DRAFT REPORT

GEOLOGICAL CONTROLS ON RESERVOIR HETEROGENITY IN DISTAL THIRTYONE FORMATION (LOWER DEVONIAN) CHERT RESERVOIRS: UNIVERSITY WADDELL FIELD, WEST TEXAS

Roger J. Barnaby and Stephen C. Ruppel

Bureau of Economic Geology

The University of Texas at Austin

Austin, TX 78713-7508

ABSTRACT

University Waddell field West Texas, has yielded more than 19.5 million barrels of oil from Lower Devonian Thirtyone Formation deep water cherts and siliceous limestones. Production rates, however, are on the decline and current recovery represents only 30 percent of the original oil–in–place. This low recovery efficiency, despite more than 50 years of primary and secondary production development reflects reservoir heterogeneity induced by complex facies relationships in a basinal turbidite channel and submarine fan depositional setting.

Analysis and interpretation of core and log data from University Waddell field illustrates that the approximately 900 ft thick Lower Devonian reservoir interval can be divided into four regionally mappable stratigraphic units that define two distal–to–proximal sequences. Production comes dominantly from porous cherts and siliceous limestones in the lowermost sequence. Reservoir units are composed of silt-size to fine-grained, siliceous skeletal packstones/grainstones derived from the platform margin/slope and transported as much as 50 mi basinward by turbidity currents. These relatively well-sorted facies represent episodic, high–energy deposition in turbidite channels to proximal submarine fan complexes. Mapping of individual facies successions indicates lobate to channel-form geometries that generally trend north to northwest, parallel with the regional depositional axis. Reservoir facies grade laterally and are interbedded with relatively nonporous facies that represent slow accumulation of mud-rich sediments in an overbank and distal submarine fan setting and background hemipelagic sedimentation. Faults and fractures also contribute to the heterogeneity of the Thirtyone reservoir at University Waddell field. Significant (50–100 ft vertical offset)

normal and reverse faults are apparent from log correlations although the 40 to 20 acre well spacing precludes detailed mapping of these steeply dipping fault planes. Open fractures are common in cores.

The estimated 17 million barrels of remaining mobile oil make this reservoir a significant target for enhanced recovery efforts. The complex, multi-tiered reservoir architecture accounts for many of the observed production anomalies, the poor communication between injection wells and flanking producers, and suggests that many areas of the reservoir have been inadequately developed. Several opportunities for targeted infill drilling and recompletion can be defined. These strategies are likely to be applicable in similar distal Thirtyone chert reservoirs in the Permian Basin.

INTRODUCTION

The Thirtyone Formation is a major hydrocarbon-bearing unit in the Permian Basin of West Texas. These rocks, which include deep-water cherts and shallow-water carbonates of Early Devonian age, have accounted for more than 900 million barrels of oil production as of January, 1997. Most of the hydrocarbon resource in these rocks lies in the porous, deep-water chert facies. As of 1997, more than 750 million barrels have been produced from Thirtyone chert reservoirs. Calculations by Ruppel and Holtz (1994) indicate that about 650 million barrels of mobile oil remains in these rocks making this one of the largest chert hydrocarbon reservoir successions in the world.

Ruppel and Holtz (1994) and Ruppel and Barnaby (2000) documented two end member styles of reservoir development in the Thirtyone Formation in the Permian Basin: a updip proximal setting and a downdip distal setting. Ruppel and Hovorka (1995) documented the proximal setting using Three Bar field as an example. In this paper, we focus on controls and styles of reservoir development in distal Thirtyone chert reservoirs as typified by the University Waddell reservoir. Geological models derived from this study provide a basis for interpreting other Thirtyone chert reservoirs in similar settings in the Permian Basin.

The purpose of this report is to report the results of the detailed characterization of the distal Devonian, Thirtyone Formation chert reservoir in University Waddell field. The major objective of this work was to develop approaches that could be used to locate and recover the remaining oil in this and other such Thirtyone reservoirs in the Permian basin. Fundamental elements of the study include: (1) description of the reservoir architecture to evaluate geologic heterogeneity responsible for the poor oil recovery; (2) delineation of the distribution of porous reservoir units and evaluation of stratigraphic, depositional, and diagenetic controls on reservoir development; (3) construction of a stratigraphic framework, and (4) delineation of opportunities for oil recovery from the University Waddell field that can be extrapolated to similar fields in this play.

PREVIOUS WORK

The age and distribution of Devonian chert-bearing rocks in West Texas were first described by Jones (1953), Wilson and Majewske (1960), and McGlasson (1967), who variously referred to them as the Siluro-Devonian, Lower Devonian, or Devonian cherty limestone. The Thirtyone Formation (Hills and Hoenig, 1979) was named for a succession of light-colored chert and cherty carbonate rocks that overly Silurian carbonates and shales (Wristen Group) and underly Upper Devonian shales (Woodford Formation). In recent years, both regional analyses (Ruppel and Holtz, 1994; Ruppel and Hovorka, 1995a; Ruppel and Barnaby, 2000) and detailed reservoir studies (Saller et al.,1991, 2000; Ruppel and Hovorka, 1995b) have contributed a wealth of a more detailed data on this important reservoir succession.

REGIONAL SETTING AND DEPOSITIONAL HISTORY

The Thirtyone Formation, which is dominantly Pragian (Early Devonian) in age , is underlain by the Silurian to lower Devonian (Lochkovian) Frame Formation and overlain by the upper Devonian Woodford Formation (Barrick, 1995) (Fig. 1). The underlying Frame Formation consists of argillaceous lime mudstone and wackestone that accumulated in a slope to basinal setting. This succession attains a maximum thickness of 800 ft in central Andrews County and thins basinward to the south to less than 100 ft in thickness (Ruppel and Holtz, 1994).

The Thirtyone Formation subcrops throughout most of the southern part of the Permian Basin, including Texas and small areas of New Mexico, and attains a maximum thickness of about 1,000 ft (300 m) in southern Crane County, Texas (Fig. 2). Thirtyone strata thin outward from this depocenter due to pre-Woodford erosion. To both the west and north, the Thirtyone subcrop margin corresponds approximately with the position of the Silurian platform margin (Ruppel and Holtz, 1994).

Throughout most of West Texas, Thirtyone Formation rocks comprise two distinct facies: (1) skeletal carbonates, primarily pelmatozoan packstones and grainstones, and (2) bedded, commonly spiculitic, chert (Saller and others, 1991; Ruppel and Holtz, 1994). Thirtyone carbonates are relatively more abundant in the upper part of the formation and to the north, whereas cherts are more abundant in the lower part of the formation and in the southern part of the subcrop area (Fig. 3). Chert is thickest in the basin depocenter, where , the Thirtyone consists of basal laminated dark cherts and lime mudstones that pass upward into light gray, laminated to massive spiculitic cherts overlain by skeletal lime packstones, recording a large-scale rise in relative sea level and successive basin infilling (Ruppel and Holtz, 1994). Skeletal packstone are overlain by an upper chert succession downdip, recording a renewed rise in relative sea level.

The top of the Thirtyone Formation is a major unconformity that records subaerial exposure and erosion. This unconformity ranges from the Emsian to at least the uppermost Givetian (Barrick, 1995), representing an estimated time span of more than 20 m.y. (Fig. 1). This unconformity is overlain by black shales of the Woodford Formation, to which faunal interpretations generally assign a Late Devonian age (Barrick, 1995 and references therein).

Similar chert-bearing successions of Thirtyone age are extensive across the southern and central midcontinent of the United States, an area that occupied the southern margin of the platform margin during the early Devonian. The equivalent New Harmony Group of the Illinois Basin (Fig. 1) contains very similar rocks (Collinson 1967; Droste and Shaver, 1987) but these deposits are not major hydrocarbon reservoirs, perhaps because they lack a top seal like the Woodford but instead are overlain by Middle Devonian carbonates. The Frisco Formation in Oklahoma is a chert-free, presumably more proximal equivalent of the Thirtyone.

REGIONAL RESERVOIR DISTRIBUTION

The distribution and internal character of Thirtyone Formation chert reservoirs reflects the complex interplay between depositional style, sea-level rise, and basin geometry. Two end-member styles of reservoir development are apparent (Ruppel and Holtz, 1994; Ruppel and Barnaby, 2000). In the northern or proximal part of the

Thirtyone depositional basin, reservoirs are developed at the base of the Thirtyone Formation in a chert interval that is remarkably uniform, continuous, and tabular throughout an area of at least 250 mi^2 (650 km^2) (Fig. 4). Thirtyone cherts in this area are dominantly spiculitic and grain-dominated but display subtle variations to more mud-rich facies that are probably the result of minor variations in topography or in delivery systems. These grain-rich, porous rocks grade into more mud-dominated facies that exhibit little porosity and permeability to the east and west along depositional strike. The uniform architecture of these updip basal Thirtyone cherts in this part of the basin suggests that they accumulated in a low-relief, proximal platform to platform-margin setting. Three Bar field (Ruppel and Hovorka, 1995) and Dollarhide field (Saller and others 1991) are representative of this subplay (Fig. 2). Downdip, into the Thirtyone depocenter, cherts grade into non-porous, hemipelagic, laminated siliceous and calcareous mudstones (Fig. 3).

Chert reservoirs in the southern or distal part of the Thirtyone basin (Fig. 4) are developed higher in the Thirtyone section overlying mud-dominated hemipelagic deposits. These cherts document basinward progradation of the Thirtyone and the southward shift of the locus of chert accumulation (Fig. 3). While these cherts were being deposited in the basin depocenter, shallower water skeletal sediments accumulated updip in more proximal areas (i.e., in the area of Three Bar field). Reservoir successions in more basinward chert deposits are thicker because of greater long-term accommodation caused by greater water depths and higher subsidence rates. Rapid progradation of northern and western carbonate platforms limited the accumulation of grain-rich siliceous deposits to a relatively small area in the basin center (Ruppel and Holtz, 1994). Reservoirs developed in this area are characterized by multiple, stacked successions of high-energy, grain-dominated chert grading upward into lower-energy, more mud-dominated, burrowed cherts (Fig. 3). These chert strata are much less continuous in their lateral extent than are those to the north. The University Waddell reservoir (described herein) typifies this reservoir type or subplay.

METHODOLOGY

Detailed study was focused on the Block B-25 area of the University Waddell field (Fig. 5). Pennzoil provided 41 digital logs from this area; gamma ray and porosity logs from an additional110 wells in surrounding areas were digitized to increase the wireline log control. This log database afforded sufficient coverage to characterize the University Waddell field and to extend the general stratigraphic correlations throughout the area.

Core representing nearly 2,000 ft of section was examined and described. More than 80 blue epoxy-impregnated thin sections of representative facies and lithologies were prepared and subjected to standard petrographic analysis to confirm the core descriptions. Cores were calibrated to wireline logs using both gamma ray and porosity logs.

Pennzoil provided digital monthly production and injection data for their leases that spanned the entire field history. A digital database of well completion histories was also provided by Pennzoil.

Petrophysical analysis was conducted on 20 wells in the Block 25 area. Porosity, water saturation, and mineralogy (chert/limestone volume)were calculated wherever appropriate logs were available. Sonic logs do a poor job of resolving porosity, because reservoir intervals contain various admixtures of chert and carbonate, complicating the differentiation of sonic log response to lithology from that induced by porosity. Comparison of core with wireline logs indicates that neutron and density logs provide the best resolution of porous intervals. Three wells had adequate log suites to compute mineralogy. These wells provided general lithologic data for stratigraphic intervals lacking core coverage and were essential for the stratigraphic and depositional interpretations presented here.

Structure, isopach, and phi-h maps were generated for each individually defined porosity unit. Cross sections, isopach maps, and phi-h maps documented that porosity units are laterally discontinuous.

SETTING OF UNIVERSITY WADDELL FIELD

University Waddell field is located in northeast Crane County approximately 50 miles south of Three Bar Field near the Thirtyone Formation depocenter (Figs. 2, 4). In Waddell field, the reservoir trap is formed by a complex L-shaped structure (Fig. 5). Upper Devonian Woodford shales unconformably overlie the Thirtyone and form the top seal of the reservoir (Fig. 6). The reservoir is underlain by carbonate mudstones and shales of the upper Silurian to lowermost Devonian Frame Formation.

University Waddell field was discovered in 1949 and by 1962, most of the field had been developed on a 40-acre well spacing. During initial primary recovery, the principal drive mechanism was fluid expansion above the bubble point pressure. As pressure declined, solution gas drive became the major drive mechanism. In 1965, a gas-injection pressure maintenance program was initiated in the northern part of the field (Cargile, 1967). This program was replaced with water injection in 1967, which has been of only limited success due to the lateral heterogeneity and low permeability of the chert reservoirs. Since its discovery, University Waddell reservoir has yielded more than 67.8 MMbbl of oil. Tyler and others, (1991) estimated the recovery efficiency of the field at 30 percent. Current low recovery efficiency, despite 50 years of primary and secondary (gas injection, waterflood) production and partially completed 20-acre infill well spacing, reflects reservoir heterogeneity induced by complex facies relationships in a basinal turbidite channel and submarine fan depositional setting. Table 1 presents the major reservoir properties of the Thirtyone Formation in University Waddell field.

GEOLOGICAL FACIES

Examination of cores and thin sections indicates that the Thirtyone Formation contains seven major facies in University Waddell field: (1) finely laminated chert and limestone; (2) nodular chert and limestone; (3) disrupted laminated chert; (4) burrowed chert; (5) thickly laminated to massive chert; (6) skeletal packstone; and (7) fractured/brecciated porous and nonporous chert (Fig. 7).

Finely Laminated Chert and Limestone

Description.

These rocks, which are confined to the basal portion of the Thirtyone Formation, comprise mm- to cm-thick parallel laminae of medium gray chert and dark brown, organic-rich lime mudstone (Fig. 8A). Chert laminae typically display fining-upward grain size trends and irregular erosional bases and consist dominantly of silt-sized indeterminate grains and siliceous sponge spicules Fig. 8B). *Zoophycos* ichnofauna and other burrow types are common. For the most part, these rocks are relatively nonporous and impermeable.

<u>Interpretation.</u>

Finely interlaminated cherts and lime mudstones represent the most distal facies in the Thirtyone Formation and accumulated in a low energy, deep water, basinal setting. Dominantly silt-sized grains within the chert units record distal turbidity sedimentation. Intercalated, organic-rich lime mudstones document hemipelagic sedimentation between episodic turbidity flow events. The well-developed lamination and the paucity of soft sediment deformation and fluid escape structures implies relatively slow accumulation rates in a stable basinal setting. *Zoophycos* trace fossils, which are formed as grazing traces and shallow feeding structures within organic-rich muds and muddy sands, are generally interpreted to record quiet, oxygen-deficient waters below storm wave base. In such settings, *Zoophycos* trace fossil assemblages represent a transition between sublittoral *Cruziana* ichnofacies and abyssal *Nereites* ichnofacies and are generally assigned to the bathyal zone, with estimated minimum water depths of several hundred feet (Frey and Pemberton, 1984 and references therein).

Nodular Chert and Limestone

<u>Description.</u>

This facies, which is closely associated with the finely laminated chert and limestone facies, consists of alternating laminae to thin-beds of medium gray chert and dark brown, organic-rich lime mudstone. Primary stratification is disrupted by nodular bedding, intense bioturbation by *Zoophycos* ichnofauna and other organisms, soft sediment deformation, early fractures, and fluid escape structures. Chert is developed as irregular nodules, discontinuous lenses, and disrupted strata (Fig. 8C). The chert is a mud-dominated packstone composed of silt-sized abraded skeletal debris, peloids, and mud; siliceous sponge spicules, pelmatozoan fragments, and ostracodes are locally common. Lime mudstones contain scattered silt-size peloids and abraded skeletal fragments. Organic-rich stylolites are common. This facies is relatively nonporous and impermeable, although minor intercrystalline porosity occurs along the outer margins of chert nodules and lenses, adjacent to the lime mudstone matrix(Fig. 8D).

Interpretation.

The silt-size skeletal debris in these deposits and their association with the finely laminated chert and limestone facies suggests they represent sediments that were transported from the platform margin via turbidity currents. Soft sediment deformation, early fractures, and fluid escape structures attest to episodic rapid deposition on an unstable slope, perhaps updip of the finely laminated chert and limestone facies. Locally intense bioturbation and *in-situ* lithification implies intermittent periods of low sediment accumulation. Nodular fabrics were formed by ductile deformation of lime mudstones around patchy, partially indurated cherts and silicified limestones during shallow burial compaction.

Disrupted Laminated Chert

Description.

These deposits consist of mm- to cm-scale, laminated to thinly bedded, light to medium gray chert and siliceous limestone with laminae, nodules, and burrow-fills of dark brown lime mudstone. Primary stratification has been highly disrupted to produce convoluted, discontinuous, and wavy laminae (Fig. 9A). Sedimentary structures include ripple lamination, soft sediment deformation, fluid escape structures, and normally graded laminae. Organic-rich laminations and stylolites are abundant. Burrowing includes *Zoophycos* ichnofauna and other burrow types are common.

Disrupted laminated cherts are incompletely silicified packstones composed of silt- to very-fine grain size peloids and skeletal fragments, including siliceous sponge spicules, abraded pelmatozoan, brachiopod, and trilobite debris, and uncommon ostracodes (Fig. 9B). Intercrystalline porosity and moldic grain dissolution porosity are locally present, although total porosity is minor. Limestone, which is less abundant than in the finely laminated and nodular chert and limestone facies, consists of wackestone to mud-dominated packstone, with grains similar in size and composition to those of the chert units. These rocks are generally nonporous and impermeable.

Interpretation.

The dominance of silt-size to very-fine grained sand-size peloid-skeletal debris implies accumulation in a depositional regime dominated by influx of platform-derived sediment rather than by hemipelagic sedimentation. Individual chert laminae display ripple lamination with normal grading, indicating that this facies records higher-energy turbidite sedimentation. Soft sediment deformation and fluid escape structures indicate episodic rapid accumulation on an unstable slope, which partially accounts for the disrupted lamination. Bioturbation, differential compaction of partially lithified sediment, and pressure solution helped create the disrupted and convoluted lamination. The *Zoophycos* ichnofauna implies that bottom waters were generally deficient in oxygen.

Burrowed Chert

Description.

This facies includes finely laminated to massive medium gray cherts and lesser dark brown siliceous limestones that are interbedded and admixed at various scales. Intense bioturbation, including *Zoophycos*, disrupted to obliterated primary depositional stratification (Fig. 9C). Sedimentary structures include ripple lamination, soft sediment deformation, fluid escape structures, and normal grading. Organic-rich laminations and stylolites are also abundant.

Chert and incompletely silicified limestone dominate this facies. The cherts are mud-dominated packstones composed of silt- to fine sand-size siliceous sponge spicules, abraded skeletal debris, peloids, and intraclasts (Fig. 9D). Pelmatozoans, brachiopods, trilobites and ostracodes dominate the fauna. Limestone is a minor component as laminae, nodules, and burrow infills composed of wackestone to mud-dominated packstone. Burrowed cherts are generally relatively nonporous and impermeable, although dissolution of siliceous sponge spicules has created minor local moldic porosity.

Interpretation.

Graded bedding and ripple lamination suggest high-energy downslope transport of platform margin-derived sediment via turbidity flows. A slight increase in the grain size (up to fine-grained sand) suggests a more proximal, higher-energy depositional setting. Individual chert laminae display ripple lamination with normal grading, indicating that this facies records higher-energy turbidite sedimentation. Local soft sediment deformation attests to episodic high sedimentation rates on an unstable slope.

This facies accumulated as alternating laminae of silt- to fine-grained packstones alternating with finer, hemipelagic muds, that were biotically admixed. *Zoophycos* ichnofacies are especially abundant in this facies, supporting a deep-water setting with oxygen deficient bottom waters. Abundant bioturbation records prolonged periods of low sediment influx. This facies is interpreted to have accumulated as distal submarine fans and overbank deposits between turbidite channels.

Thickly Laminated to Massive Chert

Description.

These rocks consist of thickly laminated to massive cherts. These, typically calcareous, cherts are generally light gray in color, although the more porous intervals are brown due to oil staining (Fig. 10A). Dark, organic-rich wispy laminations and stylolites are common. Within individual thick laminae and thin beds, normally graded successions, ripple laminations, soft sediment deformation, and fluid escape structures are present locally. Bioturbation ranges from distinct burrows, including *Zoophycos*, to complete biotic homogenization. Burrowing, soft sediment deformation, patchy silicification and differential compaction have resulted in local disrupted lamination and incipient nodular fabrics.

Chert consists of well sorted, silt-size to fine-grained, skeletal packstones/grainstones dominated by siliceous sponge spicules, along with abraded pelmatozoans, ostracodes, and brachiopods (Fig. 10B). Calcite generally represents 10 to 40 percent of the total mineralogy and occurs as corroded skeletal fragments, incompletely silicified matrix, laminae, nodules, and burrow fills. The well-sorted constituent grains give this facies a relatively homogenous appearance.

Interpretation.

Thickly laminated to massive chert facies record relatively high-energy depositional conditions, as evidenced by their good sorting, the slightly more coarse grain size dominated by sponge spicules and shallow-water skeletal fragments, and by the paucity of fine mud matrix. Local normal grading and ripple lamination implies transportation via turbidity flows from the platform margin. Rapid deposition is indicated by the sedimentary structures and by the paucity of intense bioturbation relative to the burrowed chert facies. Individual depositional events recognized in the cores are up to decimeter scale in thickness. Superposition and amalgamation of multiple depositional episodes along the axis of turbidite channel/proximal submarine fan fairways formed composite porosity units ranging up to 20 ft thick with channel-form to lobate depositional geometries. These cherts pass laterally and vertically into relatively impermeable, more distal finely-laminated to burrowed mud-rich cherts and limestones that record slower depositional rates dominated by overbank and hemipelagic sedimentation.

Porous thickly laminated to massive cherts constitute the dominant Thirtyone reservoir facies in University Waddell field. Much of the porosity, which ranges up to or exceeds 25 percent, results from moldic dissolution of siliceous sponge spicules. Intercrystalline porosity and primary interparticle porosity also contribute to total porosity although they are relatively insignificant.

Core-log relationships indicate that nearly all porosity in the Waddell reservoir is associated with this facies (Fig. 9). This relationship permits correlation and mapping of this facies within the Thirtyone succession using porosity logs and facilitates the definition of flow unit architecture. Detailed correlation and mapping of individual porous chert units demonstrates that they form highly discontinuous channel-form to lobate bodies, accounting for the heterogeneous porosity distribution in the Thirtyone Fm. reservoirs.

Skeletal Packstone

Description.

Skeletal packstones are composed of light to medium gray, thin bedded to massive limestone (Fig. 10C). These rocks dominate the approximately 200 ft thick interval between the A and C stratigraphic markers (Fig. 7). Cross-stratification is absent whereas organic-rich wispy laminae and stylolites are common. Chert occurs locally as patchy silicification as well as thin laminations and beds up to several ft thick. As in the underlying chert facies, *Zoophycos* burrows are common. For the most part, these rocks contain well-sorted skeletal packstones/grainstones composed chiefly of crinoids ranging up to very coarse grain size (Fig. 10D). Also common are siliceous sponge spicules, brachiopods, mollusks, ostracodes, bryozoans, and trilobites. The facies is relatively nonporous and impermeable because interparticle pore space is completely occluded by syntaxial and interparticle calcite cements and by lime mud.

Interpretation.

A below-storm-wave-base depositional setting is indicated by the absence of shallow-water sedimentary features including cross-stratification and upward-shoaling cycles. Skeletal grain-rich rock fabrics, with very coarse-grained, shallow-water fossil assemblages, imply basinward transport from the platform. This facies likely records allochthonous transport of skeletal sands to a foreslope, slope, and toe-of-slope platform margin setting. These rocks dominate the upper highstand portion of the Pragian 1 sequence (see below), recording more proximal deposition as the platform margin prograded basinward. Relatively minor thin limestone beds within the chert-dominated successions record episodic downslope transport of platform-derived carbonate silts and very fine sands to the basin. Limestones are essentially nonproductive facies; minor production attributed to these successions is from interbedded cherts and siliceous limestones.

Fractured/Brecciated Porous and Nonporous Chert

Description.

Cargile (1967) recognized that cherts in the upper reservoir interval in University Waddell field generally are highly fractured/brecciated, and differ from the nonfractured and nonbrecciated cherts in the lower reservoir interval. Chert fabrics (Figs. 10 e, f) are similar to fractured/brecciated porous and nonporous cherts described by Ruppel and Hovorka (1995a; 1995b) for the Thirtyone Formation at the northern basin margin. In University Waddell field, brecciated/fractured cherts occur exclusively within the upper chert interval (above the “A” marker), where they display primary depositional fabrics similar to that of the nonfractured and nonbrecciated cherts within the lower chert interval (below the “C” marker). Individual porosity zones within the lower chert interval can be correlated and mapped, whereas porosity zones in the upper chert interval are poorly developed and are laterally discontinuous (Cargile, 1967; this study). These cherts are a minor producer in University Waddell field.

Interpretation

Brecciated porous and nonporous cherts dominate the chert reservoirs in Three Bar field (Ruppel and Hovorka, 1995a; 1995b), at the updip northern basin margin. In University Waddell field, the basin depocenter, fractured/brecciated chert fabrics are confined to the upper chert interval immediately below the Middle Devonian unconformity and are absent from similar depositional facies in the lower chert interval. The proximity of fractured/brecciated porous and nonporous cherts to the overlying unconformity, both in the updip Three Bar field and in the basinal University Waddell field, implies that such fabrics may reflect later meteoric diagenetic overprinting associated with subaerial exposure, and are not closely linked to the precursor facies. The more than 20 m.y. duration of the Middle Devonian unconformity allowed time for development of a regional aquifer, perhaps analogous to the unconformity-sourced regional aquifer documented in Siluro-Devonian carbonates of the Central Appalachians by Dorobek (1987).

In updip fields such as Three Bar, the entire Thirtyone Formation may have been influenced by meteoric diagenesis (Ruppel and Hovorka, 1995a; 1995b). In the basinal University Waddell field, fractured and brecciated chert fabrics are confined to the upper chert interval, suggesting that the lower chert interval may have been isolated from extensive late meteoric diagenesis by the overlying 200 ft thick, relatively impermeable limestone interval. Diagenetic overprinting of primary depositional fabrics in the upper chert interval may account for the poorly developed, highly discontinuous porosity zones in this interval that defy correlation and mapping efforts that were successfully applied to define porosity bodies within the lower chert interval. Resolution and characterization of porosity distribution in these fractured and brecciated chert facies in University Waddell field will require better core coverage and an improved understanding of the impact of diagenetic alteration on the primary rock fabric. This meteoric diagenesis hypothesis requires thorough regional mapping, petrographic study, and isotopic analysis to adequately document its effects and importance in reservoir development.

STRATIGRAPHY AND DEPOSITIONAL SETTING

Intraformational correlations of the Thirtyone Formation have previously been unsuccessful in Waddell field because gamma ray log response is low in these typically siliciclastic-poor cherts and limestones. In the present study, however, we have identified and correlated three intraformational gamma ray markers to significant stratigraphic and lithologic surfaces (Figs. 6, 7). These markers are fundamental for defining the stratigraphic framework of the Thirtyone formation at University Waddell field.

Correlation

Within the Thirtyone Fm. gamma ray log response is attenuated because the succession consists of siliciclastic -poor chert and limestone. Nevertheless, subtle gamma ray deflections of approximately 10 to 20 API units have been recognized in this study and shown to be correlative markers for intraformational correlation (Figs. 6-7). In cored wells with relatively complete preserved core coverage, these intraformational gamma ray markers correspond to stylolite swarms.

Three such intraformational gamma ray markers (in descending stratigraphic order A, B, and C) were identified and correlated (Fig. 6-7). These markers established the stratigraphic framework required to evaluate heterogeneity within University Waddell field. The best developed reservoir interval in the Thirtyone Fm. occurs in cherts below the C gamma ray log marker (Fig. 6). A structure map generated from this marker (Fig. 5) thus more accurately represents actual reservoir structure than previous mapping efforts that utilized the top of the Thirtyone (base of the Woodford Fm.), which lies 450 ft above the major reservoir interval and is an unconformable surface with 70 ft of erosional relief (Fig. 11).

Stratigraphy

The lower Thirtyone Formation consists of approximately 500 ft of deep water cherts and siliceous limestones, locally termed the "lower chert." Mud-rich, finely laminated chert and limestone facies and nodular cherts and limestones at the base of this succession (Figs. 7, 12) record a basinal environment dominated by hemipelagic sedimentation with episodic distal turbidite deposition. These facies pass upward into disrupted laminated and burrowed cherts that contain allochthonous shallow-water skeletal grains, indicating a more proximal setting with increased turbidite influx. *Zoophycos* ichnofacies in these rocks are consistent with a deep-water, slope to basinal setting with oxygen deficient bottom waters. Disrupted laminated and burrowed cherts pass upward and grade laterally into well-sorted, skeletal grain-rich, thickly laminated to massive cherts, recording continued platform progradation. The thickly laminated to massive cherts within this stratigraphic interval comprise the major reservoir succession (Figs 7, 12).

The top of the “lower chert” is transitional from chert-dominated lithologies to overlying skeletal limestones. However, a well-defined, gamma ray marker (C) can be traced southward to at least to Block 31 field (Figs 7, 12). In the absence of better defined chronostratigraphic markers, this horizon is invaluable for correlating and subdividing the reservoir succession into mappable porosity units.

The approximately 200 ft thick succession of limestones and siliceous limestones that overlie the C marker are composed of skeletal-crinoidal packstones (Fig. 7, 10C, d, 12). The coarse grain size, moderate sorting, lack of shallow water current stratification, and predominantly shallow-water fossils in these rocks indicate limited downslope transport of skeletal sands to a foreslope, slope, to toe-of-slope progradational platform setting, interpreted to record highstand deposition. Chert is less abundant in this interval, perhaps due to rapid accumulation of platform-derived carbonate debris in this proximal setting (Ruppel and Holtz, 1994).

This limestone succession can be subdivided into two mappable intervals based on a second gamma ray log marker, here referred to as the B marker (Fig. 12). This log marker appears to coincide with another stylolite-rich zone that separates the lower and upper parts of this succession. The lower limestone is less than 90 ft thick in the northwestern portion of the study area and thickens to the southeast to attain a maximum thickness of 140 ft (Fig. 13). This thickness distribution may represent increased basinal accommodation above a gently sloping (< 0.25 degree) top surface of the lower chert.

The upper limestone extends upward to the A marker, which denotes a lithologic transition between limestones and overlying cherts and siliceous limestones of the upper chert (Fig. 12). The upper limestone maintains a relatively uniform thickness of approximately 100 ft throughout the study area (Fig. 14). Like other gamma ray markers, the B marker can be traced to Block 31 field where it occurs at the same limestone to chert and siliceous limestone transition.

The upper part of the Thirtyone section at University Waddell field consists of nodular chert and siliceous limestone referred to as the "upper chert". These deposits comprise nodular chert and limestone, disrupted laminated and burrowed chert, thickly laminated to massive chert, and interbedded skeletal packstone. .

Upper chert thicknesses range from 230 to 300 ft (Fig. 11). Thickness variations reflect Middle Devonian, pre-Woodford erosion and truncation and the development of a minimum topographic relief of 70 ft across University Waddell field. Isopach trends define a NNE trend, which may represent paleo-ridges and paleo-valleys incised during the Middle Devonian subaerial exposure event.

Depositional Model

Depositional fabrics, sedimentary structures and the dip-elongate channel-form to lobate geometries of individual high porosity chert bodies imply that these reservoir facies record a turbidite channel to submarine fan depositional setting (Fig. 15). Well sorted, high energy, reservoir-grade facies, pass vertically and laterally into relatively low permeability, mud-rich cherts and siliceous limestones that record hemipelagic, overbank, and distal turbidite sedimentation. Chert deposits appear to step progressively basinward (southward) upsection (Fig. 3), perhaps reflecting decreasing accommodation associated with declining rates of sea level rise or basinward progradation of shallow water platform carbonates. Renewed chert accumulation in the upper part of the Thirtyone (upper chert section) may indicated renewed sea level rise and backstepping possible and a sequence boundary.

Distal Thirtyone chert reservoirs are developed in both the lower and upper chert interval. Reservoir quality, however, is better developed in the lower interval, which accounts for most of the oil production in the field. Lower chert reservoirs are composed of porous, thickly laminated to massive cherts (Fig. 5) dominated by well-sorted siliceous sponge spicules and carbonate skeletal debris. Individual porosity zones within the lower chert interval can be correlated and mapped, whereas porosity zones in the upper chert interval are poorly developed and are laterally discontinuous (Cargile, 1967; this study). The upper chert is a minor producer in University Waddell field.

Sequence Stratigraphy

The successions of facies in the Thirtyone Formation at Waddell field suggests a sea level control of accommodation and facies. The succession of low energy chert and carbonate to overlying higher energy chert and shallower water limestones in the lower Thirtyone appears to represent a major upward-swallowing depositional sequence. Overlying chert deposits of the upper chert succession represent a return to deeper water deposition. This suggests that the contact between the limestones and overlying upper chert interval may define a transgressive facies tract offset and thus represent a sequence boundary at about the position of the A marker (Fig. 12).

DIAGENESIS

Fabric-selective dissolution of silica and carbonate grains created much of the porosity in the thickly laminated to massive cherts. A study of this diagenesis, however, is beyond the scope of this project. Ruppel and Hovorka (1995a, b) report data and interpretations for silica replacement and dissolution in updip Thirtyone Fm. chert reservoirs in Three Bar field. Because secondary dissolution in these cherts appears to be governed by depositional rock fabrics (Ruppel and Hovorka, 1995), porosity distribution generally adheres to that imposed by the facies distribution. In updip fields such as Three Bar, the influence of meteoric diagenesis may be greater than in basinal reservoirs like University Waddell field. However, fractured and brecciated chert fabrics are confined to the upper chert interval, suggesting that the lower chert interval may have been isolated from extensive late meteoric diagenesis by the overlying 200 ft thick, relatively impermeable limestone interval. Diagenetic overprinting of primary depositional fabrics in the upper chert interval may account for the poorly developed, highly discontinuous porosity zones in this interval that defy correlation and mapping efforts.

BRECCIATION AND FRACTURING

Chert in the upper Thirtyone reservoir interval at University Waddell field is generally highly fractured/brecciated, compared to that in the lower reservoir interval (Cargile, 1967). Fractured/brecciated chert fabrics (Fig. 10 e, f) are similar to fractured and brecciated porous and nonporous chert in Three Bar field. In University Waddell field, such chert is present exclusively within the upper chert interval (above the A marker), where they display primary depositional fabrics similar to that of the nonfractured and nonbrecciated chert within the lower chert interval (below the C marker).

The proximity of fractured/brecciated porous and nonporous chert to adjacent unconformities, both in Three Bar and University Waddell fields, implies that such fabrics may reflect later meteoric diagenetic overprinting associated with subaerial exposure, and are not closely linked to precursor facies. The long span of the Middle Devonian unconformity allowed sufficient time for development of a regional aquifer, perhaps analogous to the unconformity-sourced regional aquifer documented in Siluro-Devonian carbonates of the Central Appalachians (Dorobek, 1987).

PETROPHYSICS

Twenty wells in University Waddell field were analyzed petrophysically by Serpas Petrophysics. Core data from four wells were utilized to calibrate the porosity logs and constrain computed porosities. Neutron or density-neutron logs provide the best resolution of porous facies. Log-derived porosity curves helped refine correlations and were critical for reservoir mapping. Integration of core descriptions and analyses with corresponding wireline logs indicates that nearly all of the significant porosity can be attributed to the thickly laminated to massive chert facies (Fig. 7). Other facies exhibit little or no porosity, except in rare cases where extensive late fracturing has created minor porosity.

RESERVOIR ARCHITECTURE

The well-defined relationship between porous chert facies and their wireline log response facilitates identification and correlation of these log facies throughout the study area. Detailed correlation and mapping of individual porosity units was limited to the major reservoir interval, the upper 150 ft of the “lower chert” succession, subjacent to the C log marker, where reservoir porosity is best developed.

As stated above, most reservoir development is associated with a single facies, the thick laminated to massive chert (Fig. 7). Other facies contribute only minor porosity, except where extensive late fracturing has locally created porosity. The excellent tie of the porous chert facies identified in core to their respective porosity logs allowed delineation of these facies in logs from the remaining wells. The gamma ray correlation framework permitted confident correlation of these porous zones throughout the Pennzoil leases in University Waddell field within the lower chert interval, below the "C" gamma ray log marker (Fig. 8). Correlation and mapping efforts delineated more than 30 porosity units that comprise this major reservoir interval.

More than thirty porosity units were defined using core-calibrated wireline logs throughout the area of detailed study in Block 31 (Fig. 16). Individual units range up to 20 ft in thickness and from less than 0.1 to several square miles in areal extent (Fig. 17). Porosity zones are separated vertically from one another by non-porous chert (Fig. 16). Isopach and phi-h maps indicate that porosity units form lobate to elongate bodies that generally trend west-northwest to north, subparallel to the regional depositional axis (Fig. 2). These maps show, however, that individual porosity zones have distinctly different geometries and distribution across the field (compare Figs. 16 and 17).

Core study documents that mapped porosity units consist of vertically stacked and amalgamated, centimeter to decimeter-thick strata of thickly laminated to massive cherts. Facies data from cores combined with information on mapped geometries suggest that porosity units record multiple high-energy depositional events with sediment accumulation focussed along channel/submarine fan fairways (Fig. 15). Porosity zones which present higher energy grain-rich turbidite flows, are separated from one another by more mud-rich rocks that represent low energy deposition. Areas distal from axes of active deposition were relatively sediment-starved, receiving only mud-rich silt- to very fine-grained material from overbank and distal turbidite influx, in addition to hemipelagic sediment. Continued sedimentation along the channel/submarine fan axes created depositional highs, ultimately resulting in their abandonment by channel avulsion, and sedimentation switched to adjacent, previously sediment-starved depositional lows. This pattern of deposition created a succession of vertically and laterally segregated chert reservoirs in University Waddell field and other fields near the Thirtyone Formation basin depocenter. This complex depositional architecture is a major contributing factor for reservoir heterogeneity and accompanying low recovery efficiency.

FAULTS AND FRACTURE INDUCED HETEROGENEITY

In equivalent updip Thirtyone Formation reservoirs, including Dollarhide (Saller et al., 1991; 2000) and Three Bar (Ruppel and Hovorka, 1995a, b) fields, fault-induced reservoir compartmentalization has been documented (by 3–D seismic) or inferred. However, the role of faults and fractures is poorly understood in University Waddell field. Although 3–D seismic data indicate north-striking normal faults along the western margin of the field (Rick Ricketts, pers. comm. 1997), no significant intrafield faults have previously been identified. Detailed studies of wireline logs in the study area reveal several small-scale (<100 ft offset) reverse and normal faults. In a recently drilled well, for example, a reverse fault with a 60 ft repeat section was identified. Fault planes probably are steeply dipping, because individual faults intersecting one well are not recognized in offset wells 1,500 to 2,000 ft away. These faults offset producing zones and create discrete compartments across the field.

Open fractures, some partially infilled by quartz and/or calcite cement, are common in cores. Fracture density and orientation and the impact of fracturing on reservoir permeability and anisotropy are not understood, in part due to the incomplete core preservation. Producing wells immediately adjacent to water injection wells exhibit rapid breakthrough of injection water in the eastern parts of the field, whereas corresponding producers to the north and south do not. This implies preferential permeability along an east-west direction, perhaps due to fractures and/or small-scale faults (Larry Wagner personal. comm., 1997). This anisotropic behavior is consistent with the well-defined anticlinal ridge in this portion of the field and the accompanying stress field (Fig. 11).

The impact of fracturing on reservoir permeability in the area is not known. Simple analysis of injector-producer wells did not identify a preferred fluid flow trend. The juxtaposition of the two anticlinal trends in this part of section 3, Block 31 (Fig. 11), may have induced complex fracturing patterns near the structural crest, creating permeability anisotropy different than that for other areas in the field. However, such interpretations must await better data, including 3D seismic, new cores and core data, image logs, and perhaps well tests and tracer studies designed to test interwell connectivity.

PRODUCTION HISTORY

Significant development of the University Waddell field began in the 1950's. By 1962, most of the field had been developed on a 40 acre well spacing. During initial primary recovery, the reservoir pressure was greater than 4,000 psi at -6,400 ft subsea

(Railroad Commission of Texas, 1980) and the principal drive mechanism was fluid expansion above the bubble point pressure (2,500 psi). After reservoir pressure dropped below the bubble point, pressure solution gas drive became the major drive mechanism. In 1965, a gas-injection pressure maintenance program was initiated on the W.N. Waddell lease in the northern part of the field in Block B-25 (Cargile, 1967). This program was deemed to be unsuccessful because reservoir pressure had fallen below the bubble point and injection efforts failed to attain miscibility pressure. This program was abandoned after 1967, when water injection supplanted gas injection.

Oil production remained high throughout the middle 1960's (Fig. 18). Beginning in 1969, field production declined to a minimum in the early 1970's. In 1971, a renewed phase of drilling infill production wells to 20 acre spacing and conversion of former oil producers to water injectors in an inverted 9-spot water injection program boosted field production to a second peak in 1980. By the middle of the 1980's, however, production began to decline and water production greatly exceeded oil production. Recent production practice in the University Waddell field has been one of depletion. Estimates of the original oil-water contacts are -6635 ft to -6650 ft subsea (Cargile, 1967; Railroad Commission of Texas, 1980). Production and water injection practices in these highly heterogeneous multi-storied reservoirs, however, have resulted in development of a complex reservoir system with multiple fluid contacts. The water injection program has shown limited success in this field due to the lateral heterogeneity and low permeability of productive chert reservoirs. Figure 19, a map of cumulative production in the study area, shows no geographic trends across the area.

PRODUCTION ANALYSIS

Refunjol and Lake (1997) developed a statistical procedure to analyze trends in reservoir injection and production data. This procedure, which is based on the calculation of correlation coefficients (r-values) for the monthly rates of injection wells (barrels of water injected per month) and adjacent producing wells (total produced fluid = oil+water), offers a method to compare apparent fluid flow trends with geological models to assess the relative importance of stratigraphic and fracture controls in reservoir anisotropy. The r-values computed for each injector-producer pair are presented as vectors on well location base maps from which it is possible to evaluate reservoir anisotropy.

Correlation coefficients for each injector-producer pair were mapped as vectors to distinguish reservoir regions with good or poor associations (Fig. 20). The length of each vector indicates the magnitude of the r-value. Solid vector arrows indicate positive correlation (r-values greater than zero), and unfilled vector arrows indicate negative correlation (r-values less than zero). The resulting maps allowed assessment of the various statistical techniques utilized and facilitated evaluation of reservoir anisotropy.

In general. the vector analysis suggests better correlations between injector and producer wells in the northern area of the study area and poorer associations in the central/south part (Fig. 20). A northwest-trending along the border of the two areas shows especially poor injector-producer correlations (Fig. 20).

OPPORTUNITIES FOR INCREMENTAL OIL RECOVERY

Recompletion Opportunities

Isopach and phi-h maps were generated for thirty individual porosity units that comprise the major reservoir interval below the “A” gamma ray marker. For each porosity body, map overlays were prepared for the isopach, phi-h, and structural maps. The completion status of every well that penetrated every porosity body was displayed so that wells with good porosity development that lacked production and/or injection completions within this interval could be readily identified as potential recompletion candidates. Hydraulic connectivity computed for injector-producer pairs was useful for evaluating the oil sweep efficiency, in many cases poor interwell communication reflected incompatible injection and production completions. For these wells, appropriate recompletions in the injector and/or producer were recommended. In total, 39 nine recompletion opportunities were identified.

SUMMARY OF HETEROGENEITY IN DISTAL THIRTYONE RESERVOIRS

In contrast to proximal Thirtyone chert reservoirs like Three Bar field where there is a single, continuous porous chert reservoir, in Waddell field and related distal reservoirs, porous cherts are highly discontinuous. In these reservoirs, this lack of continuity is the primary contributing factor to heterogeneity and low recovery efficiency. The distribution of porous chert in distal settings is a function of sediment geometries associated with submarine fan and turbidite deposition. Episodic downslope transport of spiculitic sediment along the margins of the carbonate platform has resulted in vertical segregated and laterally discontinuous chert reservoir intervals. These deposits are interbedded with and grade laterally into lower energy mud-rich sediments that typically have low porosities and permeabilities. Although these muddy rocks are not flow barriers, they do act as baffles to flow and impact recovery efficiency. Detailed correlation and mapping of individual porous chert layers is critical for establishing a reservoir framework that can serve as a basis for defining recompletion and infill drilling targets. Several drilling and recompletion prospects were identified in Waddell field using this approach.

As in the case of the Three Bar reservoir, the impact of faulting and fracturing on Waddell reservoir performance is poorly known. Intrafield faults identified in the course of this study have sufficient displacement to offset porous flow units and may locally constitute lateral flow barriers. Waterflood breakthrough analysis suggests fracture contribution to permeability but insufficient data are available to develop predictive models of fracture flow in the reservoir. High resolution 3-D seismic would aid in developing a better model of the impact of faulting on reservoir compartmentalization and may help define the distribution of chert reservoir intervals.

CONCLUSIONS

Devonian chert reservoirs in West Texas contain a very large remaining oil resource that is a target for more efficient exploitation techniques based on a better understanding of the geological controls on heterogeneity. Because these controls differ systematically between chert reservoirs developed in updip, proximal settings and downdip, distal settings, it is crucial that both regional and local geologic controls be examined and integrated into modern reservoir characterization and exploitation studies. This study of University Waddell field provides crucial data on the nature of distal Thirtyone reservoirs that can serve as a model for the development and exploitation of similar reservoirs across the Permian Basin.

ACKNOWLEDGMENTS

Funding was provided by The University of Texas System as part of the University Lands Advanced Recovery Project. Ideas expressed herein evolved from discussion with several individuals, including Jerry Lucia, Bob, Folk, Evan Franseen, Art Saller, and Jim Ebanks. Our thanks to Pennzoil, and the University of Texas System, West Texas Operations for providing data. Pennzoil staff, in particular, Charlotte Glenn-Sullivan (now with The University of Houston), Barbara Lalicker, Don Hartman, and Joseph Ansah, were helpful in providing data and support. The Railroad Commission of Texas also provided production data. Jubal Grubb and Cengiz Vur assisted with data base assembly, geological correlations, and mapping. Larry Lake, with the assistance of Isolda Barros-Griffiths, analyzed production data and patterns. Calvin Serpas (CJS Petrophysics, Midland, Texas) carried out petrophysical analysis of wireline logs. Figures were prepared by the Graphics department of the Bureau of Economic Geology under the direction of Joel Lardon. Publication authorized by the Director, Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas.

REFERENCES

Barrick, J. E., 1995, Biostratigraphy of uppermost Ordovician through Devonian Depositional Sequences in the Permian Basin, West Texas and Southeastern New Mexico: *in* Pausé, P. H., and Candelaria, M. P., (eds.), Carbonate facies and sequence stratigraphy: practical applications of carbonate models, Permian Basin Section–SEPM Publication 95-36, p. 207-216.

Barton, xxxx

Becker, L. E. and J. B. Droste, 1978, Late Silurian and early Devonian sedimentological history of southwestern Indiana: Indiana Department of Natural Resources, Geological Survey Occasional Paper 24, 11 p.

Cargile, L.L., 1967, Study of Future Exploitation Methods, University Waddell Devonian Field, Crane County, Texas: Internal Engineering Report, Mobile Oil Corporation, Midland Exploration and Producing Division, 11 p.

Collinson, C. W., 1967, Devonian of the North-Central region, United States, *in* D. H. Oswald, (editor), International Symposium on the Devonian System, v. II: Alberta Society of Petroleum Geologists, Calgary, Alberta, p. 933-971.

Droste, J. B. and R. H. Shaver, 1987, Upper Silurian and Lower Devonian stratigraphy of the Central Illinois Basin: Indiana Department of Natural Resources, Geological Survey Special Report 39, 23 p.

Frey, R.W. and Pemberton, S. G., 1984, Trace fossil facies models: *in*, R. G. Walker (ed.), Facies Models, Second Edition, Geoscience Canada, Reprint Series 1, pp. 189-208.Galley, J.E., 1958, Oil and gas geology of the Permian Basin of West Texas, *in* Habitat of oil - a symposium: American Association of Petroleum Geologists Special Publication, p. 395-446.

Ham, W. E., and J. L. Wilson, 1967, Paleozoic epeirogeny and orogeny in the central United States: American Journal of Science: v. 265, p. 332-407.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G., and Smith, D. G., 1990: A Geologic Time Scale 1989, University Press, Cambridge, 263 pp.

Hills, J. M., and M. A. Hoenig, 1979, Proposed type sections for Upper Silurian and Lower Devonian subsurface units in Permian Basin, West Texas: American Association of Petroleum Geologists Bulletin, v. 63, no. 9, p. 1510-1521.

Jones, T. S., 1953, Stratigraphy of the Permian Basin of West Texas: West Texas

Geological Society, 57 p.

Keller, W. D., 1978, Textures of tripoli illustrated by scanning electron micrographs: Economic Geology, v. 73, p. 442-446.

Kluth, C. F., and P. J. Coney, 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, V. 9, p. 10-15.

McGlasson, E. H., 1967, The Siluro-Devonian of west Texas and southeast New Mexico, *in* D. H. Oswald, (editor), Proceedings of International Symposium of the Devonian System: Alberta Society of Petroleum Geologists, v. 2, p. 937-948.

Reblin, M., G. Chapel, C. Keller, and S. Roche, 1990, A three-dimensional seismic survey over Dollarhide Field, Andrews County, Texas: AAPG Bulletin, v. 74, p. 746-747.

Ruppel, S. C., and M. H. Holtz, 1994, The Silurian and Devonian of the Permian Basin: patterns of depositional and diagenetic facies and reservoir development: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 216, 89 p.

Ruppel, S. C., and Hovorka, S. D., 1995a, Controls on Reservoir Development in Devonian Chert: Permian Basin, Southwestern USA: AAPG Bulletin, 1757-1785.

Ruppel, S. C. and Hovorka, S. D., 1995b, Chert Reservoir Development in the Devonian Thirtyone Formation: Three Bar Field, West Texas: Bureau of Economic Geology, Report of Investigations, 50 pages.

Saller, A. H., Donna Van Horn, James Miller, and B. T. Guy, 1991, Reservoir geology of Devonian carbonates and chert - implications for tertiary recovery, Dollarhide field, Andrews County, Texas: American Association of Petroleum Geologists

Bulletin, v. 75, no. 1, p. 86-107.

Tinker, C. N.,1963, Pore space and silicification – their relationship and original lithologic controls exemplified by carbonate rocks from Crossett Devonian field, Texas: Shell Development Company EPR report No. 767, 34p.

Tucker, R. D., and McKerrow, W. S., 1995, Early Paleozoic chronology: a review in light of new U-Pb zircon ages from Newfoundland and Britain: Canadian Journal of Earth Sciences, v. 32, p. 368-379.

Tyler, N., Bebout, D. G., Garrett, C. M., Jr., Guevara, E. H., Hocott, C.R., Holtz, M. H., Hovorka, S. D., Kerans, C., Lucia, F. J., Major, R. P., Ruppel, S. C., and Vander Stoep, G. W., 1991, Integrated characterization of Permian Basin reservoirs, University Lands, West Texas: Targeting the remaining resource for advanced oil recovery: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 203, 136 p.

Wilson, J. L., and O. P. Majewske, 1960, Conjectured Middle Paleozoic history of Central and West Texas, *in* Aspects of the geology of Texas: a symposium: University of Texas, Austin, Bureau of Economic Geology Publication no. 6017, p. 65-86.

FIGURE CAPTIONS

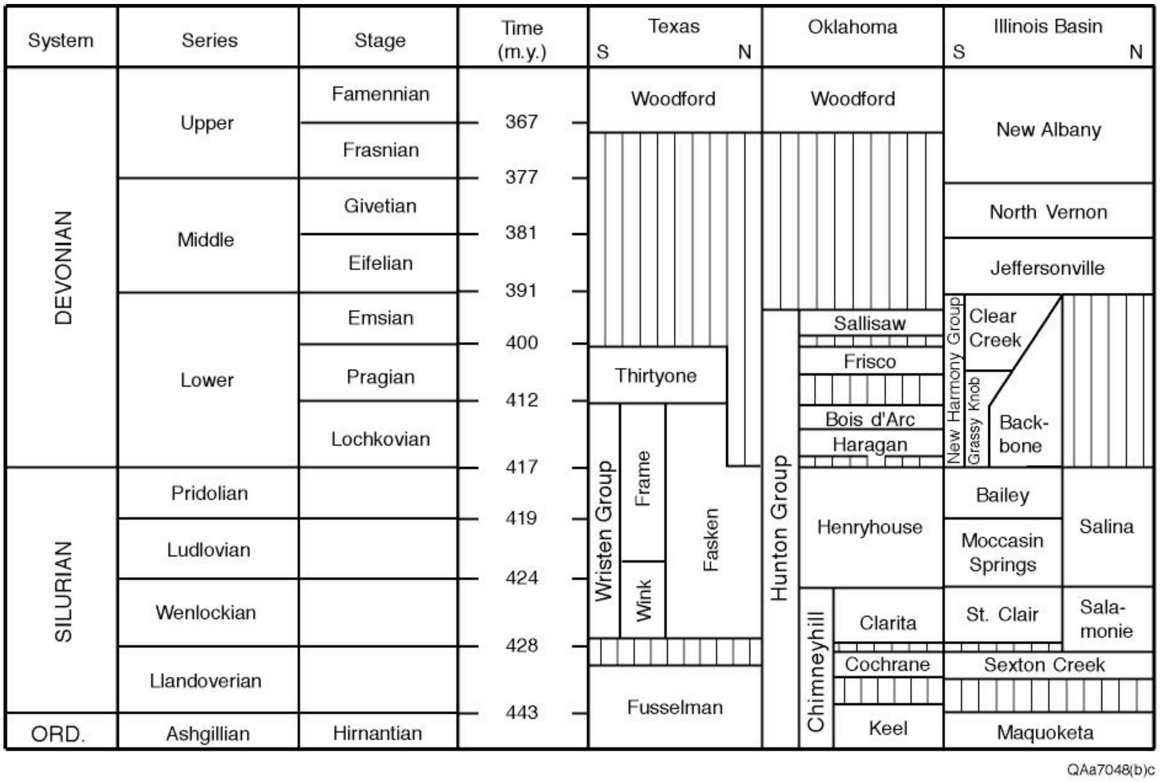

Figure 1 Correlation of the Devonian Thirtyone Formation in West Texas with equivalent successions in Oklahoma and the Illinois Basin. Age dates from Harland and others (1989).

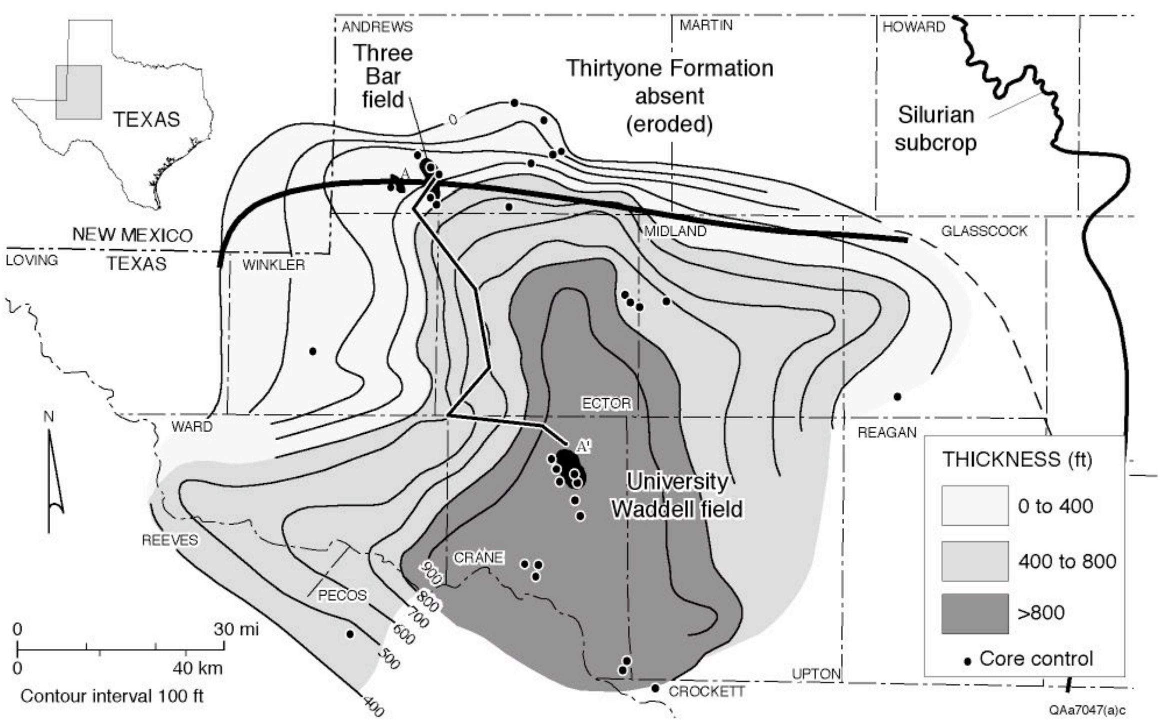

Figure 2. Thickness and distribution of the Devonian Thirtyone Formation in West Texas showing the location of Three Bar and University Waddell fields.

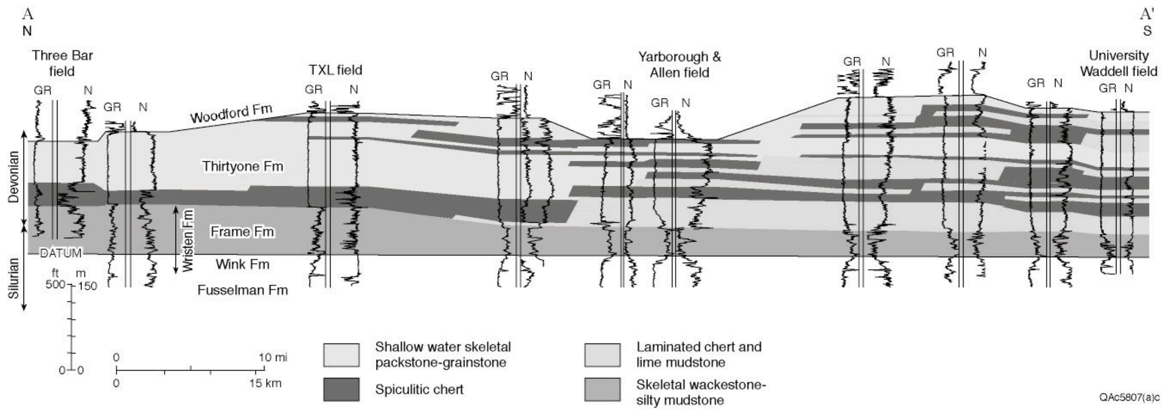

Figure 3. Cross-section (A-A') depicting stratigraphic relationships of Thirtyone Formation along basin axis. Note contrast between high continuity, tabular chert in northern, distal area, and laterally and vertically discontinuous chert in the southern, distal area. Location of cross section is shown in figure 2.

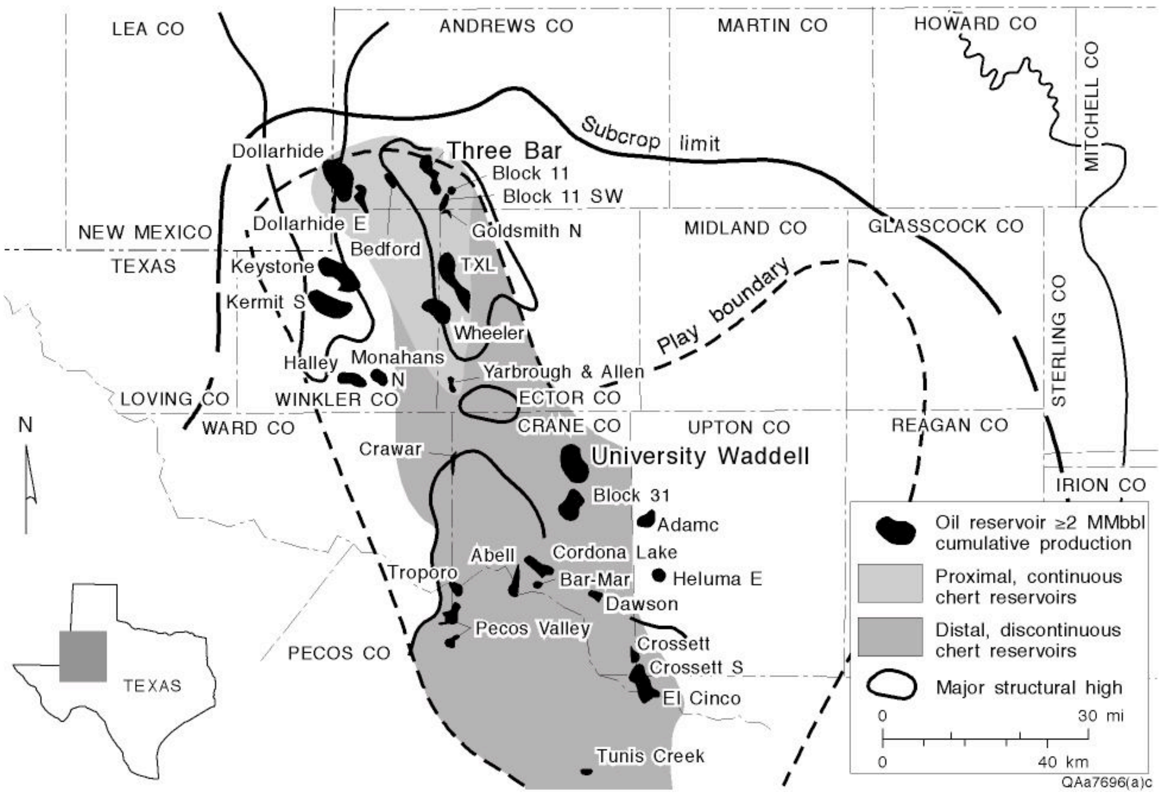

Figure 4. Distribution of major Thirtyone Formation chert reservoirs and structures in West Texas. Note that chert is minor in the northern part of the Thirtyone subcrop area (Ector and Midland Counties).

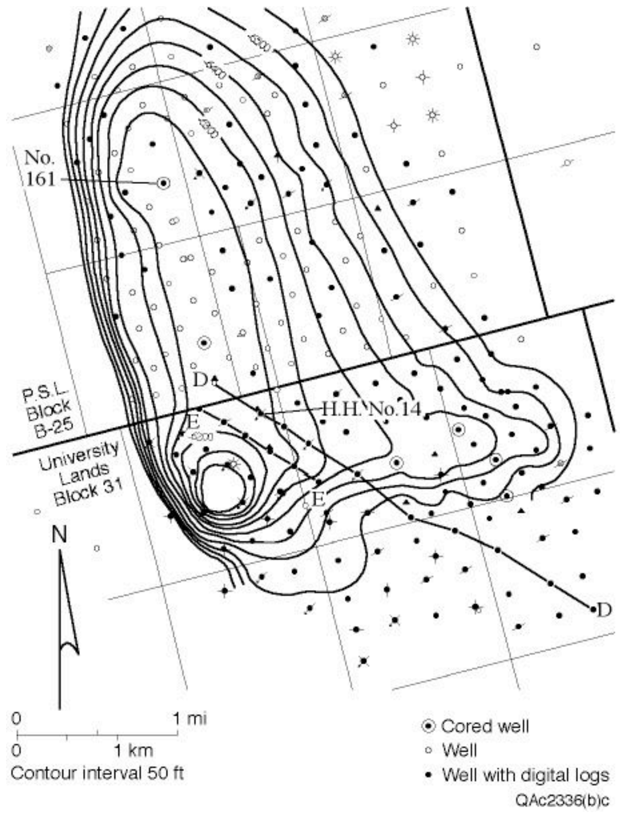

Figure 5. Structure of the Thirtyone Formation in the study area. Structural contours are on the C gamma ray log marker at the top of the primary oil-producing chert reservoir.

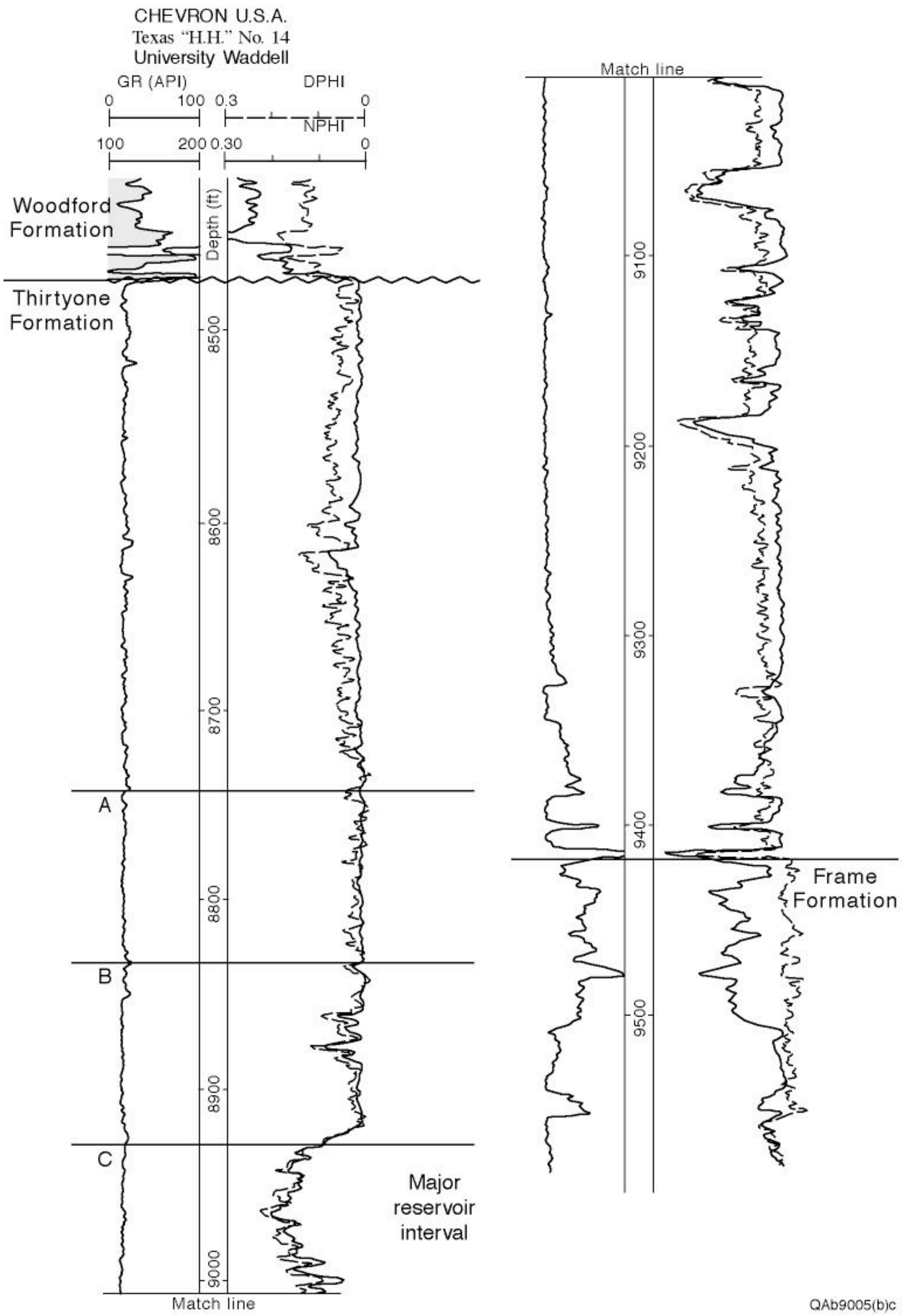

Figure 6. Type log for the Thirtyone Formation in University Waddell field, depicting major gamma ray markers and reservoir intervals.

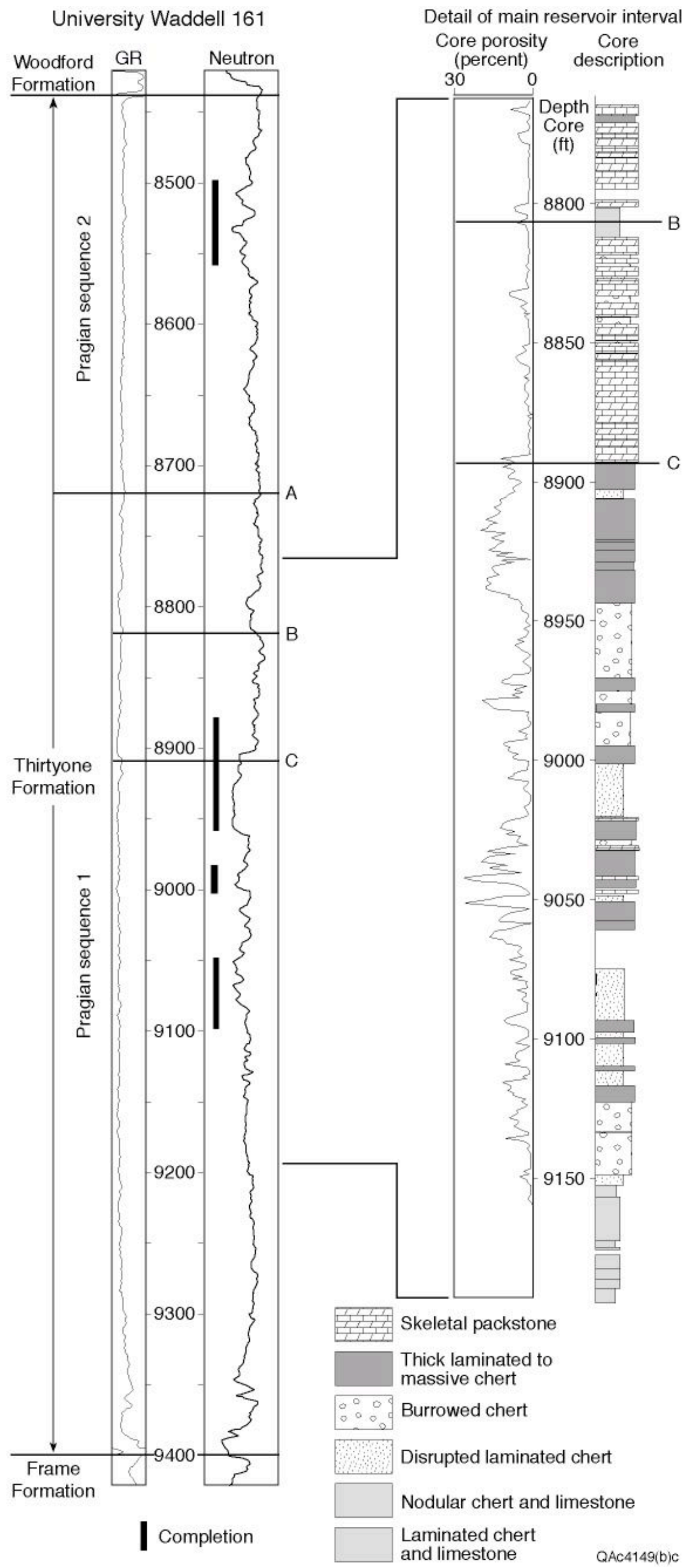

Figure 7. Vertical facies succession through the primary chert reservoir at University Waddell field defined by core descriptions.

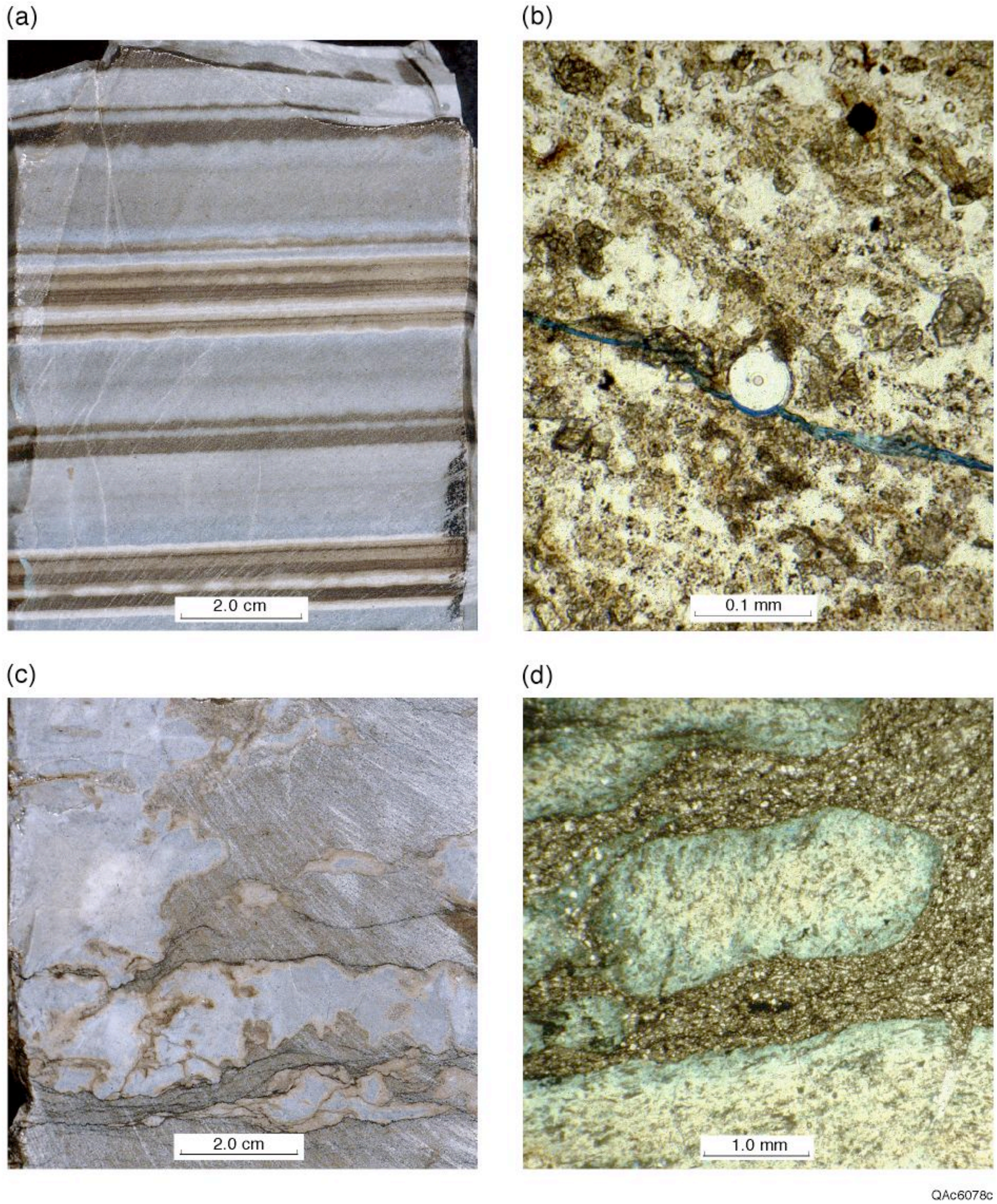

Figure 8. Textures of cherty rocks at University Waddell field. Finely laminated chert and limestone facies (a, b) and the nonporous nodular chert and limestone facies (c, d). (a) Slab of gray chert layers displaying irregular bases and normal grading of silt-size grains, and interlaminated brown lime mudstone. (b) Thin section of chert laminae contain silica sponge spicules and indeterminate carbonate grains in siliceous matrix. (c) Slab of irregular, replacement chert nodules in lime mudstone matrix. (d) Thin section of chert nodules in organic-rich lime mudstone matrix showing minor intercrystalline porosity indicated by blue-dyed epoxy along periphery of silica nodules.

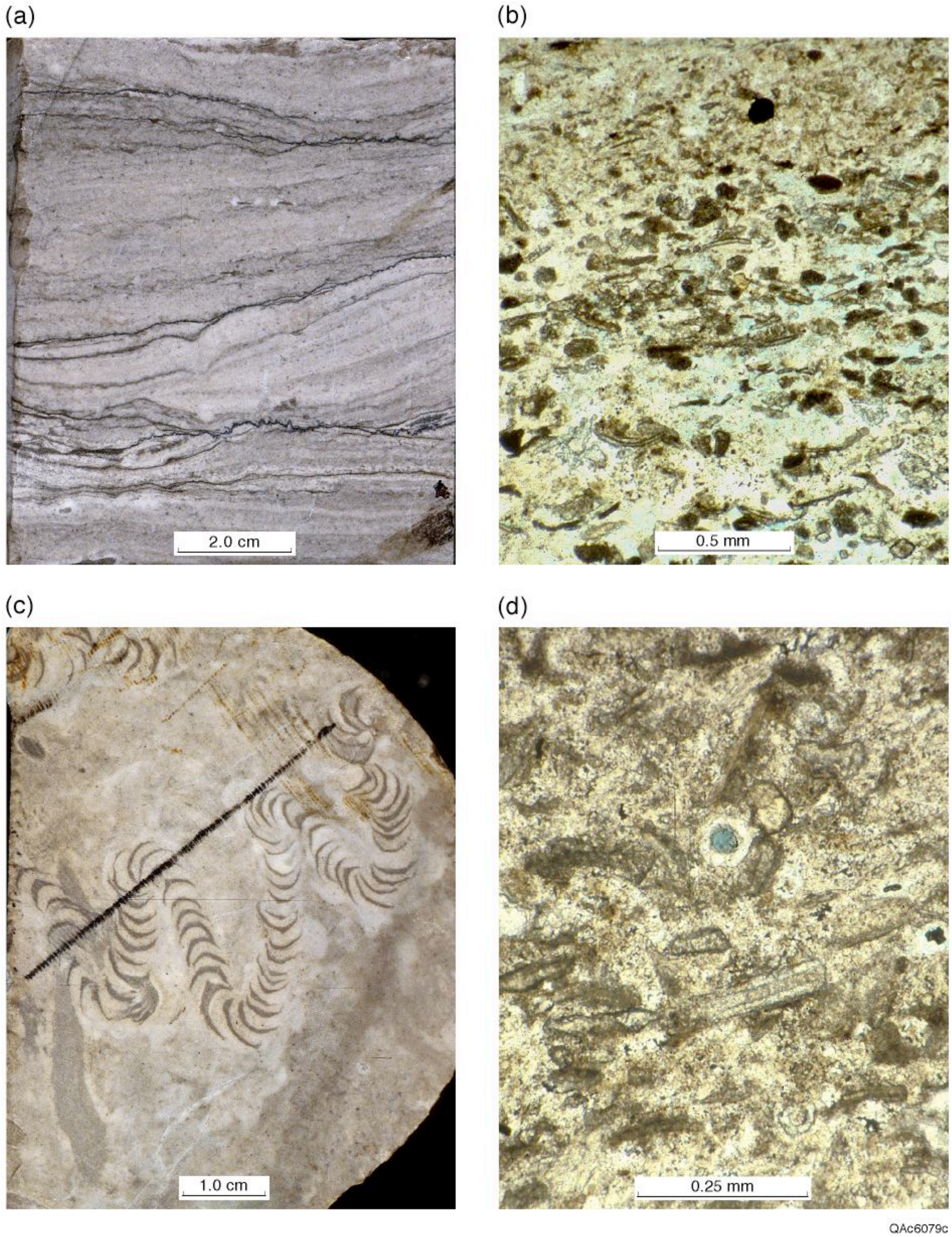

Figure 9. Textures of cherty rocks at University Waddell field. Nonporous disrupted laminated chert facies (a, b) and largely nonporous burrowed chert facies (c, d). (a) Slab of highly convoluted laminated cherts with abundant stylolitic dissolution seams. (b) Thin section showing that cherts are incompletely silicified packstones composed of silt-size to very-fine-grained peloids and skeletal material. (c) Slab showing *Zoophycos* burrow parallel to bedding plane, (d) Thin section showing similar incompletely silicified, poorly sorted, silt-size to very fine-grained skeletal packstones dominated by sponge spicules.

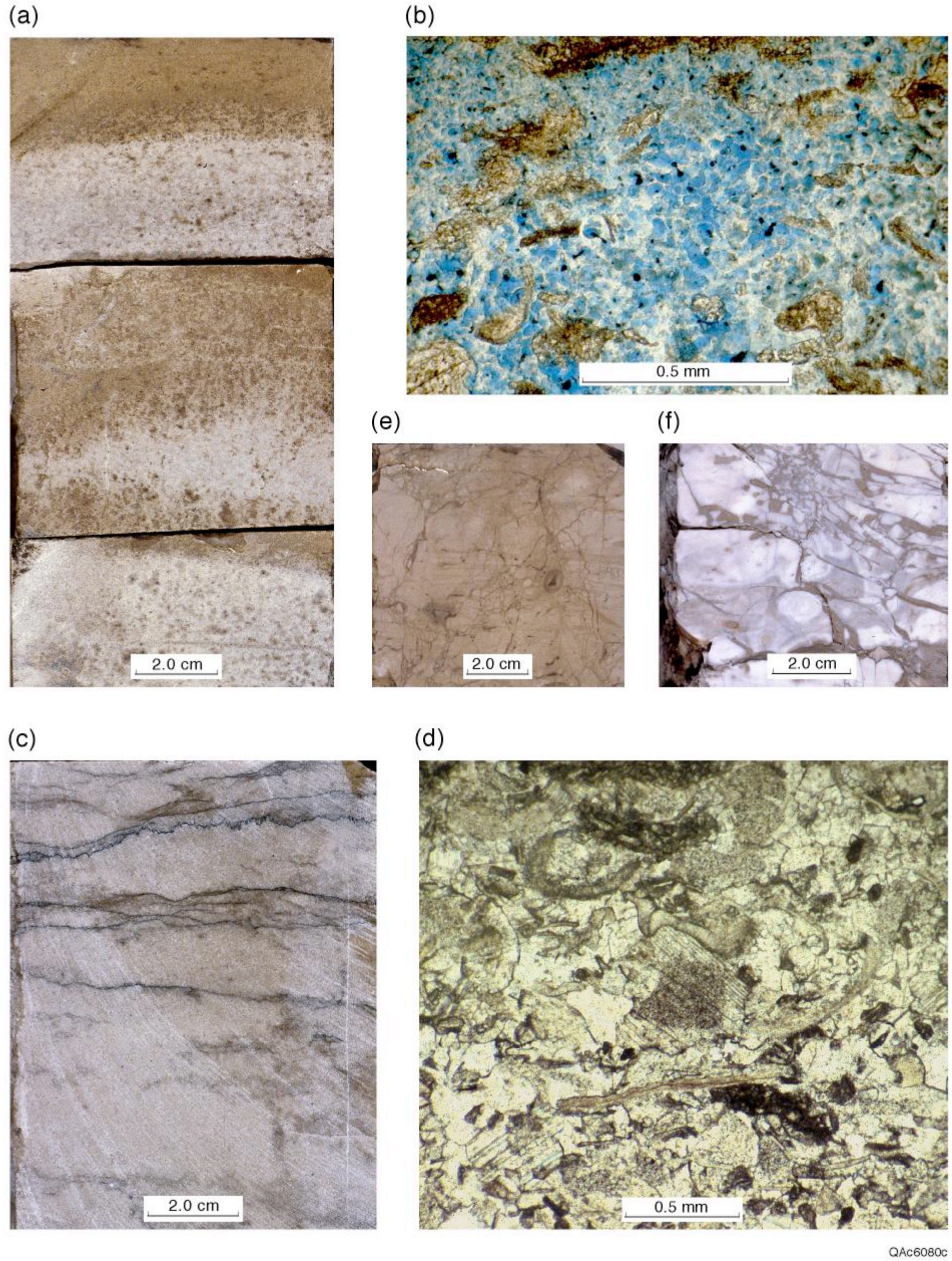

Figure 10. Textures of Thirtyone reservoir and non-reservoir rocks at University Waddell field. Highly porous, thickly laminated to massive chert facies (a, b), nonporous skeletal packstone facies (c, d), and brecciated porous and nonporous chert (e, f). (a) Core slabs showing highly porous hydrocarbon-stained intervals and lighter gray, more tightly cemented patches. (b) Thin section showing abundant sponge spicule molds and incompletely silicified carbonate skeletal debris in a well-sorted skeletal packstone. Moldic dissolution porosity is up to 25%.(c) Core slab of light-colored thin bedded to massive skeletal packstone with local burrows and stylolites. (d) Thin section showing a skeletal packstone with abundant coarse-grained crinoids, and common brachiopods and other skeletal grains. This facies is essentially nonporous due to syntaxial calcite cements. (e) Core slab of oil-stained fractured/brecciated porous chert. (f) Core slab of brecciated, nonporous porcelaneous chert.

Figure 11. Isopach map of the upper chert interval (top of A marker to the top of the Thirtyone Formation) showing marked variations in thickness due to differential erosion below the Woodford Formation. Figure not available.

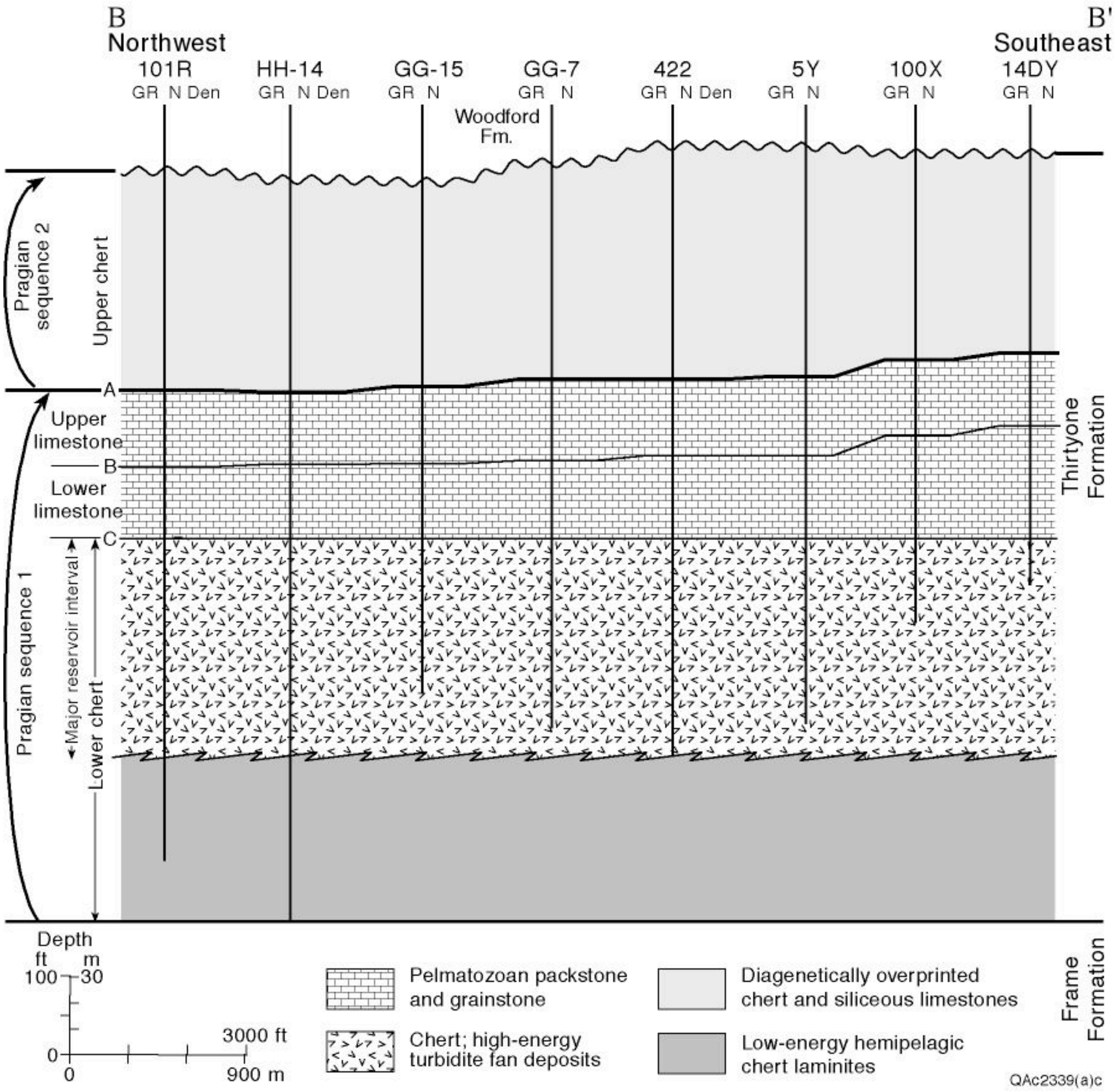

Figure 12. Stratigraphic cross section (B-B') depicting reservoir architecture and proposed sequence stratigraphy in the Thirtyone Formation. Line of section depicted in Figures 3 and 11.

Figure 13. Thickness of the lower limestone unit. Figure not available.

Figure 14. Thickness of the upper limestone unit. Figure not available.

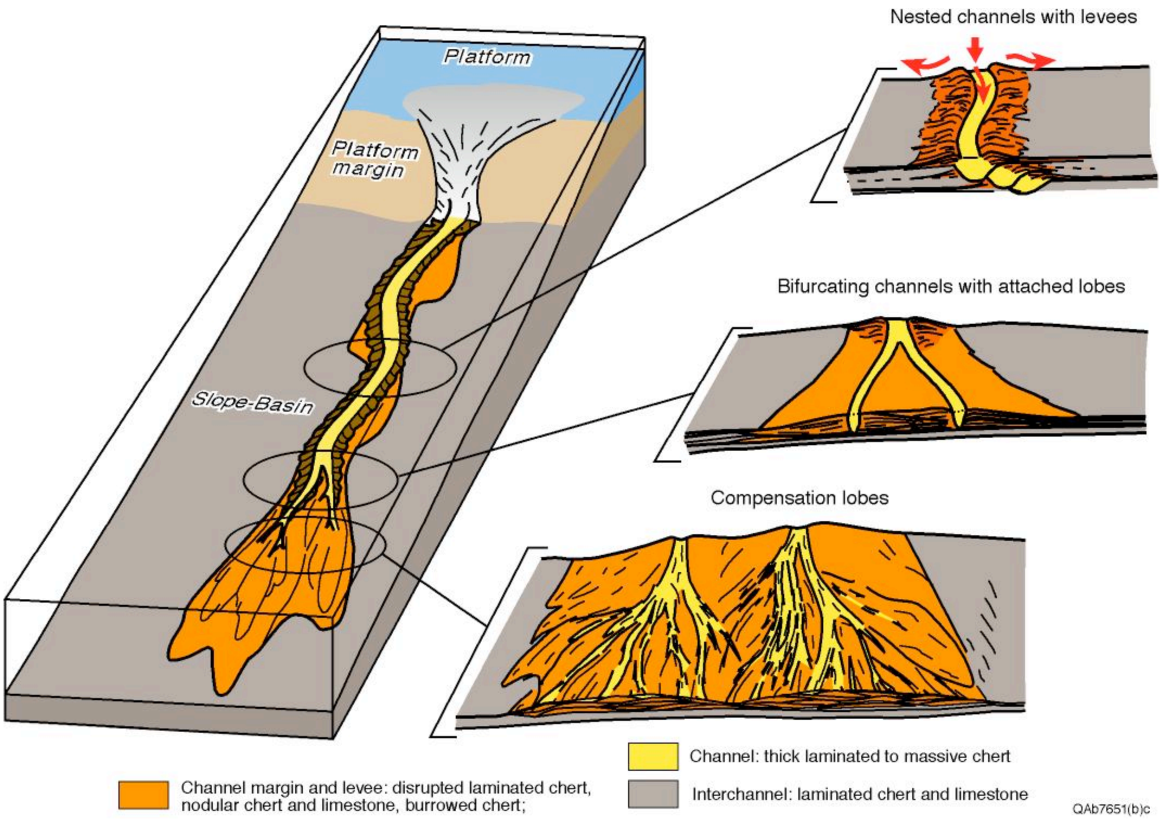

Figure 15. Depositional model for distal chert deposition in the Permian Basin and proposed relationship to chert reservoir development in University Waddell field.

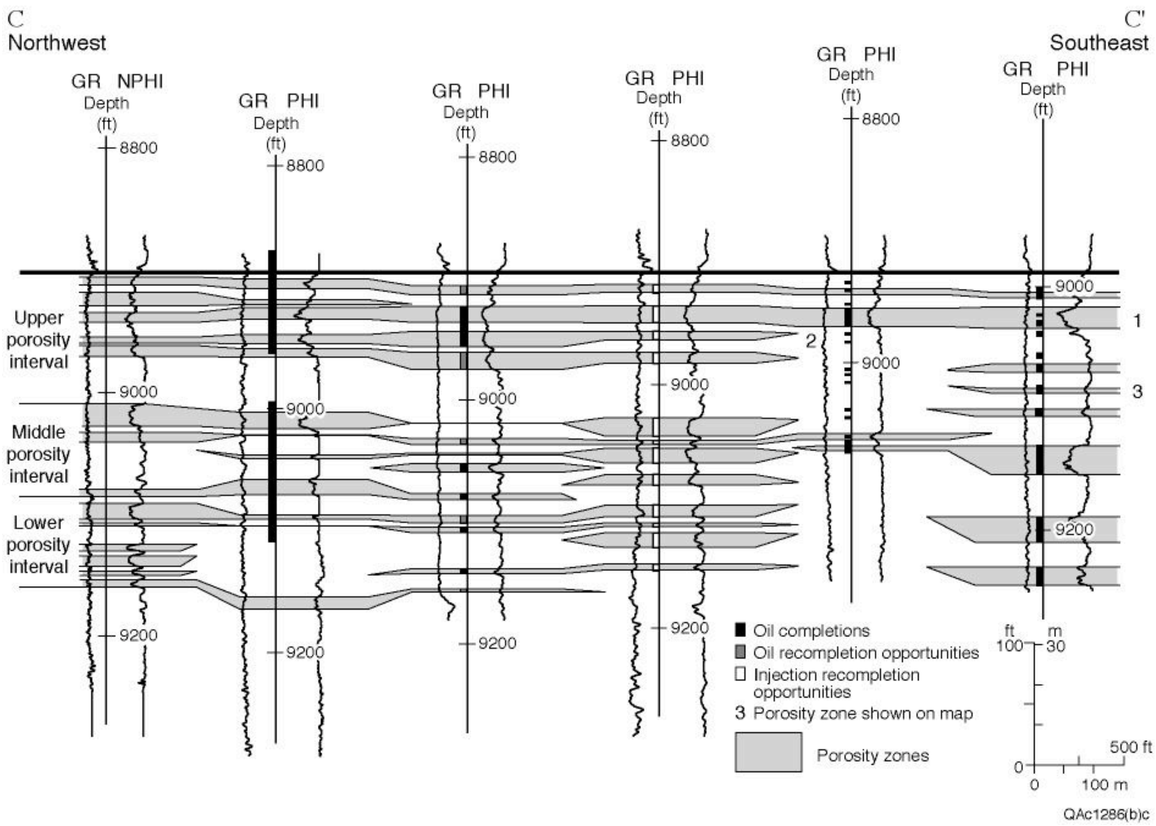

Figure 16. Dip-oriented stratigraphic cross section (C-C')) showing distribution and continuity of major porosity units. Line of section is shown in Figure 11.

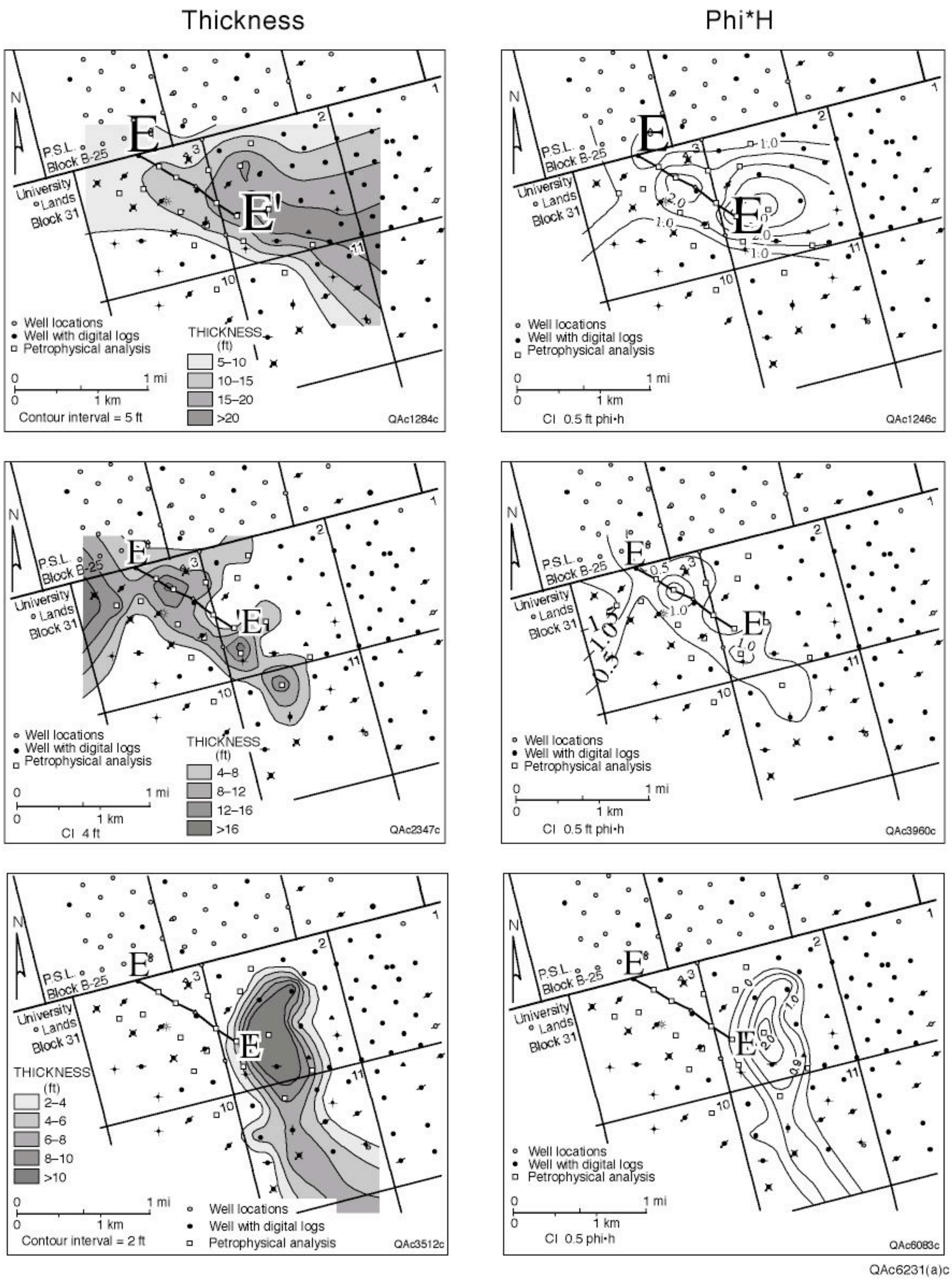

Figure 17. Paired maps of phih (a, c, e) and thickness (b, d, f) for selected porosity units. Note the markedly dissimilar distribution of these potential flow units. Maps correspond to numbered porosity zones shown in figure 16 (a, b: unit 1; c, d: unit 2).

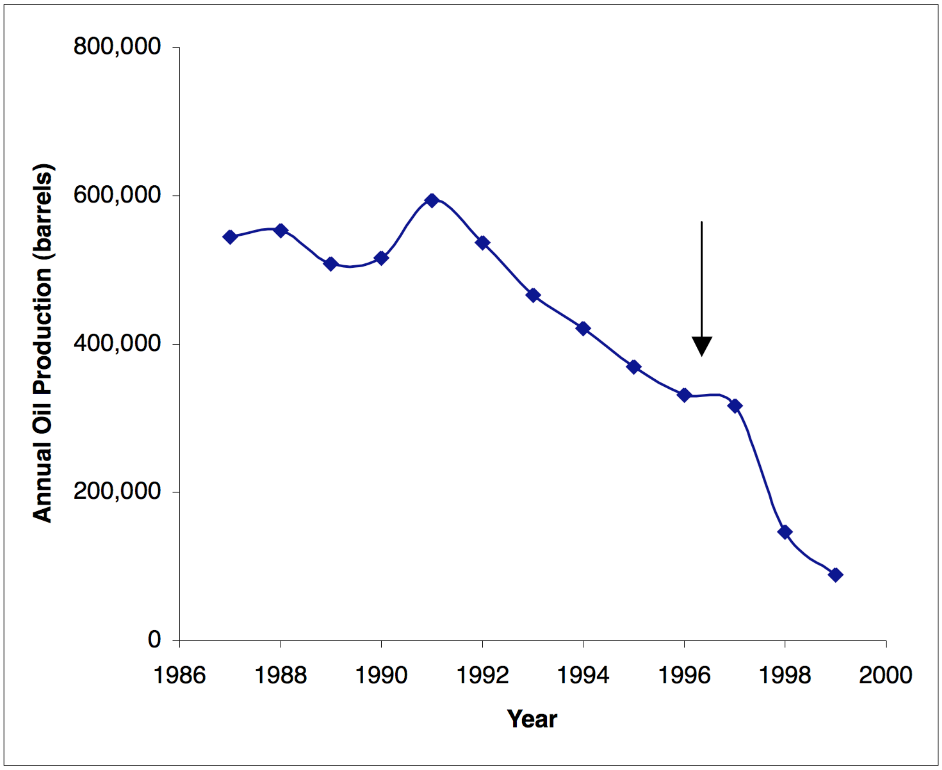

Fig. 18. Plot of oil production through 1998.

Fig. 19. Bubble map showing cumulative oil production. Figure not available.

Table1. Reservoir characteristics and volumetrics, University Waddell Thirtyone Formation Field.

Discovery Date:	1949
Average Depth:	8,600 ft (2620 m)
Area:	8,700 acres (3510 hectares)
Well Spacing:	20-40 acres (8-16 hectares)
Top Seal	Woodford Formation
Bottom Seal:	Frame Formation (Silurian/Devonian Wristen Gp.)
Trap:	Anticline
Hydrocarbon Source:	Woodford Formation
Producing Unit:	Thirtyone Formation (Lower Devonian)
Reservoir lithology:	Chert
Oil/water Contact	-6,650 ft (2,030 m) subsea elevation
Average Gross Pay:	900 ft (27 m)
Average Net Pay:	100 ft (21 m)
Average Porosity:	9 per cent
Average Permeability:	1 md
Water Saturation:	0.37
Residual Oil Saturation (S_{or}):	0.23
Oil gravity	44 degrees API @ 60 degrees F
Original Bottom Hole Pressure	4,200 Psia
Temperature	140 degrees F (50 degrees C)
Formation Volume Factor	1.73 (at original bottom hole pressure)
Oil Viscosity	0.475 centipoise (at original bottom hole pressure)
Solution gas/oil ratio	1,330 SCF/STB (original)