder being feldspars and volcanic rock fragments. Intergranular, pore-filling matrix and cements are generally less than 10 percent of bulk composition, and secondary dissolution porosity is well developed (fig. 4). In the Pleasant Bayou No. 2 well, the main C zone sandstone displays relatively low vertical variability in reservoir properties and is an unusually good quality reservoir compared to other Frio Formation sandstones at similar depths of burial.

Sandstone Thickness Patterns

Large growth faults form major lateral boundaries for Pleasant Bayou reservoirs (fig. 2), but within the Pleasant Bayou fault block, lateral variations in sandstone thickness also affect reservoir volume. A net-sandstone isopach map of the C zone (fig. 5) shows thickness patterns of the reservoir sandstone as well as closely associated but thinner sandstones, many of which are interconnected with the perforated interval. The C zone is 200 to 500 ft thick, and net sandstone in the C zone ranges from about 20 to 270 ft. At the Pleasant Bayou No. 2 well site, 125 ft of sandstone and 109 ft of mudstone comprise the C zone. Sandstone thickness, as well as thickness of the entire C zone, increases toward the northern boundary fault (fig. 5). Active fault displacement

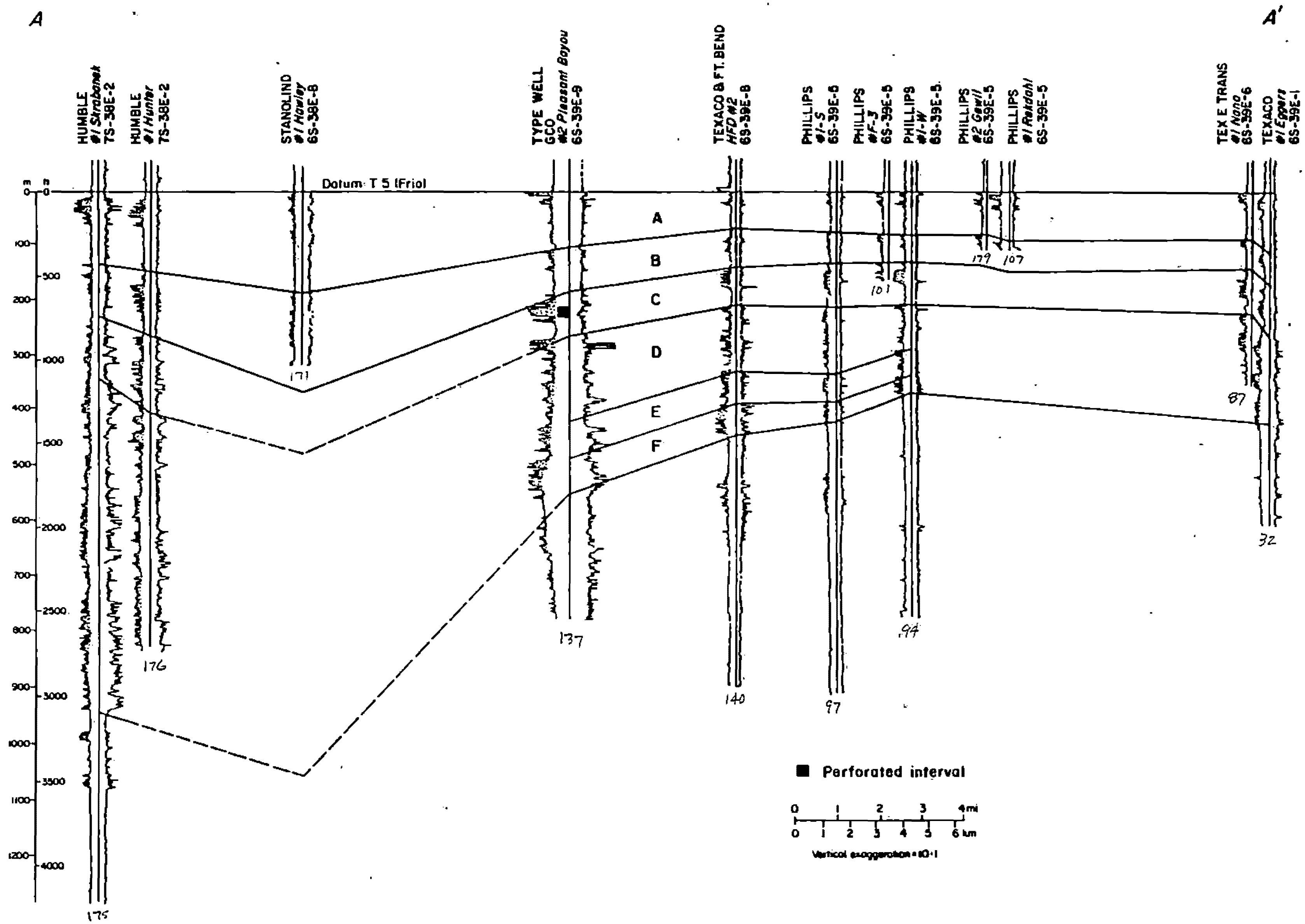

Figure 3. Electric log cross section of the lower Frio Formation, *Anomalina bilateralis* zone, showing the main geopressured correlation intervals in the Pleasant Bayou fault block and the perforated interval in the test well. Location of section line is shown in figure 2. Modified from Winker and others (1983).

Table 1. Phase I testing of Pleasant Bayou No. 2 during 1980. From Morton (1981).

Formation	Frio
Perforated interval	14,644 to 14,704 ft
Porosity	19 percent
Reservoir Data	
Initial pressure	11,050 psi
Temperature	301°F
Permeability	200 md
Barriers	Partial at 3,700 ft
	Fault at 3 mi
Radial explored distance	16,525 ft
Estimated area	25 mi^2
Testing	
Duration	45 days
Flow: maximum	22,752 BPD
average	13,106 BPD
Surface temperature	255°F
Sand production	None
Fluid Analyses	
Total dissolved solids	131,320 mg/L
Methane	85.5 percent
Carbon dioxide	10.5 percent
Gas/water	29 SCF/bbl

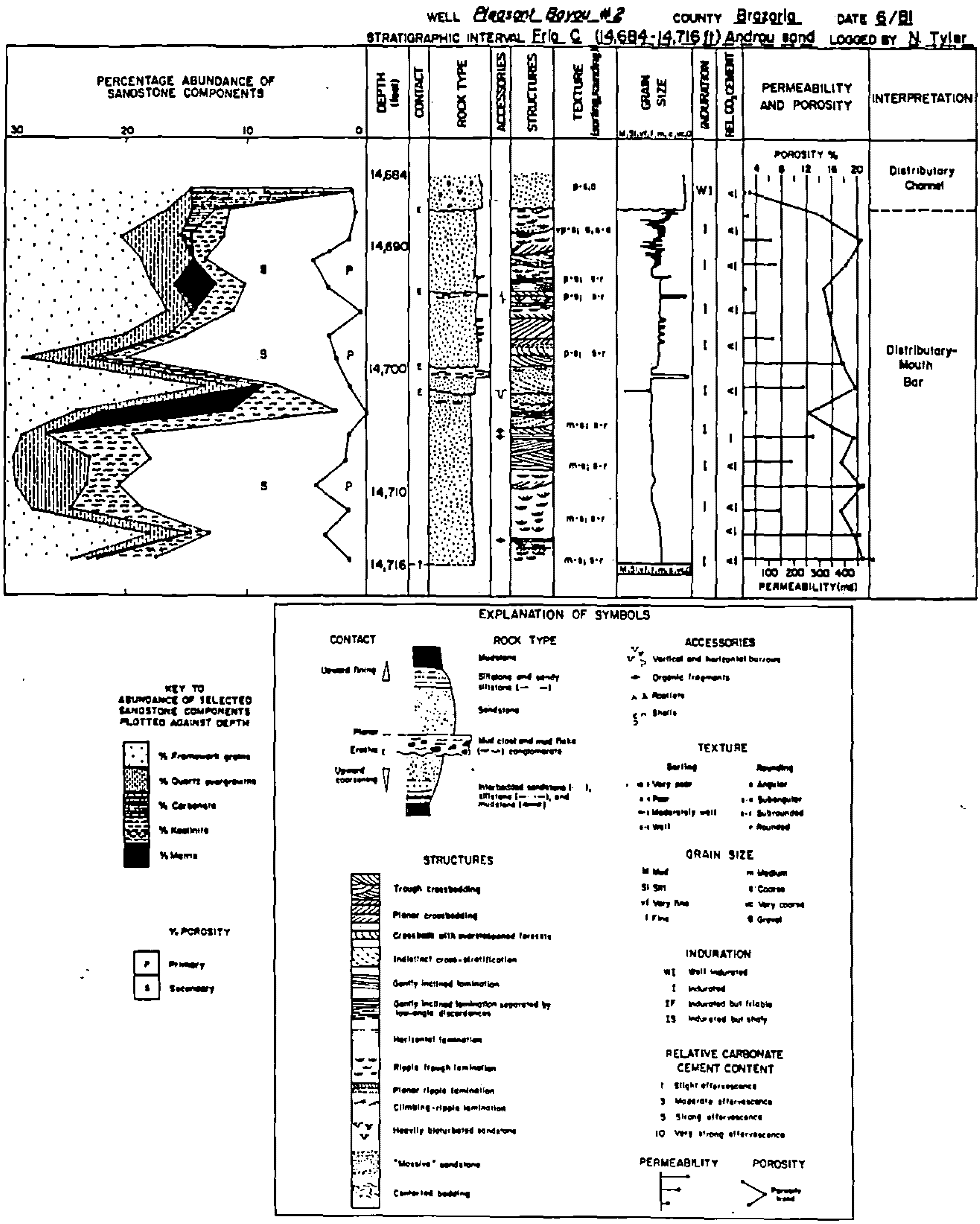

Figure 4. Detailed core description, pore properties, composition, and depositional interpretation of the C zone perforated interval at the Pleasant Bayou No. 2 well. Modified from Ewing and others (1984).

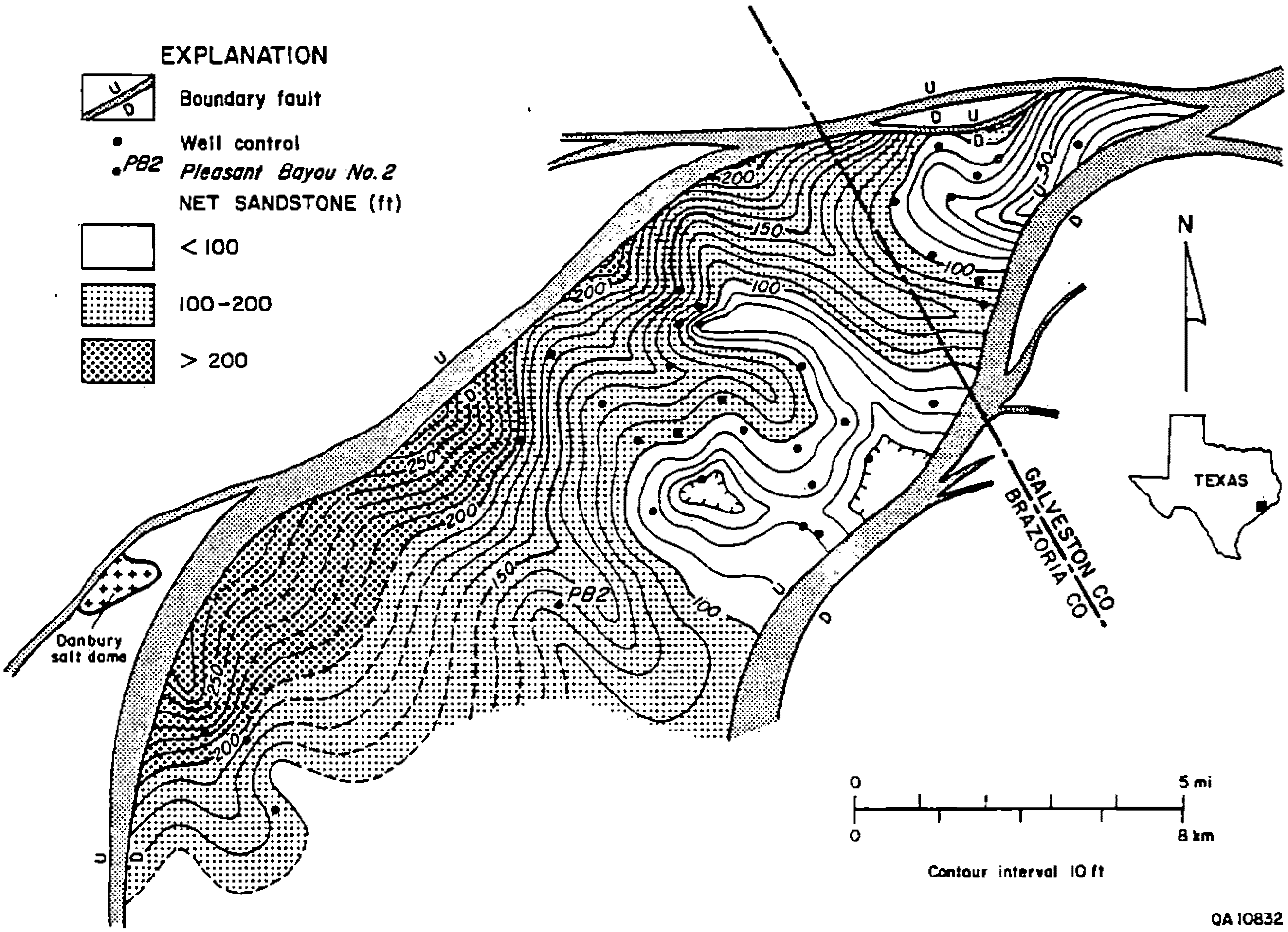

Figure 5. Net-sandstone isopach map of the C zone in Pleasant Bayou fault block.

during sedimentation influenced patterns of accumulation, as relatively thicker sequences of sand and mud became trapped along the subsiding downthrown sides of large growth faults.

Dip-oriented (northwest to southeast), sandstone thickness trends (fig. 5) confirm interpretations based on core analysis (fig. 4) that C zone sandstones were deposited primarily in the distributary channels and channel-mouth bars of a high-constructive but wave-modified delta system (Tyler and Han, 1982) (fig. 6). Former channel axes are delineated by elongate sandstone thicks that are separated by areas of lower sandstone content (fig. 5). Thicker channel-fill and channel-mouth bar sandstones are generally coarser grained and more permeable than are thinner channel-flank and delta-front shoreface sandstones (Morton and others, 1983).

Spontaneous potential (SP) curves from electric logs through the C zone show patterns of sandstone and mudstone thicknesses and interbedding across the Pleasant Bayou fault block (fig. 7). The thick reservoir sandstone is best developed across Chocolate Bayou field and southwest to the Pleasant Bayou area. To the northeast in Galveston County and to the southwest near Danbury salt dome, the C zone consists primarily of more thinly interbedded sandstones and mudstones (fig. 7).

No wells penetrate the C zone in a large area south of the Pleasant Bayou No. 2 well (fig. 5). The nearest deep well south is 6.5 mi away, but the C zone there is 100 percent mudstone. Thus, the reservoir sandstone pinches out somewhere across this southern area of no data. Since no large growth fault has been mapped south and southwest of the test well (Winker and others, 1983), porosity pinch-out probably forms the reservoir boundary, although smaller faults may form partial barriers to flow. Sandstone thickness trends and SP patterns suggest that the distributary channels passed mainly to the northeast of Pleasant Bayou No. 2, although a secondary channel system may have existed in the Danbury Dome area (figs. 5 and 7). Because the southern area appears to have been largely bypassed by the major sand-depositing channel systems, the southern boundary of the Pleasant Bayou fault block was fixed (for reservoir volume calculations) 3 mi south of the test well.

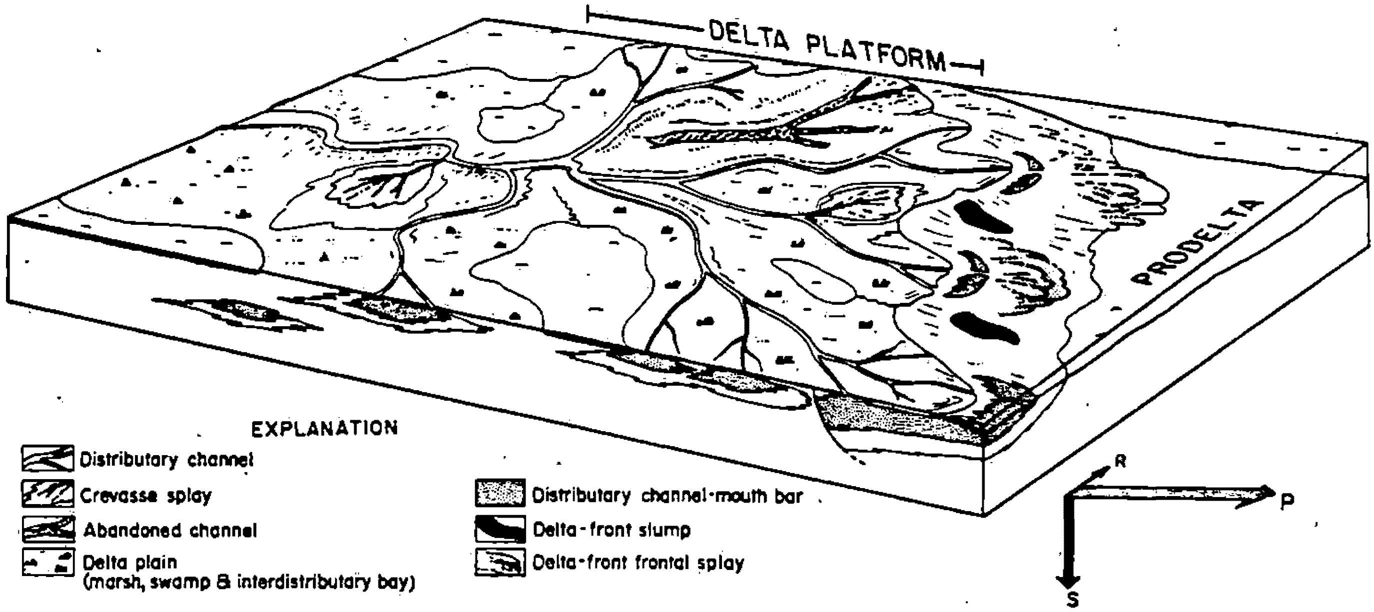

Figure 6. Depositional model of high-constructive, wave-modified deltaic deposits of the lower Frio Formation, Brazoria County, Texas. From Tyler and Han (1982).

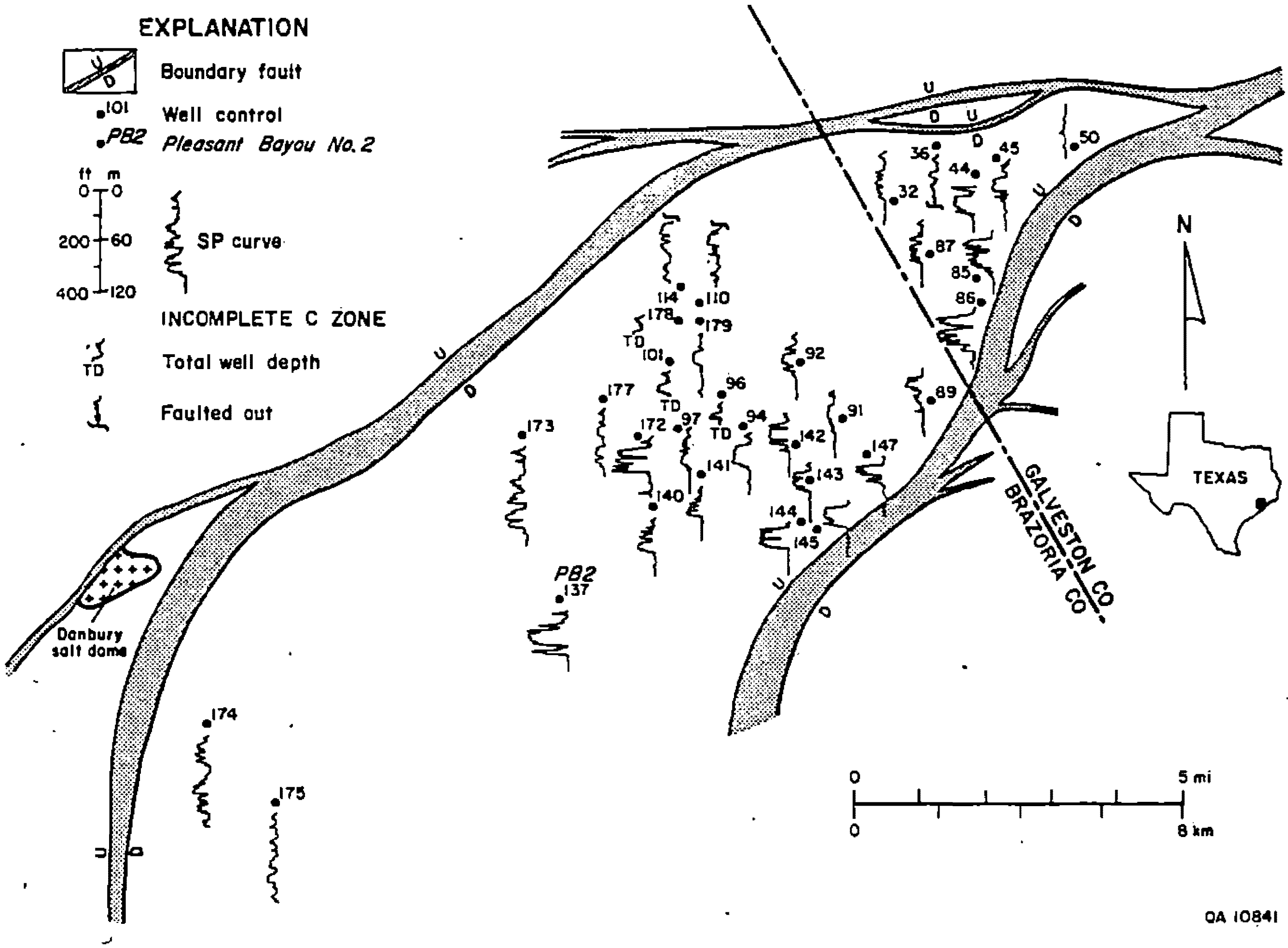

Figure 7. Map showing SP curves from electric logs through the C zone in the Pleasant Bayou fault block.

Reservoir Continuity

Thickness patterns show the total volume of sandstone in the Pleasant Bayou fault block, but sandstone interconnectedness controls effective producible pore volume. The lateral continuity of the perforated interval and its communication with the other C zone sandstones were traced by correlating interbedded mudstones. If a mudstone is at least 10 ft thick and is continuous throughout the fault block, then it isolates sandstones above it from those below it. On the other hand, discontinuous mudstones allow sandstones to come into direct contact locally within the fault block. Sandstones that are in vertical or lateral contact with the perforated interval in the test well can be included as part of the total reservoir volume. Only two mudstones in the C zone are continuous throughout the Pleasant Bayou fault block: the upper and basal mudstones (fig. 8). These mudstones form the upper and lower boundaries of the reservoir. Although numerous discontinuous mudstones occur within the reservoir, it can be subdivided into three relatively persistent units: the lower, middle (perforated zone), and upper sandstones (fig. 8).

Careful correlation of mudstone interbeds enabled construction of a series of cross sections and a fence diagram, which show the complex pattern of sandstone and mudstone interbedding in the C zone across the Pleasant Bayou fault block. The fence diagram displays a three-dimensional view of the reservoir and enclosing mudstones (fig. 9). The basal mudstone interval is 50 to 150 ft thick and includes several thin discontinuous sandstones. The reservoir is a single thick sandstone in the Chocolate Bayou area but is segmented in other areas by mudstone interbeds. At the test well, for instance, three-part subdivision is clearcut (figs. 8 and 9). Sandstone and mudstone interbedding is most pronounced to the west and southwest toward Danbury Dome, to the north and northwest along the boundary fault, and in the northeastern corner of the fault block. The upper mudstone interval is 30 to 150 ft thick and includes several relatively continuous thin sandstones (fig. 9). The C zone is overlain by thick mudstones at the base of the B zone and is underlain by sandstones and mudstones in the upper part of the D zone (fig. 3).

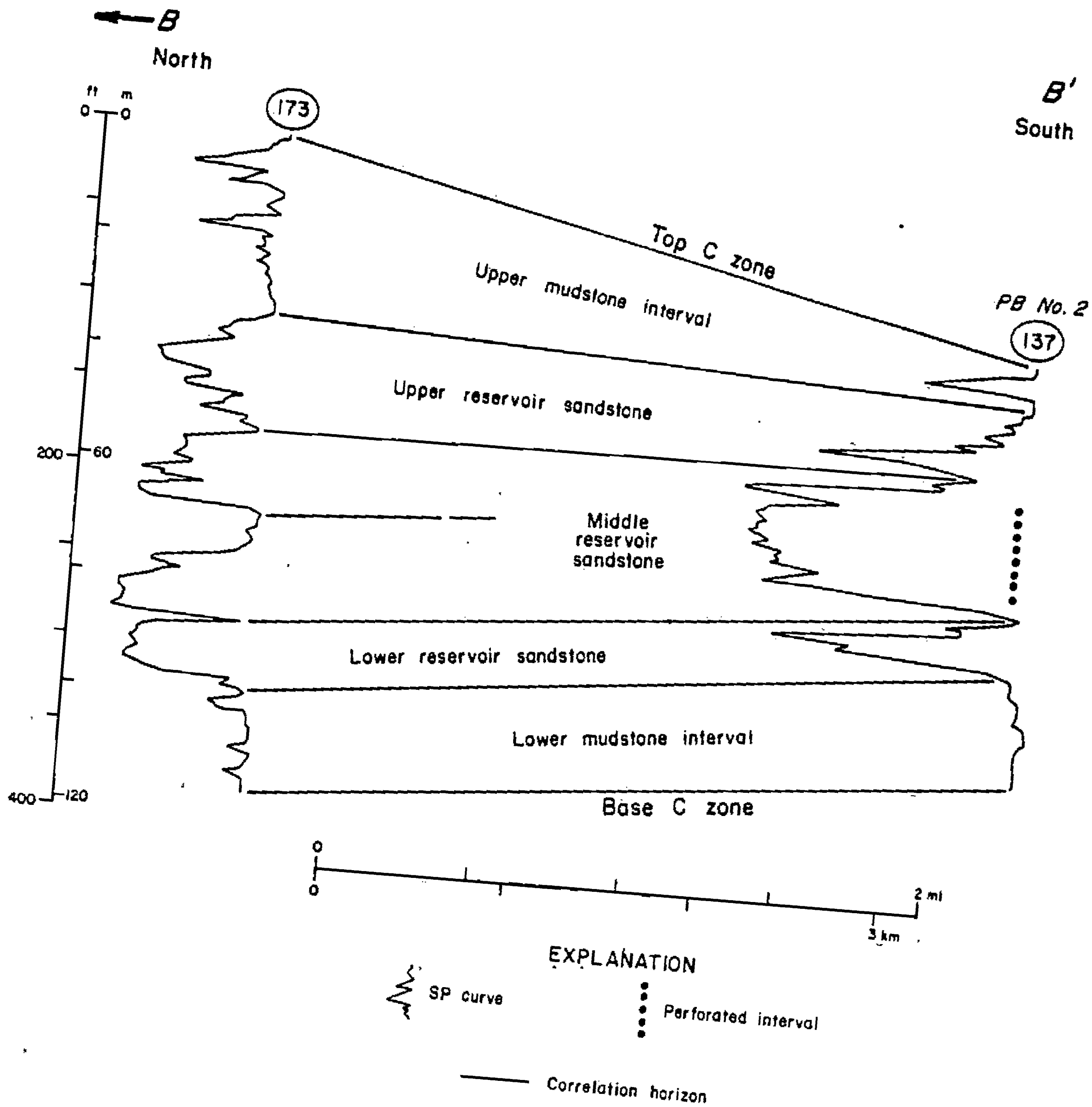

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Figure 8. Cross section B-B' showing the major sandstone and mudstone intervals, key correlation horizons, and typical SP patterns of the C zone. Location of section line shown in figure 2.

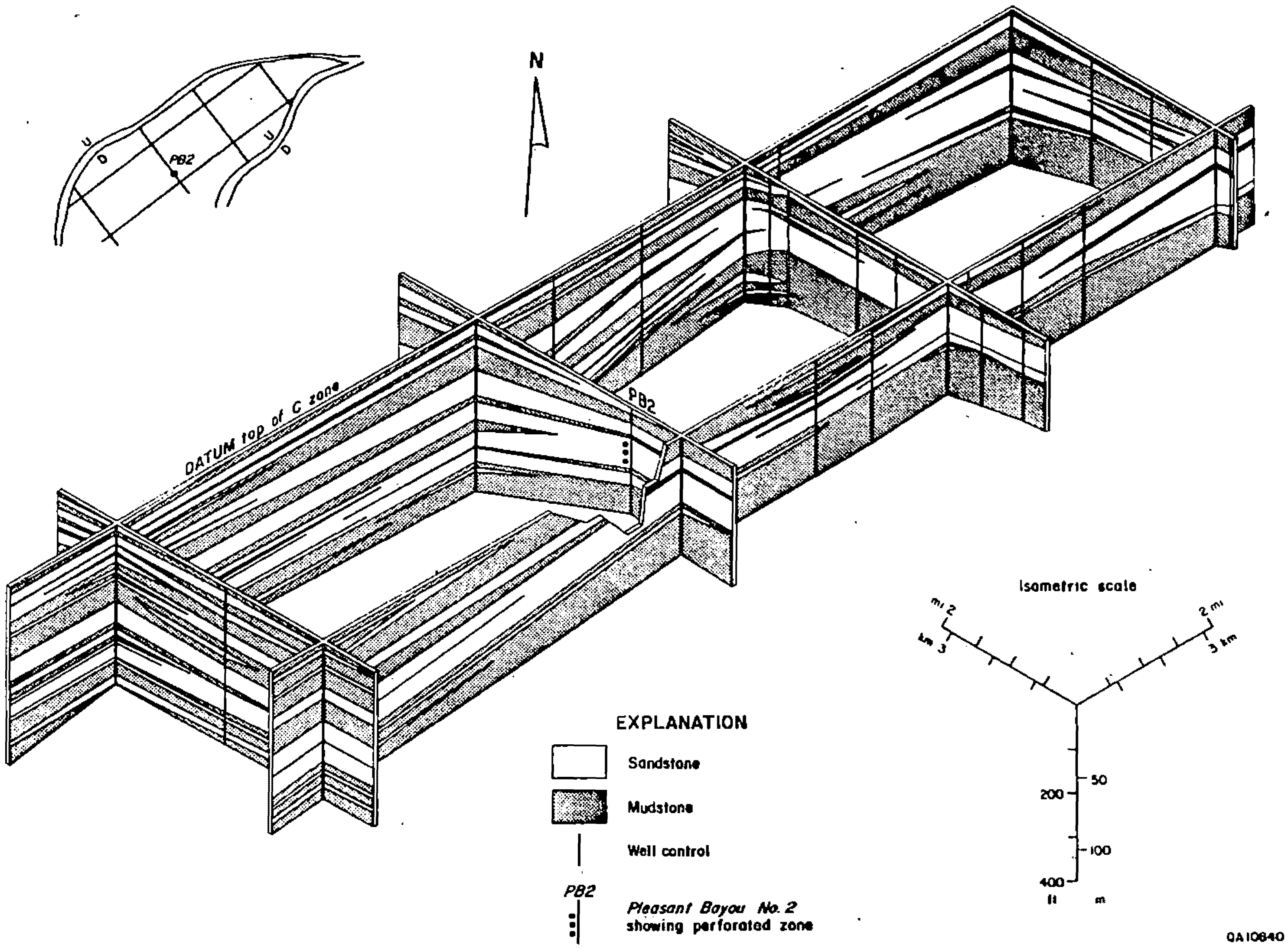

Figure 9. Fence diagram of the C zone illustrating sandstone and mudstone interbedding throughout the Pleasant Bayou fault block. Location and well control are shown in figure 2.

The cross sections illustrate the details of reservoir continuity in key locations. From the Pleasant Bayou No. 2 well, the reservoir thickens northward toward the boundary fault (fig. 10). Along this north-south line, the lower sandstone is in communication with the middle (perforated) sandstone, but the upper sandstone is isolated by a continuous mudstone (fig. 10). In the northwestern and western parts of the Pleasant Bayou fault block, the middle sandstone is split by a thick mudstone (figs. 9 and 10). This mudstone pinches out southward toward the test well (fig. 10) and northeastward toward Chocolate Bayou field (fig. 11). Across Chocolate Bayou field the reservoir is a single massive sandstone with only isolated thin mudstone interbeds (fig. 12). A strike-oriented cross section that extends along the long axis of the fault block (fig. 13) illustrates multiple thick sandstones and mudstones in Danbury salt-withdrawal basin, the three main reservoir sandstones at the test well, the single massive sandstone at Chocolate Bayou, and thinly interbedded sandstones and mudstones to the northeast in Galveston County. Thus, Chocolate Bayou field is an important area of vertical interconnection within the reservoir.

Depositional Framework

Depositional styles and patterns are important controls on reservoir quality, continuity, and volume. In the southwestern part of the Pleasant Bayou fault block, the greater thickness of the C zone (figs. 9 and 13) is related to greater subsidence in the Danbury salt withdrawal basin, but the higher degree of mudstone interbedding is probably a result of the area's distance from the main axes of channel deposition. Because it was a zone of recurrent deltaic-distributary-channel and channel-mouth bar deposition (Tyler and Han, 1982; Morton and others, 1983), the Pleasant Bayou to Chocolate Bayou area is characterized by thicker sandstones with fewer mudstone interbeds than are areas to the southwest and northeast (figs. 9 and 13). Bebout and others (1978) confirmed that porosity and permeability of reservoirs in the Pleasant Bayou fault block decrease to the southwest, and petrographic analysis by Loucks and others (1980) found that the highest reservoir quality at Pleasant Bayou was in channel-fill sandstones. Therefore, for calculating reservoir volume and

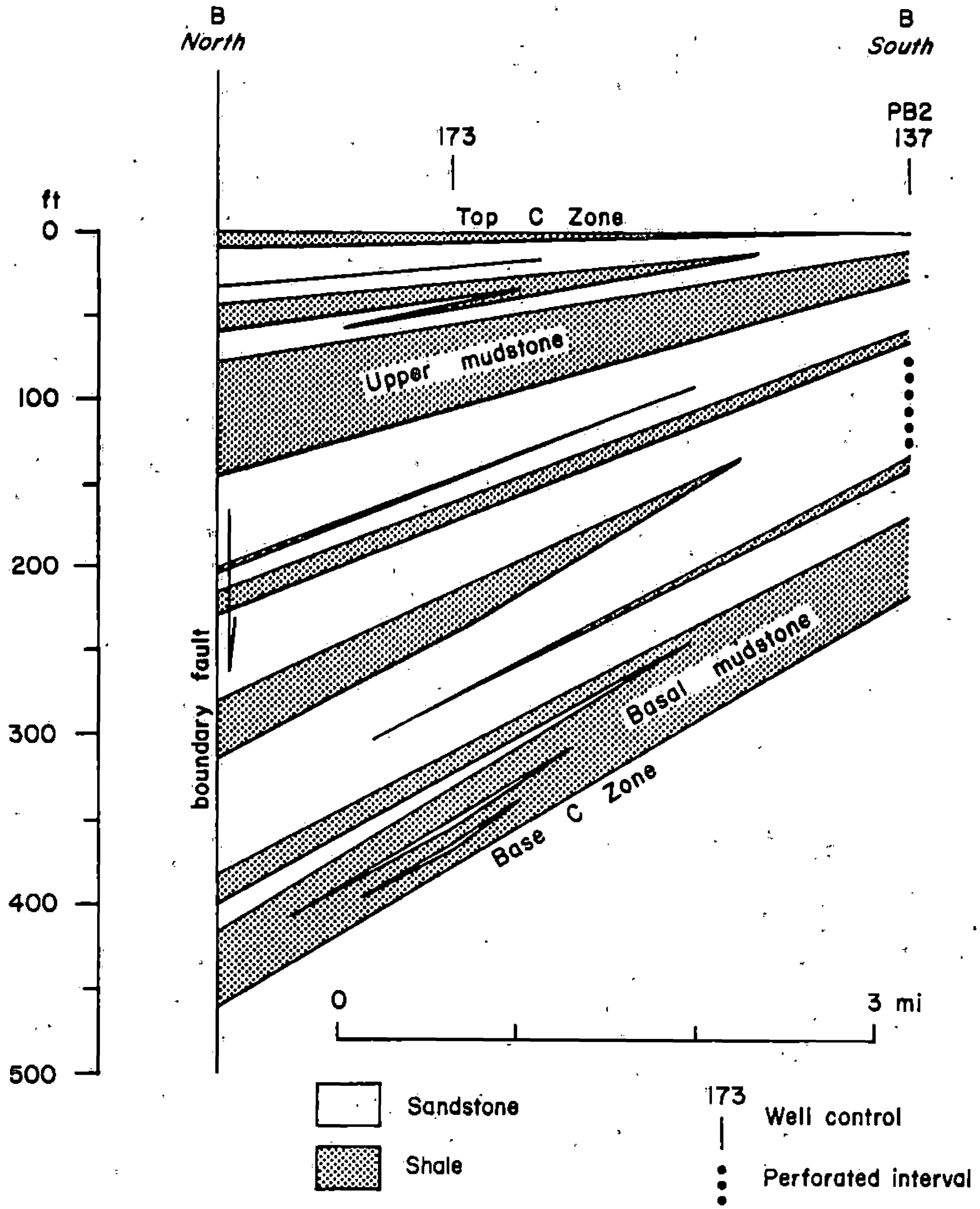

Figure 10. Cross section B-B' showing details of sandstone and mudstone interbedding from the test well to the northern boundary fault in the C zone. Mudstone interbeds in the lower and middle reservoir sandstones are discontinuous along this profile, whereas the upper sandstone is isolated by a continuous mudstone. Location of section line is shown in figure 2.

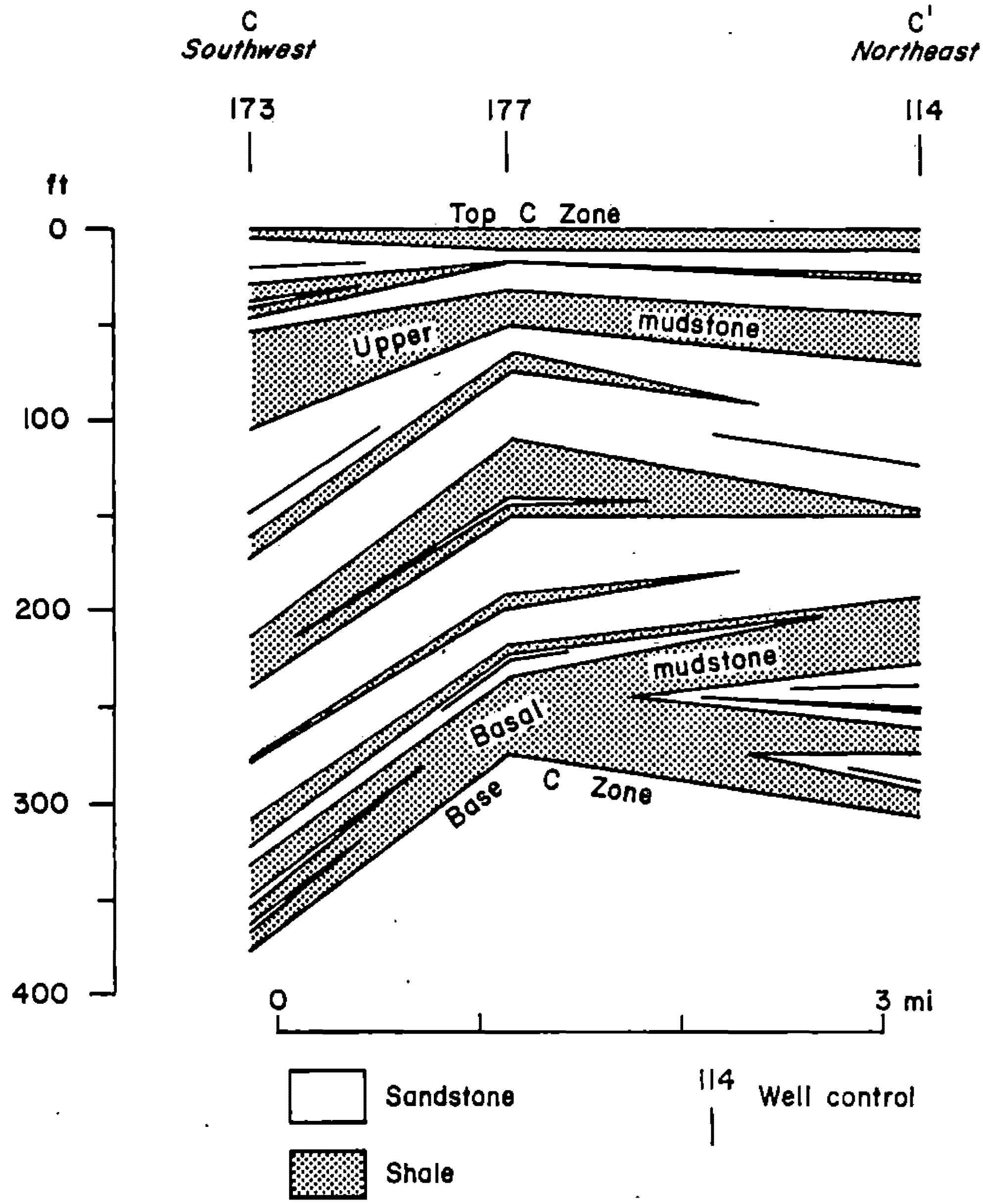

Figure 11. Cross section C-C' showing details of sandstone and mudstone interbedding along strike near the northern boundary fault. Thick mudstones segment the reservoir to the southwest but thin and pinch out northeastward. Well 114 is in Chocolate Bayou field (fig. 12). Location of section line is shown in figure 2.

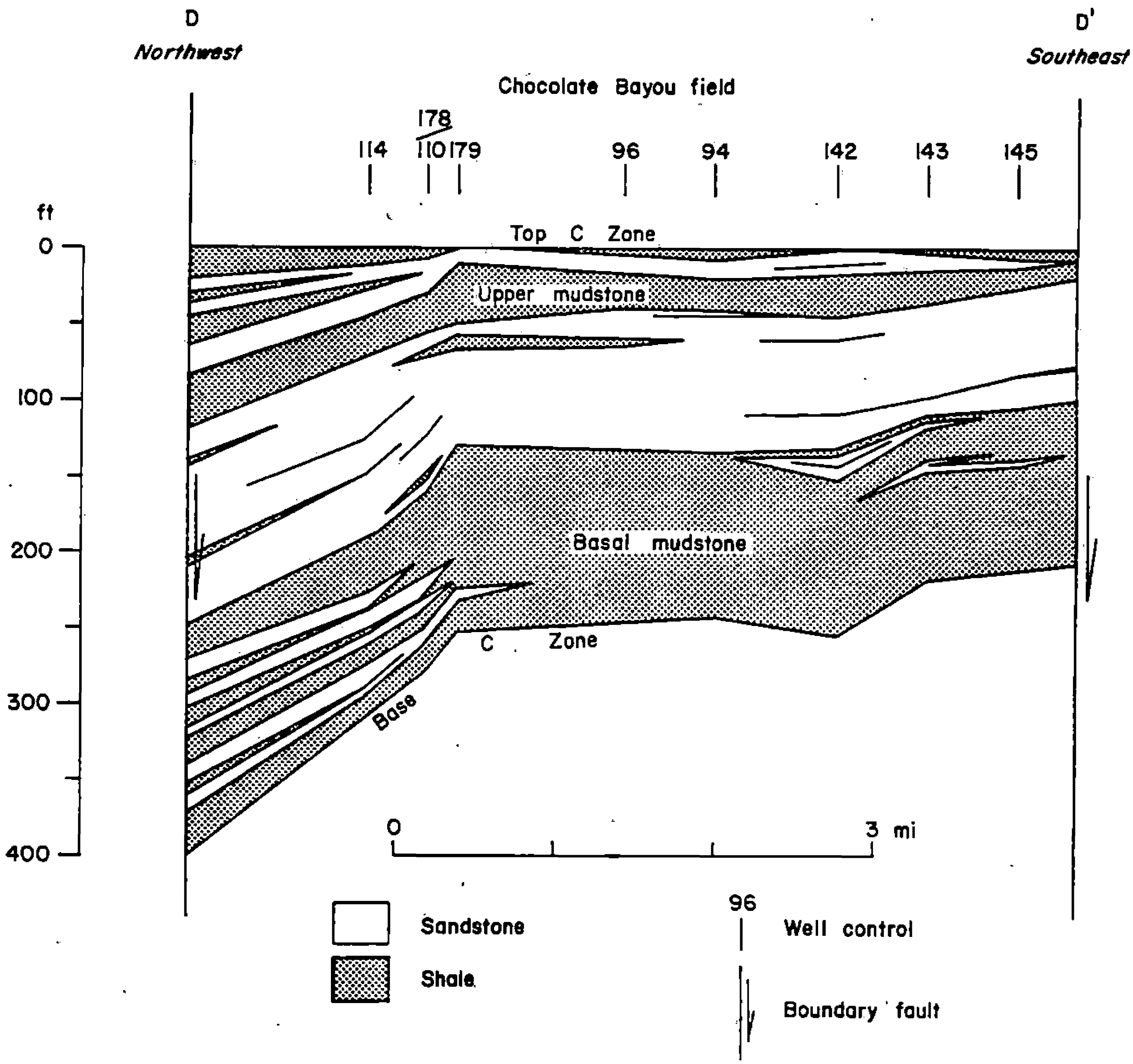

Figure 12. Cross section D-D' showing details of sandstone and mudstone interbedding in a dip-oriented profile across Chocolate Bayou field, where the reservoir contains only thin isolated mudstones. Well 178 produces gas from the thin sandstone overlying the upper mudstone. Location of section line is shown in figure 2.

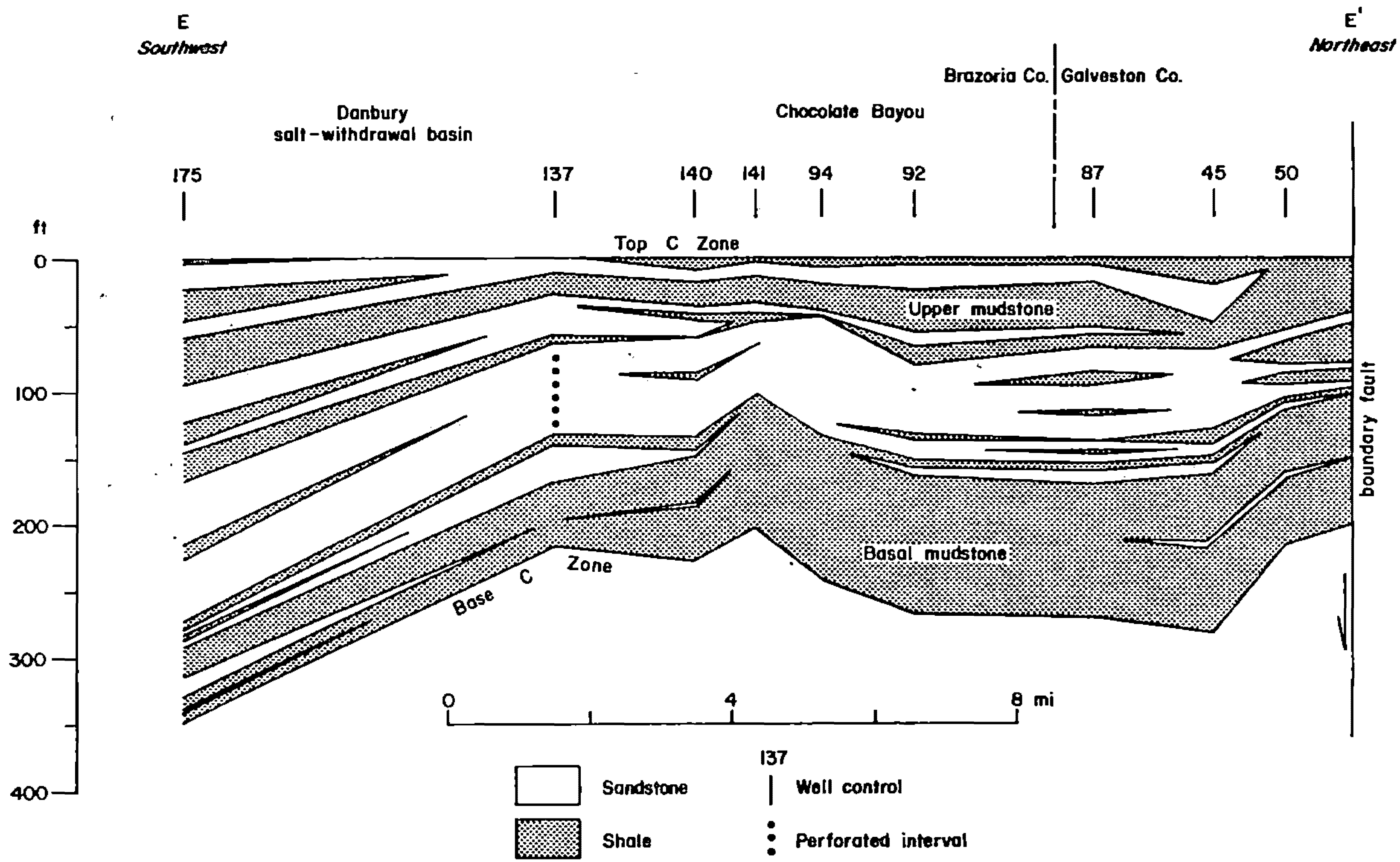

Figure 13. Cross section E-E' showing details of sandstone and mudstone interbedding along strike down the long axis of the fault block. Location of section line is shown in figure 2.

constructing models, it was assumed that thicker sandstones with fewer mudstone interbeds have higher porosity, but thinner sandstones interbedded with abundant mudstone have lower porosity.

Depositional facies interpretations and facies-distribution patterns at Pleasant Bayou have been thoroughly analyzed (Bebout and others, 1980; Tyler and Han, 1982; Morton and others, 1983; Winker and others, 1983). This well-established depositional framework meant that this study could focus on detailed mapping of sandstone geometry and continuity. However, electric logs from several recently drilled wells (fig. 2) were used to initiate an extension of earlier facies analyses. A dip-oriented facies tract, extending several miles between the test well and a new well in a key location near the northern boundary fault, is shown in figure 14. Using detailed correlations and distinctive log patterns, we extrapolated core-based facies interpretations of the test well to the new well. The lower half of the C zone is clearly progradational, recording the seaward advance of a sandy delta lobe over a muddy prodelta platform (figs. 6 and 14). In the lowermost sandstone, channel-mouth bar facies grade seaward into delta-front shoreface facies. As progradation continued the distributary channel cut through its own mouth bar, but a new bar formed farther downdip at the site of the test well (fig. 14). That distributary channel-fill sandstone is overlain by a thick but discontinuous mudstone that exists only in updip parts of the Pleasant Bayou fault block. The relatively high resistivity of this mudstone, when compared to low-resistivity prodeltaic and marine mudstones, and its position in the facies tract indicate that it records interchannel deposition on a heavily vegetated delta plain (fig. 6). Progradation reached a maximum as a younger distributary channel cut across the delta plain and extended beyond the test-well site (fig. 14). The upper half of the C zone comprises a series of progradational pulses that diminish in size upward, recording delta-flank shoreface deposition and reflecting net retrogradation and shoreline retreat. The C zone is both overlain and underlain by transgressive marine mudstones, which provided the widespread correlatable markers that have been used to subdivide the lower Frio Formation into genetic sequences (fig. 3). In FY 1989 facies analysis and sequence stratigraphy will be used to estimate reservoir continuity and quality in areas where well data are sparse, especially south and southwest of the test well.

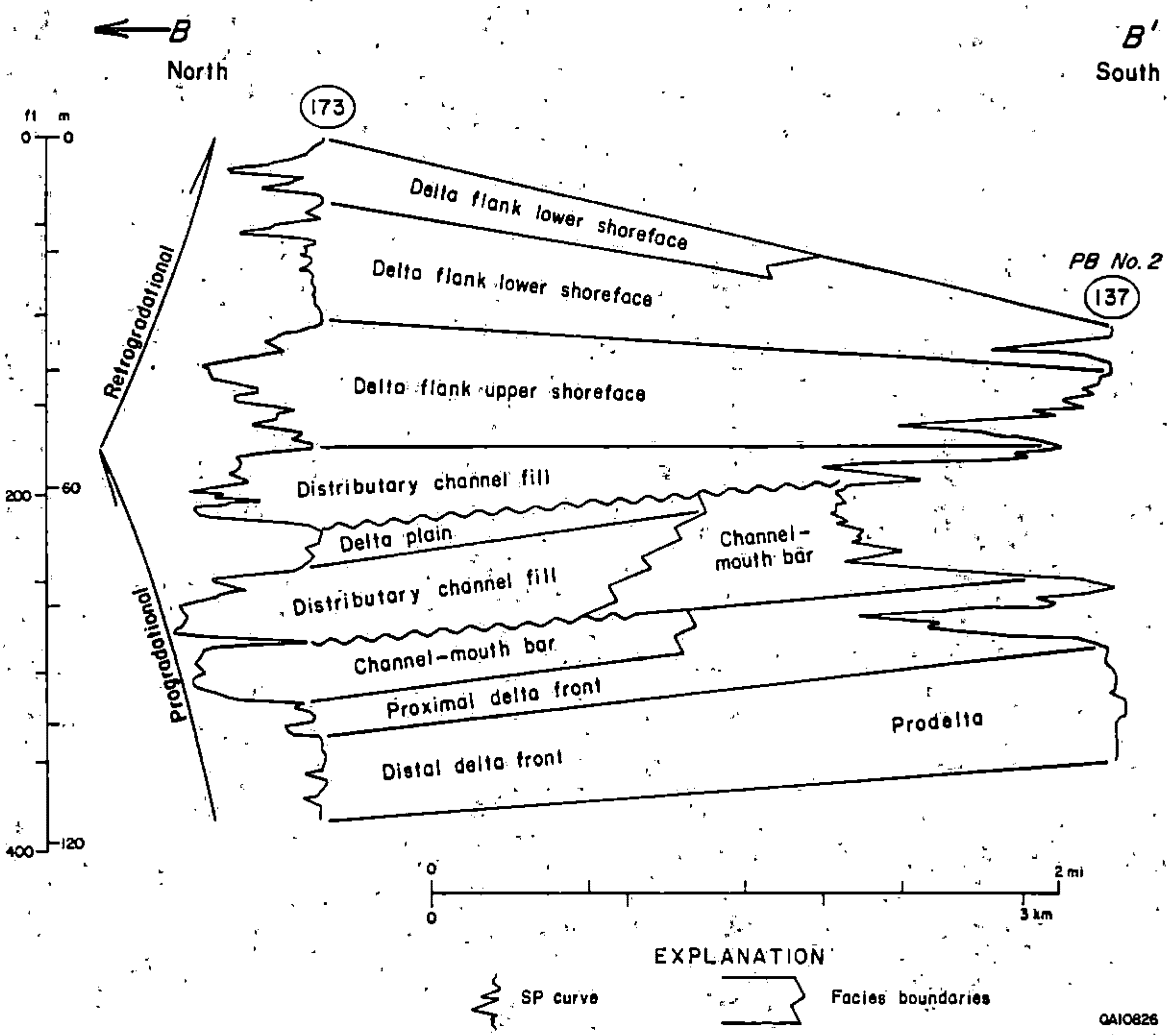

Figure 14. Dip-oriented depositional facies tract along C zone cross section B-B'. Location of section line is shown in figure 2.

Structural Setting

The structural configuration of the Pleasant Bayou fault block has been the subject of ongoing analysis, first using well control alone (Bebout and others, 1978) and later using both well and seismic data (Winker and others, 1983; Ewing and others, 1984). Positions of the major boundary-forming growth faults are well established, but the geometries and distributions of smaller internal faults remain problematic. Although displacements across these internal faults may reach several hundred feet, they are generally too small to be resolved on seismic cross sections. Numerous such small faults probably occur within the Pleasant Bayou fault block, but only those that have been identified with well and seismic data are shown on the structure map (fig. 15).

The major structural features around the Pleasant Bayou No. 2 well are two large growth faults, Danbury salt dome and salt-withdrawal basin, and Chocolate Bayou dome (fig. 15). At the level of the C zone, displacements across the large growth faults range from 500 to greater than 1,000 ft and are accompanied by pronounced stratigraphic changes. Pressure and fluid-chemistry changes across the growth faults (Fowler, 1970) confirm that they are essentially impermeable boundaries for the aquifers within the fault block. Danbury salt dome pierces basal Miocene strata at a depth of about 4,500 ft (Ewing and others, 1984). Uplift of deep Frio strata extends into the Pleasant Bayou fault block (fig. 15). As deeply buried salt flows upward into a growing dome, the area that it evacuates becomes structurally low, forming a salt-withdrawal basin that accumulates thick sequences of sediments. Salt withdrawal into Danbury Dome has created a large synclinal depression in the southern part of the Pleasant Bayou fault block. The test well is on the northeastern flank of the syncline and is one of the structurally lowest wells in the fault block (fig. 15). Chocolate Bayou dome, which is the highest part of the fault block, may overlie a deep-seated salt uplift (Ewing and others, 1984).

Faults within the Pleasant Bayou fault block (internal faults) form potential barriers to flow. Displacements across internal faults may reach 400 ft but are more typically less than 200 ft

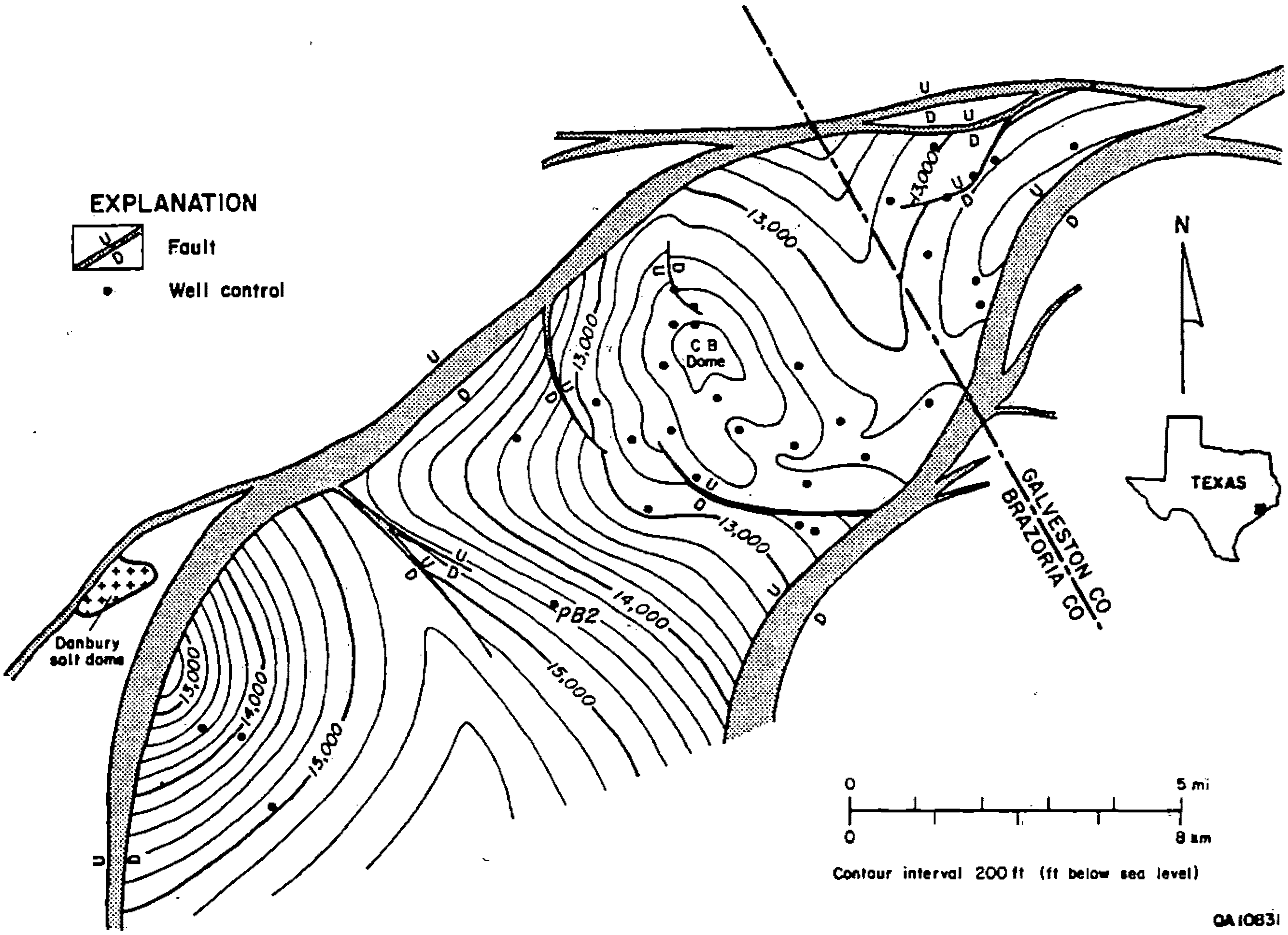

Figure 15. Structure map on the top of the C zone. This map is a revision, on the basis of new well data, of earlier Pleasant Bayou structure maps (Winker and others, 1983; Ewing and others, 1984).

(fig. 15). No internal fault has yet proved to be completely continuous across the fault block (Ewing and others, 1984). Thus, internal faults form partial barriers to flow and separate proximal from remote reservoir volume. These effects were detected by pressure-decline analysis during early flow testing at Pleasant Bayou (Garg and others, 1981). In terms of influencing production performance, the most significant internal faults occur between the test well and Chocolate Bayou dome (fig. 15). Of these two faults, the southeastern one is the better documented by well data and was used to analyze potential effects of internal faulting.

Variable displacement along the length of an internal fault results in three basic configurations of reservoir sandstones on either side of the fault plane. The C zone reservoir is completely isolated where it is displaced against mudstone (fig. 16a) but is only partly isolated where displacement is less than reservoir thickness (fig. 16b). In the third situation, additional volume may augment the reservoir where it is displaced against other sandstones (fig. 16c). Because displacement varies along the fault plane, the reservoir comes into contact with a range of permeable and impermeable strata. At the end of the fault where displacement decreases to zero, complete reservoir continuity exists.

A potential barrier to fluid flow is fault gouge, which is crushed rock that occurs along some fault planes. Fault gouge is the result of deformation caused by the shearing stress of fault displacement. Although the effects of fault gouge on fluid flow are poorly understood, it may form a barrier to flow across a fault plane or may be a conduit to both lateral and vertical flow. The common occurrence of mineralization in gouge zones indicates that ground water does flow through these materials. Hydrologic and geochemical analysis of production data and fluid samples can help resolve questions concerning the relationship between faults and fluid flow at Pleasant Bayou.

Reservoir Volume

As a first step toward constructing models for simulation, the total effective pore volume of the C zone reservoir in the Pleasant Bayou fault block was calculated (table 2). The fault block

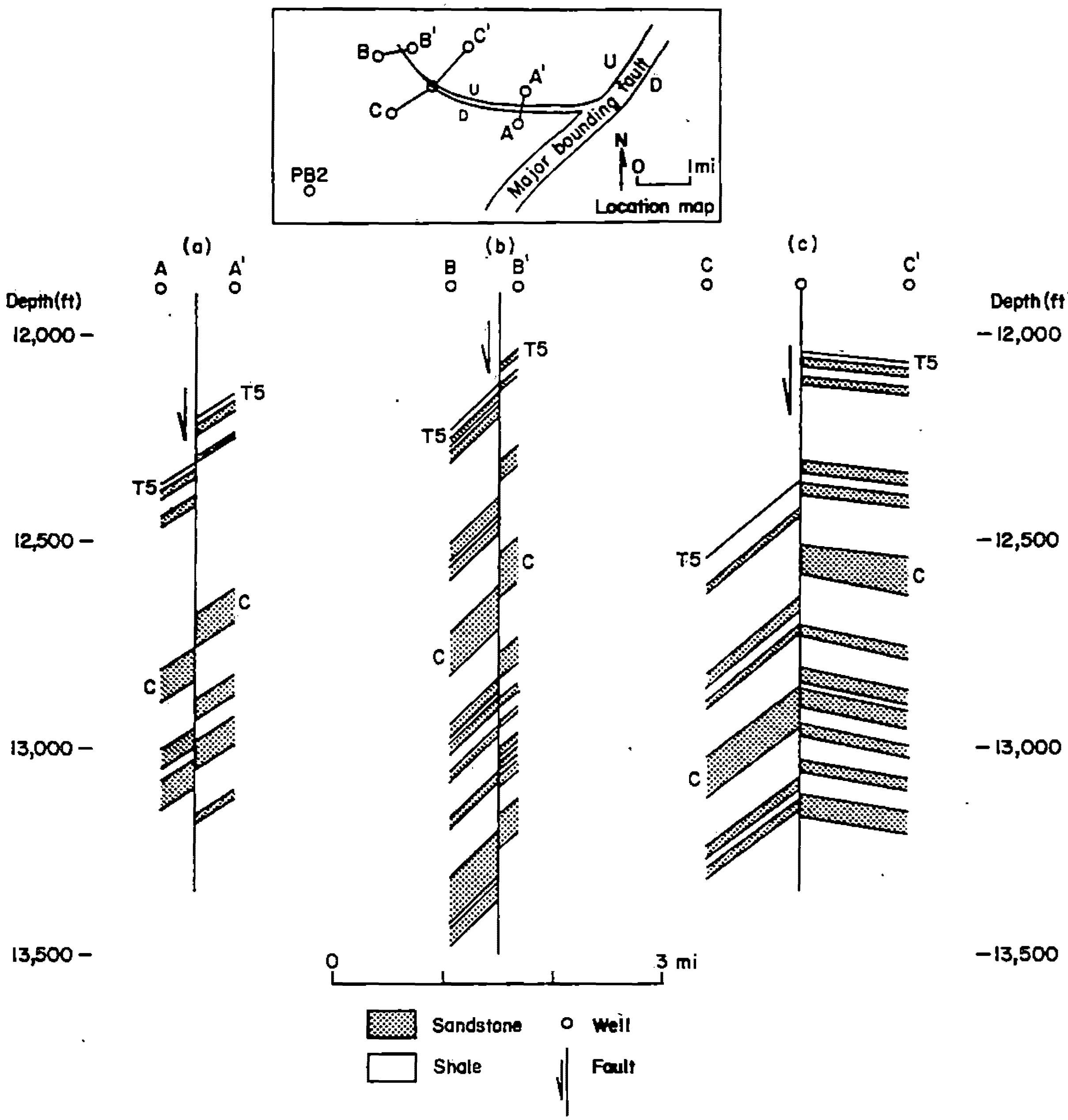

Figure 16. Schematic cross sections across an internal fault that forms a partial barrier between the test well and Chocolate Bayou field.

Table 2. Reservoir volume of the Pleasant Bayou C zone.

Measured parameters	
Fault block area	87.8 mi^2
Sandstone volume	2.3 mi^3
Porosity assumptions	
One-half volume has good porosity	18 percent
One-half volume has poor porosity	9 percent
Total C zone pore volume	8.3 billion bbl
Continuity estimation	
Porosity interconnectedness	75-80 percent
Total effective pore volume	6.2-6.6 billion bbl
Pore-space distribution	
Proximal volume	2.0-2.2 billion bbl
Remote volume	4.2-4.6 billion bbl

encompasses 87.8 mi^2. By planimetering the net-sandstone map, total C zone sandstone volume within this area was found to be 344.3 billion ft^3, or 2.3 mi^3. To obtain total reservoir pore volume from sandstone volume, porosity distribution had to be estimated. For this purpose it is assumed that thicker (>50 ft) sandstones are mostly amalgamated distributary channel-fill and channel-mouth bar deposits that have average porosities similar to the perforated interval in the test well (18 percent). Thinner sandstones, in contrast, are channel-flank or delta-front facies that have lower porosities (estimated to be 9 percent). About half of the sandstone in the C zone occurs in thick beds, and the other half is more thinly bedded. On the basis of measured sandstone volume and assumed porosity distribution, total C zone sandstone pore volume is 46.5 billion ft^3 or 8.3 billion barrels (bbl) (table 2). The analysis of sandstone continuity indicates that 75 to 80 percent of the total pore volume, 6.2 to 6.6 billion bbl, is interconnected or effective porosity.

The above assumptions will be tested by (1) mapping the distribution of thick versus thin sandstones and quantifying their volumes, (2) more detailed depositional facies interpretations, and (3) determination of typical facies-specific porosities.

For large reservoirs, production and pressure data from several years of flow testing are required to verify geologically determined volumes, because in the early stages of production, pressure-decline rates are similar for reservoirs with widely varying volumes. During an early 45-day flow test of the Pleasant Bayou reservoir (table 1), 1.6 billion bbl of volume were explored over an estimated area of 25 mi^2 (Morton, 1981). This volume includes the middle (perforated) sandstone within 3 mi of the test well, but excludes the upper and lower reservoir sandstones as well as the entire reservoir across most of Chocolate Bayou field. For reservoir simulation purposes, this near-well volume can be termed proximal, whereas the rest is remote volume. Fluids must follow long and circuitous flow paths to reach the well from remote volume. On the basis of sandstone volume and continuity analysis, about one-third of the total reservoir effective pore volume (2 billion bbl) is proximal, and about two-thirds (4.5 billion bbl) is remote (table 2).

Geologically based volume calculations describe total available pore space and pore-space distribution but do not take into account formation compressibility and transmissibility, in situ fluid properties, and well-bore effects (Garg and others, 1981). Thus, reservoir volumes presented here (table 2) are part of the pre-production geologic framework, to which subsequent pressure-decline analysis and reservoir simulation can be related.

Reservoir Models

Simple models of the Pleasant Bayou reservoir, designed to approximate reservoir geometry, volume, and porosity distribution, were constructed for use in computer-based simulations. The models consist of rectangular elements that can be used in two-dimensional numerical simulations. Reservoir model 1 is a single rectangular block (fig. 17) whose boundaries represent average reservoir length, width, and thickness. Horizontal porosity layers approximate the configuration of the major reservoir sandstones. Reservoir model 2 includes three rectangular blocks (fig. 18), each representing average dimensions and pore-space distributions of one-third of the reservoir. Model 2 has a small low-porosity area in the northeast, an intermediate-sized central area that is dominated by a high-porosity layer, and a large area in the southwest that includes thick low-porosity layers (fig. 18). Clearly, the more complex model 2 simulates the reservoir more closely than does the simpler model 1. Neither model, however, distinguishes between proximal and remote volume or between isolated and interconnected porosity. In the early stages of the current testing program at Pleasant Bayou, the configuration of proximal volume, especially pore-space distribution and fault-related flow barriers, will be a key factor in accurate simulation. Only later will modeling of remote volume be necessary. The models illustrated here represent a preliminary step in an ongoing process. As pressure-decline analysis proceeds in FY 1989, interaction between the simulators and geologists will involve numerous stages of model modification and refinement.

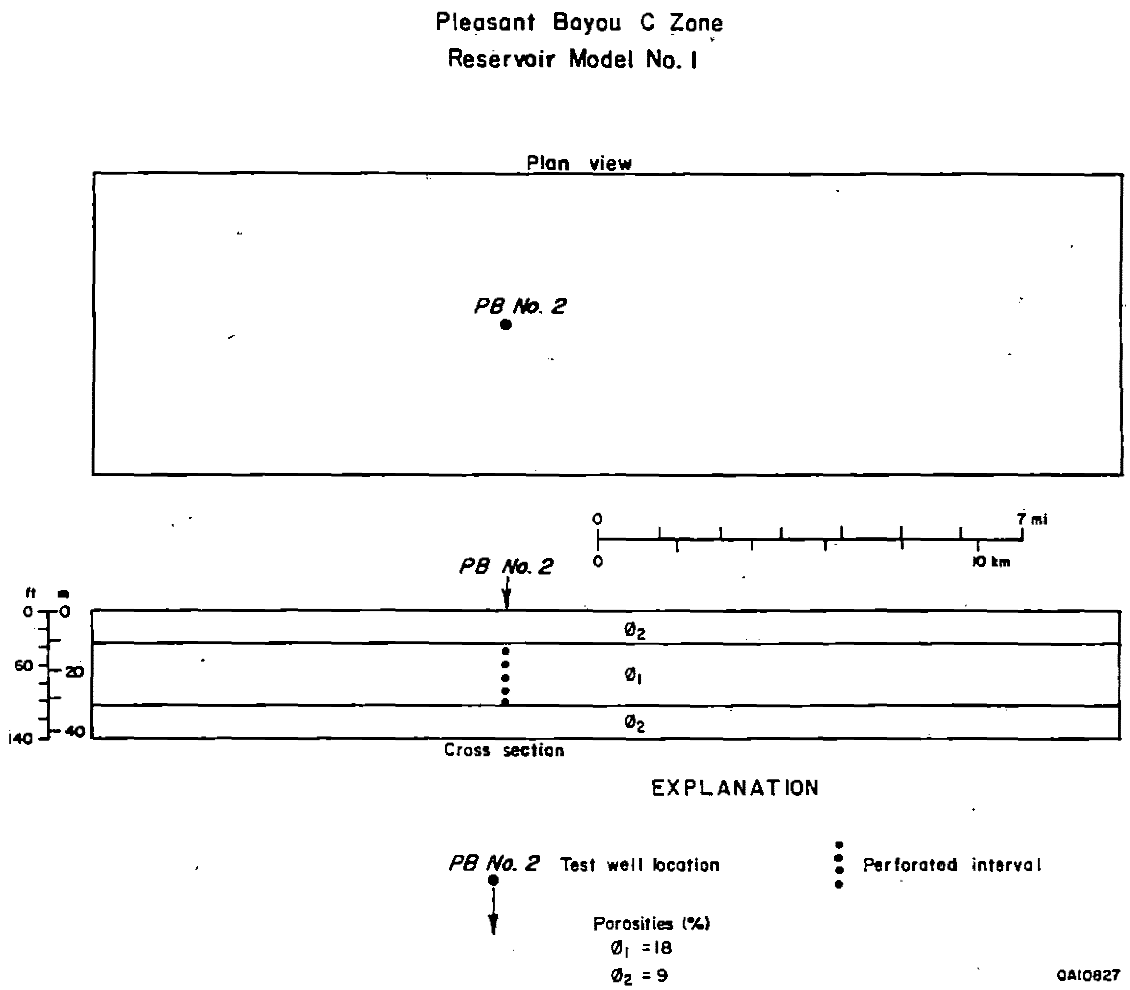

Figure 17. Reservoir model 1 shown in plan view and in cross section.

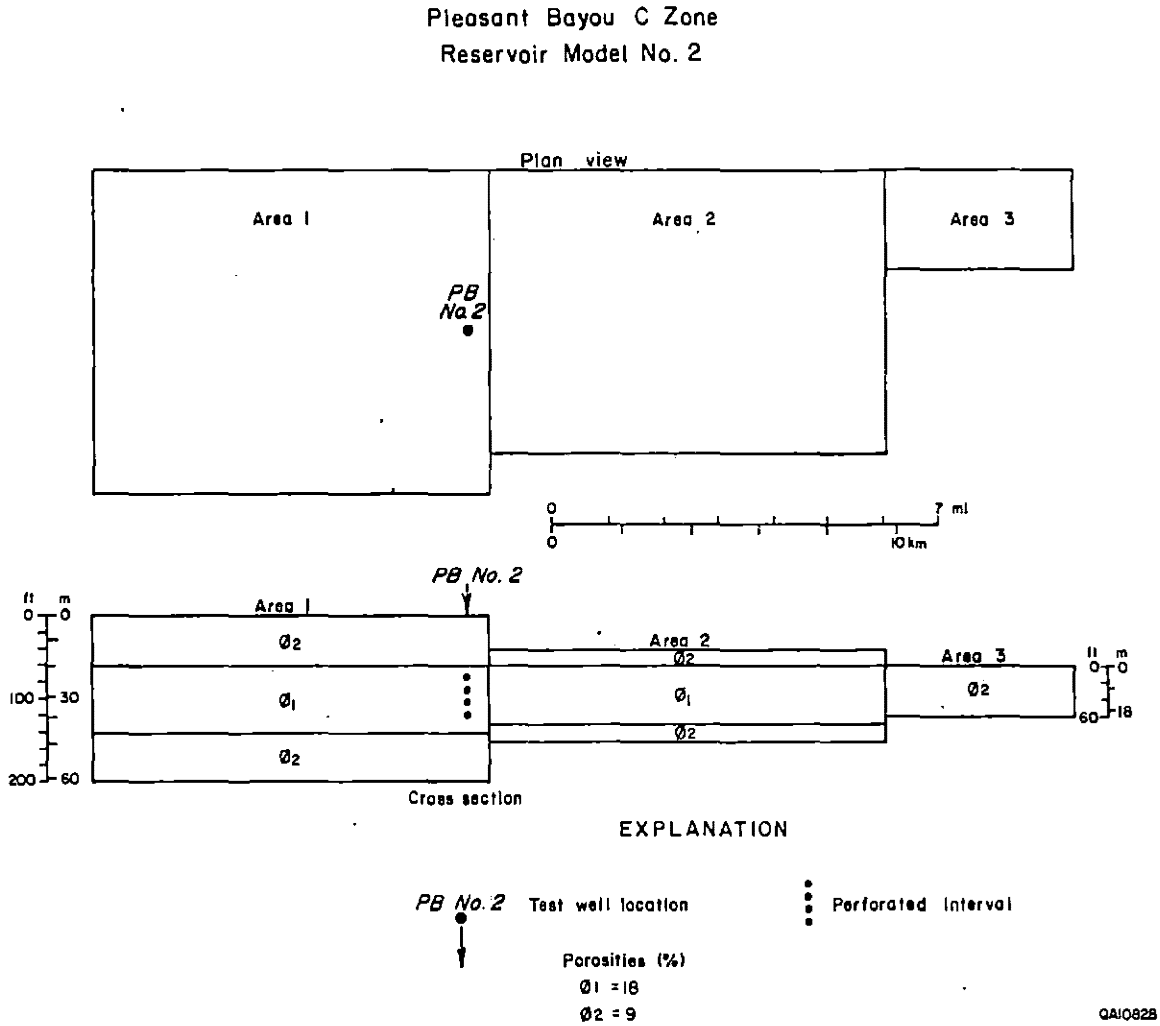

Figure 18. Reservoir model 2 shown in plan view and in cross section.

Hydrocarbon Production

Detection of pressure changes in wells within the Pleasant Bayou fault block that can be related to long-term production testing of the Pleasant Bayou No. 2 well would enable more definitive modeling and simulation of the C zone reservoir than can be achieved with data from the test well alone. To be relevant, pressure changes would have to be measured in the C zone or closely associated reservoirs. Production and development activity in the Chocolate Bayou field was reviewed to see if any wells are currently producing from the C zone or adjacent zones. Apparently, there has never been commercial production directly from the C zone reservoir in the Pleasant Bayou fault block, although the zone has been productive in fields north and southeast of the fault block. However, three wells are currently producing from sandstones overlying the C zone reservoir (table 3). Pressure and production data (reported semiannually) from these three wells are being monitored.

Deep gas production in Chocolate Bayou field is the result of recent development activity. The wells listed in table 3 were all completed or recompleted in 1986 and together have produced more than 3.7 billion ft^3 of gas and 190,000 bbl of condensate since then. The productive intervals are relatively thin sandstones that occur at the tops of the A, B, and C zones and that are overlain by thick mudstones (fig. 3). The productive intervals are separated from the main C zone reservoir by 500, 200, and 40 ft of intervening sandstones and mudstones (table 3). The Chocolate Bayou (middle Andrau) reservoir in the Phillips Cozby No. 5 well produces from the relatively continuous sandstone that occurs near the top of the C zone in the upper mudstone interval (fig. 13). Although this sandstone does not appear to be interconnected with the main C zone reservoir, long-term pressure trends from the Cozby No. 5 well may indicate otherwise. As discussed previously, any of these producing zones may be in contact locally with the C zone reservoir across internal faults.

Table 3. Currently active deep wells in Chocolate Bayou field.

Well	Phillips No. 4 Cozby	Texaco No. 6 Wilson	Phillips No. 5 Cozby
Well no. (fig. 2)	110	179	178
Perforations (ft)	11,870-11,876	12,098-12,120	12,320-12,330
Correlation zone (fig. 3)	upper A	upper B	upper C
Depth to C zone reservoir (ft)	500	200	40
Pressure (BHP/z) Date measured	6311 11/22/87	9219 12/15/87	?
Cumulative production to 4/30/88:			
Condensate (Mbbl)	43.1	137.8	9.6
Gas (MMcf)	1,086.6	2,392.5	223.0
First production date	4/86	2/86	4/86

Discussion

The generally excellent deep-well control in the Pleasant Bayou fault block has permitted more detailed mapping of the C zone reservoir than any other Gulf Coast geopressured-geothermal reservoir to date. Total reservoir pore volume calculated during this study (greater than 6 billion bbl) is three times that of earlier estimations, which were based on pressure-decline analysis of short-term flow tests and on limited geologic analysis (Morton, 1981). Pressure-decline trends of several years' duration are needed for reliable volume calculations (Riney, 1987). At the Gladys McCall test well in Louisiana, insufficient well control precluded accurate geologically based volume determination. During long-term testing at the Gladys McCall well, pressures remained unexpectedly high, and reservoir volume seemed to increase with time. This phenomenon led to various theories of recharge mechanisms, all of which were essentially untestable with the available data. Because sandstones are interconnected across discontinuous mudstone interbeds, calculations that use only the thickness of the perforated interval may result in underestimation of volume. In addition, inability to accurately locate lateral fault boundaries necessitates reliance on more or less arbitrarily defined lateral boundaries. Available data at Pleasant Bayou allowed us to minimize geologic uncertainty and provide a pre-production volume that approximates reality and that can be useful in predicting and modeling long-term well performance.

PLANULINA ZONE RESERVOIR, HULIN WELL

The DOE Hulin No. 1 well in Vermilion Parish, Louisiana penetrates the deepest known Gulf Coast geopressured-geothermal reservoir and is a prime candidate for production testing in the near future. The well was donated to DOE by Superior Oil Company, but little was known about the geology of the prospective reservoir. Therefore, we compiled the available data and conducted a geological investigation of the main reservoir sandstone (20,200 ft sandstone). Unfortunately, insufficient deep-well control exists to adequately characterize the 20,200 ft reservoir or to calculate its volume.

From near top of geopressure (13,000 ft) to total depth (21,546 ft), the Hulin well penetrates the lower Miocene, *Planulina* zone, an interval restricted to southwestern Louisiana and offshore Jefferson County, Texas (Goheen, 1959; Sloane, 1971). The *Planulina* zone consists of deep-water (bathyal), continental slope sequences that grade updip and up section into shelf-margin deltaic deposits (fig. 19). The *Planulina* zone overlies bathyal to abyssal mudstones in the Anahuac Formation (Abbeville zone) and underlies the fluvial-deltaic Oakville Formation. The prospective sandstone is 550 ft thick and appears to be a slope canyon fill or proximal submarine fan deposit similar to thick, Frio Hackberry sandstones at the Port Arthur field, Jefferson County, Texas (fig. 20). It is probably dip elongate but unattached to shelf-margin deltaic sandstones upslope. At least four thin (less than 10 ft) mudstone interbeds vertically compartmentalize the reservoir. Regionally, the *Planulina* zone is characterized by complex structural configuration and heterogeneous facies distribution that have made correlation difficult (Sloane, 1971).

The Hulin well is located on the axis of a dip-oriented, north-south trending structural trough adjacent and subparallel to an uplifted ridge of salt that includes the Five Islands salt domes (fig. 21). The structural trough is related to deep-seated salt withdrawal. Interval-isopach and net-sandstone patterns indicate that the trough was a persistent zone of sediment transport and deposition on the *Planulina* continental slope and rise (Conover, 1987). Net-sandstone contours of the entire *Planulina* zone (about 7,000-ft thick at the Hulin well) are closely spaced and dip directed at the Hulin well site but diverge into more lobate patterns several miles southward, toward the basin (fig. 21). These sandstone geometries, along with the occurrence of deep-water fauna in associated mudstones (Stuckey, 1964; Conover, 1987), support a submarine canyon and fan interpretation. The Hulin Well is located in a fault block that is approximately 12 mi long (east-west) by 5 mi wide (north-south) and bounded by large arcuate growth faults (fig. 21). Smaller faults occur within the block.

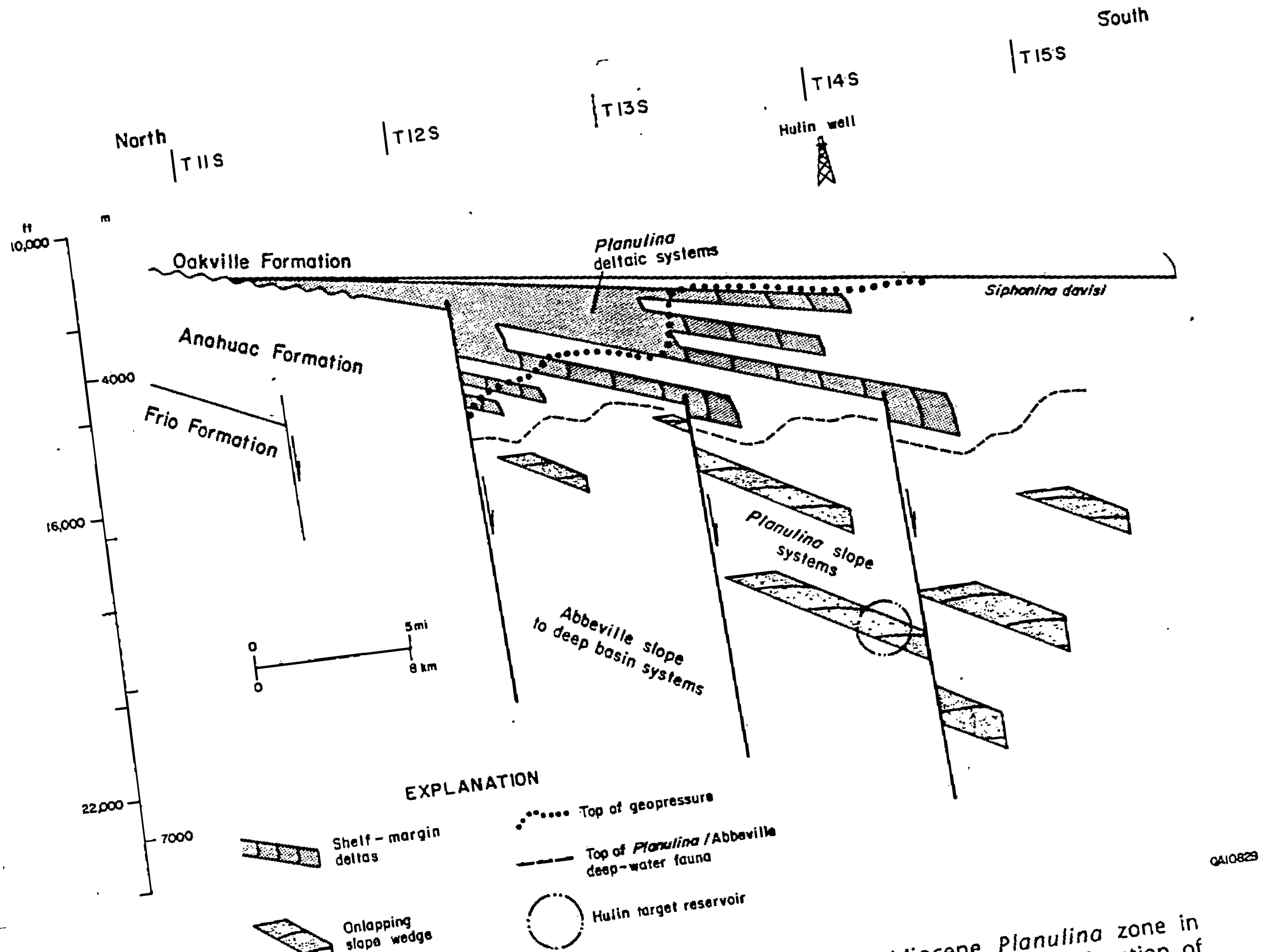

Figure 19. Schematic dip-oriented cross section of the lower Miocene *Planulina* zone in southwestern Louisiana showing stratigraphic relationships, depositional systems, and location of the target reservoir in the Hulin well.

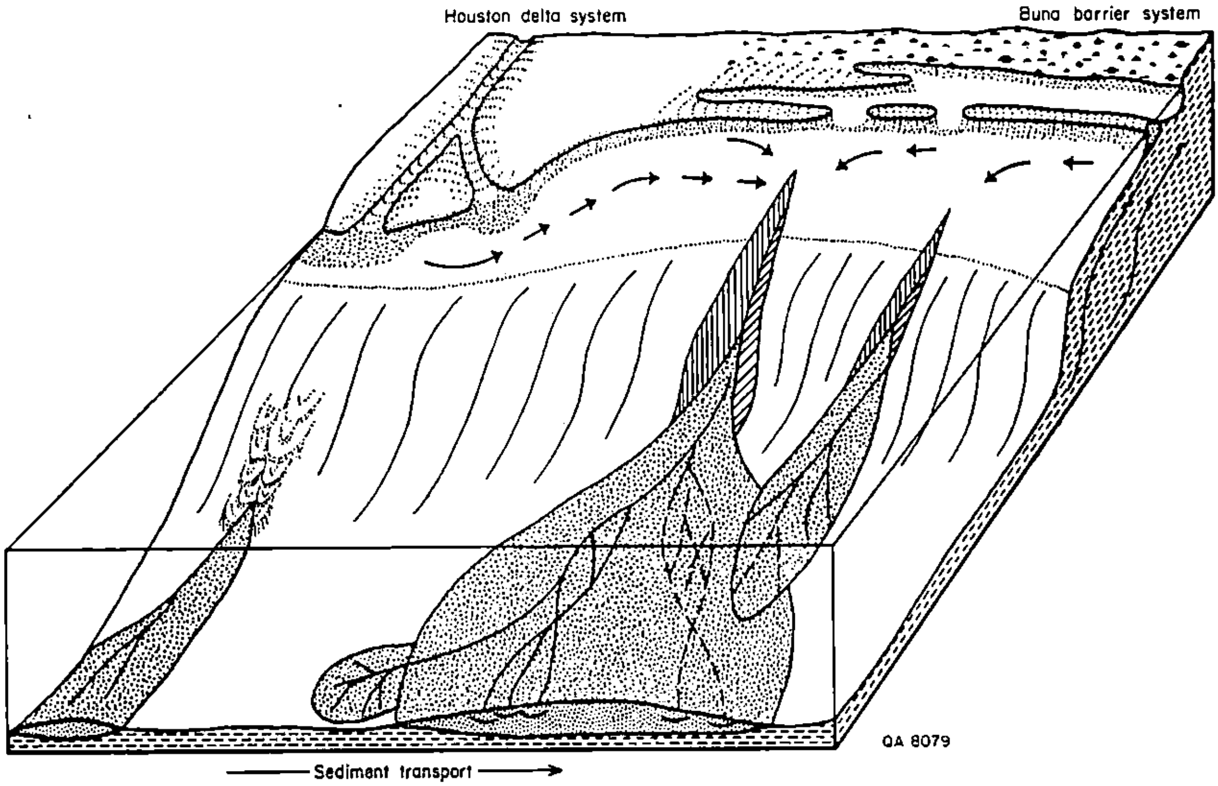

Figure 20. Depositional model of Frio Hackberry reservoirs, Port Arthur field, Jefferson County, Texas. From Tyler (1987).

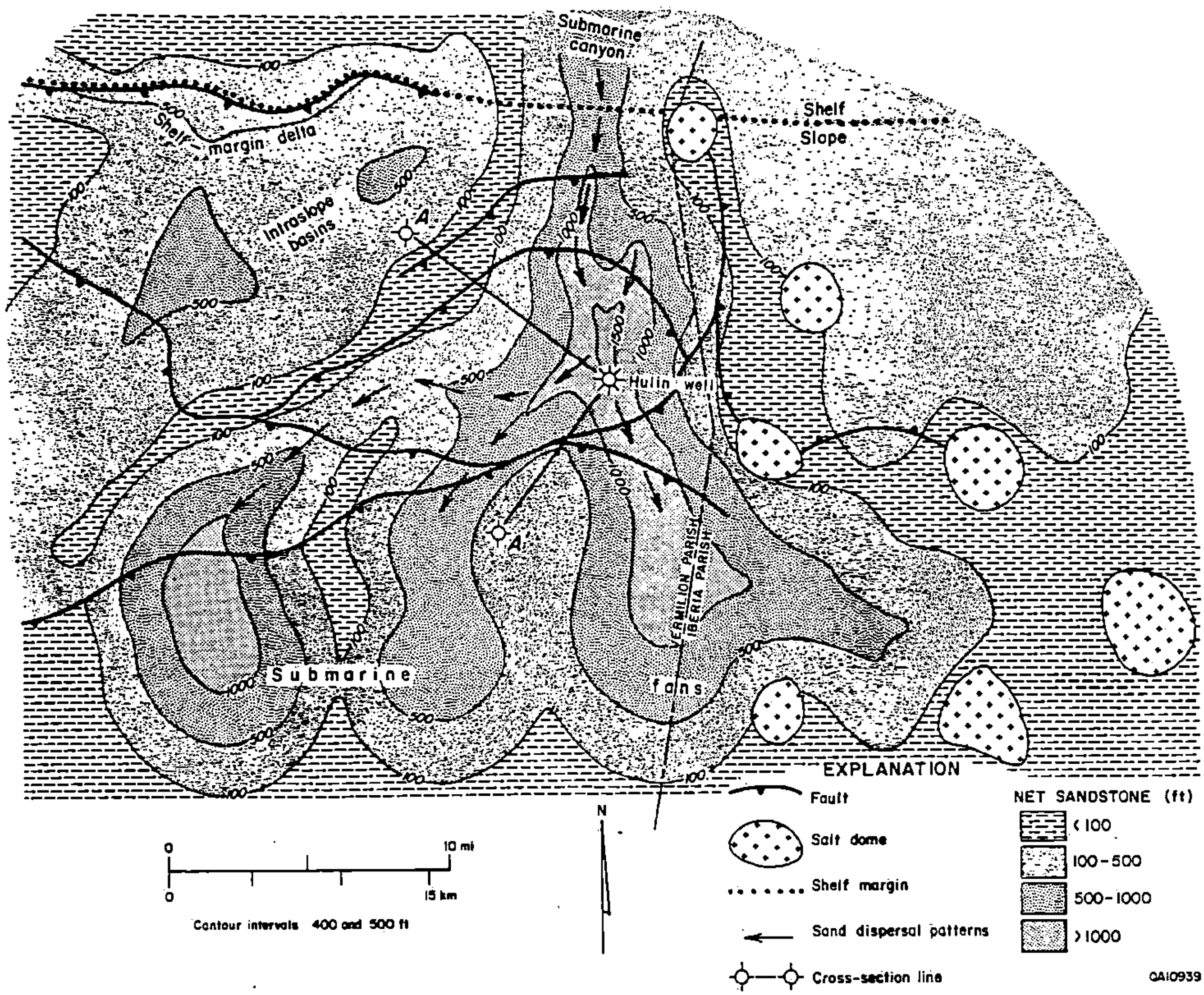

Figure 21. Net-sandstone isopach map of the *Planulina* zone around the Hulin well site, also showing major structural features and depositional setting.

Because it is penetrated only by the Hulin Well (fig. 22), a more precise depositional setting for the prospective sandstone could not be determined. If the sandstone is confined in a narrow erosional channel, it may extend only a few miles east-west. Alternatively, the structural trough may have been the site of a broader, topographically irregular, slope canyon, produced and filled by slumping and mass-movement processes. A third possibility is as a series of intraslope fault-bounded salt-withdrawal basins. Ponded sediments would accumulate in each basin to the filling point before spilling over into the next lower basin. All these features exist on the Pleistocene-Holocene continental slope in the northwestern Gulf of Mexico (Bouma, 1982), which is analogous to the *Planulina* depositional setting.

Abrupt sandstone thickness changes and internal reservoir heterogeneity characterize slope systems (Tyler, 1987). The thin mudstones that vertically compartmentalize the main reservoir sandstone probably record pelagic to hemipelagic sedimentation during sea-level highstands, when clays gradually blanketed the sea floor and created laterally continuous seals. But because these mudstone interbeds are thin, vertical flow communication across them may be affected by faulting.

Because of its great depth, the Hulin Well offers a unique research opportunity. Little is known about fluid compositions and sources in the deep Gulf Coast Basin. High temperatures and pressures must have a significant impact on fluid-rock reactions and flow patterns. The thick sandstone at 20,200 ft may be a major pathway for fluid migration from deeper in the system. The compositions of dissolved organic species may provide information about the origin of thermally generated gas. Along with compositional analysis, production and pressure-decline data can be used to evaluate long-term productivity of the Hulin Well and ultimately the resource potential of very deep Gulf Coast reservoirs.

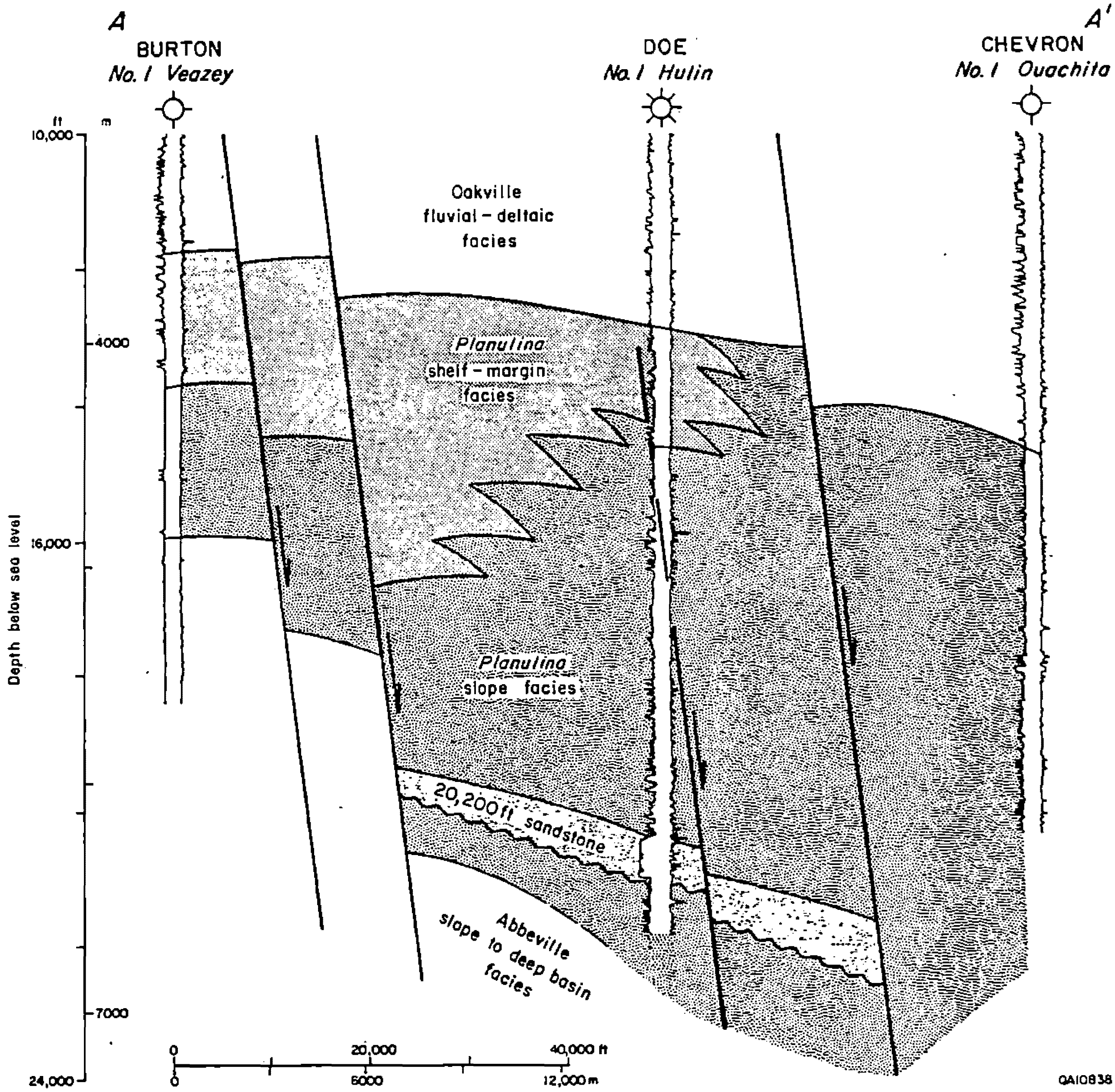

Figure 22. Dip cross section A-A' showing electric logs from the three deepest wells in the Hulin area and depositional systems interpretations. Only the Hulin well penetrates the 20,200 ft reservoir. Location of section line is shown in figure 21.

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