THE LOWER DEVONIAN THIRTYONE FORMATION OF THE PERMIAN BASIN: DOMINANCE OF DEEP-WATER, SILICEOUS SEDIMENTATION

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ABSTRACT

Devonian carbonate and chert rocks in the Permian Basin constitute an important hydrocarbon-bearing succession in West Texas and New Mexico; production from nearly 650 reservoirs developed in these rocks totals almost 2 billion barrels of oil. Patterns and styles of reservoir development and distribution in this nearly 2,000-ft-thick carbonate succession are a function of basin evolution. Three distinct stages of basin evolution can be recognized.

A major rise in sea level during the Early Devonian resulted in basin infilling, first by transgressive, slope/basin, spiculitic chert and then by progradational, highstand, skeletal carbonate. Reservoirs in these rocks (Thirtyone Formation) are developed in downdip cherts whose distribution is the result of cyclic sea-level rise and fall and processes of gravity mass transport, and in updip grain-rich carbonates that underwent leaching during regional Middle Devonian uplift.

Devonian rocks comprise three distinct hydrocarbon reservoir plays: Ramp Carbonates, Deep-Water Cherts, and Siliceous Shallow Water Carbonates. Analysis of play volumetrics illustrates that although these reservoirs contain relatively low current reserves compared with their cumulative production, a mobile oil resource of more than 900 million barrels, virtually equal to the amount already produced from these rocks, remains. In addition, recent discoveries have demonstrated that additional volumes of hydrocarbons exist in undiscovered traps.

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 800 million barrels of oil production as of January 1990. Most of the hydrocarbon resource in these rocks lies in the porous, deep-water chert facies. Ruppel and Holtz (1994) estimated that more than 700 million barrels has been produced from Thirtyone Formation chert reservoirs and that a similar amount of mobile oil remains. Carbonate and chert rocks of Devonian age constitute a thick (as much as 1,000 ft) hydrocarbon-bearing succession in the Permian Basin of West Texas and New Mexico. Nearly 1 billion stock-tank barrels (STB) of oil has been produced from reservoirs developed in these rocks, and current estimates suggest that another 900 million barrels of mobile oil remains.

PREVIOUS WORK

Although the Thirtyone Formation was not defined until 1979 (Hills and Hoenig, 1979), general aspects of the age and distribution of these rocks in West Texas were presented 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 was named for a succession of light-colored chert and cherty carbonate rocks overlying Silurian carbonates and shales and underlying Upper Devonian shales (Woodford Formation) primarily based on analysis of well cuttings and wireline log character (Hills and Hoenig, 1979). Ruppel and Holtz (1994) presented a regional analysis of the Thirtyone as part of a study of the geology and reservoir development of the entire Silurian and Devonian section on the Permian Basin. Saller and others (1991, 2001) and Ruppel and Hovorka (1995b) presented detailed analyses of the Thirtyone Formation reservoirs in Dollarhide and Three Bar fields, respectively, in Andrews County, Texas. Montgomery (1998) summarized some of these published results and presented some previously unpublished reservoir data. Ruppel and Hovorka (1995a) analyzed the depositional and diagenetic controls on reservoir formation in the Thirtyone on the basis of regional and field-specific studies. Ruppel and Barnaby (2001) compared and contrasted facies architecture and reservoir development in updip and downdip parts of the Thirtyone.

REGIONAL SETTING

Recent conodont biostratigraphy indicates that the Thirtyone Formation is dominantly Pragian (Early Devonian) in age (Barrick, 1995) (fig. 1). Similar chert-bearing successions of Thirtyone age are extensive along the southern margins of the United States, including the Penters Formation of the Arkoma Basin of Arkansas (Medlock and Fritz, 1993), the New Harmony Group in the Illinois Basin (Collinson 1967; Droste and Shaver, 1987), and unnamed facies in the Black Warrior Basin of Alabama and Mississippi (Medlock and Fritz, 1993). These rocks were deposited in the Early Devonian in an extensive seaway developed along the southern margin of the Laurussian paleocontinent between the Transcontinental Arch and the developing Acadian mountains in the eastern United States (fig. 2). Reservoirs developed in the Hunton Group in the Anadarko Basin of the Texas Panhandle and Oklahoma are more proximal carbonate-dominated equivalents of the Thirtyone (Galloway and others, 1983; Kosters and others, 1989; Bebout and others, 1993).

The top of the Thirtyone Formation is a major unconformity that records subaerial exposure and erosion. Overlying rocks range from upper Devonian to Permian in age. The hiatus represented by this unconformity ranges from about 17 m.y. to as much as 127 m.y. (fig. 1). Across most of the Permian Basin, the Thirtyone Formation is overlain by black shales and mudstones of the Woodford Formation of Middle to Late Devonian age, which is both a top seal and a regional hydrocarbon source rock.

Underlying the Thirtyone is the Frame Formation, which consists of argillaceous lime mudstone and wackestone that accumulated in a slope to basinal setting (Ruppel and Holtz, 1994). This succession attains a maximum thickness of 800 ft in central Andrews County and thins basinward to the south to less than 100 ft (Ruppel and Holtz, 1994). Recent faunal data (Barrick, 1995) indicate a Middle Silurian to Early Devonian (Lochkovian) age for these rocks (fig. 1).

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 in southern Crane County, Texas (fig. 3). Thirtyone strata thin outward from this depocenter owing largely to pre-Woodford erosion and perhaps to some extent to decreased accommodation. To both the west and the north, the Thirtyone subcrop margin corresponds approximately to the position of the Silurian platform margin (Ruppel and Holtz, 1994). The eastern extent of the Thirtyone is poorly constrained because of the lack of core control, but work by McGlasson (1967) suggests that the unit extends eastward to the Silurian/Devonian carbonate subcrop.

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 up depositional dip 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. 4).

Chert is most abundant in the basin depocenter. In this region, the general stratigraphic succession consists of basal laminated dark cherts and lime mudstones that pass upward into laminated to massive spiculitic cherts overlain by skeletal lime packstones (Ruppel and Holtz, 1994; Ruppel and Barnaby, 2001). Skeletal packstones are overlain by an upper chert succession downdip, recording a renewed rise in relative sea level.

The Caballos Formation, which crops out in the Marathon Basin in the Ouachita overthrust belt, is a partial distal equivalent of the Thirtyone Formation (fig. 1). The "upper chert and shale" member of the Caballos, which is apparently of about the same age as the Thirtyone, averages about 250 ft in thickness (Folk and McBride, 1977), which is markedly thinner than the Thirtyone except where the latter has been truncated by erosion.

REGIONAL STRATIGRAPHY AND FACIES

Facies

Thirtyone chert facies are most abundant in the southern part of the region and downsection; carbonate facies are more abundant upsection and to the north (fig. 4). Chert intervals typically contain varying amounts of carbonate that is interbedded and intermixed at all scales. Vertical facies successions through the Thirtyone vary across the basin in part owing to differences in the proportions of these two end-member lithologies.

Cherty Thirtyone lithofacies are particularly well developed in the south-central part of the basin (Crane County), where thicknesses reach at least 1,000 ft (fig. 3). The stratigraphic section in this area displays a spectrum of lithofacies that encompasses most of the range seen in the Thirtyone across the basin. These facies are well represented in Block 31 and University Waddell fields (Ruppel and Holtz, 1994; Ruppel and Barnaby, 2001). The Thirtyone section in this area constitutes an upward-shallowing succession that is chert rich at the base and carbonate rich at the top. Four facies, listed in order of generally decreasing water depth and chert/limestone ratio, can be defined from the base of the section up (fig. 5): (1) dark-colored, chert/carbonate laminite, (2) light-colored, thickly laminated to massive chert, (3) burrowed/laminated chert, and (4) skeletal packstone (Ruppel and Holtz, 1994; Ruppel and Barnaby, 2001) .

Dark-colored, abiotic, chert/carbonate laminites (fig. 6a) constitute basal Thirtyone deposits in the thickest parts of the basin, where they typically overlie carbonate mudstones and shales of the Silurian-Devonian Frame Formation (fig. 4). These deposits typically display centimeter-thick interbeds of structureless or finely laminated chert and carbonate mudstone. Carbonate beds are generally composed of dolomite but are locally calcitic. These characteristically nonporous, chert/carbonate laminites are thickest (nearly 300 ft) in the central area of the Thirtyone depocenter and thin toward the margins.

Thick-bedded, laminated to massive chert (figs, 6b), in striking contrast to the dark-colored chert and mudstone interval it typically overlies, is light colored, highly porous, and finely laminated to early massive in some instances. Dark-colored, organic-rich laminations are common at the tops of some successions of more massive chert, which can range to as much as 3 ft in thickness (fig. 6b). Fluid escape structures and vague wispy laminations are locally common ((fig. 6b). These rocks typically contain significant amounts of carbonate in the form of small, irregular patches of calcite and isolated dolomite rhombs. Rarely, patches are identifiable as corroded fragments of skeletal debris. Carbonate content is highly variable, ranging from less than 20 percent to more than 40 percent, and generally increases upsection. Thick-bedded, laminated chert constitutes the most important reservoir facies in the Thirtyone Formation. At many localities these deposits contain abundant sponge spicules. Spicules are well sorted and preserved both as open and quartz- or chalcedony-cemented molds. In the latter case, their recognition is difficult. Successions of thick-bedded, laminated chert reach thicknesses of as much as 150 ft (Ruppel and Holtz, 1994; Ruppel and Barnaby, 2001).

Burrowed/laminated chert includes both fine-laminated (2- to 3-mm laminations) chert and burrowed chert (fig. 6c). These two facies are interbedded on several scales. Like the thick-bedded, laminated chert facies, these rocks contain abundant carbonate “clasts,” although recognizable skeletal debris is rare. Laminated chert is more common in the lower parts of the Thirtyone, where it is interbedded with the thick-bedded, laminated chert facies. Burrowed chert is increasingly abundant upsection, where it is commonly interbedded with carbonate packstone. The nodular chert and limestone facies, disrupted laminated chert facies, and burrowed chert facies of Ruppel and Barnaby (2001) are subfacies of this facies. Nodular chert and limestone facies are typified by alternating laminae to thin beds of gray chert and brown, organic, locally skeletal-rich lime mudstone to wackestone. These rocks are probably the result of differential compaction of alternating layers of carbonate and chert silica sediment. Burrowed facies display intensive bioturbation by *Zoophycos* and other burrowers that has locally obliterated much of the primary depositional stratification. Disrupted laminated facies are intergradational to both of the preceding facies. Stratification is locally disrupted by burrowing and soft-sediment deformation, resulting in convoluted, discontinuous, and wavy laminae.

Carbonate packstone dominates the upper part of the Thirtyone throughout all but the extreme southern parts of its distribution, where the upper part of the section has been removed by erosion that is, in the vicinity of the Fort Stockton Uplift). These deposits are primarily composed of fine-grained, well-sorted, grain-supported, skeletal packstones that contain abundant pelmatozoans and locally common bryozoans and ostracodes. Typically, these deposits are burrowed, although locally they are laminated and may display normal grading. As in cherty facies, *Zoophycos* burrows are common. Coarse-grained debris beds containing phosphatized clasts of shallow-water skeletal allochems including bryozoans, pelmatozoans, and calcareous algae are also are locally common. Chert is present as patches of silicified carbonate and as thin laminations and beds up to several feet thick.

Thirtyone facies exhibit cyclic facies stacking patterns on at least two scales. The lower part of the section in the Thirtyone depocenter is characterized by cyclic alternations between chert/carbonate laminites and laminated, thick-bedded, calcareous chert (fig. 5). Farther upsection, cycles are composed of burrowed/laminated chert and thick-bedded chert. Yet farther upsection, cycles are composed of burrowed/laminated chert and skeletal wackestone-packstone. Laminated, thick-bedded, calcareous chert units are composed of thin, 10- to 50-cm-thick cycles characterized by grain-dominated bases and laminated, mud-dominated tops (fig. 6b).

In central Crane County (fig. 3), chert accounts for about 50 percent of the total section (although this varies widely). To the north, the percentage of carbonate increases dramatically. In Ector County, immediately north along the axis of the Thirtyone depocenter, the Thirtyone is almost entirely carbonate. Here, the section comprises an upward-shallowing succession of fine-grained, burrowed, skeletal packstones and wackestones that are overlain by progressively coarser grained and higher energy, grain-dominated, skeletal grainstones and packstones. Chert is represented in this area primarily by a thin zone at the base of the section, although siliceous zones are locally present within the overlying carbonate section. Farther north, in southern central Andrews County, Thirtyone carbonates are composed of coarser grained, pelmatozoan and bryozoan packstone and grainstone. The distribution of coeval carbonate facies north of the Thirtyone chert subcrop in central Andrews County (fig. 4) is poorly constrained because of poor lithologic and biostratigraphic control. Potentially correlative rocks in this area are very similar to those that characterize the Fasken Formation. Isolated biostratigraphic data (conodonts and brachiopods), however, suggest at least isolated outliers of Thirtyone-equivalent carbonates are present (Wilson and Majewske, 1960; J. E. Barrick, personal communication, 1992).

Thirtyone chert facies also vary northward from the depocenter. Chert facies encountered in Winkler and southern Andrews Counties, Texas, for example, include about 100 ft of laminated, spicule grainstone and burrowed chert at the base of the Thirtyone section (fig. 4). Laminated spicule grainstone is similar to the laminated thick-bedded chert observed farther south but contains abundant spicules (fig. 6d). These spicule-rich rocks are found primarily along a northwest trend through eastern Winkler County and into southwestern Andrews County (Saller and others, 1991, 2001; Ruppel and Hovorka, 1995a, b).

Depositional Setting

Most authors (Saller and others, 1991; Ruppel and Holtz, 1994; Ruppel and Hovorka, 1995a; Montgomery, 1998; Ruppel and Barnaby, 2001) have interpreted the Thirtyone Formation to have been deposited in an outer platform to basin setting (fig. 7). These authors suggested chert sediments accumulated in a deep-water setting by processes of submarine gravity flow and hemipelagic sedimentation. Chert/carbonate laminites at the base of the section accumulated as hemipelagic muds on the basin floor in the southern part of the area. Alternations between silica mudstone and carbonate mudstone may reflect shifting sources of pelagic influx or variations in ocean chemistry, which in turn caused fluctuations in calcite or silica compensation depths. Thick-bedded, laminated cherts were deposited by turbidity or fluidized flow. The thick bedding and grading exhibited by many of these deposits are typical of sand- and silt-sized turbidites of both carbonate and siliciclastic composition (Howell and Normark, 1982; Cook, 1983; Walker, 1984; Piper, 1978). The presence of dewatering structures in some of these deposits indicates that these sediments were transported at least partially by fluidized flow

(Cook, 1983). Burrow-laminated cherts are typically cyclically interbedded with these thick-bedded cherts, suggesting that the former were deposited under lower energy conditions developed during cessations in flow or distal to active flow axes.

Ruppel and Hovorka (1995a) suggested that the distribution of thick-bedded, laminated chert deposits along a generally northwest-trending axis indicates that deposition was controlled by basin topography. The succession of alternating beds of higher energy, grain-dominated turbidites and lower energy, distal, more mud-rich deposits that characterizes lower Thirtyone deposition is typical of deposits recorded on submarine fans (Saller and others, 1991). Regional thickness trends indicate that siliceous sediment, like carbonate sediment, was sourced from Thirtyone platform areas to the north and/or west of the basin and accumulated along basin axes and depocenters.

The presence of carbonate in the upper part of the Thirtyone reflects a change in sedimentation style in the Early Devonian of the Permian Basin. Burrowed to laminated skeletal carbonate packstones mark the onset of rapid progradation of the Early Devonian carbonate platform from the north (fig. 7). The first appearance of significant carbonates in the section marks a change in depositional style from siliceous, submarine-fan deposition to carbonate-dominated deposition. Locally the first occurrences of carbonate in the section are associated with features suggestive of rapid downslope transport including poor sorting, lithoclasts, and a mixed faunal assemblage. These lowest carbonates in the section are typically interbedded with muddy burrowed/laminated chert that accumulated when episodic carbonate influx was low. Alternations between these two facies are thus a function of carbonate input and may reflect sea-level rise-fall patterns.

In several areas, primarily along the basin axis, thick-bedded, fan-deposited cherts are also encountered again in the upper part of the Thirtyone section above a thick carbonate section (fig. 4). Ruppel and Holtz (1994; see also Ruppel and Barnaby, 2001) interpreted these younger chert deposits to indicate relative sea-level rise creating additional accommodation and temporarily shutting off carbonate influx from the platform, thus facilitating renewed silica sediment deposition.

Current thickness patterns do not accurately reflect basin topography during Thirtyone deposition. Although the southern part of the Thirtyone depocenter in Crane County appears to have occupied a relatively deeper water position during the Early Devonian, patterns of chert distribution indicate that the axis of deeper water deposition extended to the northwest from

Crane County through Winkler County and into southwestern Andrews County, rather than trending north-south, as suggested by thickness patterns. The thick Thirtyone section in Ector County (fig. 3) is primarily composed of detrital carbonate deposited as a result of rapid progradation of the carbonate platform to the north. Progradation and upward shallowing in this area are demonstrated by grain-dominated carbonates that reflect increasingly higher energy conditions upsection.

The absence of basal chert deposits in central Andrews County, coupled with the presence of coarser grained, skeletal carbonates having more diverse faunal assemblages, suggests that Early Devonian paleotopography was controlled by the position of the Late Silurian (Wristen) platform margin. Sedimentation to the south was characterized by downslope transport and progradation of platform-derived carbonate and silica sediments. Sedimentation north of the hingeline was probably characterized by muddier, shallow-water deposits similar to those typical of the Wristen inner platform. Although pre-Woodford erosion has removed most of these shallow-water, Thirtyone-equivalent Devonian carbonates, isolated remnants have been identified biostratigraphically (Wilson and Majewske, 1960; J. E. Barrick, 1992, personal communication).

Diagenesis

Both the carbonates and the chert deposits of the Thirtyone Formation have undergone significant alteration since deposition. Chert facies have undergone both early and late episodes of diagenesis that have played important roles in reservoir development. Ruppel and Hovorka (1990, 1995a, b) and Saller and others (1991) addressed some aspects of this diagenesis in fields along the northern limit of the Thirtyone subcrop. It seems clear from these studies that chert diagenesis affected silica sediments very soon after deposition. On the basis of patterns of brecciation and chert porosity development, Ruppel and Hovorka (1995a,b) suggested that rates of silica diagenesis were closely associated with the distribution of carbonate-rich sediment layers. Williams and Crerar (1985) and Williams and others (1985) postulated that Mg++ released during carbonate diagenesis acts as a catalyst for chert diagenesis. This implies that opaline sediment adjacent to carbonate-rich sediment is more likely to undergo earlier and more complete diagenetic alteration from biogenic opal to more stable silica. Complete alteration to chert and quartz is likely to result in porosity loss, whereas slower rates favor retention of matrix microporosity. Ruppel and Hovorka (1995a,b) observed that nonporous chert is typically associated with definable beds and patches of carbonate rock. The beds commonly also display more fracturing, suggesting earlier transformation to chert. Chert sediments distal to carbonate beds are typically porous, and fractures are uncommon, or more commonly indicative of more ductile deformation.

Ruppel and Hovorka (1995a, b) also concluded that the Thirtyone has been at least locally affected by late carbonate dissolution and cementation. Carbonate dissolution is apparent near the top of the Thirtyone section and along major fault zones. Areas of dissolution are commonly recognizable on wireline logs by high gamma-ray signatures caused by associated infiltrating clays. Although many of these karst zones are partly filled with calcite cement and clays, as shown by their log response, some are porous and large enough to have contributed to oil production in the field. Carbonate dissolution is important only locally in the Thirtyone. Along the northern extent of the Thirtyone subcrop, for example, where the Thirtyone was uplifted and partly truncated during the Pennsylvanian, dissolution of carbonate has locally formed vugs and enhanced matrix porosity.

Thirtyone carbonate facies have undergone diagenetic alteration much like that seen in similar facies in the Fasken and Fusselman Formations. Leaching of carbonate mud in skeletal packstone is the most important product of this alteration. Locally, these leached zones are dolomitized (for example, in Bakke and Andrews South fields, central Andrews County).

The present distribution of chert and carbonate in the Thirtyone Formation is probably a function of both depositional and diagenetic processes. Sedimentary structures and facies geometries indicate that chert-bearing rocks in the Thirtyone Formation were mostly deposited by deeper water processes (Ruppel and Hovorka, 1995a,b) It is apparent from the abundant spicules in many parts of the basin that these rocks had a high silica content during deposition. As McBride and Folk (1979) pointed out, however, it is difficult to accurately determine the original carbonate content of chert deposits. It is, therefore, possible that significant parts of Thirtyone cherty rocks may be the result of silica replacement of carbonate. This is certainly the case in parts of the mixed carbonate and chert successions in the upper Thirtyone, where silicified carbonate allochems are common, but it may also be true of the largely carbonate-free lower Thirtyone.

DEVONIAN BASIN EVOLUTION

Ruppel and Holtz (1994; Ruppel and Hovorka, 1995a,b) demonstrated that a major rise in relative sea level began in the region during the middle Silurian and continued into the Early Devonian. These authors also interpreted the depositional history of the Thirtyone on the basis of facies and stratigraphic relationships across the region (fig. 8). Basal Thirtyone sedimentation (fig. 8a) was marked initially by pelagic mud accumulation throughout the Thirtyone subcrop area. The distribution of these deposits is coincident with deeper water areas of the basin developed during the Silurian. Along the proximal, northwestern margin of the basin, accumulation of siliceous muds rapidly gave way to submarine-fan deposition of grain-rich, spiculitic sands (fig. 8b). These early chert deposits appear to have been derived from point sources on the platform in western Andrews County. At this time, siliceous muds (chert/carbonate laminite facies) continued to accumulate distal to these higher energy deposits and downdip (fig. 8c). Decreasing rates of sea-level rise and aggradation of the carbonate platform to the north resulted in basinward progradation along the northern platform margin. Progradation of the platform was most rapid in the Ector County area where skeletal carbonate deposits constitute the bulk of the rocks in the northern part of the Thirtyone depocenter.

Ruppel and Holtz (1994) and Ruppel and Hovorka (1995a,b)submarine-fan deposition of high-energy, grain-dominated cherts shifted southward in front of the advancing carbonate platform. They tied the geometries and textures of Thirtyone siliceous sediments to fan depositional processes with high-energy, grain-dominated sediments forming along fan/channel axes and more mud-dominated deposits accumulating in off-axis areas (fig. 9). With continued progradation, deposition of siliceous sediment was replaced by carbonate sediment consisting of debris derived from the platform to the north. Platform progradation produced progressive shallowing of the basin and terminated chert accumulation in all but extreme southern continental margin areas (that is, Caballos sediments of the Ouachita overthrust). The recurrence of similar chert deposits above these shallow-water, carbonate platform-derived, outer ramp/slope deposits suggests a later episode of relative sea-level rise and renewed chert sediment accumulation across the area (fig. 8d).

Truncation of the Thirtyone Formation, as well as underlying Wristen Group and Fusselman Formation strata, probably occurred by the Middle Devonian. Regional studies suggest that uplift and truncation of much of the craton of the southwestern United States occurred at this time (Ham and Wilson, 1967). Work by Johnson and others (1985) also indicates a global sea-level lowstand during the late Pragian. Many of the carbonate platform equivalents of the Thirtyone Formation were apparently removed by erosion at that time, although several erosional remnants still survive within the thick, predominantly Silurian, Wristen section of carbonate rocks present in the northern part of the area (Wilson and Majewske, 1960; J. E. Barrick, personal communication, 1992). Leaching of uppermost Thirtyone Formation rocks at several localities (for example, Bakke field) indicates that significant diagenetic alteration occurred during the Middle Devonian uplift.

SEQUENCE STRATIGRAPHY

Ruppel and Holtz (1994; Ruppel and Hovorka, 1995a,b) characterized several scales of cyclic sedimentation in the Thirtyone. Considering the deep-water setting of these deposits, however, most of these cycles relate to episodic flux of mass gravity flows (grain flows, turbidites) and perhaps the shifting of axes of deposition. These cycles are marked by changes in mud content (that is, grain size) and energy regime. Cyclic porosity development in these rocks (fig. 5) appears to reflect similar variations in energy of deposition and resultant facies. A connection between these depositional cycles and sea-level rise and fall is unclear.

The documented major shift from chert-dominated to carbonate-dominated deposition in the middle of the Thirtyone and the subsequent return to chert-dominated sedimentation may reflect sea-level-related control. Ruppel and Barnaby (2001) interpreted the presence of shallow-water carbonate sediments to reflect basinward progradation of the platform. They placed a sequence boundary at the top of these carbonate deposits, suggesting that the return to chert-dominated sediments above reflected sea-level rise and the landward backstep of the platform. However, no such sequence boundary was recognized by Johnson and others (1985), so further work will be necessary to document its existence.

RESERVOIR TYPES

Thirtyone Formation oil reservoirs in the Permian Basin can be grouped into two major depositional systems: (1) Deep-Water Cherts, and (2) Ramp Carbonates. Deep-water chert reservoirs dominate the central part of the Thirtyone subcrop. Ramp carbonate reservoirs are found along the northern margin, and siliceous ramp limestone reservoirs are found along the eastern part of the subcrop area (fig. 10). By far the greatest volumes of oil production have come from chert-bearing and siliceous reservoirs (more than 88 percent of the total from the Thirtyone). Each of these plays has unique reservoir characteristics that must be considered in any detailed assessment of reservoir properties and resource potential.

Thirtyone Deep-Water Chert Reservoirs

Nearly all production from this play comes from Texas; the Thirtyone is absent from all but the extreme southeastern part of New Mexico (fig. 3). Two end-member styles of reservoir development are apparent. In the northern, or proximal, part of the Thirtyone depositional basin, reservoirs are developed at the base of the Thirtyone Formation (fig. 4) in a chert interval that is remarkably uniform, continuous, and tabular throughout an area of at least 250 mi^2 (fig. 10). 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 laterally into more mud-dominated, low-porosity and low-permeability facies. 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, Dollarhide, and Bedford fields are representative of this reservoir play (fig. 10). Downdip, into the Thirtyone depocenter, these basal cherts grade into nonporous, hemipelagic, laminated siliceous and calcareous mudstones (fig. 4).

Chert reservoirs in the southern or distal part of the Thirtyone basin are developed higher in the Thirtyone section overlying mud-dominated hemipelagic deposits (fig. 4). These cherts document basinward progradation of the Thirtyone and the southward shift of the locus of chert accumulation (fig. 4). While cherts were being deposited in the basin depocenter, shallower water skeletal carbonate sediments accumulated updip in more proximal areas (that is, at 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. 4). These chert strata are much less continuous in their lateral extent than are those to the north. Block 31 and University Waddell reservoirs are good examples of this reservoir type or subplay.

Proximal Thirtyone Chert Deposits

Proximal chert deposits are typified by those at Dollarhide, Bedford, and Three Bar fields in southern Andrews County near the northern limit of the Thirtyone Formation subcrop (fig. 10).

The Thirtyone Formation at Three Bar field typifies northern, more proximal chert reservoir successions (Ruppel and Hovorka, 1995). Other analogous reservoirs include Dollarhide (Saller and others, 1991, 2001) and Bedford, among others. At Three Bar, the Thirtyone is characterized by a rather stratiform basal succession of about 90 ft of chert and an overlying carbonate-dominated section of as much as 300 ft of largely nonporous limestone (fig. 11). Except where truncated, these units generally display sheetlike geometries with typically only subtle lateral variations in thickness. The chert-dominated interval contains mixtures of three facies: (1) translucent, nonporous chert, (2) porcelaneous, porous chert, and (3) skeletal carbonate. Chert intervals typically contain thin, discontinuous beds and irregular patches of skeletal lime wackestone to packstone composed of silt-sized allochems.

Chert Facies

Porous and nonporous chert differ primarily in allochem preservation and porosity. Both chert facies are massive to indistinctly laminated and pervasively burrowed (fig. 12A). Small *Planolites* and *Zoophycos* burrow traces are filled with carbonate or chert. Burrow-filling carbonate consists of skeletal packstone containing abundant ostracodes and is similar to that in carbonate interbeds within the chert section. Both cherts contains abundant sponge spicule molds as much as 300 μm long and 50 μm in diameter. These spicules, which make up 5 to 30 percent of the chert by volume, typically exhibit round and tubular cross sections of straight and curved monaxons (fig. 12B). Other allochems include peloids and carbonate skeletal debris, including primarily ostracodes and lesser amounts of fragmented pelmatozoans and brachiopods. This skeletal assemblage is identical to that found in carbonate interbeds within the lower, chert-dominated section but is notably different from that in the thick carbonate succession at the top of the Thirtyone Formation, which contains primarily pelmatozoan debris. Spicules are less well preserved in porous chert (fig. 12C) but are readily identified by their hollow round cross sections and similarity of shape, size, and occurrence to the better preserved spicules in nonporous chert (fig. 12B).

Porous chert contains as much as 35 percent porosity comprising six pore types: (1) hollow axial channels of sponge spicules, (2) molds of dissolved spicules, (3) molds of dissolved calcitic and aragonitic bivalves, (4) molds of carbonate rhombs, (5) intercrystalline microporosity within the chert matrix, and (6) pores formed by solution enlargement of each pore type. Spicule molds, which measure 5 to 50 µm in diameter, and intercrystalline micropores in the interspicular matrix are dominant. Spicule molds are lined and partly filled with 2- to 10-µm euhedral, microquartz crystals and chalcedony cements (fig. 12D). Interspicular matrix areas contain loosely packed, 0.5-µm microquartz ellipsoids that are aggregated into irregular, 2- to 3-µm spheroidal masses (fig. 12E). Intergranular micropores between microquartz ellipsoids measure fractions of micrometers in diameter; larger pores are present between the spheroidal aggregates (fig. 12E). These microtextures have been observed in porous Thirtyone Formation cherts throughout West Texas, including Bedford, Cordona Lake, Block 31, and University Waddell fields.

Examination of depositional fabrics in porous and nonporous chert shows that both originated as thick beds of spicules in a finer siliceous matrix, with thin beds of carbonate admixed by pervasive burrowing. Preserved fabrics indicate no systematic contrast in original sediment composition between porous and nonporous chert. In hand sample, the two chert types are gradational, with local mottles of nonporous chert within porous chert (fig. 12A).

Carbonate Facies

The upper part of the Thirtyone Formation in Three Bar field is composed primarily of brownish-gray limestone that contains light-colored chert lenses and nodules. These rocks comprise predominantly skeletal packstone with well-sorted and abraded silt-sized pelmatozoan debris, less common brachiopods and mollusks, and relatively rare ostracodes. Although nearly massive in appearance, these rocks are burrowed and locally display normal grading, especially near the base of the carbonate interval. Sponge spicules are common, especially where larger masses of chert are developed (as nodules or lenses). Siliceous zones are associated with muddier carbonate textures but are very rarely developed in grain-rich pelmatozoan packstone and grainstone. Thirtyone carbonate rocks are largely nonporous; most intergranular pores are filled with syntaxial overgrowths around pelmatozoan grains.

Facies Architecture

Major Thirtyone Formation facies are remarkably uniform in thickness at Three Bar field. The lower chert-rich interval of the Thirtyone Formation is essentially constant in thickness throughout the field except where truncated along the updip margin (fig. 13). This architecture continues westward to New Mexico and southward into Ector and Winkler Counties (fig. 10).

Depositional Setting

The Thirtyone Formation succession at Three Bar field documents progressive upward shallowing. Basal chert is interbedded with fine-grained ostracode-bearing carbonate packstone suggestive of a distal quiet-water setting. Carbonates at the top of the section, however, contain predominantly pelmatozoan packstones. Regionally, these packstones grade into cross-laminated grainstones documenting high-energy, shallow-water conditions (Ruppel and Holtz, 1994). The presence of a relatively restricted marine fauna (ostracodes) in carbonates associated with the basal Thirtyone chert compared with a more diverse shallow-water fauna in the overlying carbonates supports the regional model that siliceous sediments accumulated in a distal, quieter water setting basinward of the prograding carbonate platform. Fine-scale interbedding observed in the chert section probably reflects minor fluctuations in delivery of siliceous and carbonate sediment. The basal Thirtyone chert section at Three Bar grades basinward into chert and carbonate mudstones suggestive of hemipelagic deposition (fig. 4; Ruppel and Holtz, 1994). Updip, cherts grade into proximal skeletal carbonates.

Fracturing and Faulting

Open and closed fractures are common in both chert and carbonate facies at Three Bar; however, cherts contain two to six times as many fractures as associated limestones. In addition, fractures detected in available cores are more abundant within or close to identified fault zones along the northern and southern edges of the field. The density of fractures is much less in the apparently less densely faulted middle and northern parts of the field (Ruppel and Hovorka, 1995b).

Styles of fracturing or brecciation also differ between porous and nonporous chert, reflecting the diagenetic history of these siliceous sediments. Nonporous cherts are characterized by angular to subangular, rotated clasts, open fractures, and incompletely detached blocks (fig. 12A). Porous cherts contain rounded and generally smaller clasts in a matrix that is virtually identical in composition to that of the clasts. Brecciated porous chert commonly displays indistinct small-scale soft-sediment offsets that are completely healed, suggesting ductility at the time of deformation (Ruppel and Hovorka, 1995b). The contrast between chert brecciation styles indicates that nonporous chert sediments were better lithified than their porous counterparts at the time of brecciation.

Diagenesis

Both early and late episodes of diagenesis have played important roles in reservoir development. As previously discussed, Ruppel and Hovorka (1995a) showed that the distribution of porous and nonporous chert in the reservoir is a direct result of early chert diagenesis and the distribution of carbonate interbeds within the section. Their work showed that chert sediment distal to carbonate beds underwent slower chert lithification and porosity preservation. This scenario is consistent with the distribution of porous and nonporous chert in the Thirtyone at Three Bar—cherts adjacent to carbonate are invariably nonporous. Because most of the carbonate at Three Bar is stratiform and limited to two major intervals (fig. 13), porous chert is continuous throughout the field.

Late carbonate dissolution and cementation contributed to both development and reduction of porosity. Carbonate dissolution is apparent near the top of the Thirtyone section and along major fault zones. Areas of dissolution are commonly recognizable on wireline logs by high gamma-ray signatures caused by associated infiltrating clays. Although many of these karst zones are partly filled with calcite cement and clays, as shown by their log response, some are porous and large enough to have contributed to oil production in the field.

Porosity and Permeability

Core analyses indicate that porosity in Thirtyone cherts in Three Bar field ranges up to about 25 percent (fig. 14). Three types of pores are present: (1) molds, (2) intercrystalline to micro-intercrystalline pores within the chert matrix, and (3) fractures. Molds (fig. 12C) average 30 to 40 µm and typically constitute up to half of the pore space. Chert matrix porosity is composed of interparticle pores between quartz aggregates and micropores within aggregates (fig. 12D, 12E). Micropores average less than 5 µm in diameter. Capillary-pressure analysis of petrologically identical cherts in the nearby Bedford field (3 mi west) indicates that as much as half of the total chert porosity is composed of intercrystalline and micro-intercrystalline pores.

This result is consistent with the findings of Tinker (1963) and Saller and others (1991), who suggested that micropores account for at least 50 percent of the total porosity in Thirtyone Formation chert. A similar relationship is probable in the Three Bar reservoir; scanning electron microscope analysis and transmitted-light petrography of chert in Three Bar field confirm such pores are common. Although fractures are common throughout the chert section at Three Bar field, point-count data show they typically contribute less than 1 percent porosity.

Chert permeability at Three Bar field averages about 5 md (fig. 14). Core analyses suggest that permeability has both matrix and fracture components. Much of the scatter in these data is the result of fractures. True matrix porosity/permeability relationships in Thirtyone chert rocks were established by analyzing core plugs especially selected to have no fractures (fig. 14). These data suggest that maximum matrix permeability is generally about 10 to 20 md.

Reservoir Heterogeneity

Primary causes of heterogeneity and incomplete drainage and sweep of remaining mobile oil at Three Bar are (1) faulting and fracturing, (2) carbonate dissolution, and (3) small-scale facies architecture. Faults and fractures are abundant in the field and affect reservoir heterogeneity on several scales. In addition to promoting access to diagenetic fluids, faults and fractures may also facilitate or inhibit movement of hydrocarbons and injection waters. In the southern part of the field, zones of abundant faults and fractures are associated with areas of increased fracture permeability that are typically highly productive, suggesting that variations in fracture density may locally contribute to productivity by facilitating flow across facies-controlled permeability boundaries. Production and waterflood patterns reveal poor sweep efficiency and support the contention that fracture zones control fluid movement in parts of the reservoir.

Some faults may also be flow barriers. Bottom-hole-pressure data confirm that at least one fault separates distinct reservoir compartments. It is probable that other faults in the reservoir have produced complete or partial offset in major reservoir pay zones, thus creating reservoir compartmentalization. Correlation and mapping studies indicate that faulting is most common in the northeastern and southwestern parts of the Three Bar Unit, largely coincident with areas of interpreted karsting. More abundant faults and fractures in these areas have two consequences. First, some faults may act as flow barriers and thus create additional reservoir compartmentalization. Acquisition of modern high-resolution, 3-D seismic data is required to accurately delineate fault distribution and fully evaluate the implications of potential compartmentalization due to faulting in the reservoir. Second, variations in fracture density across the reservoir may cause nonuniform water injection sweep. If this is the case, significant areas of matrix porosity are likely to have been bypassed by waterflood. These areas of the reservoir are possible sites of targeted infill drilling and selective completion and recompletion of existing wells. Borehole image logs may provide critical data for detecting the presence and distribution of fractures and faults within the reservoir.

Leaching and dissolution of carbonate intervals are also major causes of reservoir heterogeneity. Most carbonate porosity development is probably the result of leaching by diagenetic fluids that entered along the truncated and exposed updip margin of the field during the Pennsylvanian. Evidence of carbonate dissolution is apparent in cores, especially in areas of greater fault density, suggesting that faults have acted as flow pathways for diagenetic fluids. Porosity development in the carbonate interval that separates the two major chert intervals also appears to be more common on upthrown fault blocks and near the faults that offset them. Erosion on these high blocks and fluid movement along the bounding faults may have facilitated diagenesis. In areas in which carbonate interbeds are absent or have become porous because of subsequent leaching and diagenesis, for example, in the easternmost part of the field, vertical communication is enhanced and productivity is higher.

Distal Thirtyone Chert Deposits

University Waddell field (figs. 10, 15) contains a Thirtyone reservoir succession that is typical of those in a more distal depositional setting.

Geological Facies

Ruppel and Barnaby (2001) defined six major facies in the Thirtyone Formation at University Waddell field (fig. 16): (1) finely laminated chert and limestone; (2) nodular chert and limestone; (3) disrupted laminated chert; (4) burrowed chert; (5) thickly laminated to massive chert; and (6) skeletal packstone. All chert facies are intergradational and possess many common features, suggesting they were deposited under very similar conditions.

Finely Laminated Chert and Limestone

These rocks, which are confined to the base of the Thirtyone Formation and are generally nonporous and impermeable, comprise millimeter- to centimeter-thick parallel laminae of gray chert and brown, organic-rich lime mudstone (fig. 17A). Chert laminae display erosional bases and upward-fining grain-size trends of silt-sized indeterminate grains and siliceous sponge spicules (fig. 17B). Although burrowing is not extensive, Zoophycos burrows are locally present.

This facies, which accumulated in a low-energy, deep-water, basinal setting, represents the most distal of Thirtyone Formation deposits at University Waddell field. The silt-sized chert grains record distal turbidity sedimentation, whereas 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 imply relatively slow accumulation rates in a stable basinal setting (fig. 9). *Zoophycos* trace fossils are consistent with deposition in quiet, oxygen-deficient waters below storm wave base (Frey and Pemberton, 1984).

Nodular Chert and Limestone

Like the finely laminated chert and limestone facies to which they are closely related, these rocks consist of alternating laminae to thin beds of gray chert and brown, organic-rich lime mudstone. These rocks differ, however, in containing prominent nodular bedding, early fractures, fluid escape structures, and evidence of soft-sediment deformation, (fig. 17C). Chert consists of 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-sized peloids and abraded skeletal fragments. Burrowing by *Zoophycos* and other infauna is locally intense. Although these rocks typically display low porosity and permeability, they do contain minor intercrystalline porosity (fig. 17D).

The presence of peloid-skeletal debris in these rocks indicates deposition by influx of platform-derived sediment via turbidity currents rather than strictly by hemipelagic sedimentation. Soft-sediment deformation, early fractures, and fluid escape structures attest to episodic rapid deposition on an unstable slope. Locally intense bioturbation and in situ lithification imply intermittent periods of low sediment accumulation.

Disrupted Laminated Chert

These rocks display features of and gradational to both of the preceding facies. Stratification is locally disrupted by burrowing and soft-sediment deformation that result in convoluted, discontinuous, and wavy laminae (fig. 18A), although not to the degree seen in the nodular chert and limestone facies. Chert laminae, which display ripple laminations and normal grading, comprise packstones composed of fine-grained peloids, sponge spicules, abraded pelmatozoan, brachiopod, trilobite debris, and ostracodes (fig. 18B). Limestone laminae consist primarily of wackestone to mud-rich packstone, although lime mudstone is locally common as burrow fills. *Zoophycos* burrows are common, as are fluid escape structures. Intercrystalline and moldic grain dissolution pores are locally present, but these rocks are generally nonporous and impermeable.

The presence of ripple laminated peloid-skeletal debris in these rocks indicates they represent higher energy transport of platform-derived sediment than observed in preceding facies. This suggests a more proximal position relative to sediment delivery axes. Stratification is better preserved than in the nodular chert and limestone facies, suggesting dominance of sediment delivery over burrowing.

Burrowed Chert

Although burrowed cherts exhibit most of the features of the preceding facies in terms of sedimentary structures, grain size and grain composition, intensive bioturbation by *Zoophycos* and other burrowers has obliterated much of the primary depositional stratification (fig. 18C). Despite the extensive burrowing, however, ripple laminations, soft-sediment deformation, fluid escape structures, organic-rich laminations, and normal grading are locally apparent. Like other chert facies, these rocks contain silt- to fine sand-sized siliceous sponge spicules, abraded skeletal debris, peloids, and intraclasts (fig. 18D). Pelmatozoans, brachiopods, trilobites, and ostracodes dominate the fauna. Burrowed cherts are generally relatively nonporous and impermeable, although dissolution of siliceous sponge spicules has created minor local moldic porosity.

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. This facies is interpreted to have accumulated as distal submarine fans and overbank deposits on the margin of turbidite channels (fig. 9).

Thickly Laminated to Massive Chert

These rocks consist of thickly laminated to massive gray cherts (fig. 19A). Within individual thick laminae and thin beds, normal grading, ripple laminations, soft-sediment deformation, and fluid escape structures are locally present. Dark, organic-rich wispy laminations and stylolites are common at the tops of upward-fining successions. Bioturbation ranges from distinct burrows, including *Zoophycos*, to complete sediment homogenization. Burrowing, soft-sediment deformation, patchy silicification, and differential compaction have locally resulted in disrupted lamination and incipient nodular fabrics.

The chert in this facies consists of well-sorted, silt-sized to fine-grained, skeletal packstones/grainstones dominated by siliceous sponge spicules but also containing abraded pelmatozoans, ostracodes, and brachiopods (fig. 19B). Calcite generally represents 10 to 40 percent of the total mineralogy as corroded skeletal fragments, incompletely silicified matrix, laminae, nodules, and burrow fills.

This chert facies constitutes the dominant Thirtyone reservoir facies in University Waddell field. Much of the porosity, which locally exceeds 25 percent, takes the form of molds caused by dissolution of siliceous sponge spicules. Intercrystalline and primary interparticle pores are less significant contributors to total porosity. Core-log relationships indicate that nearly all porosity in the Waddell reservoir is associated with this facies (fig. 16). This relationship permits correlation and mapping of this facies within the Thirtyone succession using porosity logs and facilitates the definition of flow-unit architecture.

Thickly laminated to massive cherts record relatively high energy depositional conditions, as evidenced by good sorting, the slightly coarser grain size dominated by sponge spicules and shallow-water skeletal fragments, and the paucity of fine mud matrix. Normal grading and ripple laminations imply transportation via turbidity flows from the platform margin (fig. 9). Rapid deposition is indicated by the sedimentary structures and by the paucity of intense bioturbation relative to the burrowed chert facies. Individual depositional events, which are characterized by upward-fining successions with organic laminations at their tops, range up to the decimeter scale in thickness. Superposition and amalgamation of multiple depositional units 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.

Skeletal Packstone

These gray, thin-bedded to massive limestones are composed of well-sorted skeletal packstones/grainstones that contain chiefly crinoids and minor siliceous sponge spicules, brachiopods, mollusks, ostracodes, bryozoans, and trilobites (figs. 19C, 19D). Chert is locally common as patchy silicification, as well as thin laminations and beds as much as several feet thick. As in cherty facies, *Zoophycos* burrows are common. The facies is relatively nonporous and impermeable because interparticle pore space is completely occluded by syntaxial and interparticle calcite cements and by lime mud.

A below-storm-wave-base depositional setting is indicated for these deposits 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, suggest basinward transport from the platform. This facies most 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.

Stratigraphy and Depositional Setting

Delineation of reservoir architecture in the Thirtyone Formation at Waddell field and surrounding areas has previously been inhibited by the difficulty of establishing intraformational correlations because of the low gamma-ray log response in these typically siliciclastic-poor cherts and limestones. We have identified three intraformational gamma-ray markers, however, that can be correlated to significant stratigraphic and lithologic surfaces (fig. 16). These markers (fig. 20) are fundamental for defining the stratigraphic framework of the Thirtyone Formation at University Waddell field.

The lower Thirtyone Formation consists of approximately 500 ft of deep-water cherts and siliceous limestones, commonly referred to as the “lower chert.” Mud-rich, finely laminated chert and limestone facies and nodular cherts and limestones at the base of this succession (fig. 20) record a basinal environment dominated by hemipelagic sedimentation with episodic distal turbidite deposition (fig. 9). 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. Extensive burrowing suggests these rocks were deposited in areas of slower sediment accumulation on the margins of more active axes of sedimentation (fig. 9). Disrupted laminated and burrowed cherts are overlain by and grade laterally into well-sorted, skeletal grain-rich, thickly laminated to massive chert, that represent high-energy channel and fan deposition. These high-energy chert deposits compose the major reservoir succession in the field (figs. 16, 20).

The top of the “lower chert” is transitional from chert-dominated lithologies to overlying skeletal limestones. However, a gamma-ray marker (C; fig. 20) is well defined at this point in the section in University Waddell field and can be traced southward at least to Block 31 field. In the absence of known chronostratigraphic markers, this horizon is invaluable for correlating and subdividing the reservoir succession into mappable porosity units.

The lower chert is overlain by approximately 200 ft of skeletal-crinoidal packstones and siliceous limestones (fig. 20). 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 the slope during highstand progradation. Cherts are less abundant in this interval, because of rapid deposition of platform-derived carbonate debris (Ruppel and Barnaby, 2001).

The limestone section is overlain by another interval of chert and siliceous limestones termed the “upper chert” (fig. 20). These younger chert deposits document a return to deeper water deposition, suggesting renewed rise in relative sea level. Ruppel and Barnaby (2001) tentatively defined a sequence boundary at the base of this upper chert succession (fig. 20).

Upper chert facies consist of nodular chert and limestone, disrupted laminated and burrowed chert, thickly laminated to massive chert, and interbedded skeletal packstone. These strata are typical deeper water facies and thus define a transgressive facies tract offset, consistent with interpretation of the A marker as a sequence boundary. The upper chert extends to the eroded top of the Thirtyone Formation (fig. 20).

The upper chert ranges from 230 to 300 ft in thickness. This variation in thickness reflects Middle Devonian, pre-Woodford erosion and truncation that resulted in a minimum topographic relief of 70 ft across University Waddell field. Isopach trends suggest a north-northeast trend, which may represent paleoridges and paleovalleys incised during Middle Devonian subaerial exposure. Because of erosional truncation at the unconformity, the thickness of Pragian 2 sequence is unknown.

Reservoir Development

Although reservoir porosity is developed in both the lower and upper chert intervals, reservoir quality is highest 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. 16) dominated by well-sorted siliceous sponge spicules and carbonate skeletal debris. Depositional fabrics, sedimentary structures, and the dip-elongate channel-form to lobate geometry of individual porosity bodies suggest that these reservoir facies record a turbidite channel to fan depositional setting. 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 (fig. 9). Chert deposits appear to step progressively basinward (southward) upsection (fig. 4), perhaps reflecting decreasing accommodation associated with declining rates of sea-level rise. Renewed chert accumulation in the upper part of the Thirtyone (upper chert section) may indicate renewed sea-level rise and transgression.

Brecciation, Fracturing, and Diagenesis

According to Ruppel and Barnaby (2001), the fractured/brecciated cherts at Waddell resemble brecciated chert fabrics developed at the base of the chert section at Three Bar field, which have been interpreted to have formed by the entry of dissolution fluids along the contact between the Thirtyone and the underlying Frame Formation (Ruppel and Hovorka, 1995b). At Waddell, fractured/brecciated cherts are restricted to the top of the Thirtyone, below the pre-Woodford unconformity. This relationship suggests that such fabrics at Waddell were also created by diagenesis associated with entry of meteoric fluids during subaerial exposure, in this case along the exposed top of the Thirtyone Formation. Irregular 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.

Petrophysics

Both neutron or density-neutron logs provide good resolution of porous facies; acoustic logs do a poorer job, because of the differing acoustic response to the highly variable admixtures of chert and carbonate in the reservoir facies. Log-derived porosity curves were used to refine correlations and were critical for reservoir mapping. Integration of core descriptions and core analyses with corresponding wireline logs indicates that nearly all of the significant porosity in the reservoir can be attributed to the thickly laminated to massive chert facies (fig. 16). 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 were 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.

Using core and wireline data, Ruppel and Barnaby (2001) correlated and mapped more than 30 porosity units in the area of detailed study in University Waddell field. Individual units range up to 20 ft in thickness and from less than 0.1 mi to several square miles in areal extent. Porosity zones are separated vertically from one another by nonporous chert facies (fig. 21). 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. These maps show that porosity zones have distinctly different geometries and distribution across the field (fig. 22).

Core studies by Ruppel and Barnaby (2001) show 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 focused along channel/submarine-fan fairways (fig. 9). Porosity zones representing higher energy grain-rich turbidite flows are separated from one another by more mud-rich rocks that reflect 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 to reservoir heterogeneity and accompanying low recovery efficiency.

Fault and Fracture Induced Heterogeneity

In equivalent updip Thirtyone Formation reservoirs, including Dollarhide (Saller and others, 1991, 2001) and Three Bar (Ruppel and Hovorka, 1995a, b) fields, fault-induced reservoir compartmentalization has been documented (by 3-D seismic) or inferred. Ruppel and Barnaby (2001) documented several small-scale (<100 ft offset) reverse and normal faults at Waddell field that they inferred to be steeply dipping. They also found that open fractures, some partly infilled by quartz and/or calcite cement, are common. Although fracture patterns and their impact on reservoir permeability and anisotropy are not understood, production response suggested they play an important part in reservoir fluid flow. Producing wells immediately adjacent to water injection wells exhibited rapid breakthrough of injection water in the eastern parts of the field, whereas corresponding producers to the north and south did not. Such production trends indicate preferential permeability along an east-west direction, perhaps due to fractures and/or small-scale faults.

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, Waddell field and related distal chert reservoirs contain numerous separate and discontinuous stacked porous chert units. In these reservoirs, 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 siliceous 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 porosity and permeability. 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 are critical for establishing a reservoir framework that can serve as a basis for defining recompletion and infill drilling targets. Such an approach has led to the identification of several drilling and recompletion prospects in Waddell field.

As in the case of Three Bar reservoir, the impact of faulting and fracturing on Waddell reservoir performance is not well 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. Better resolution in the form of modern 3-D seismic would aid in developing a better model of the impact of faulting on reservoir compartmentalization and help define the distribution of chert reservoir intervals.

Thirtyone Formation Ramp Carbonate Reservoirs

The Thirtyone Ramp Carbonate play is the smaller of the two plays defined by Dutton and others (2005). Through 2001, production from reservoirs having produced at least 1 million barrels was 110 million barrels. Ruppel and Holtz (1994) showed that that these reservoirs typically exhibit low recovery efficiencies and thus contain the highest percentage of remaining oil among all Silurian and Devonian reservoirs.

Distribution

Nearly all of these reservoirs are located in Texas (fig. 23). They are located along the northern limit of the Thirtyone Formation subcrop and apparently represent the margin of the Thirtyone platform (fig. 10). In some fields, production also comes from underlying Thirtyone deep-water cherts (for example, Dollarhide and Bedford fields).

Depositional Facies and Paleoenvironments

Thirtyone ramp carbonate reservoirs are dominantly composed of skeletal grainstones and packstones (fig. 24a) Crinoids dominate the fauna, but bryozoans (both ramose and fenestrate) are locally abundant (fig. 24b,c). As described earlier, Thirtyone carbonate facies are dominantly grain rich. Downdip and downsection, carbonate facies are fine-grained, skeletal calcarenites that are locally graded. Upsection and updip these distal, transported carbonates grade into coarser grained, in situ, grain-rich, high-energy, platform-top shoal successions (fig. 25). Reservoirs assigned to the Thirtyone Ramp Carbonate play are developed in both of these end-member facies.

Diagenesis and Porosity Development

Four major types of diagenesis have affected Thirtyone carbonates of the Thirtyone Ramp Carbonate play: (1) early cementation and pore occlusion by syntaxial cement, (2) leaching of carbonate mud in packstones, (3) dolomitization, and (4) silicification. The first caused substantial porosity occlusion of original depositional pore space; the other three caused porosity retention or enhancement.

Because of the abundance of crinoids in virtually all of the succession, syntaxial cement is omnipresent in these rocks (figs. 24b,c). These cements (which grow as optically continuous rim cements around crinoids) apparently formed during early diagenesis in the marine realm. Crinoid grainstones are commonly composed of as much as 50 percent syntaxial cement and rarely contain significant porosity.

Evidence of postdepositional leaching or dissolution of selective grains is most common in packstones (fig. 24c). Leaching seems to have targeted carbonate mud and, to a lesser extent, bryozoans. Because of the leaching, carbonate packstones contain higher porosity than grainstones.

Dolomitized Thirtyone rocks contain the highest porosities observed in the play. Dolomite is most abundant at the top of the Thirtyone section, specifically in Andrews County (fig. 26). In these rocks, dolomite is locally pervasive and associated with extensive interparticle porosity (fig. 24d). Locally, porosity in these reservoirs reaches 10 to 15 percent. Dolomite is also present, although much less abundant, downsection. In these rocks (for example, at Bedford field, fig. 27), porosity and permeability are generally lower but still sufficient to facilitate oil production (fig. 28).

Thirtyone carbonates also locally display significant amounts of chert. Although this chert is present in small amounts throughout much of the carbonate section, it is most abundant in the eastern and southeastern parts of the play. This chert differs significantly from chert present in the lower and more distal parts of the formation (that is, deep-water chert facies) by being present only in carbonate packstones where it is entirely restricted to the matrix. As with dolomitized sections to the west, porosity is associated with the silicified matrix of packstones (fig. 24e); grainstones contain no mud, no silica, and no porosity. In some parts of the succession, packstones and grainstones form cycles of cycle-base porous rocks and cycle-top nonporous rocks (fig. 24f).

Reservoir Development

As a whole, the reservoirs of this play exhibit the lowest porosity values among Devonian plays. This is largely the result of the abundance of crinoid grainstones. Reservoir development is limited to areas that have undergone postdepositional diagenesis. In the western part of the play area this diagenesis is typically a combination of dolomitization and selective matrix leaching. Highest porosity is associated with rocks that been dolomitized. Dolomite is most common immediately below the unconformity that forms the top of the Thirtyone section (fig. 26). Several fields in central Andrews County are productive from reservoirs developed in these dolomites at the top of the Thirtyone (for example, Block 9 field, Bakke field). Some reservoirs are also developed in limestones that, although not extensively dolomitized, have undergone sufficient leaching and selective dissolution of matrix to develop and/or retain porosity. Such reservoirs (for example, at Dollarhide, Bedford, and Andrews South fields) typically display porosities less than 5 percent (fig. 28).

Production from the eastern part of the play area is commonly associated with successions that have been partially silicified. Pore space appears to be formed by silicification of carbonate mud matrix in skeletal packstones (Ruppel and Holtz, 1994). These reservoirs (including fields at Headlee, Parks, and Byant G) typically produce dominantly gas and condensate from these low-porosity/low-permeability rocks.

TRAPS, SEALS, AND SOURCES

Essentially all productive Thirtyone reservoirs are overlain by the shales of the Woodford Formation, which provides both a seal and a hydrocarbon source. Most of the large reservoirs are formed over large anticlinal closures (for example, Block 31, University Waddell). However, in several reservoirs the Woodford has been partly (for example, Dollarhide, Three Bar) or completely (for example, Crossett, Cordona Lake) removed by Pennsylvanian erosion. These reservoirs are typically overlain and sealed by Permian carbonate mudstones. It should be noted that some production from some of these breached sections also comes from chert residuum and reworked chert conglomerates formed by weathering and erosion of the Thirtyone (for example, Tunis Creek, TXL).

OPPORTUNITIES FOR ADDITIONAL RESOURCE RECOVERY

Despite the large volume of oil already produced from the Thirtyone, significant oil remains in existing reservoirs. Distal deep-water chert reservoirs are especially good candidates for targeted infill drilling and recompletion programs based on modern, detailed geological characterization because their complex flow-unit geometries have not been well been defined in many reservoirs. These reservoirs offer perhaps the best opportunity to delineate reservoir flow units through detailed geological mapping and modeling of depositional facies.

Many Thirtyone reservoirs are candidates for application of enhanced oil recovery technologies for increased production. Results of CO_2 injection in such reservoirs as Dollarhide (Saller and others, 1990, 1991) illustrates how better reservoir management and reservoir characterization and targeted infill drilling and recompletion coupled with gas injection can substantially increase production.

Recovery efficiency from the Thirtyone carbonate play is among the lowest of all carbonate reservoir plays in the Permian Basin and suggests that these reservoirs contain especially high potential for recovery of remaining mobile oil. Recent successes in fields like University Block 9 (Weiner and Heyer, 1999), Bryant G, and Headlee have demonstrated the value of horizontal wells in enhancing recovery from these rocks. There is also potential for the development of upper Thirtyone carbonate section in existing Thirtyone chert reservoirs because of the likelihood that these low-porosity carbonate reservoirs have been overlooked.

Finally, it is highly likely that significant potential exists for reservoir step-out and new field discovery if new and developing models are applied to reexploration of the Permian Basin. Occidental, for example, has had excellent success (more than 40 successful wells drilled) in greatly extending production from the Thirtyone in the TXL–Goldsmith field area of Ector

County, Texas, by applying models of upper Thirtyone chert development presented by Ruppel and Holtz (1994).

SUMMARY

The Thirtyone Formation documents the Early Devonian infilling of a significant platform-marginal slope/basin area developed during the Silurian on the southern margin of the Laurussian paleocontinent. Deposition was dominated by deep-water gravity transport and redistribution of platform-derived carbonate debris and siliceous fauna (sponge spicules and radiolarians). Depositional architecture in distal areas is a function of distributary pathways that evolved substantially in alignment and position through time. Facies vary from hemipelagic mudstones to relatively high energy, grain-rich, silica (chert) packstones, reflecting vastly differing energy regimes ranging from high-energy gravity flows to low-energy, below-wave-base conditions. Updip areas, in stark contrast, comprise high-energy, shallow-water carbonate shoal grainstones that reflect basinward progradation and accommodation filling.

Most reservoir development is associated with high-porosity/moderate-permeability chert facies whose character reflects a combination of depositional regime and early silica diagenesis. Best reservoir quality is associated with grain-rich chert facies that were deposited as debris flows. Lower energy burrowed facies are less porous and usually of poorer reservoir quality; however, variations in chert diagenesis locally overprint this trend. Updip carbonate facies are generally of much lower porosity but still locally quite productive. Reservoir quality in these rocks is controlled by diagenesis. Strongly dolomitized intervals provide the best porosity development, but partially dolomitized, leached, and/or silicified sections are also locally very productive.

Thirtyone chert and carbonate reservoirs contain a 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, and among updip carbonate sections exposed to different styles of diagenesis, it is crucial that both regional and local geologic models of deposition and diagenesis be incorporated into modern reservoir characterization and exploitation efforts.

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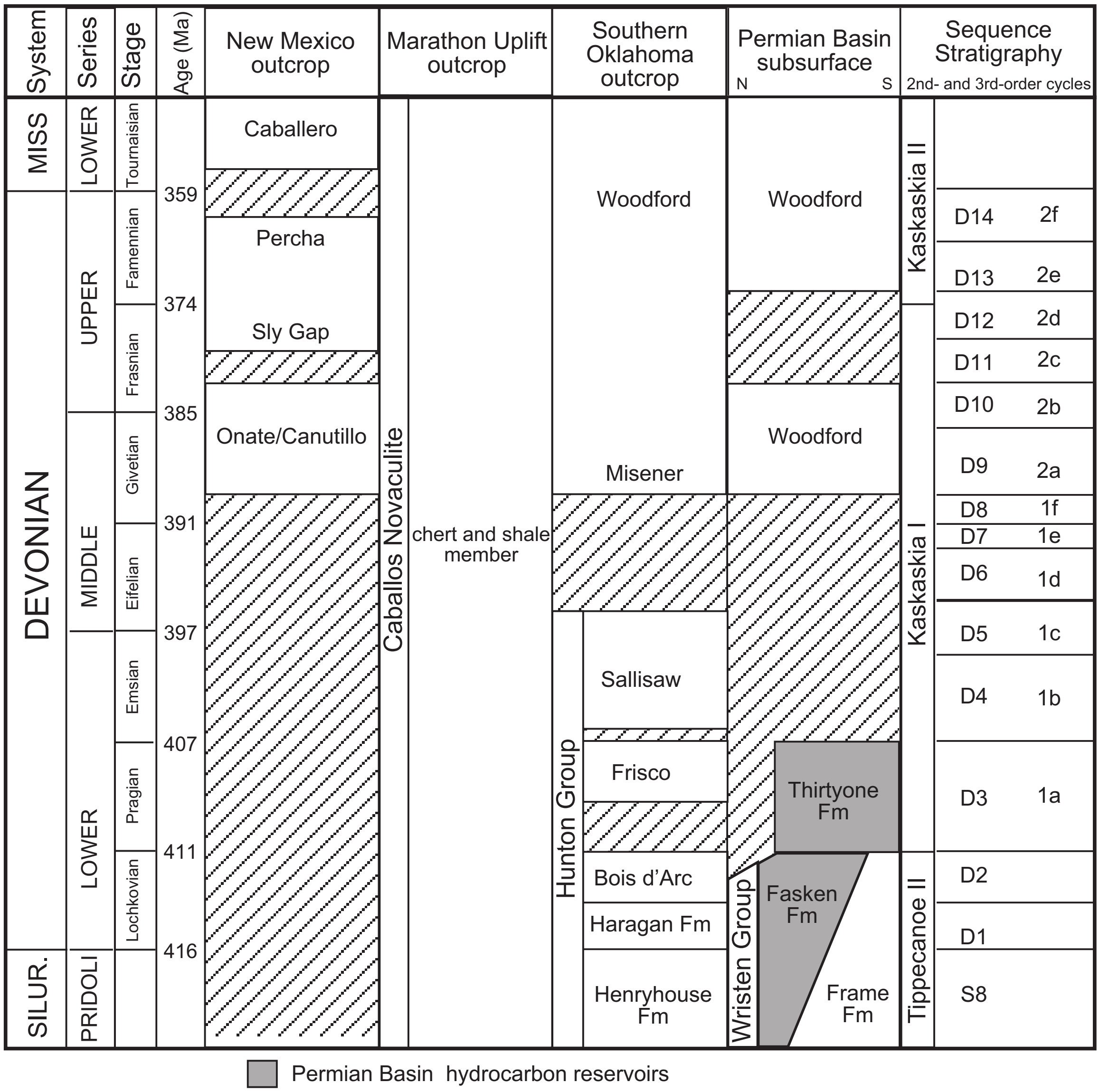
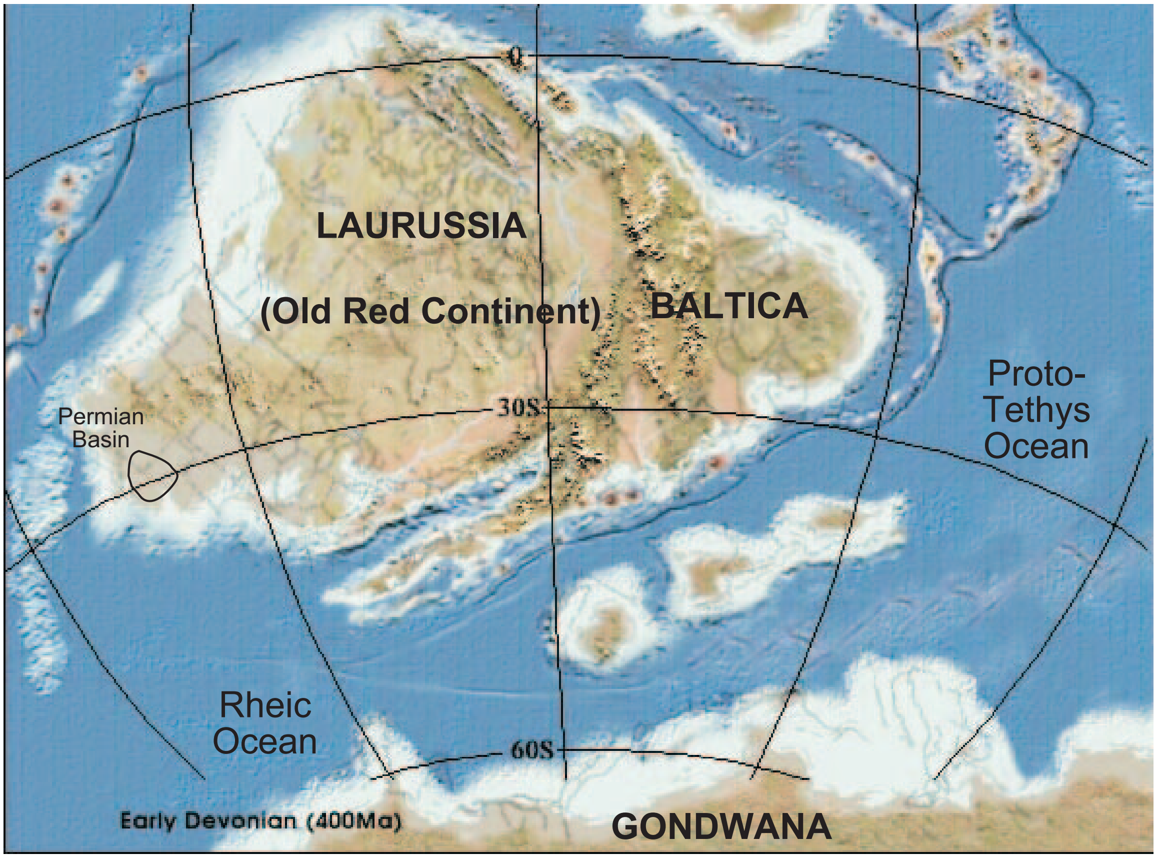


Figure 1. Correlation of the Devonian Thirtyone Formation in West Texas with equivalent successions in Oklahoma and the Illinois Basin. Age dates from International Stratigraphic Commission (2004). Numbered sequences (1a–2f) are from Johnson and others (1985). Lettered sequences (S8–D14) are from this study.



from Blakey (2004): http://jan.ucc.nau.edu/~rcb7/400NAt.jpg

Figure 2. Paleogeographic plate reconstruction of the Laurussian paleocontinent during the Early Devonian showing position of Permian Basin area on the southern continental margin. From Blakey (2004).

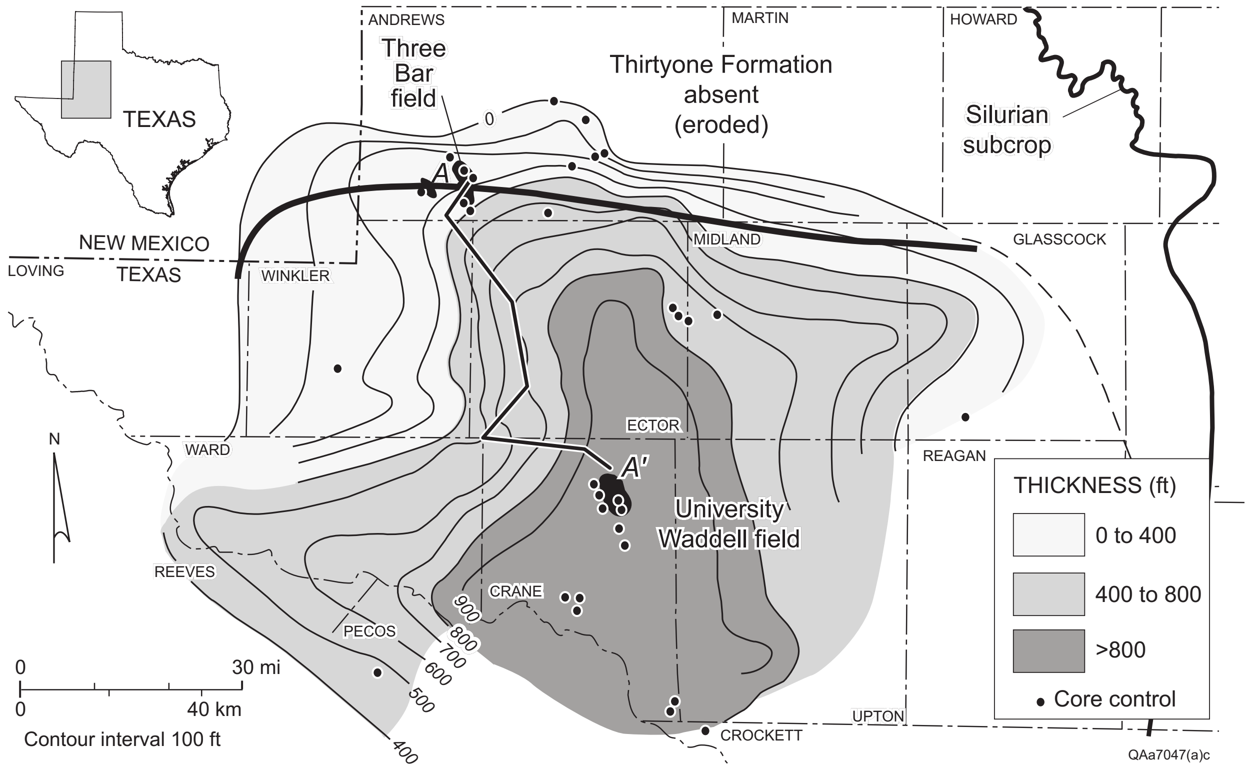


Figure 3. Thickness and distribution of the Devonian Thirtyone Formation in West Texas showing location of key fields. From Ruppel and Barnaby (2001).

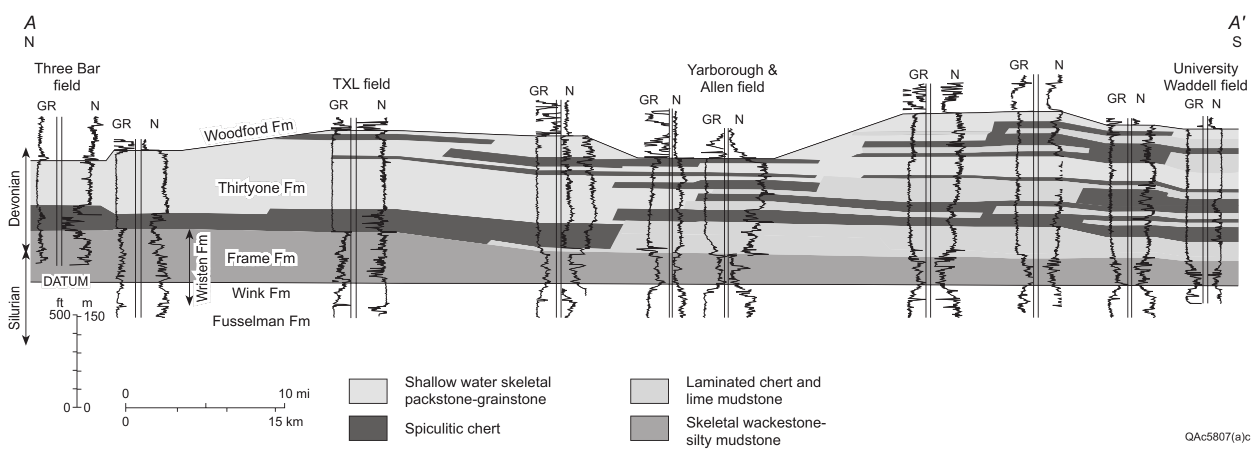


Figure 4. Cross section depicting Thirtyone Formation stratigraphy. Note contrast between high-continuity, tabular chert in northern (proximal) area and laterally and vertically discontinuous chert in southern (distal) area. Location of cross section shown in figure 3. From Ruppel and Barnaby (2001).

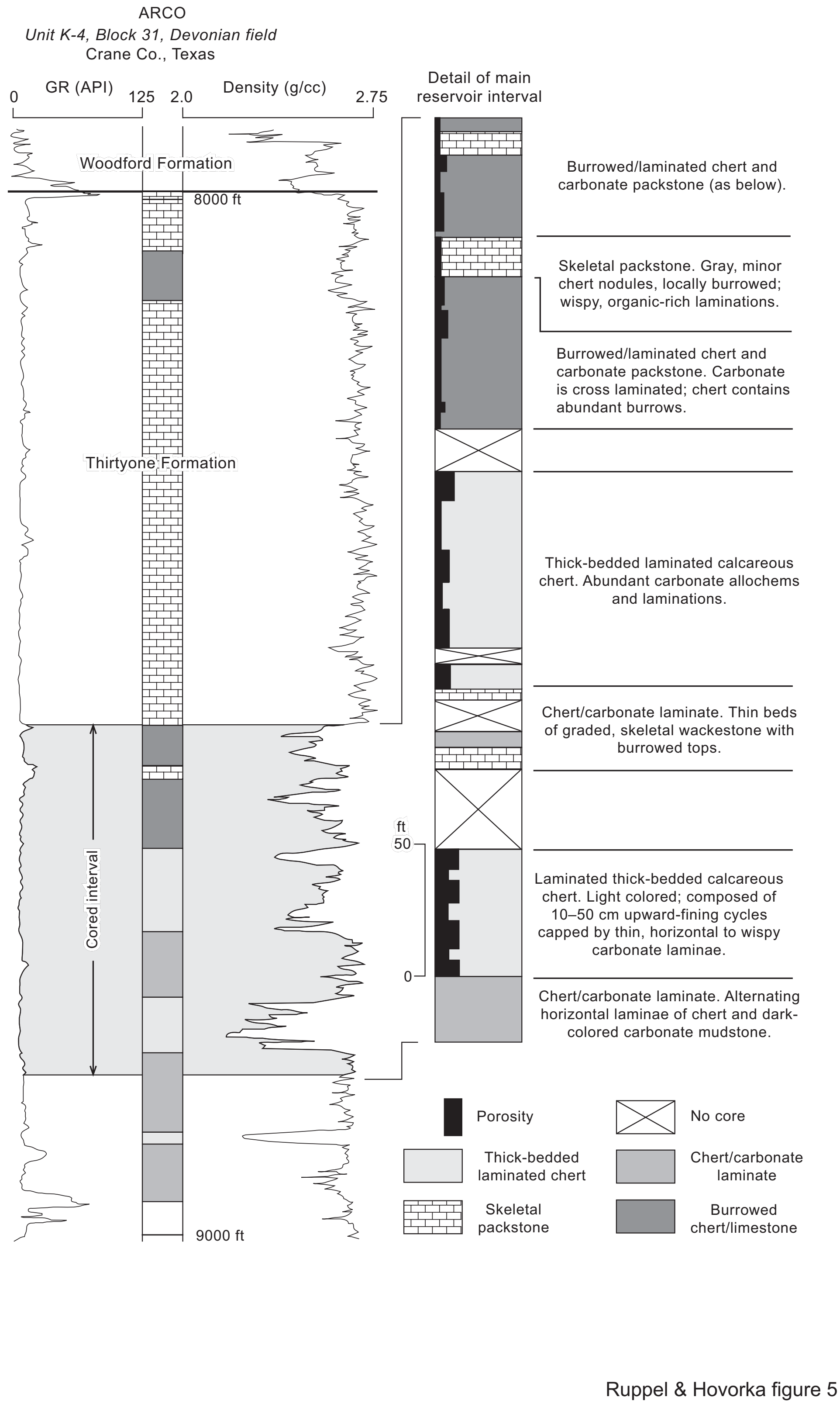


Figure 5. Stratigraphic section and log character of the Thirtyone in the southern, thickest part of the Thirtyone Formation depocenter. From Ruppel and Hovorka (1995b).

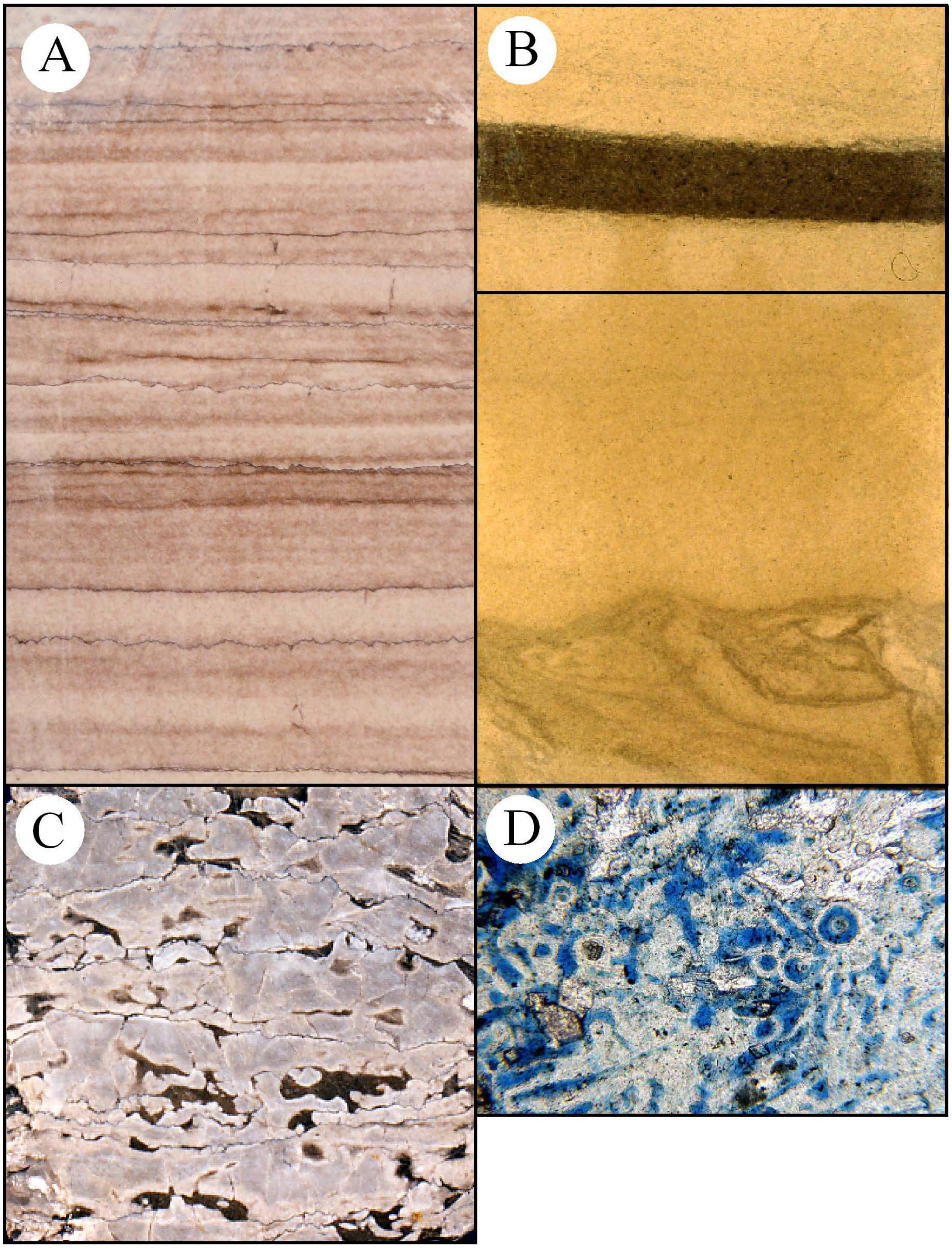


Figure 6. Thirtyone Formation facies. A. Chert/carbonate laminite facies representing hemipelagic deposition in a quiet-water, below-wave-base setting. Depth: 8,850 ft. B. Thick-bedded, laminated chert facies with organic-rich laminae at top. Depth: 8,800 ft. C. Burrowed chert facies. Dark patches, which are carbonate mudstone, are the result of burrowing and/or soft-sediment deformation. A, B, and C from ARCO Block 31 Unit No. K-4, Crane County, Texas. D. Photomicrograph of grain-supported, spiculitic chert of the thick-bedded, laminated chert facies, Thirtyone Formation. Porosity (31 percent) is developed as obvious, large (50–100 µm) molds and smaller (<5 mm), intercrystalline pores. Permeability is 27 md. Depth: 8,155 ft. Unocal, Dollarhide 46-5- D, Andrews County, Texas.

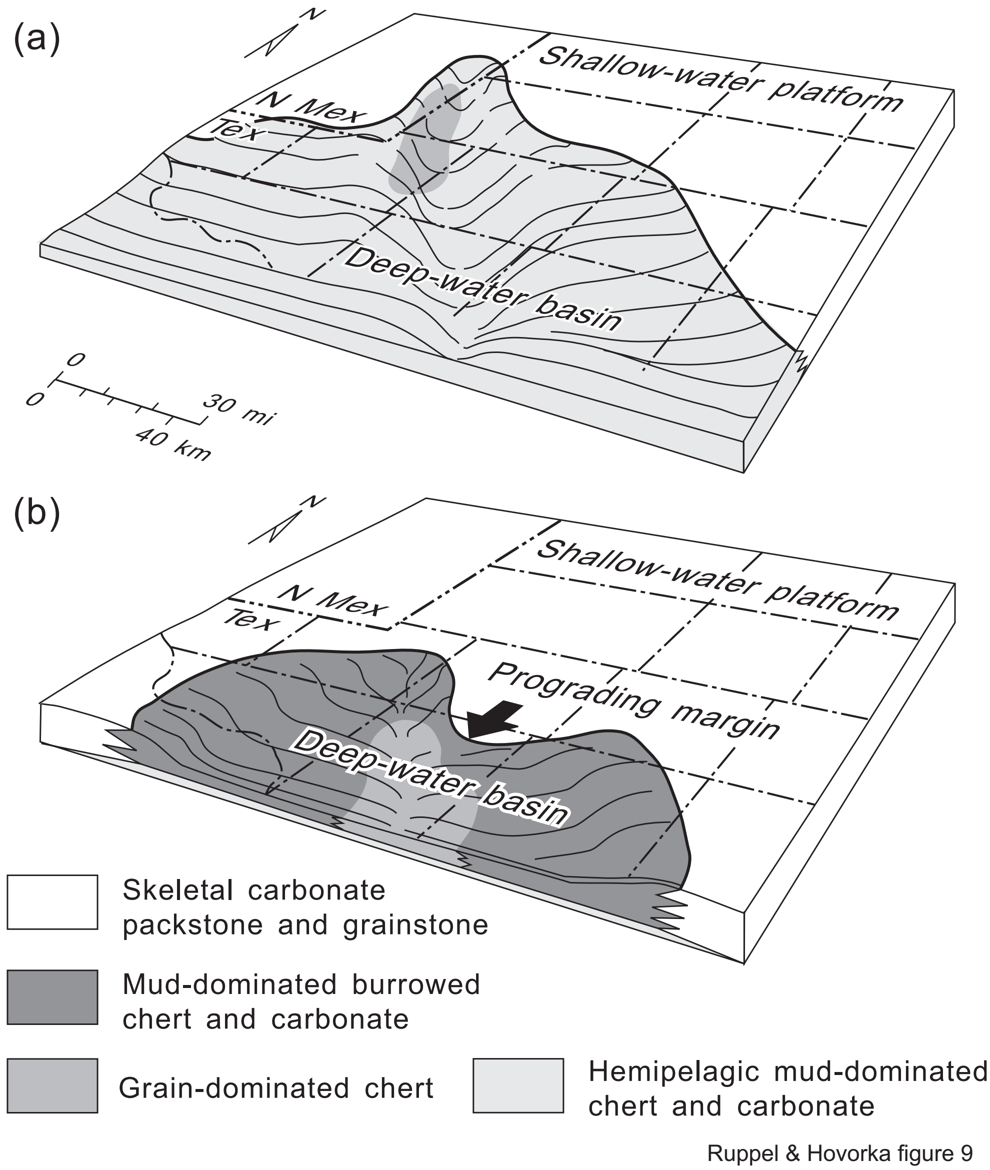


Figure 7. Paleogeographic evolution of the Permian Basin area during the Early Devonian. (A) Initial Early Devonian flooding of the Wristen (Silurian) platform was marked by hemipelagic chert-and-carbonate mud accumulation in the distal (southern) part of the region and grain-rich, spiculitic cherts in more northerly areas proximal to the carbonate platform. (B) Rapid southward progradation of the platform shifted the focus of high-energy, submarine-fan deposition southward. Chert reservoirs are, thus, developed in two spatially and temporally discrete stratigraphic successions. From Ruppel and Hovorka (1995a)

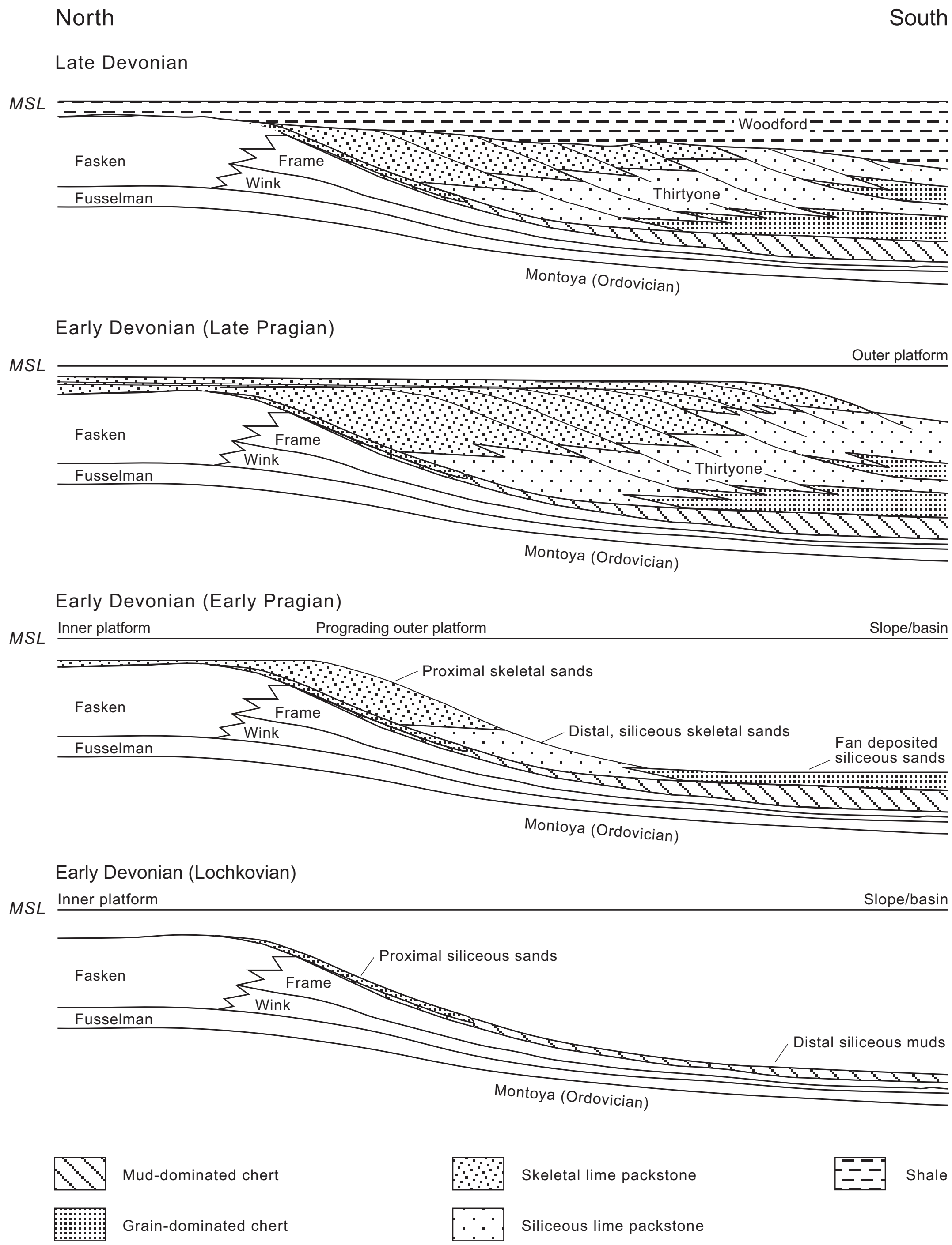


Figure 8. Diagrammatic north-south cross section depicting stratigraphic relationships and depositional history of Thirtyone Formation along approximate depositional dip. From Ruppel and Hovorka (1995a, b).

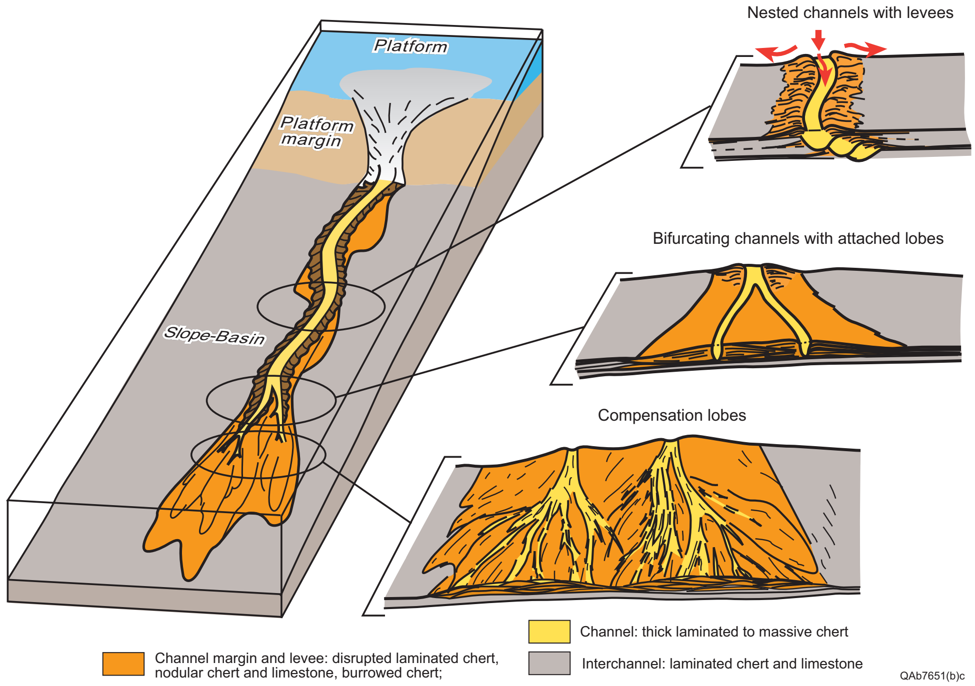


Figure 9. Model of deposition in distal Thirtyone chert reservoirs showing general morphology of turbidite channels and fans and proposed relationship to chert facies. From Ruppel and Barnaby (2001).

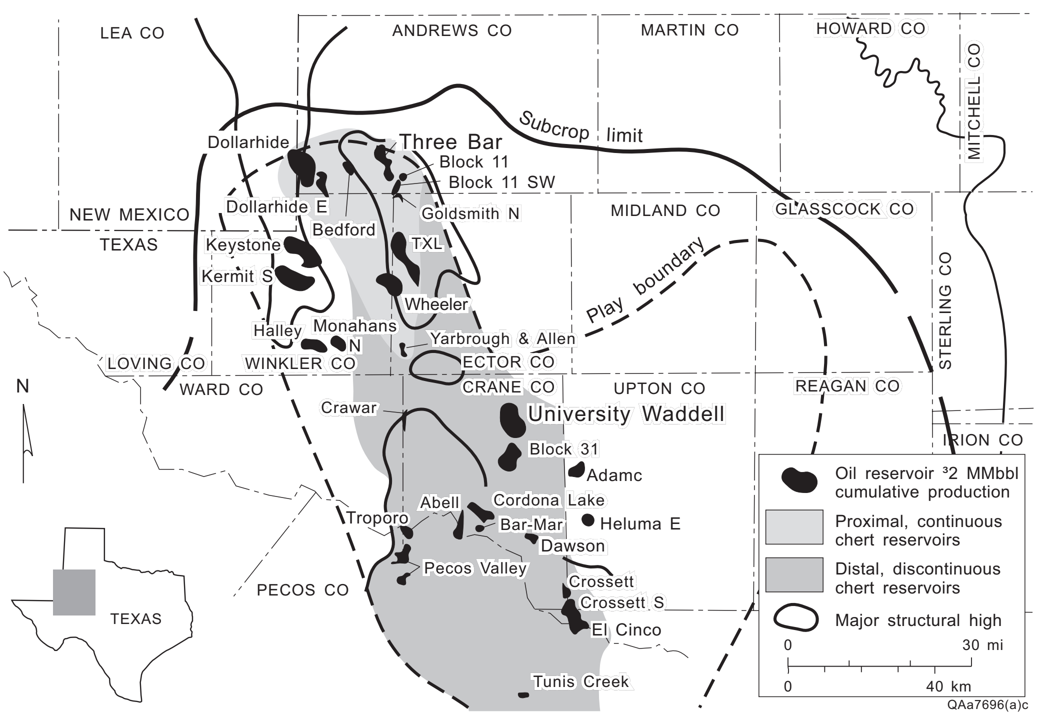


Figure 10. Distribution of proximal and distal reservoir styles. From Ruppel and Barnaby (2001).

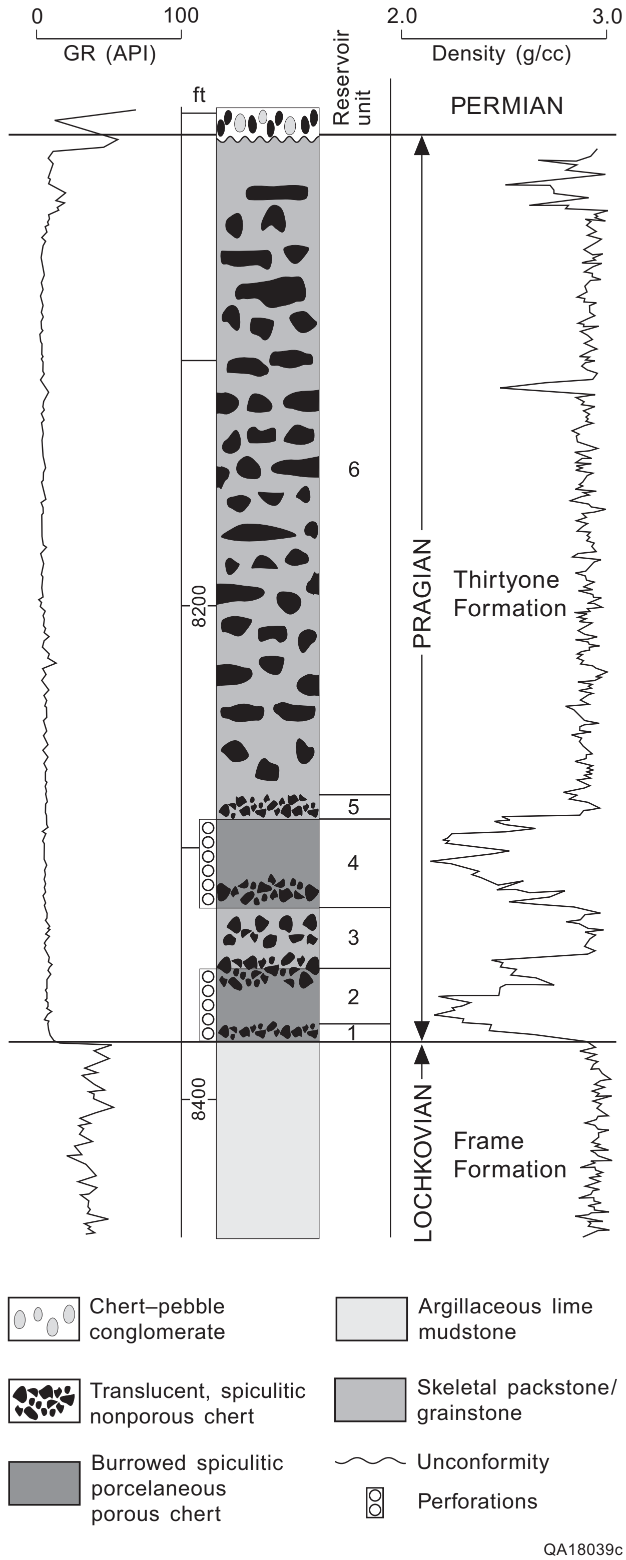


Figure 11. Typical stratigraphic succession and wireline log signature of Thirtyone Formation in Three Bar field. Amoco Three Bar Unit No. 80. From Ruppel and Barnaby (2001).

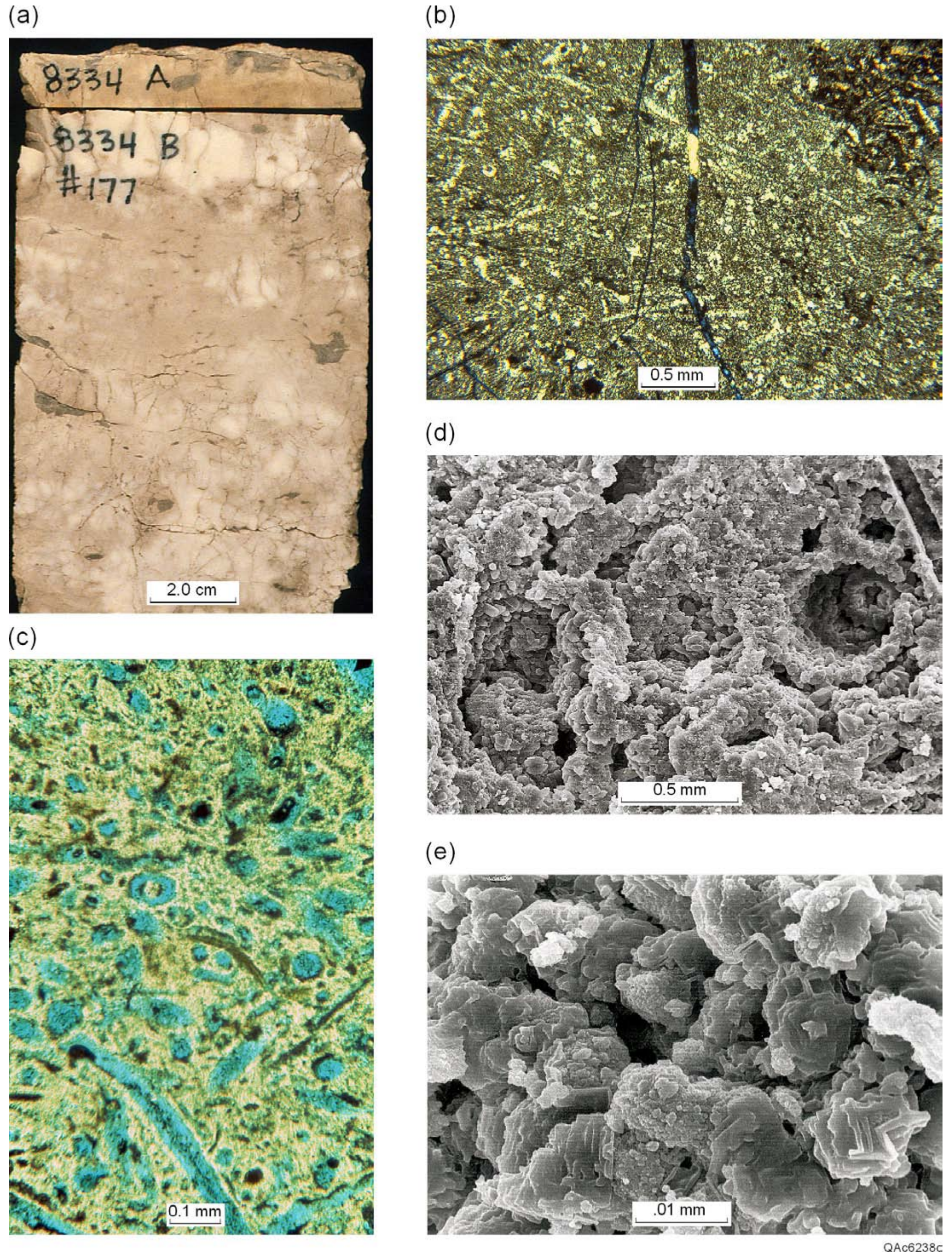


Figure 12. Textures of cherty rocks in the Thirtyone Formation at Three Bar field. (A) Core slab of white translucent chert with abundant vertical fractures containing dark chert and late calcite cements. Amoco Production Co., Three Bar Unit No. 80, 8,306 ft. (B) Photomicrograph of nonporous chert showing spicules replaced by chalcedony and microquartz. Matrix between spicules and in axial canals of spicules consists of finer grained chert. Crossed nicols. Three Bar Unit No. 80, 8,306 ft. (C) Photomicrograph of sponge spicule molds in porous chert. Plane light, Three Bar Unit No. 80, 8,305 ft. (D) Scanning electron microscope (SEM) photomicrograph of porous chert showing spicule molds and micropores in a matrix of aggregated chert ellipsoids. Three Bar Unit No. 55, 8,175 ft. (E) SEM photomicrograph of porous chert microstructure. Microporosity is developed between rounded 1-µm ellipsoids and between larger aggregates of ellipsoids. Three Bar Unit No. 55, 8,137 ft, (F) Core slab showing styles of brecciation in Thirtyone chert. Contrasts between brittle and more ductile deformation are related to rates of silica diagenesis. From Ruppel and Barnaby (2001).

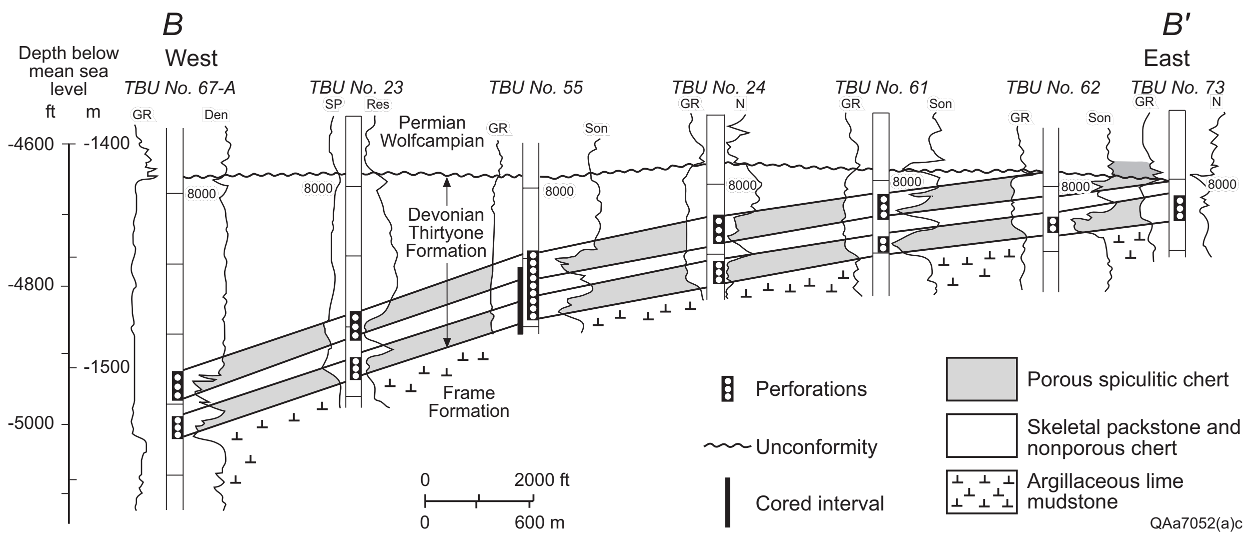


Figure 13. Structural cross section across Three Bar field, perpendicular to the structural axis, showing updip truncation of reservoir pay zone beneath the sub-Permian unconformity. Note continuity of chert pay zones. From Ruppel and Barnaby (2001).

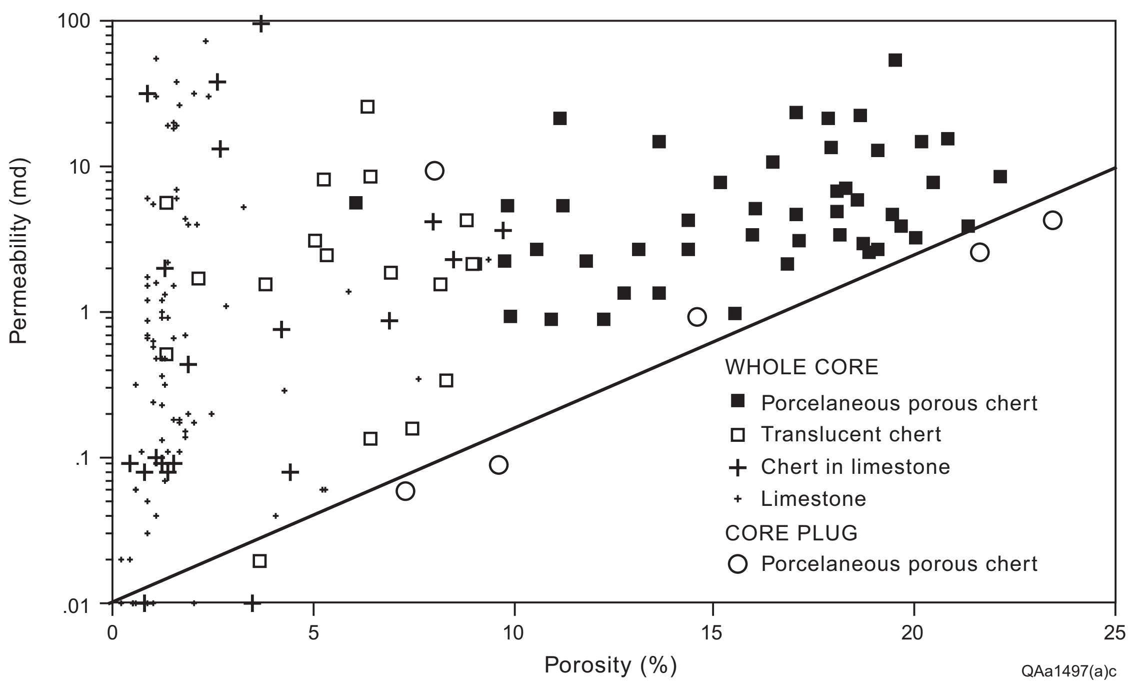


Figure 14. Porosity-permeability relationships in the Thirtyone Formation at Three Bar field. Because of abundant brecciation and fractures, most conventional core plug analysis displays fracture-enhanced permeability. True matrix porosity and permeability are best represented by specially selected, fracture-free plugs. From Ruppel and Barnaby (2001).

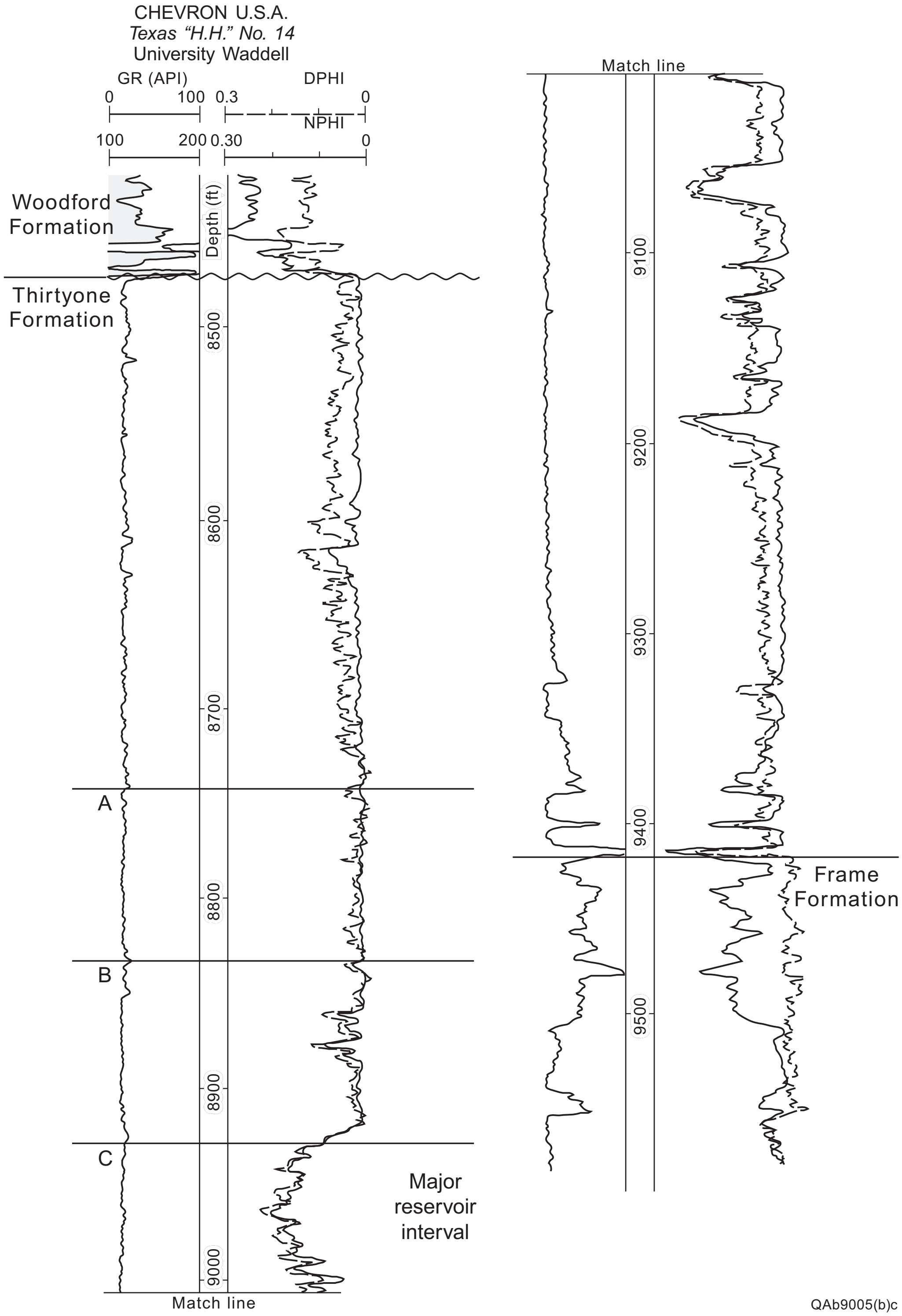


Figure 15. Type log for the Thirtyone Formation in University Waddell field. From Ruppel and Barnaby (2001).

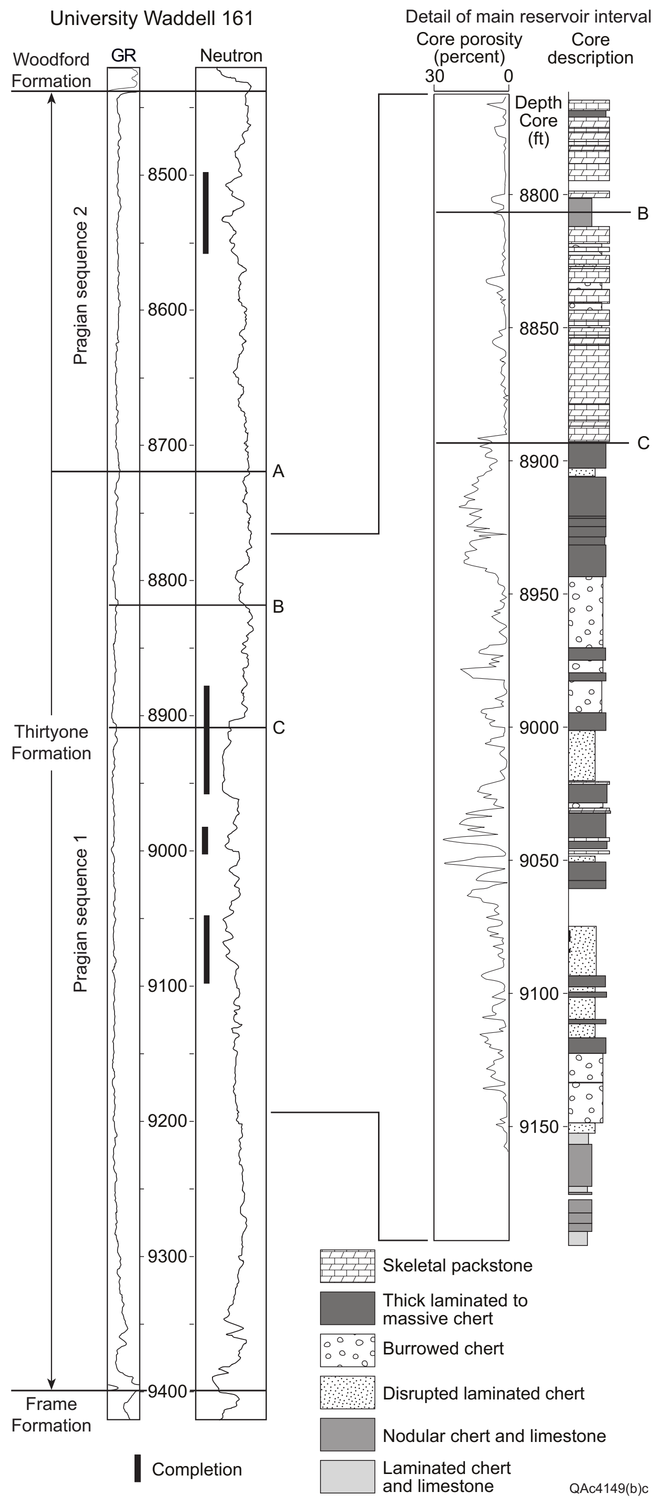


Figure 16. Reservoir facies at University Waddell field. From Ruppel and Barnaby (2001).

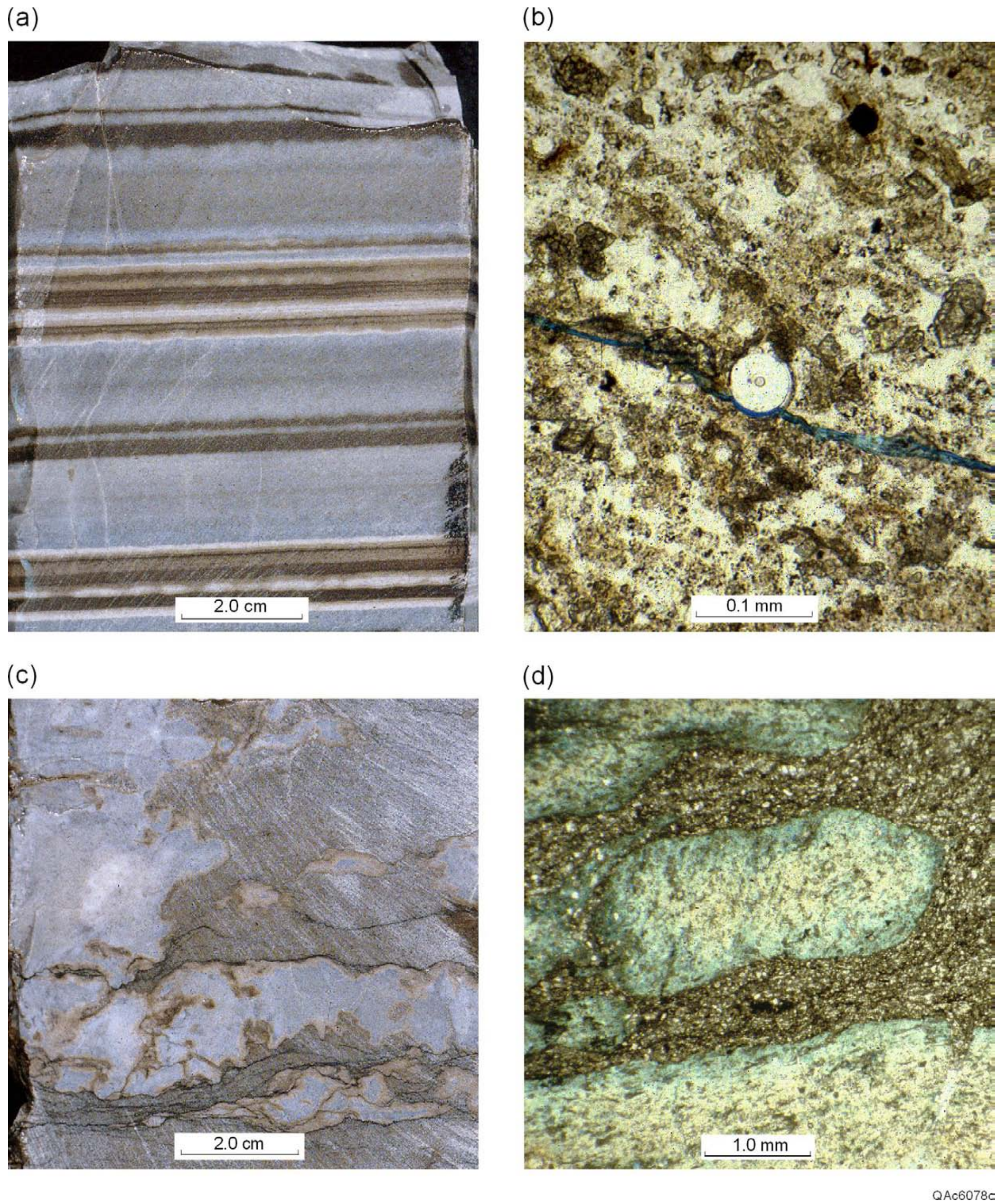


Figure 17. Textures of cherty rocks at University Waddell field. Finely laminated chert and limestone facies (A, B) and the disrupted laminated chert facies (C, D). (A) Core slab of alternating layers of gray chert, which display irregular bases and normal grading of silt-sized grains, and brown lime mudstone, University Waddell No. 161, 9,171 ft. (B) Thin section of chert laminae containing silica sponge spicules and indeterminate carbonate grains in siliceous matrix, University Waddell No. 161, 9,172 ft. (C) Core slab of highly convoluted laminated chert with abundant stylolitic dissolution seams, University Waddell No. 161, 8,577 ft. (D) Thin section of incompletely silicified chert packstone composed of silt-sized to very fine grained peloids and skeletal material, University Waddell No. 161, 9,128 ft. From Ruppel and Barnaby (2001).

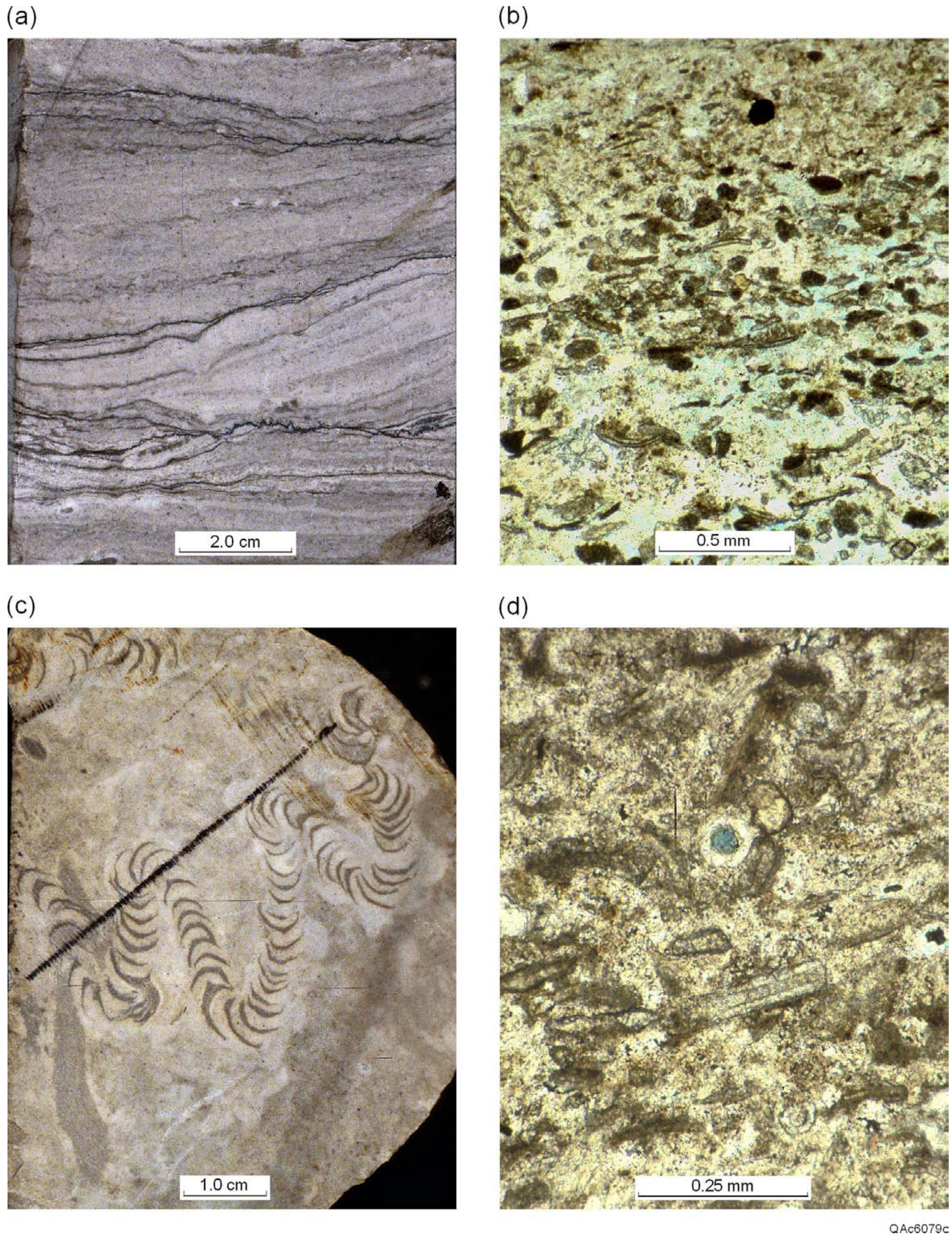


Figure 18. Textures of cherty rocks at University Waddell field. Nodular chert and limestone facies (A, B) and burrowed chert facies (C, D). (A) Core slab of irregular replacement chert nodules in lime mudstone matrix, University Waddell No. 161, 9,103 ft. (B) Thin section of chert nodules in organic-rich lime mudstone matrix showing minor intercrystalline porosity indicated by blue epoxy along periphery of silica nodules, University Waddell No. 161, 9,103 ft. (C) Core slab showing *Zoophycos* burrow parallel to bedding plane, University Waddell No. 161, 9,087 ft. (D) Thin section of incompletely silicified, poorly sorted, silt-sized to very fine grained skeletal packstones dominated by sponge spicules, University Waddell KK No. 10, 9,258 ft. From Ruppel and Barnaby (2001).

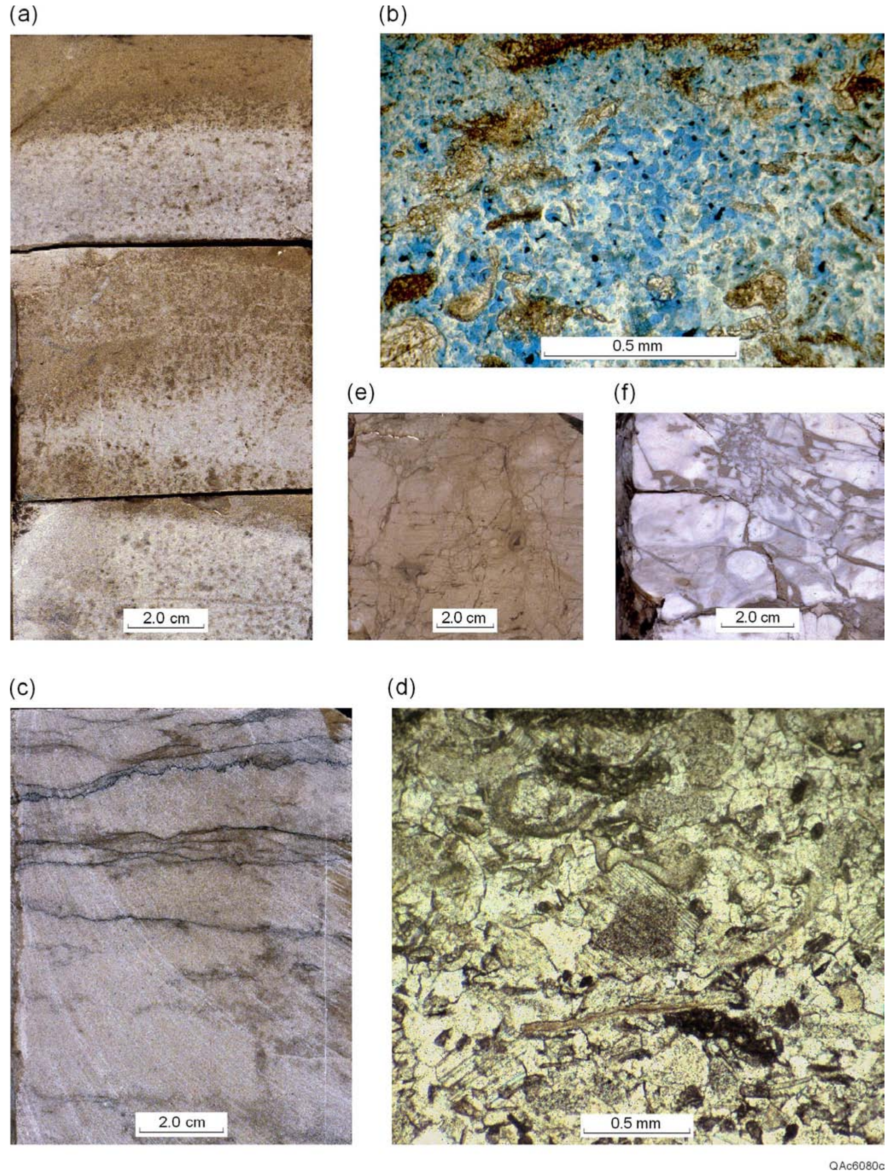


Figure 19. Textures of porous cherty rocks at University Waddell field. Highly porous, thickly laminated to massive chert facies (A, B), nonporous skeletal packstone facies (C, D), and brecciated porous and nonporous chert (E, F). (A) Core slabs showing highly porous hydrocarbon-stained intervals and lighter gray, more tightly cemented patches, University Waddell No. 161, 9,032 ft. (B) Thin section showing abundant sponge spicule molds and incompletely silicified carbonate skeletal debris in a well-sorted skeletal packstone. Moldic dissolution porosity is as much as 25 percent, University Waddell No. 161, 9,041 ft. (C) Core slab of light-colored thin-bedded to massive skeletal packstone with local burrows and stylolites, University Waddell No. 161, 8,828 ft. (D) Thin section of skeletal packstone with abundant coarse-grained crinoids, common brachiopods, and other skeletal grains. This facies is essentially nonporous owing to syntaxial calcite cements, University Waddell No. 161, 9,037 ft. (E) Core slab of oil-stained fractured/brecciated porous chert, University Waddell No. 161, 8,562 ft. (F) Core slab of brecciated, nonporous porcelaneous chert, University Waddell No. 161, 8,547 ft. From Ruppel and Barnaby (2001).

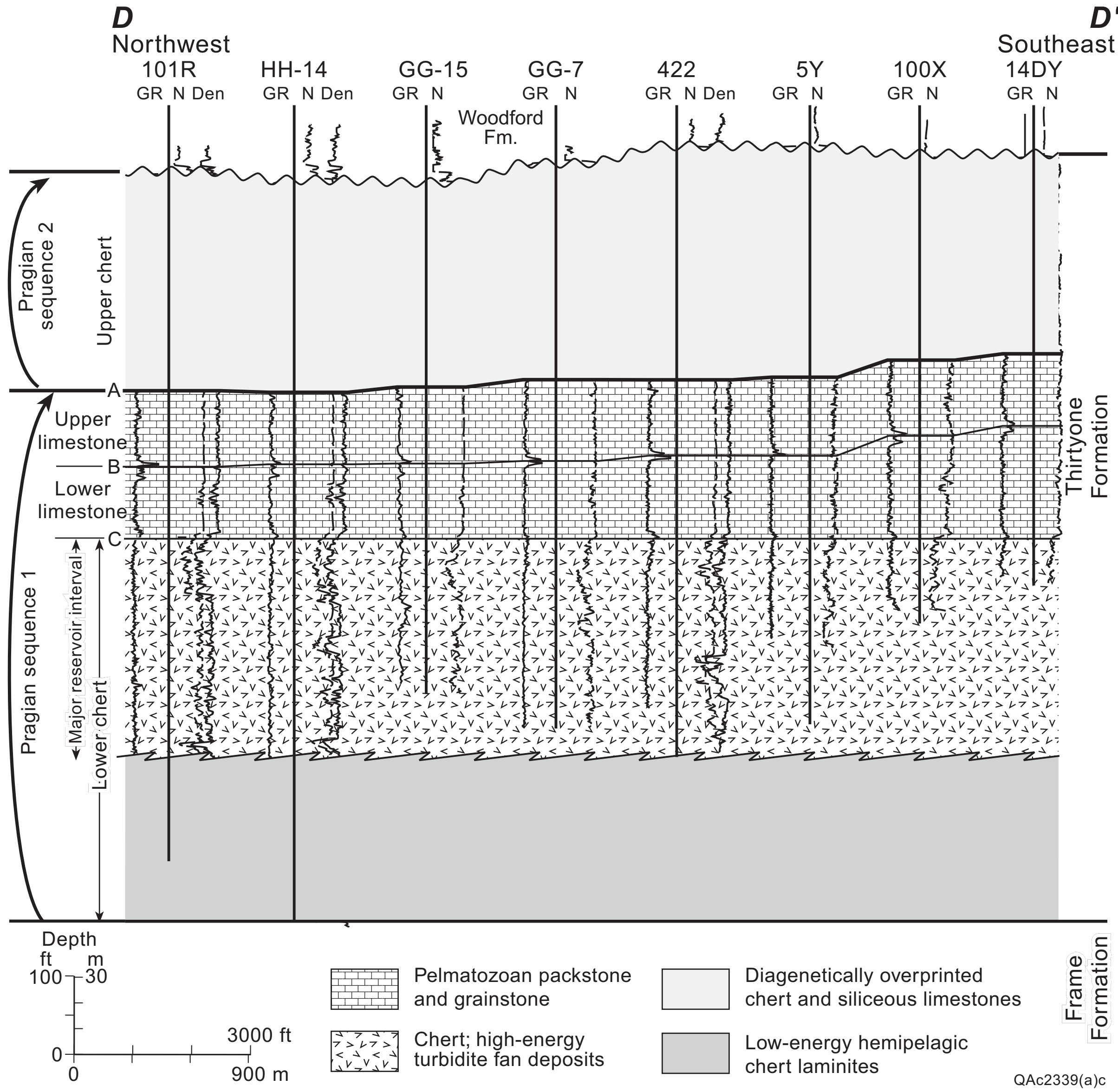


Figure 20. Stratigraphic cross section depicting reservoir architecture and sequence stratigraphy of the Thirtyone Formation. From Ruppel and Barnaby (2001).

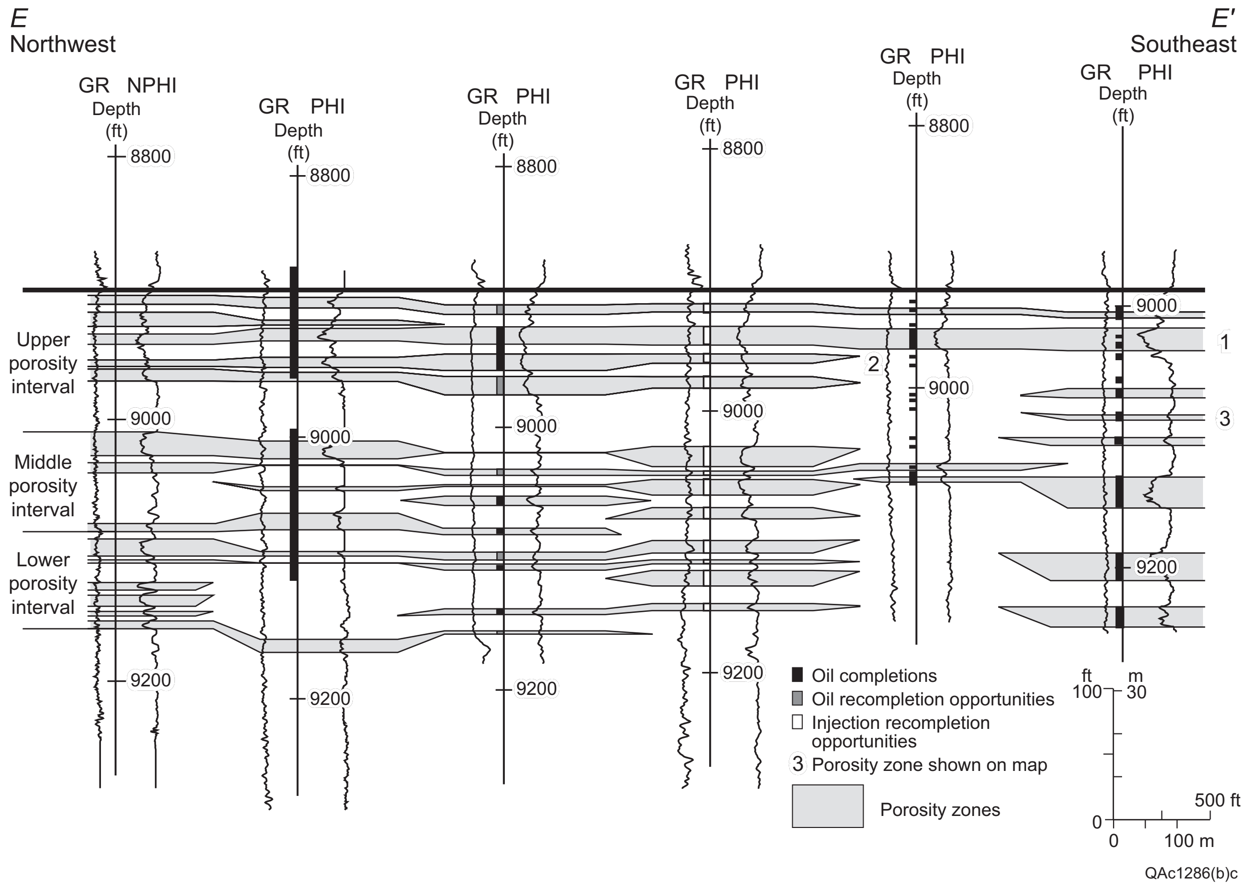


Figure 21. Dip-oriented stratigraphic cross section showing distribution and continuity of major porosity units. From Ruppel and Barnaby (2001).

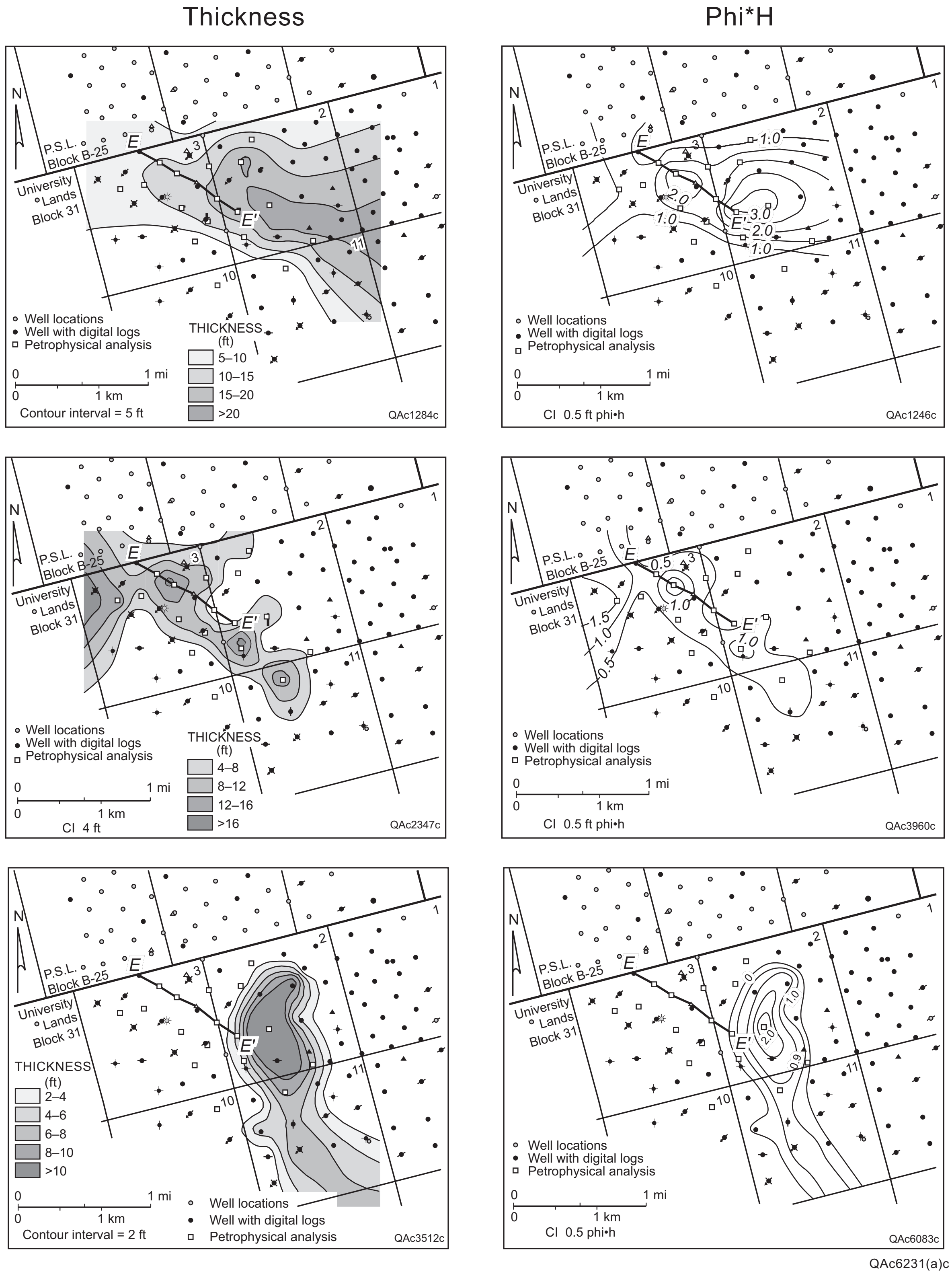


Figure 22. Paired maps of phi*h and thickness for selected chert depositional units. Note the markedly dissimilar distribution of these potential flow units. Numbers correspond to units shown in figure 21. From Ruppel and Barnaby (2001)

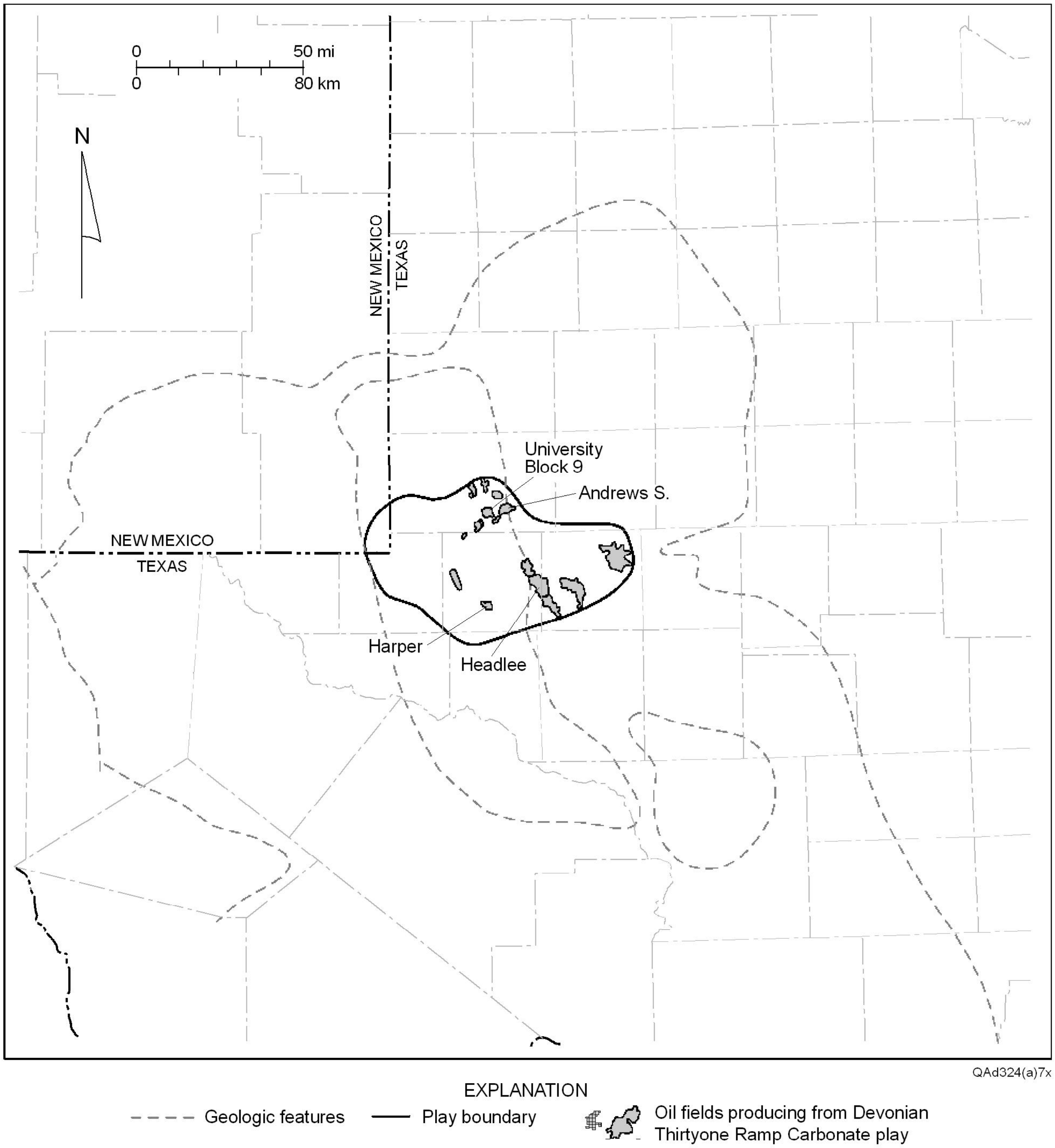


Figure 23. Map showing play boundary and the distribution of major reservoirs of the Thirtyone Carbonate Ramp play.

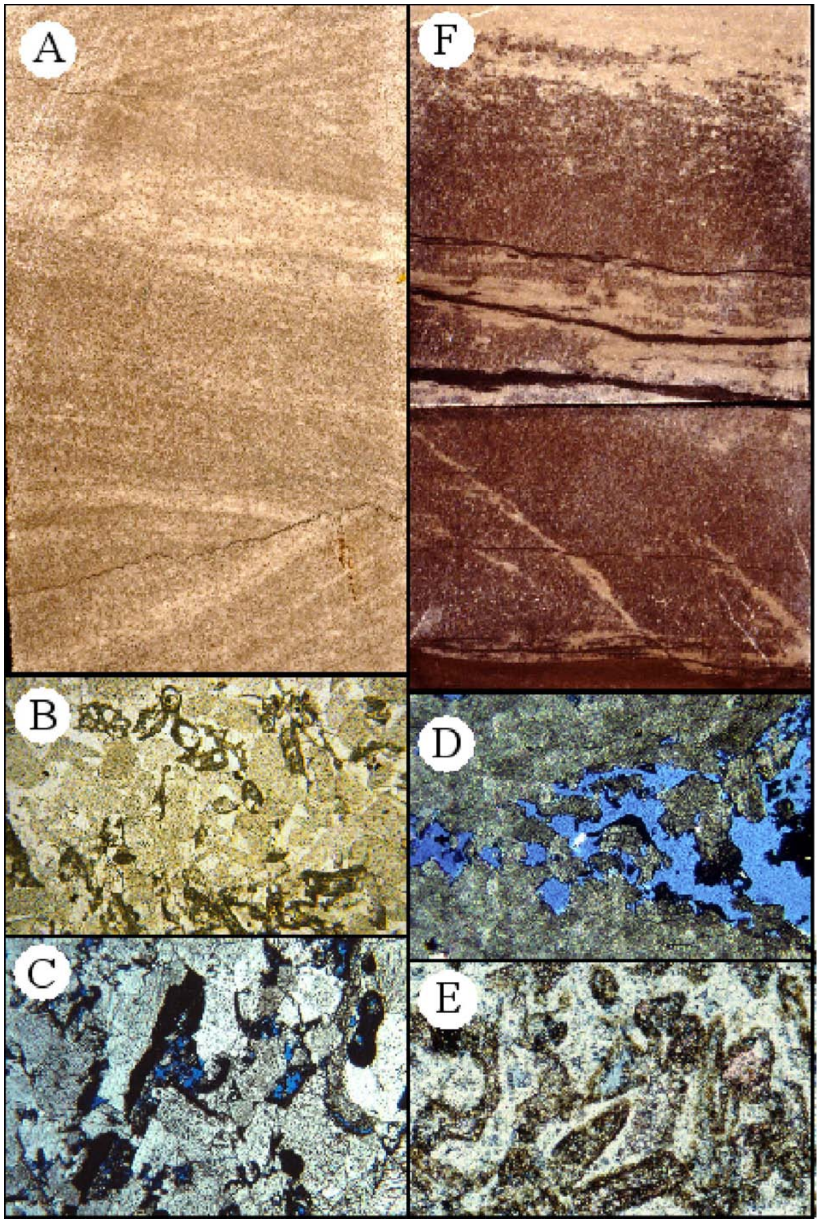


Figure. 24. Typical facies of the Thirtyone Ramp Carbonate play. A. Slab of crinoid grainstone facies showing cross laminations. Depth: 11,783 ft. Getty Headlee Unit No. 10-6, Midland County, Texas. B. Thin-section photomicrograph of crinoid/bryozoan grainstone. Note that pore space is entirely occluded by pore-filling syntaxial cements. Depth: 10,648 ft. Sinclair Emma Cowden No. 36, Andrews County, Texas. C. Thin-section photomicrograph of syntaxially cemented, crinoid/bryozoan grainstone. Note minor pore space associated with leached mud and within bryozoans. Depth: 10,519 ft. ARCO University No. 9 B-4, Andrews County, Texas. D. Thin-section photomicrograph of coarse crystalline dolostone. Note extensive interparticle pore space. Depth: 10,516 ft. ARCO University No. 9 B-4. E. Thin-section photomicrograph of siliceous skeletal packstone. Note interparticle porosity associated with siliceous matrix. Depth: 10,472 ft. ARCO University No. 9 B-4.F. Slab showing porous crinoid packstone overlain by nonporous grainstone. Depth: 11,798 ft. Getty Headlee Unit No. 10-6, Midland County, Texas.

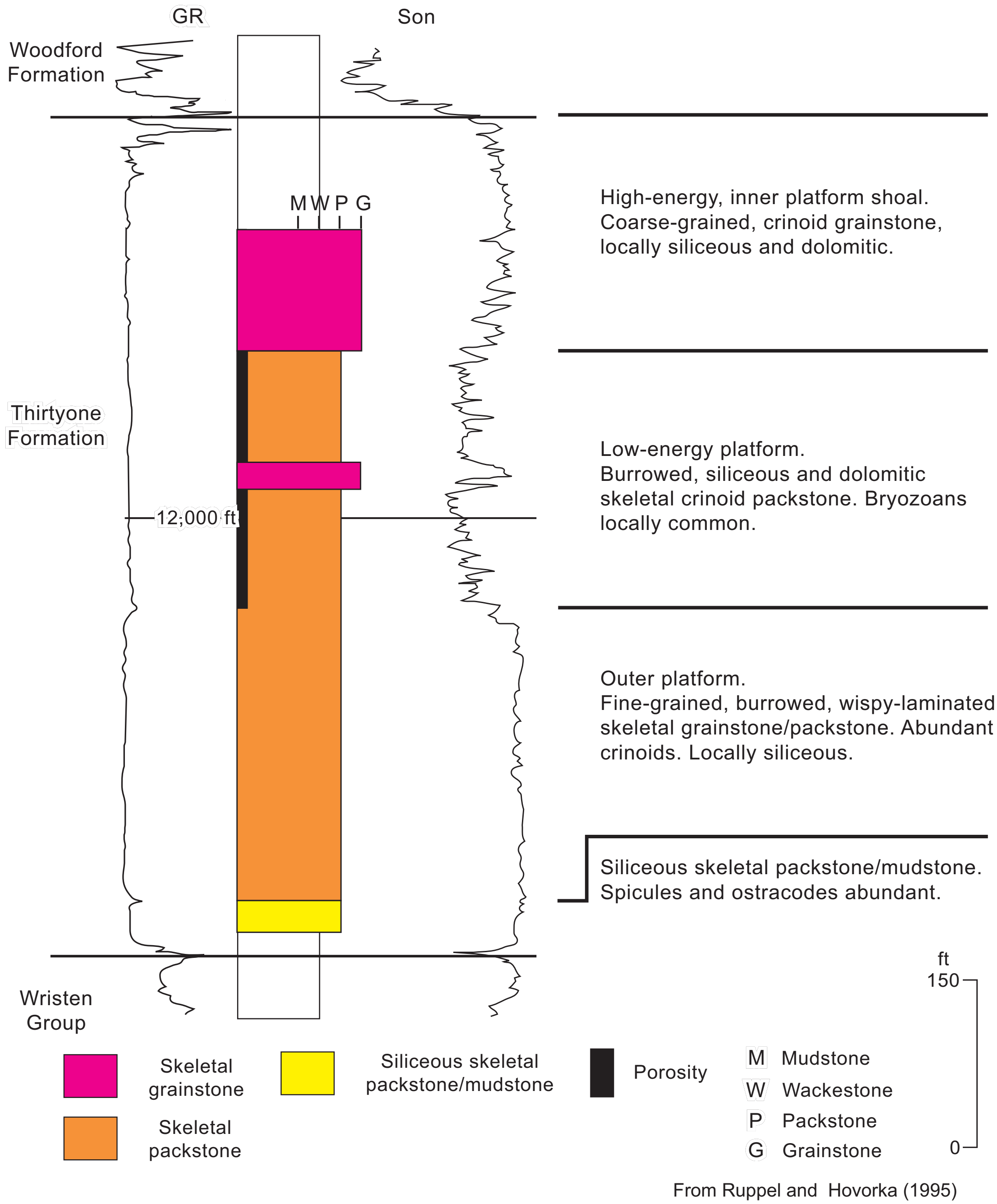


Figure 25. Composite log from Headlee field showing typical development of Thirtyone carbonate section in eastern and southeastern part of area. From Ruppel and Hovorka (1995a).

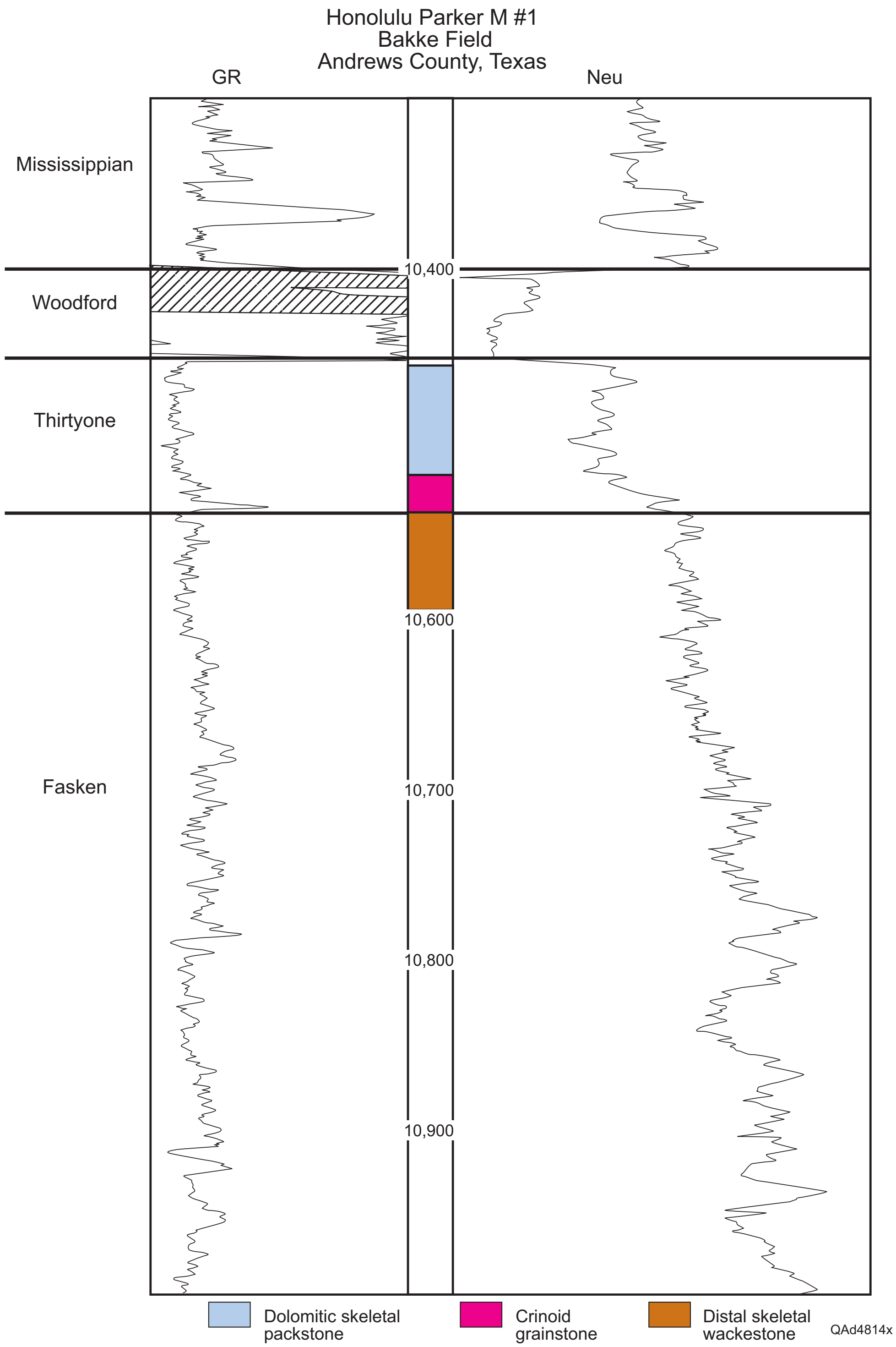


Figure 26. Typical development of facies and porosity in upper Thirtyone ramp carbonates. Note that essentially all reservoir porosity in the well is associated with dolomitized Thirtyone skeletal packstones. Bakke Field. Honolulu Parker M No. 1, Andrews County, Texas.

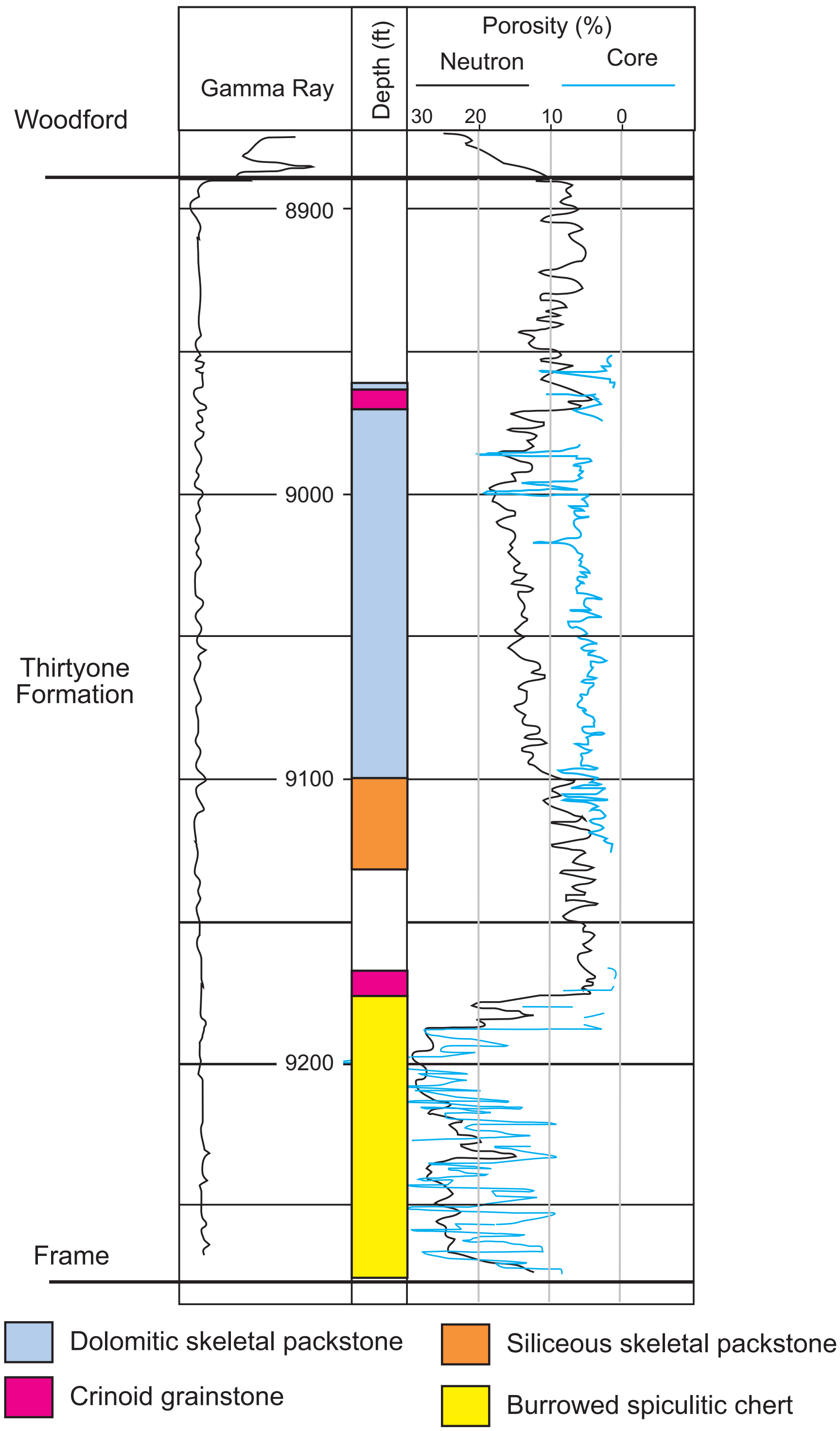


Figure 27. Facies development and porosity in upper Thirtyone ramp carbonates at Bedford field. Porosity in the upper Thirtyone is associated with dolomitized, graded, skeletal packstones. Note that much higher porosity is developed in Thirtyone deep-water cherts of the lower Thirtyone Formation. Bedford field, Shell Ratliff Bedford No. 20, Andrews County, Texas.

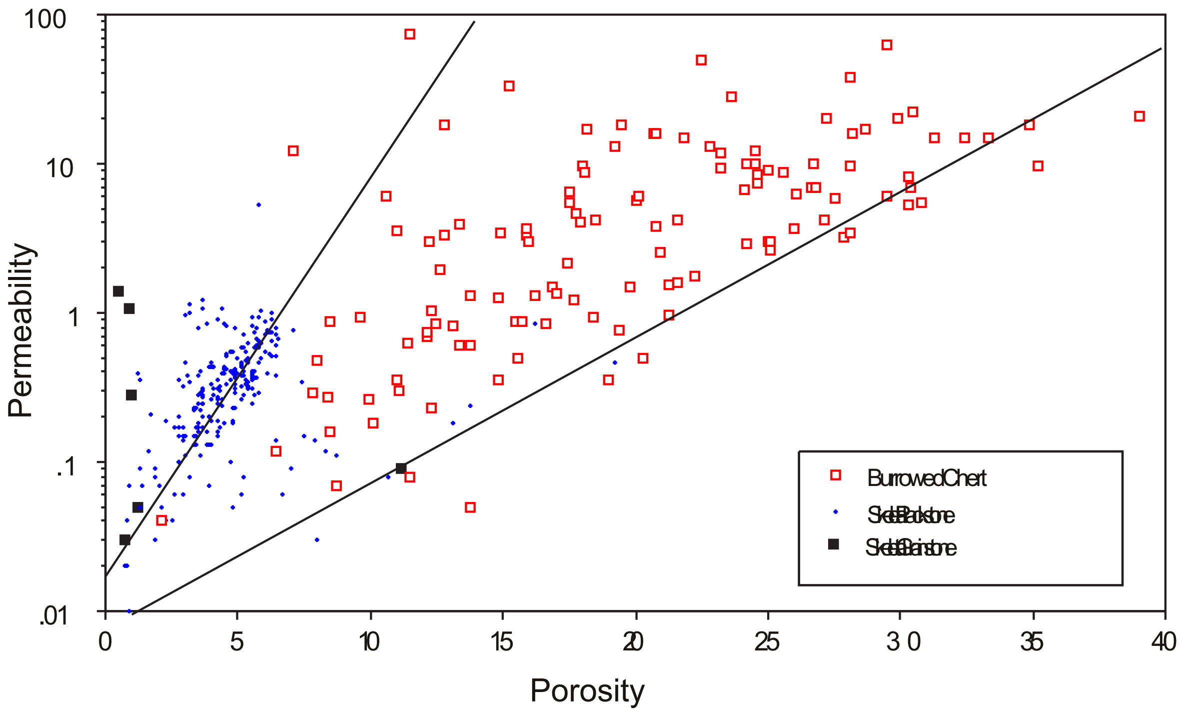


Figure 28. Porosity/permeability relationships in the Thirtyone section at Bedford field. Despite their low porosity and permeability, Thirtyone carbonates are productive at Bedford.