SAN ANDRES/GRAYBURG RESERVOIR CHARACTERIZATION RESEARCH LABORATORY

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EXECUTIVE SUMMARY

The Bureau of Economic Geology's Reservoir Characterization Research Laboratory project, "Characterization of San Andres and Grayburg Reservoirs," was initiated in September 1988 and has completed the first year of a proposed 2-year program. Substantial progress has been made toward the goals of this program, which are focused on development of advanced approaches to reservoir characterization for improving recovery efficiency of substantial remaining mobile oil resources in these prolific reservoirs. Key research results are in the areas of (1) quantitative description and geostatistical modeling of interwell and reservoir-scale heterogeneity from San Andres outcrops, and (2) preliminary studies on integration of the quantitative outcrop models with a geologic/engineering characterization of the Seminole San Andres Unit.

Outcrop geologic studies were carried out at play, reservoir, and interwell scales along the Algerita Escarpment, Guadalupe Mountains, New Mexico. This 17-mile play-scale study area provides a dip-section framework for detailed investigations and serves as an analogous reservoir framework for comparison with producing San Andres fields. Reservoir-scale mapping of a 4-mile dip section of the upper San Andres with measured sections spaced 1,000 to 2,000 ft apart demonstrates the compartmentalization of individual grainstone shoal complexes on the scale of several thousand feet laterally and 50 to 100 ft vertically.

Outcrop work was focused on interwell-scale studies because data on this critical scale of heterogeneity are unavailable from subsurface reservoir investigations. Detailed geologic mapping of a 160 ft (vertical) by 2,700 ft (lateral) continuous exposure of an upper San Andres grainstone shoal complex revealed an internal architecture dominated by multiple upward-shallowing parasequences (10 to 40 ft thick) that were continuous across the 2,700-ft area. The parasequence framework provided an excellent method for documenting lateral facies variability on the interwell scale, revealing dramatic lateral facies changes, particularly in the reservoir quality grainstones. For example, a 38-ft-thick grainstone bar was documented to thin and pinch-out laterally in less than 500 ft.

Nearly 2,000 permeability measurements were made on two parasequences at 1-ft vertical intervals along 10- to 50-ft laterally spaced profiles. This provides an extremely detailed representation of vertical and lateral permeability variability on the interwell scale. Complex patterns of lateral variability of permeability showing three orders of magnitude of variance on the interwell scale were observed, further corroborating the geologic observations. These data are currently the basis for geostatistical and flow simulation analysis.

The parallel study of the Seminole San Andres Unit will include detailed analysis of a 2-section, 80-well area, with modern log suites, more than 5,000 ft of core, and production data. Geologic description of 7 of the 19 cores revealed a parasequence framework similar to that of

the outcrop study area. Many of the parasequence boundaries have distinct log characteristics, allowing excellent correlation at least in the area of the detailed study. The SSAU No. 2505 well, with 350 ft of core and a full log suite, has been selected for foot-by-foot analysis of porosity/pore-type/permeability/mineralogy relationships using thin sections, XRD, core analysis, and logs. This well will serve as the control for developing key petrophysical relationships. Engineering efforts to date have largely focused on collection and organization of data.

INTRODUCTION

The purpose of the San Andres/Grayburg Reservoir Characterization Research Laboratory (RCRL) is to develop advanced approaches to reservoir characterization to promote maximum recovery of the substantial mobile oil resources in the prolific San Andres and Grayburg reservoirs. Sponsors of the project include Amoco, ARCO, Chevron, Exxon, Marathon, Mobil, Shell, Texaco, and Unocal, as well as Stratamodel, Radian, and Silicon Graphics, who provided in-kind software and hardware. Key research goals are to (1) quantitatively describe and geostatistically model interwell and reservoir-scale heterogeneity of the outcropping San Andres, and (2) integrate outcrop modeling and geologic/engineering characterization of part of the Seminole San Andres Unit to test the utility of outcrop-based quantitative heterogeneity models in reservoir simulation.

The RCRL has now completed the first year of a proposed 2-year project, and results of the first year of research are summarized in this annual report. Much of the information presented in the geologic and petrophysical sections was previously reviewed at the May 1989 RCRL meeting in Carlsbad, New Mexico. New data from permeability mapping, geostatistics, and the Seminole reservoir study are included here. All illustrations and data contained herein are preliminary and will be updated for the September 1990 report.

OUTCROP CHARACTERIZATION AND MODELING

Characterization of the San Andres Formation in outcrop along the Algerita Escarpment of southeastern New Mexico (fig. 1) was carried out at the play, reservoir, and interwell scales. Reservoir and interwell scale studies focused on the grainstone-dominated facies tracts of the upper San Andres because Bureau and industry studies of San Andres and Grayburg reservoirs identified these as areas of greatest heterogeneity and hence most in need of detailed investigation.

Play-Scale Mapping

Objectives: The goal of the play-scale mapping was to develop a subregional stratigraphic framework for the San Andres in outcrop that would serve as a basis for identifying geometry and interrelationships of key facies tracts. Delineating facies architecture at the scale of several miles laterally and hundreds of feet vertically allows selection of an optimum area for outcrop/subsurface comparison studies.

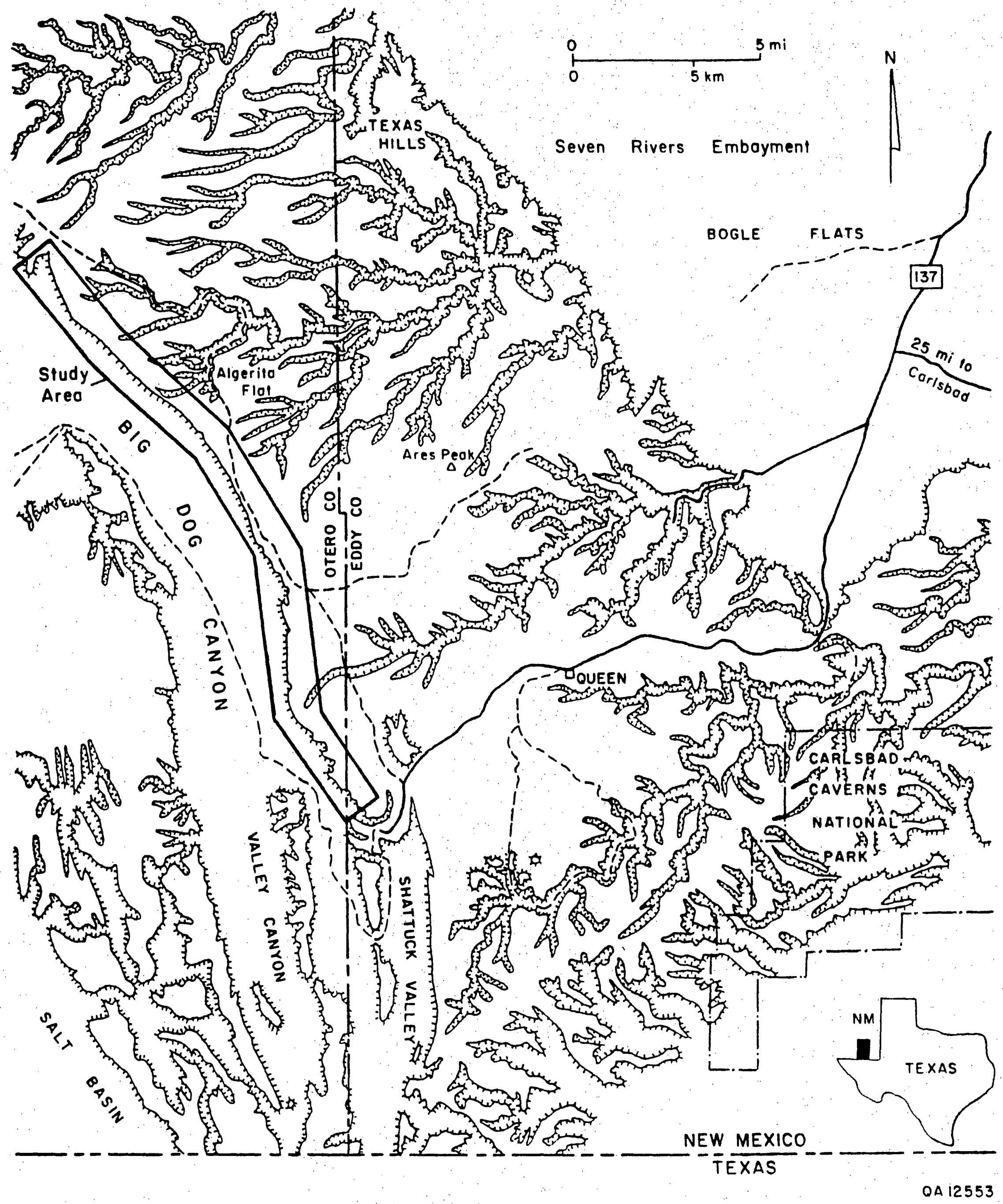

Figure 1. Location of "play"-scale dip cross section (see figure 2) along the Algerita Escarpment. Map modified after Bebout and others (1986).

Results: Play-scale mapping of the San Andres Formation was based on integration of photogeologic mapping and 11 measured sections of the exposed San Andres interval (average 1,000 ft) along a 17-mile, oblique-dip outcrop of the Algerita Escarpment. Measured sections were spaced from 2 to 4 miles apart and were correlated by bed tracing and photogeologic mapping. This provided the basis for development of an oblique dip-oriented cross section that compares favorably with the sequence stratigraphic framework developed by Sarg and Lehmann (1986) for the Algerita Escarpment–Last Chance Canyon area.

Stratigraphic units recognized (fig. 2) include:

SEQUENCE 1

(1) lower San Andres - thick cyclically bedded bryozoan/brachiopod/pelmatozoan packstone-grainstone averaging 500 ft thick (Woods Canyon through Rawhide sections) with laterally equivalent cherty mudstone exposed downdip (Rawhide through Cougar Canyon sections, fig. 3).

(2) middle San Andres - basal thin-bedded cherty mudstone with thin allodapic fusulinid/coral grainstone beds (0-400 ft thick) grading into massive to cyclically bedded fusulinid-peloid packstone-grainstone (100-300 ft thick).

SEQUENCE 2

(3) upper San Andres - laterally highly variable sequence, in Lawyer Canyon area consists of (1) a lower 160-185 ft section of upward-shallowing mudstone to fusulinid/ooid/peloid packstone-grainstone cycles each 10 to 40 ft thick, and, (2) an upper 150 ft of mudstones and wackestones with thin dasyclad/peloid packstone/grainstone and tidal-flat algal laminite beds. Two 1- to 5-ft sandstone marker beds in the upper 100 ft of the upper San Andres (sections LC-CC) may be equivalent to "Lovington sandstone" of the subsurface. Sequence 2 is overlain by thick basal sandstones of the Grayburg Formation (Premier sandstone).

Interpretation: The play-scale dip-oriented section from the Algerita Escarpment shows two discrete sequences (fig. 3). The lower sequence (S1) includes the lower and middle San Andres members (all stratigraphic terminology within the San Andres is informal)(fig. 2). The vertically stacked to backstepping arrangement of individual parasequences (upward-shallowing 5- to 50-ft depositional cycles) in the lower San Andres suggests that this unit formed during a

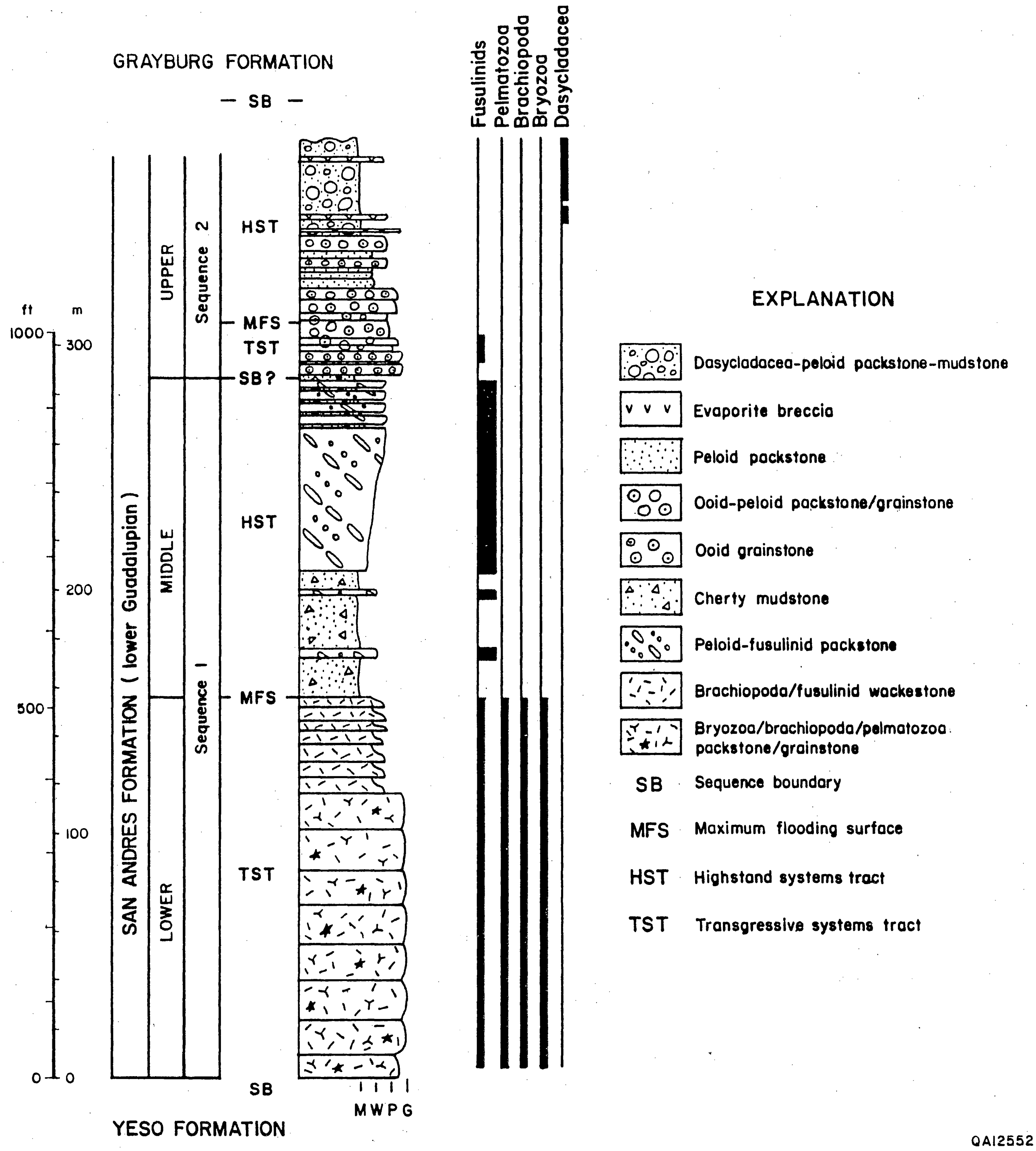

Figure 2. Simplified measured section of San Andres Formation, Lawyer Canyon, with sequence stratigraphic interpretation of major (third-order) sequences. Lithologic key also applies for figure 3 (lower/middle/upper terminology and sequence stratigraphic interpretation of sequence 1 from Sarg and Lehman, 1986).

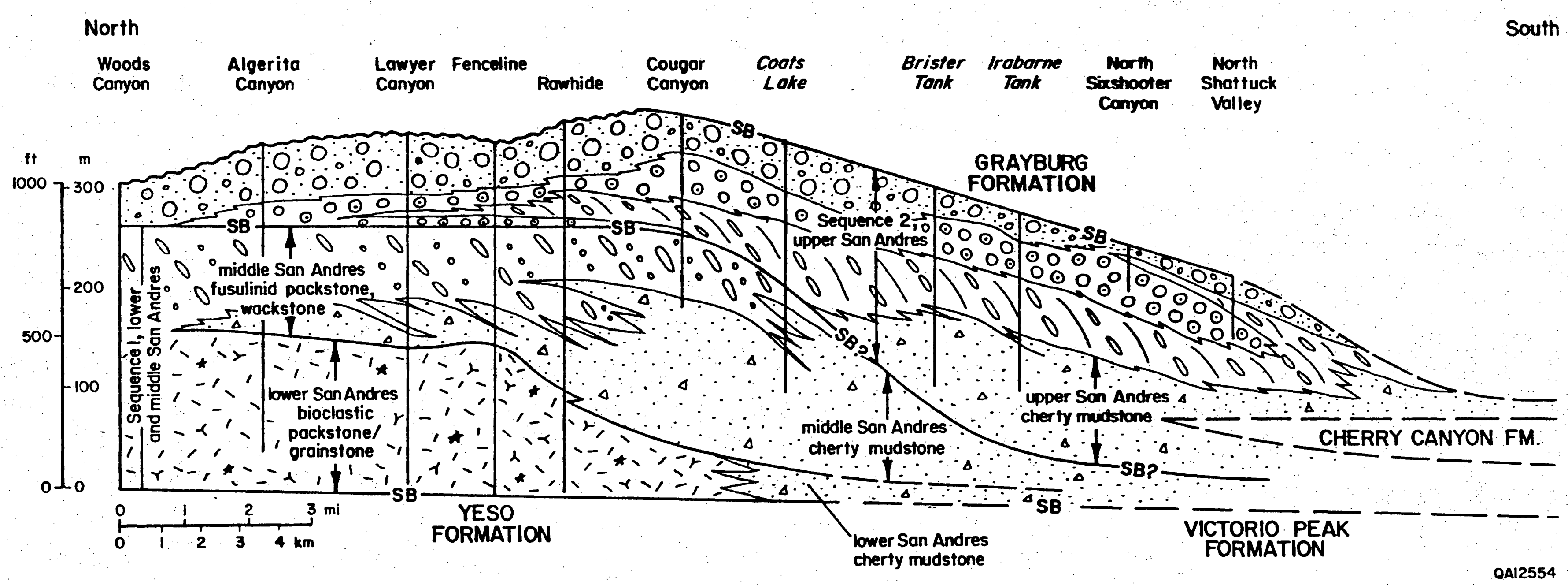

Figure 3. Simplified geologic cross section of San Andres Formation along the Algerita Escarpment (see figure 1 for location). Key for lithologies shown in figure 2. SB = sequence boundary. Position of Cherry Canyon Formation is tentative.

relative sea-level rise that outpaced platform aggradation. The diverse fauna indicates open marine conditions throughout. This unit represents the transgressive systems tract of sequence 1. Seaward of the RH section the skeletal grainstones of the lower San Andres grade into outer ramp (slope) cherty mudstones that are indistinguishable from those of the middle San Andres (fig. 3) and are probably correlative with the Cutoff Shale of the Brokeoff Mountains and western escarpment of the Guadalupe Mountains (Sarg and Lehmann, 1986; Wilde, 1986).

The upper portion of S1 is the middle San Andres, which can be subdivided into a lower cherty dolomudstone that grades upward into fusulinid-peloid dolopackstone. Deposition of the deeper water outer ramp cherty mudstone across the shallow-water lower San Andres ramp records a drowning event during maximum flooding of sequence 1 (Sarg and Lehmann, 1986). Upper portions of the cherty mudstone were deposited as distal clinoform toe deposits of the prograding middle San Andres ramp. The fusulinid-peloid packstone-grainstone of the upper half of the middle San Andres was deposited on the outer ramp updip of the cherty mudstone facies in several tens of feet of water. Shallow-water ramp-crest grainstones of the middle San Andres were not encountered in any of the sections studied. This facies tract probably crops out north of Woods Canyon along the northern segment of the Algerita Escarpment. The seaward facies change from outer ramp fusulinid packstone/grainstone to cherty mudstone occurs in the Cougar Canyon area. The upper part of the middle San Andres (fusulinid packstone/grainstone and prograding portion of cherty mudstone) forms the highstand regressive systems tract of Sequence 1 (Sarg and Lehmann, 1986).

Lateral variability on the subregional scale is much greater in the upper San Andres sequence (S2) than in the lower-middle San Andres sequence (S1). In S2, a single timeline from the Woods Canyon section to the Coats Lake section (fig. 3) would include all facies tracts from evaporitic tidal flat (Woods Canyon) through lagoon (Algerita Canyon, Lawyer Canyon, Fenceline), ramp-crest grainstone barrier complex (Rawhide), outer ramp fusulinid packstone/wackestone (Cougar Canyon), into distal ramp slope cherty mudstone (Coats Lake) in a dip distance of 10 miles. In contrast, the outer ramp fusulinid-peloid packstone-grainstone facies tract of the S1 highstand itself covers at least that distance.

Significance to Reservoir Studies: Several key conclusions can be derived from this subregional framework that are useful for consideration of more detailed outcrop and reservoir studies:

(1) The grainstone facies tract, identified as the critical element for analysis in this project, has been placed into perspective relative to its adjacent facies by the

subregional framework study. This step was critical for locating the interwell and reservoir scale study areas.

(2) The outer ramp fusulinid packstone/grainstone facies tract may be equally or more important than the grainstone shoal tract in terms of original oil in place in many San Andres and Grayburg reservoirs. The subregional framework provides a basis for designing study of the different style of heterogeneity within the outer ramp San Andres. An area has been selected immediately below the current upper San Andres study area at Lawyer Canyon for this detailed middle San Andres study.

(3) The different scales of lateral heterogeneity and the overall ramp geometries for sequences 1 and 2 in outcrop can be used as a frame of reference for predicting facies geometry and lateral variability in the subsurface reservoirs of the Northern Shelf and Central Basin Platform, as will be demonstrated by the Seminole field study.

Reservoir-Scale Mapping

Objectives: Reservoir-scale mapping was carried out in the upper San Andres (S2) to further characterize the complex lateral facies changes occurring between the two key reservoir zones of most San Andres/Grayburg reservoirs, the ramp-crest ooid-peloid grainstone bar complex and the outer-ramp fusulinid wackestone/packstone/grainstone. This relationship is typically described as a single 200- to 400-ft-thick, upward-shallowing sequence that comprises basal subtidal fusulinid facies, shallow subtidal/intertidal ooid-peloid grainstone, intertidal/supratidal laminites, and supratidal anhydritic mudstones. A similar vertical succession is observed along the Algerita Escarpment, but with the continuous lateral exposure an opportunity exists to document more precisely the lateral relationship between facies.

Results: Data collected for this phase of the study include 18 300- to 400-ft sections of S2 (figs. 4 and 5) at lateral spacings of 1,000 to 2,500 ft for a total length of 4 miles. Lateral correlation was through bed tracing and detailed photogeologic interpretation. Key results of this scale of mapping, which most closely compares with that of a section across a medium-scale San Andres/Grayburg reservoir are as follows.

(1) Four subsequences (fourth-order sequences ?) within the S2 sequence were recognized. Each subsequence consists of 9 to 12 parasequences and is capped by either a karst surface (top of subsequences 1, 2, and locally 4) or a siliciclastic sand-rich bypass surface (subsequences 3 and 4). In subsequence 1, a transgressive facies tract could be defined in sections LC through FL that consisted of six ooid-peloid-

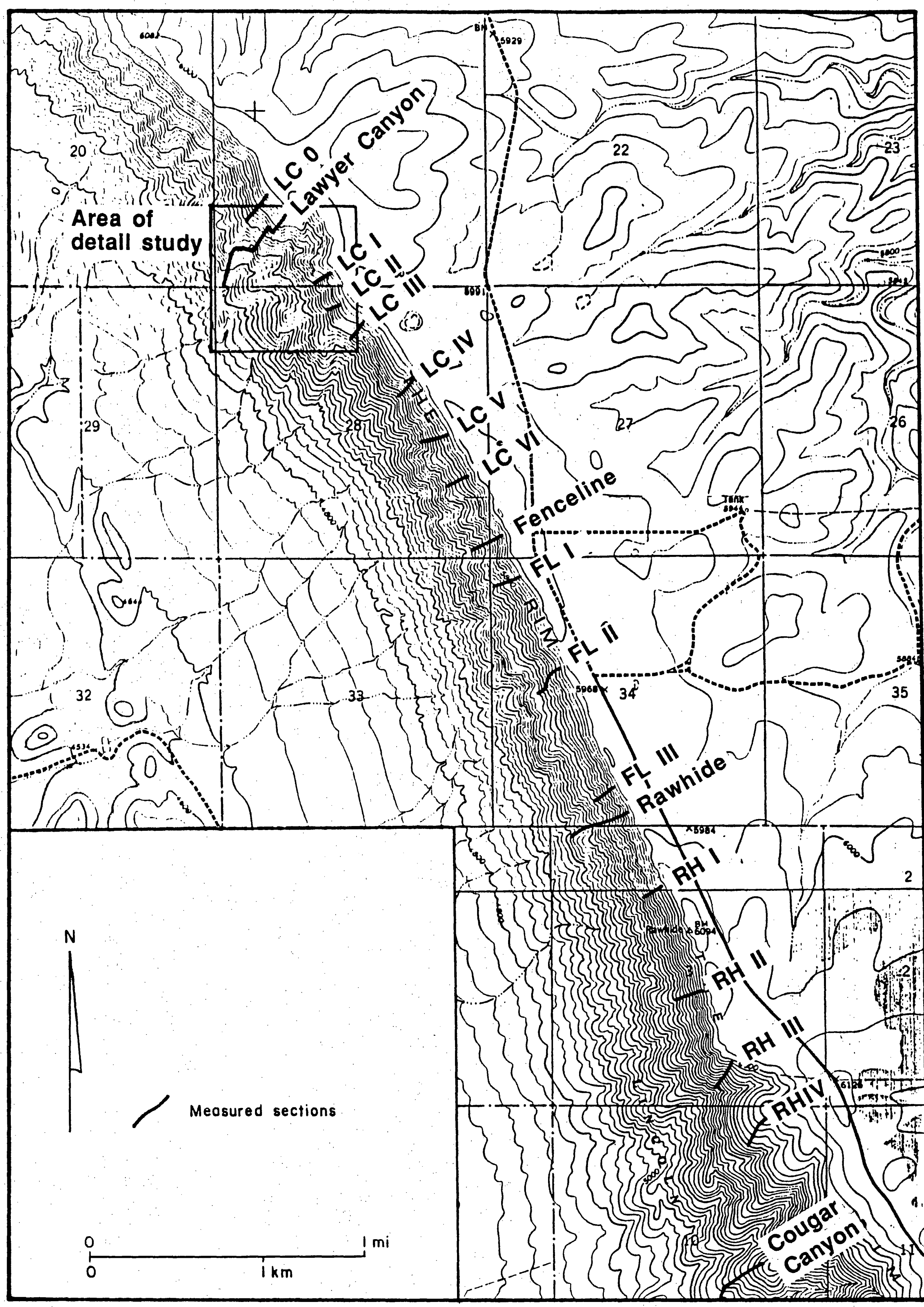

Figure 4. Location of measured sections for the reservoir-scale mapping of the upper San Andres Formation (see figure 5 for cross section). Inset shows the area covered by the interwell-scale mapping (plate 1). From Algerita Canyon, New Mexico, 7.5-minute quadrangle sheet.

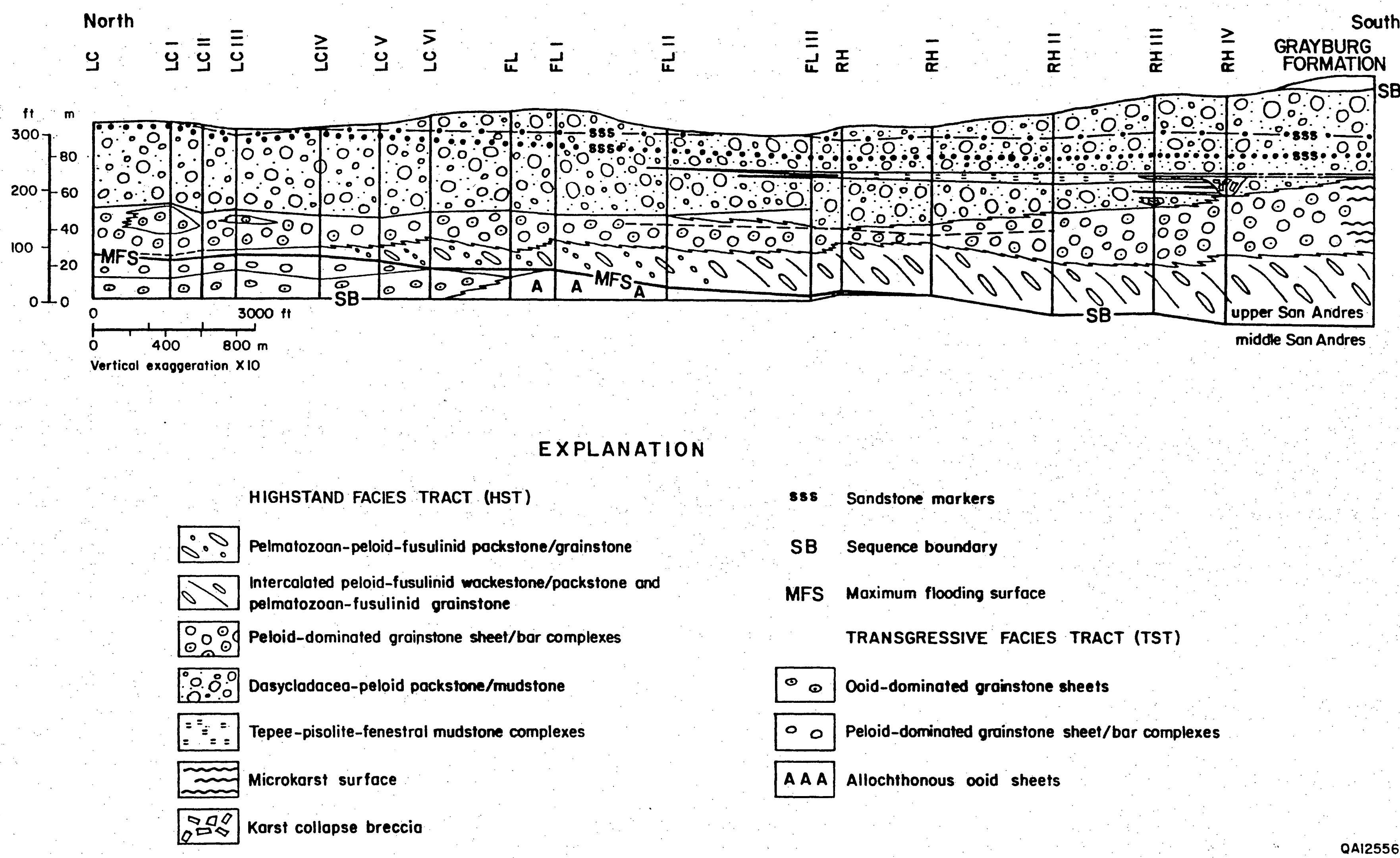

Figure 5. Reservoir-scale cross section of the upper San Andres Formation along a 5-mi transect from Lawyer Canyon to Cougar Canyon. Subsequences are not specifically denoted on the cross section. Note that ooid-peloid grainstones are climbing in the section from north to south (downdip). Sections are depicted in figure 4.

grainstone-dominated parasequences (0 to 80 ft thick). This transgressive tract is overlain by a 0- to 100-ft-thick fusulinid wackestone to packstone tongue and capped by a series of well-developed prograding bioclastic-peloid shoal parasequences (60 to 80 ft thick).

(2) Detailed mapping and bed tracing of the lower subsequence (ss1) have demonstrated the lateral equivalence of the ramp-crest grainstone shoals in the Lawyer Canyon area with the downdip fusulinid-rich outer ramp facies in the Rawhide–Cougar Canyon area.

(3) Detailed tracing of the karst surfaces bounding subsequences 1 and 2 from their paleotopographic crests to surfaces of apparent conformity illustrates local relief of 30 to 40 ft on the grainstone shoal complexes.

Interpretation: The four subsequences defined during the reservoir-scale mapping indicate that, at least in the upper San Andres of the Algerita Escarpment, lateral juxtaposition of ramp crest grainstone shoals and outer ramp fusulinid facies can occur on the scale of 1 to 2 mi. In addition, the successive subsequences are shingled in a seaward (progradational) direction, such that the ramp-crest grainstone complex of subsequence 2 is offset 2 mi seaward of the subsequence 1 ramp crest. This is in large part due to controlling influence of depositional topography from the precursor subsequence.

Significance to Reservoir Studies: The observation that the upper San Andres sequence (S2) consists of basinward-shingled subsequences separated by exposure/bypass surfaces has important implications in terms of pay continuity. Our data demonstrate that the ramp-crest grainstone facies tract of S2 consists of four separate shoal complexes whose crests (probably equivalent to increased reservoir quality "sweet spots") are offset progressively basinward several thousand feet from one another. Furthermore, any flow continuity between these shoal complexes would be across bedding, thus implying that the shoal-crest portions of the subsequences may act as isolated reservoir compartments.

Interwell-Scale Mapping

Objectives: Subsurface data available from the Permian Basin are sufficient to produce both subregional and reservoir-scale cross sections where good log and core control exist. Thus, although subtle but important aspects may be missed in these scales of subsurface mapping (such as the importance of depositional topography or shingling of pay intervals), good facsimiles of reservoir stratigraphy can be constructed. In contrast, data on interwell scale heterogeneity are by definition unavailable in the subsurface. For this reason, interwell-scale mapping forms the focus of the outcrop geologic and modeling studies of the RCRL.

The objective of this part of the project is to describe quantitatively a continuous window of geologic and permeability data on the scale of two to three 10-acre well spacings (2,000 to 3,000 ft in lateral dimension) in the ramp-crest grainstone shoal facies tract. These data will be used as a quantitative basis for geostatistical modeling and flow simulation experiments with the goal of improving modeling parameters for simulation of flow in reservoirs.

Results: The geologic description of this detailed study area provides an excellent picture of the internal architecture of a San Andres ramp-crest grainstone complex (figs. 6 through 8). Seventeen sections at 100- to 300-ft spacing (total 2,700 ft lateral dimension) were described geologically. The most striking feature of the interwell scale mapping was the well-developed small-scale cyclicity. The grainstone-dominated part of the upper San Andres at Lawyer Canyon (lowermost of the four subsequences) was shown to consist of 12 upward-shallowing cycles or parasequences ranging from 10 to 40 ft thick (fig. 6). A complete parasequence is characteristically a basal mudstone to wackestone up to 5 ft thick that coarsens upward into massive to cross-stratified ooid-peloid or bioclastic-peloid grainstone, with or without a capping tidal-flat fenestral algal laminite. The lateral variability observed within a single parasequence is exemplified by parasequences 1 and 7 (figs. 7 and 8). Less complete parasequences have discontinuous mudstone bases, and several thin units (parasequences 3 through 6) never developed a crossbedded shoal-crest facies. Thinner parasequences (10 to 20 ft) had minimal lateral facies variability whereas the thicker units (30 to 40 ft) showed highly variable lateral facies patterns (figs. 7 and 8). Parasequence 9 shows dramatic thickness variation of the bioclastic-peloid grainstone facies, from 0 to 38 ft in a lateral distance of only 500 ft.

Interpretation: A key conclusion of the interwell geologic mapping was that the selected grainstone-dominated study area could be divided into upward-shallowing parasequences of 10- to 40-ft thickness that were laterally continuous over 2,700 ft. These parasequences with their laterally continuous low-permeability mudstone bases provide an excellent genetic framework for collection of petrophysical data.

Each parasequence is interpreted to have formed by initial rapid relative sea-level rise and subsequent fall. Basal mudstones were deposited during the initial rise, during which time the platform was blanketed by quiet-water subtidal muds. Subsequent aggradation of sediment to sea level produces an upward-shallowing profile. Depending on the magnitude and duration of the subsequent relative sea-level fall, a disconformity, a tidal-flat deposit, or a karst surface may cap the parasequence. The sequence of facies produced is similar to that produced during the

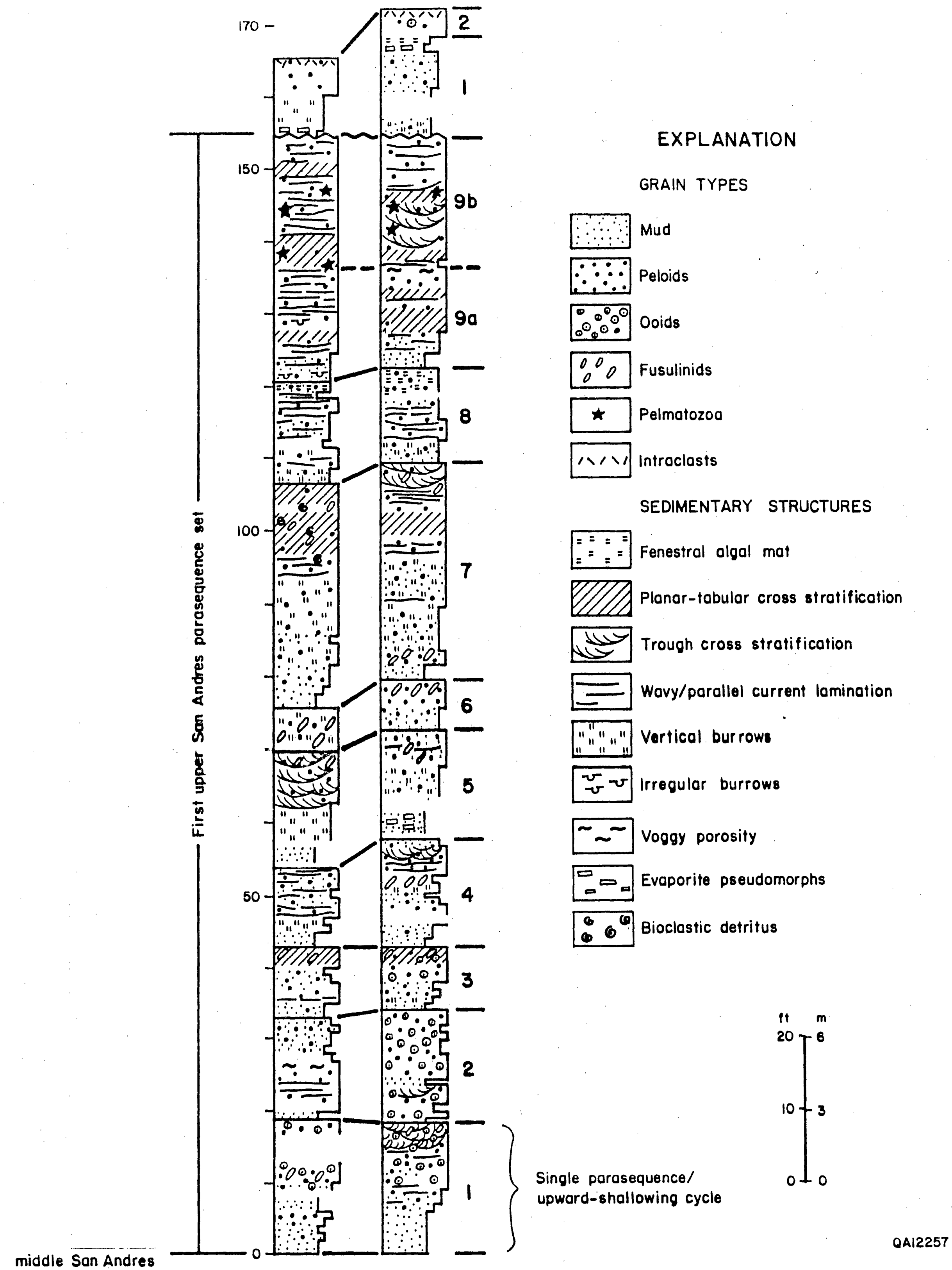

Figure 6. Two of the 17 detailed measured sections used in constructing the interwell-scale geologic cross section. Location of sections shown in figure 5. Each of the 11 parasequences shows a basic upward-coarsening trend though each cycle has only partial development of the ideal facies succession (mudstone through wackestones and packstones to crossbedded grainstones and fenestral tidal-flat cap). Parasequences 1 through 9 represent the first parasequence set.

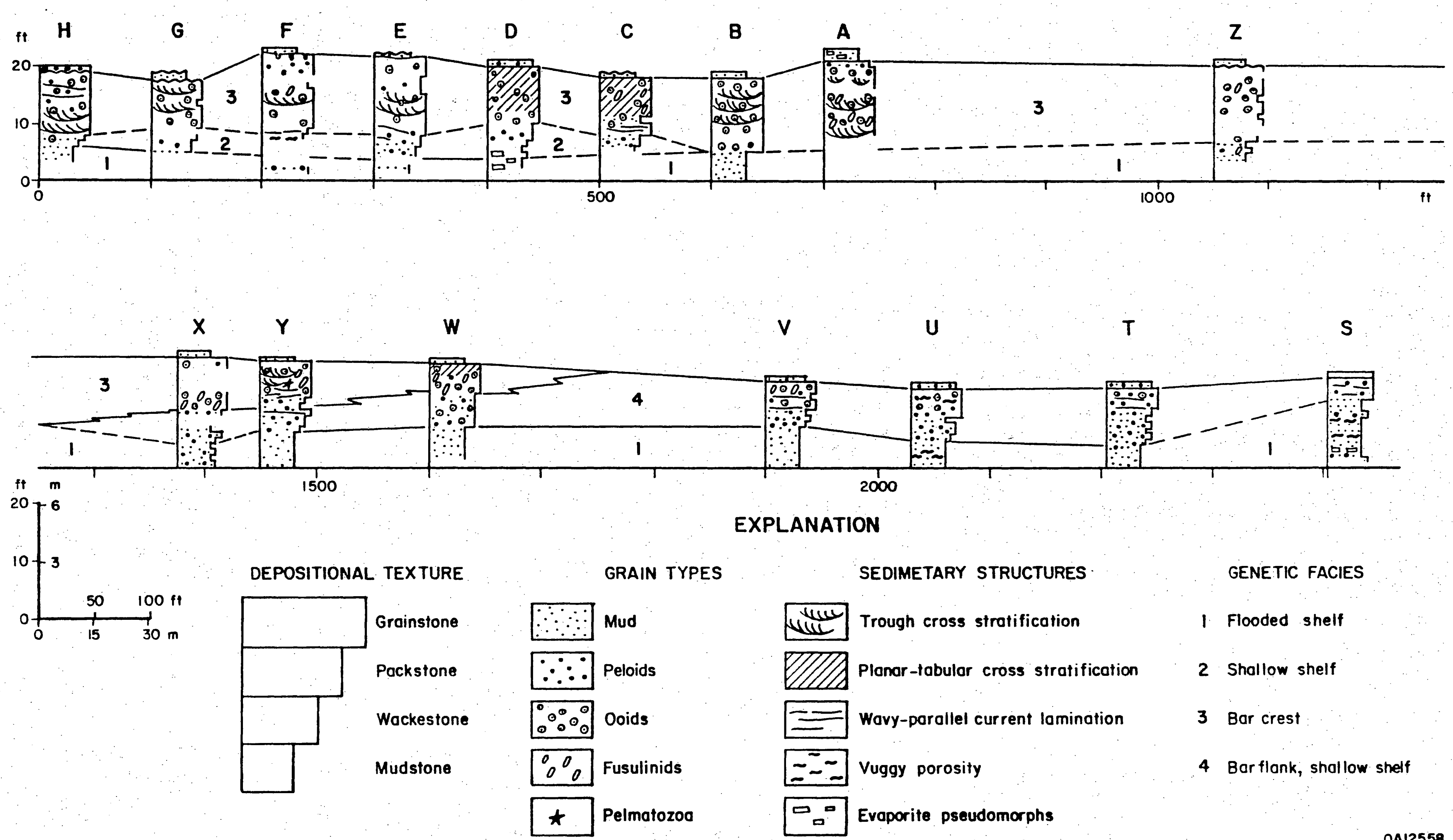

Figure 7. Detailed geologic cross section of parasequence 1 showing lateral variability within a single parasequence. Letter designations at top of sections denote the lateral position of the data, and are the same for figures 6, 8, and plate 1.

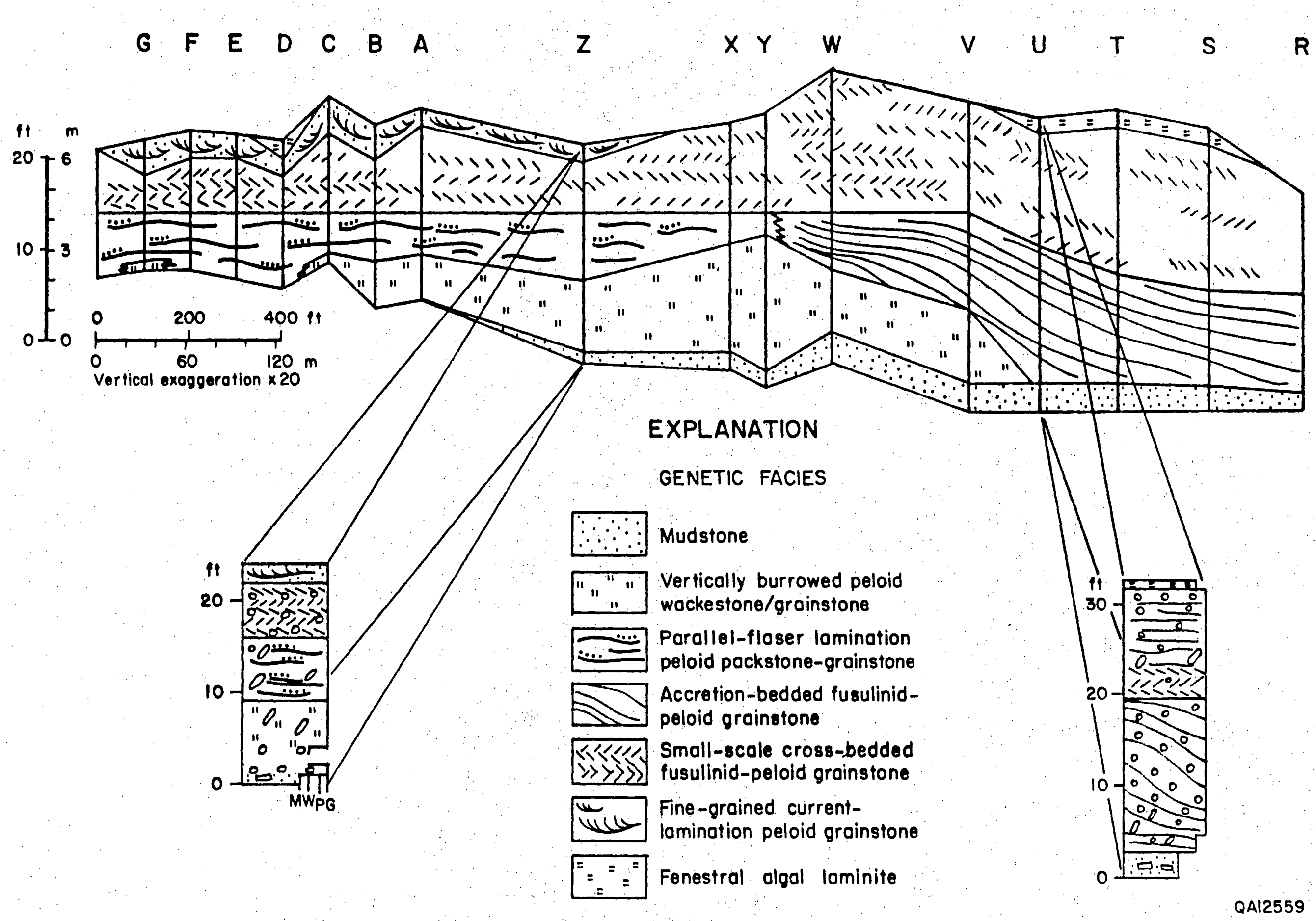

Figure 8. Detailed geologic cross section of parasequence 7 showing lateral variability of geologic facies within a single parasequence. Letter designations at top of sections are as for figure 7.

present Holocene sea-level rise as recorded in the shallow-water platforms of the Bahamas (e.g., Harris, 1979).

The greater lateral facies variability observed in thicker parasequences may be a reflection of either (1) the increased timespan for equilibrium sedimentation in the thicker cycles allowing full development of facies associations or (2) the increased water depth/accommodation space due to larger relative sea-level fluctuations.

Significance to Reservoir Studies: Interwell scale mapping of the grainstone-dominated lower subsequence of the upper San Andres has demonstrated several key relationships:

(1) The grainstone shoal facies tract of the subregional and reservoir-scale mapping can be divided into mappable, small-scale, upward-shallowing cycles or parasequences, 10 to 40 ft thick, that are laterally continuous on the interwell scale (660-ft or 10-acre spacing).

(2) Within the parasequence framework, rapid lateral facies changes are best observed within a single parasequence, where a systematic lateral variation in facies can be related to the original depositional geometry of grainstone shoals and their associated off-shoal deposits. Changes of as much as an order of magnitude in thickness of bar-crest grainstone facies over lateral distances of a few hundred feet were observed for several parasequences, providing a clear analog for the poor interwell communication often observed in San Andres reservoirs. This positive correlation between parasequence thickness and facies variability may be useful in the reservoir setting. Thick parasequences identified in reservoir core studies should be correlated with greater caution, anticipating significant variability in rock fabric and permeability.

(3) With their low-permeability mudstone boundaries, most parasequences may serve as flow units, thus allowing porosity/permeability data to be collected within a genetically meaningful framework. Additionally, these mudstones may show a strong control over vertical permeability, a characteristic that will be tested by flow modeling experiments.

Petrophysical Studies

Objectives: Petrophysical studies of the San Andres outcrop are focused on relating porosity, permeability, and pore size distribution measurements to rock fabrics for the purpose of defining the most important geologic parameters controlling the distribution of petrophysical properties in San Andres reservoirs. Closely spaced outcrop samples are taken in

areas where the geology has been mapped in detail and porosity and permeability measured in the laboratory. Thin sections and rock slabs are used to study the pore size distribution and rock textures. Transform functions between porosity, permeability, and rock fabric are developed from this data, and these transform functions define the geologic parameters controlling the flow characteristics of San Andres reservoirs.

Results: Rock fabric studies of parasequences 1 and 7 are under way. Ninety-two samples of parasequence 1 have been collected, described on slabbed surface, and measured for porosity and permeability. These samples cover an area about 20 ft high and 2,700 ft long. Initial results indicate that permeability values can be related to the size and volume of intergranular and intercrystalline pore space. The volume of pore space appears to be controlled by dolomite cement and the presence of calcite. Calcite crystals are commonly pseudomorphic after gypsum/anhydrite.

Rock fabrics of parasequence 1 have been divided into mud-dominated and grain-dominated fabrics. Grain-dominated fabrics are characterized by the presence of intergranular pore space or cement, whereas mud-dominated fabrics contain intercrystalline pores and are characterized by the absence of intergranular pore space or cement. Highest porosity and permeability values are found in the grain-dominated fabrics (average k = 142 md, average ø = 14 percent), whereas the mud-dominated fabrics tend to have low porosity and permeability values (average k = 3 md, average ø = 8 percent).

Sampling of parasequence 7 is in the initial phase. Eighty-seven samples have been collected over a lateral distance of 2,700 ft. Initial results show parasequence 7 is characterized by high volumes of separate-vug pore space in a grain-dominated fabric with some intergranular pore space. Porosity values range from 13 to 21 percent with pore space concentrated in separate vugs. Permeability values range from less than 0.1 md to 10 md.

Interpretation: The grain-dominated fabric in parasequence 1 constitutes the reservoir-quality rock and is the most important geologic parameter controlling permeability distribution. Parasequence 1 is an upward-shallowing cycle in which grain-dominated fabrics in the upper measures overlie mud-dominated fabrics. The upper, grain-dominated unit defines a major flow unit. The grain-dominated fabrics are gradually replaced by mud-dominated fabrics in a southerly direction defining the southern boundary of the flow unit. The northern boundary has not yet been defined.

The grain-dominated fabric is also the reservoir-quality rock in parasequence 7, but the permeability values are significantly lower because of the concentration of pore space in

separate vugs. The presence of separate vugs is interpreted to be related to the dissolution of allochems that were originally composed of aragonite.

Significance to Reservoir Studies: Flow units are defined by the distribution of grain-dominated fabrics, and flow barriers are defined by the distribution of mud-dominated fabrics. Bodies of grain-dominated fabrics are formed in high-energy depositional environments, and the geometries of these bodies will control the production characteristics of the reservoir. However, the grainstones of parasequences 1 and 7 have significantly different flow characteristics as a result of differences in the volume of separate-vug pore space. This contrast is related to a change in the original mineralogy of the allochems. Therefore, the distribution of grain-dominated bodies and the distribution and kind of allochems within these bodies are important geologic parameters controlling the flow characteristics of the San Andres outcrop.

Geostatistical Studies

Objectives: Specifically, the geostatistical objectives are to (1) determine the degree of correlation between geologic facies and permeability, (2) characterize the spatial pattern of permeability, (3) test the utility of variograms for characterizing or representing spatial correlation, (4) test whether the stochastic technique known as conditional simulation generates realistic spatial patterns, (5) test how much data are needed to condition the stochastic results, and (6) determine whether stochastically generated heterogeneity provides an accurate picture of how fluid moves through the rocks.

Results: A total of 1,972 mini-air-permeameter measurements have been made within the detailed Lawyer Canyon interwell study area grid. Of these, 1,666 measurements were in parasequence 1, of which 112 measurements were acquired in parasequence 7. Resampling of data points for most of the parasequence 1 grid has been carried out, resulting in good repeatability of data. A large (1 ft^3) slabbed block of ooid grainstone was collected from parasequence 1, and 511 measurements were made at centimeter-scale spacing on this block in the laboratory.

Lower flow-range rotameters that provide an increased sensitivity on low permeability samples are now being used in the mini-permeameter. A total of 1,113 of the outcrop measurements and all 511 measurements on the block were made using this equipment. Use of this equipment has allowed a more precise definition of low-permeability boundaries on the outcrop.

Spatial variability of permeability data from 324 mini-air-permeameter measurements in parasequence 1 (analysis of first data set) was analyzed by contouring the data and by applying population statistics and geostatistics. These data are only part of the data available from the northern half of the cross section shown in plate 1. Four facies, listed in table 1, were analyzed (see figure 7 for facies distribution). Each facies can be characterized by the percentage of grainstone and packstone; the remainder is composed of wackestone and packstone. The basic statistics show good correlation between mean log permeability and packstone/grainstone percent, as shown in table 1.

Table 1. Permeability data for four facies of parasequence 1 based on 324 mini-air-permeameter measurements.

FACIES	PERCENT PACKSTONE & GRAINSTONE	PERMEABILITY		
		Mean	Log_{10}Mean	Log_{10}Std. Dev.
Parasequence 1	72.3	83.4	0.753	1.140
Flooded Shelf	2.5	11.5	0.037	1.140
Shallow Shelf	60.0	14.6	0.389	0.746
Bar Flank	86.1	69.9	0.732	1.213
Bar Crest	100.0	109.7	0.949	1.159

Contouring of permeability data shows mappable permeability patterns varying on a scale of 3 orders of magnitude throughout the cross section shown in plate 1 in the upper unit. A significant drop in permeability occurs at the southern end of the section, corresponding to the termination of the bar-flank and bar-crest facies. In the northern half of parasequence 1, the discontinuous high-permeability zones measure 200 to 400 ft long. Several elongate, high-permeability trends appear to dip northward at roughly 2 to 3 degrees.

Several variogram trials were run with various forms and subgroups of the data. Virtually all horizontal variograms generated with lumped data from parasequence 1 or from individual facies within parasequence 1 showed no appreciable spatial correlation (pure nugget effect). Only when separate variograms were computed for the low and high permeabilities of the bar-crest facies did the variograms begin to show some evidence of the correlation exhibited in the contour maps. Importantly, variogram structure in the bar- crest facies became clear only after the horizontal azimuth in the variogram computation was inclined 2 degrees northward, in accordance with the dipping high-permeability zones. The bar-crest facies yielded an

experimental variogram with a range of approximately 100 ft. Other versions of this variogram yielded subtle correlation structures that fit nested-variogram models having ranges between 35 and 375 ft. The vertical variograms exhibit nested structures having ranges of 1 to 7 ft and 5 to 14 ft, similar to ranges reported from the Dune (Grayburg) field.

Interpretation: These results are highly preliminary, and they may be altered substantially as new data are collected and analyzed. Nevertheless, the following conclusions can be made.

(1) The mapped depositional facies show noticeable differences in mean permeability.
(2) Significant permeability variation occurs within the depositional facies. Within the bar-crest facies, permeabilities exhibit mappable patterns in which high-permeability (>50 md) areas measure 200 to 400 ft long.
(3) Considerable manipulation of the data and variogram search window is required to produce horizontal variograms that weakly reflect the spatial correlation evident in the contour maps. This reinforces earlier warnings that blind application of variography to permeability data cannot be expected to reveal true spatial correlations. The variogram is not a device for detecting correlation; rather, it is a means of quantitatively representing measured or inferred correlation.

Coring Activities

Objectives: An outcrop drilling program was initiated in conjunction with outcrop investigations to address the following objectives: (1) construction of a three-dimensional geologic framework for reservoir analog assessment; (2) construction of an outcrop/subsurface data set, including well logs and core analyses; (3) determination of interwell variability at scales characteristic of San Andres reservoirs (5 to 10 acre spacing); and (4) determination of surface weathering effects on permeability and porosity data.

Results: The original plan included drilling/coring four wells in the upper San Andres Formation in the Lawyer Canyon area in the immediate vicinity of the interwell mapping area (figs. 3, 4, and 9). Porosity and permeability analyses were to be performed on core and a complete suite of geophysical well logs was to be recorded at each site. The plan was modified because of generally poor upper San Andres core recovery. Only three wells will be drilled, the No. 1, which cored the entire upper San Andres and 20 ft of the middle San Andres, the No. 3, which has neared completion having cored portions of the upper San Andres and the entire upper half of the middle San Andres, and the No. 2 (not yet spudded) that will attempt to core

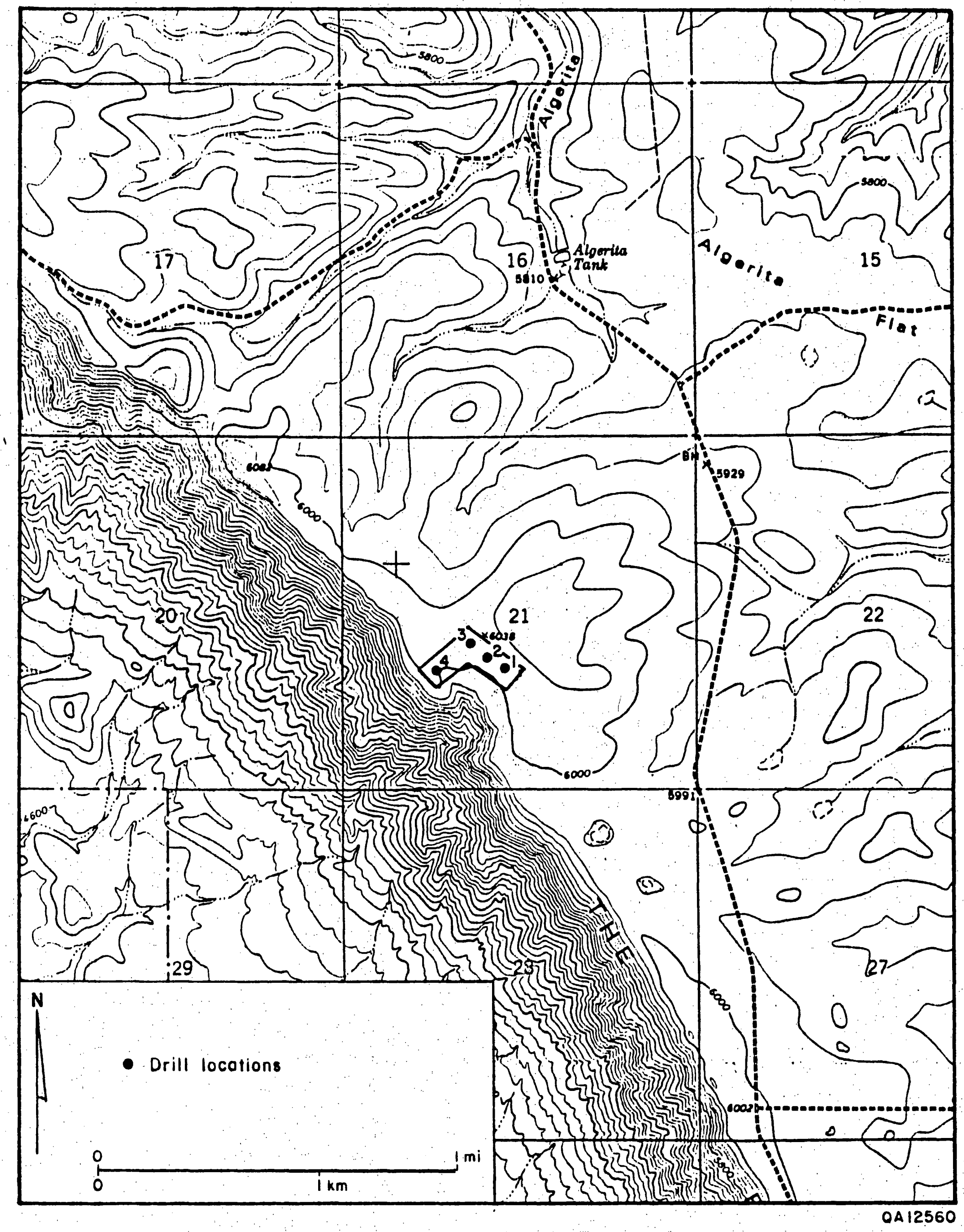

Figure 9. Location of drill sites in Lawyer Canyon area. Sites 1, 2, and 3 will be drilled; Site 4 will not. From Algerita Canyon, New Mexico, 7.5-minute quadrangle sheet.

both the upper San Andres and upper half of the middle San Andres. Funds are insufficient to permit drilling the No. 4 well. Additionally, well logging will include only gamma ray and lithodensity logs in wells 2 and 3 because borehole conditions will not permit use of other tools. The extensive use of cement to drill the No. 1 borehole precludes obtaining meaningful logs from this well.

No. 1 Algerita was drilled from March 27 to May 10, 1989, from the surface (approximate top of San Andres) to 403 ft deep (uppermost middle San Andres) by Byrl Binkley Drilling Company using mud circulation. Core recovery and quality were generally insufficient for the detail required for the study. The continual need for water delivery to the site and for repeated cementing of fractured intervals in the borehole resulted in excessive down time. From the 350 ft of upper San Andres and 33 ft of middle San Andres core, 97 whole-core samples (maximum, 90°, and vertical permeability) and 57 plug analyses of permeability and porosity were obtained, or 1 analysis every 2.5 ft.

No. 3 Algerita was spudded August 30, 1989, at Site No. 3 by W. Perry Smith Exploration/Homco Coring Services. After drilling to 170 ft, coring began in the lower half of the upper San Andres. Poor recovery (less than 35 percent) and poor core quality in the upper San Andres resulted in the decision to discontinue coring, drill to the base of the upper San Andres, and core the upper half of the middle San Andres. Coring of the middle San Andres has produced 90 to 100 percent recovery with good to excellent core quality. No. 3 Algerita reached TD (approximately 620 ft) on September 21, 1989.

No. 2 Algerita was spudded at Site No. 2 on September 22, 1989. Present plans are to drill to 170 ft and to core the lower half of the upper San Andres through the upper half of the middle San Andres. Modified coring techniques may improve recovery efficiency in the upper San Andres to 90 to 95 percent. However, if core recovery is poor in the upper San Andres, only the upper half of the middle San Andres will be cored.

RESERVOIR DESCRIPTION AND MODELING, SEMINOLE FIELD

Objectives: The RCRL Seminole study is designed to run in conjunction with the outcrop characterization work to serve as a test area for application of outcrop modeling results. A critical hypothesis being tested by the RCRL research is that the geologic and permeability relationships controlling flow characteristics and potential compartmentalization in shallow-water grainstone shoals of the San Andres and Grayburg outcrops are similar to those in comparable facies tracts of the subsurface reservoirs, while accepting possible variability attributable to differing paleogeographic settings.

Data: A portion of Seminole San Andres Unit operated by Amerada Hess was selected for outcrop comparison because of geologic similarity, high-quality data base (core, log, and production data), and data availability. Figure 10 shows the detailed study area in the north-central portion of Seminole. Sixty-eight wells exist, of which 11 are cored, and an additional 8 cored wells outside the study area will provide the broader geologic framework. Nearly all wells in the study area have three porosity logs. Well spacing is 10 acre.

Geologic Results: As of September 1, 1989, 7 of the 19 cores have been described in detail, all within or immediately adjacent to the detailed two-section study area (fig. 10). Preliminary results of the core descriptions indicate that the facies stacking at Seminole can be compared closely with that observed from the outcrop. Small-scale cyclicity identical to that of the detailed interwell mapping can be used to divide the upper 150 ft of the reservoir interval into seven parasequences that extend for at least 2 mi in an east-west direction and an undetermined distance in a north-south direction. Individual parasequences are 10 to 40 ft thick and have mudstone-wackestone bases, grainstone cores, and locally developed fenestral algal laminite caps. Significantly, many of the cycle caps and bases are shale-prone and therefore have detectable gamma-ray signatures, allowing correlation beyond the area of core control using logs only. Current plans for this geologic portion of the reservoir study are to develop as detailed as possible a parasequence framework through core description and detailed gamma-ray log correlation, within which petrophysical, engineering, geostatistical, and flow simulation studies will be carried out.

Petrophysical Studies: The SSAU No. 2505, having 350 ft of core and three porosity logs (dual laterolog and microlog), has been selected as a candidate well for developing rock-fabric/porosity/permeability/log relationships. The core has been sampled at 1-ft intervals for thin section and X-ray diffraction (XRD) analysis. Sections 231 and 250 of the unit have been selected for detailed analysis. Most of the logs have been digitized, and an initial attempt at calculating mineralogy from these logs has been made. Porosity and permeability data from core analysis have been entered into the computer.

Engineering Studies: Much of the well test, completion, production, pressure, and well history information has been collected from the two-section study area. Production data for each well in sections 231 and 250 from 1970 to the present have been collected. Repeat formation test

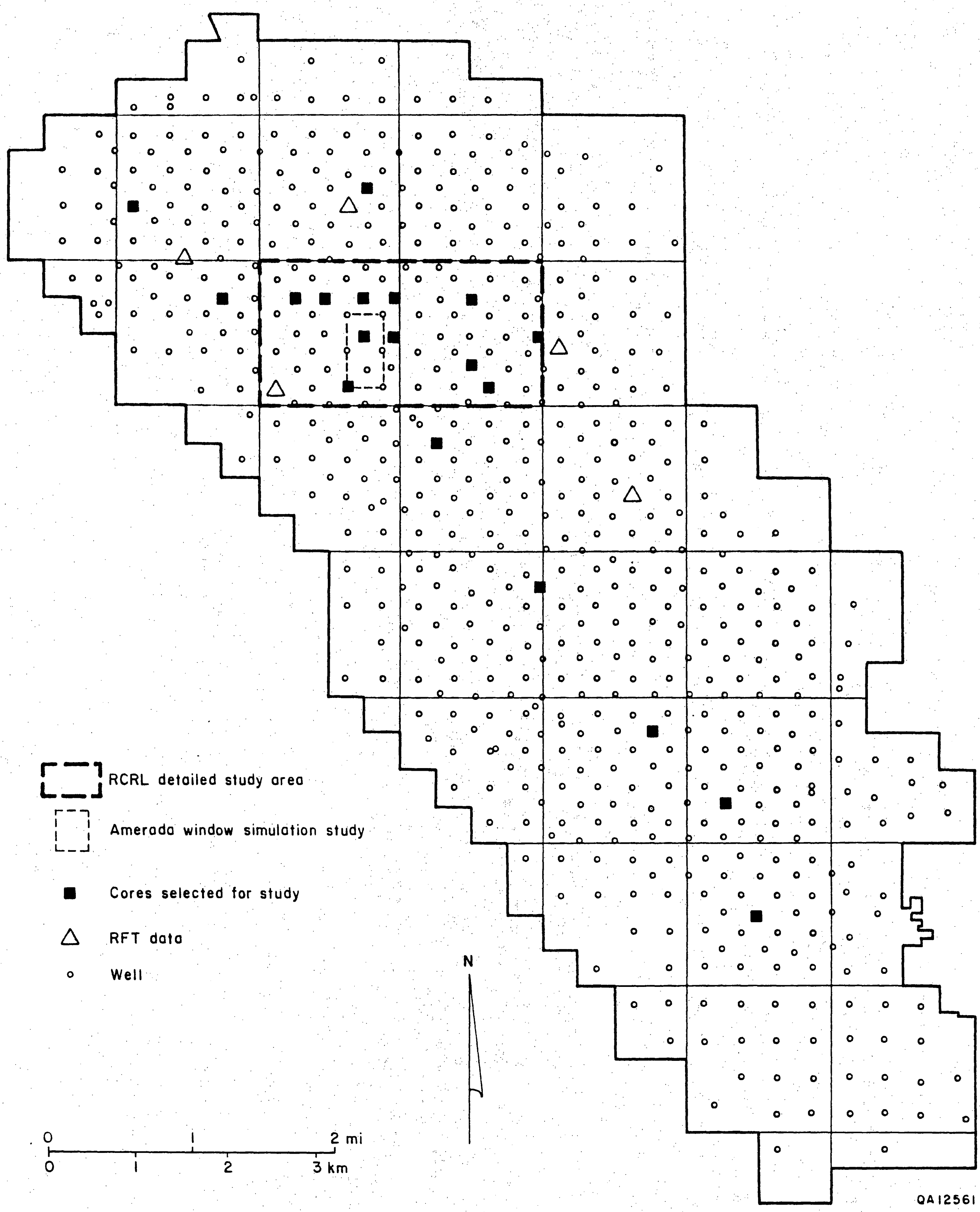

Figure 10. Map of Seminole San Andres Unit showing location of detailed study area and related data.

(RFT) data are available for three wells, and a well-history summary has been obtained for each well. Initial completion data from the original 40-acre development wells have been obtained. A contour map of this data shows a gradual reduction in flow rate from northwest to southeast across the two-section area.

Geostatistical and Flow Modeling Studies: Geostatistical studies are dependent on development of an integrated geologic/engineering analysis and will not be begun until these studies are more advanced (early 1990).

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