MIDDLE PERMIAN BASINAL SILICICLASTIC DEPOSITION IN THE DELAWARE BASIN: THE DELAWARE MOUNTAIN GROUP (GUADALUPIAN)

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ABSTRACT

The Delaware Mountain Group (DMG) of the Delaware Basin of Texas and New Mexico comprises up to 4,500 ft (1,375 m) of Guadalupian-age arkosic to subarkosic sandstone, siltstone, and detrital limestone that was deposited in deep water, mainly during lowstand and early transgressive sea-level stages. Primary depositional processes include density-current flow and suspension settling. Regionally extensive organic-rich siltstones record largely highstand deposition and provided hydrocarbons to sandstone reservoirs. Authigenic illite and chlorite are present, but there is little detrital clay. The DMG is restricted to the slope and basin, was sourced from shelf-sediment source areas through poorly exposed incised valleys, and generally is not depositionally correlative with siliciclastics on the shelf. Interbedded carbonate units thicken shelfward and are typically correlative to “reef”-margin-complex carbonate sources along the shelf margin.

Gamma-ray and porosity logs are useful for differentiating primary sandstone, siltstone, and carbonate end-member rock types, although application of outcrop models is critical for differentiating channel, levee, and splay sandstone subfacies using well logs.

The basin succession is formally divided into the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations. The Brushy Canyon, the coarsest grained, contains little detrital carbonate. The other formations contain prominent carbonate members that are used extensively for subsurface correlations and to subdivide the intervals into informally named productive units. The DMG has been interpreted to contain 28 high-frequency depositional sequences aggregated into 6 composite sequences.

The DMG contains more than 260 hydrocarbon reservoirs at 900 to 9,820 ft depth (274–2,993 m) that have produced more than 262.2 MMbbl of oil and 280,517,264 Mcf of gas from channel/lobe complexes and associated levee and splay facies deposited by turbidites. Hydrocarbon source beds are intraformational, organic-rich siltstones that accumulated by suspension settling between episodes of turbidite activity. Hydrocarbon traps include both stratigraphic and structural components. Stratigraphic traps are formed where reservoir sandstone facies pinch out laterally into siltstone. Siltstone and calcite cements form stratigraphic seals. Hydrocarbon-bearing and water-bearing intervals alternate stratigraphically. Hydrocarbon migration is focused into stratigraphic traps that are located favorably on structural highs or in updip positions on structural ramps.

Structure is variably controlled by four processes, two of which are regional and two of which are reservoir-scale: (1) basin-slope rise toward shelf near shelf margins, (2) Laramide-generated regional eastward dip, (3) compaction over subjacent sandbodies, and (4) slumping in areas that are updip of reservoirs. Primary production is by solution-gas drive, and recovery efficiency is less than 15 percent in most reservoirs.

Development challenges include delineating productive sandbody geometries, controlling hydrofracture extension to avoid connecting water-bearing with hydrocarbon-productive intervals, preventing formation damage from interactions between acid treatments and Fe-bearing chlorite, and optimizing location of injection wells in continuous-permeability fields with production wells for EOR operations.

INTRODUCTION

The Guadalupian-age Delaware Mountain Group (DMG) of the Delaware Basin consists of as much as 4,500 ft (1,372 m) of stratigraphically cyclic, mixed siliciclastic/carbonate slope, and basin-floor strata (Dutton and others, 2005). The section hosts many economically important hydrocarbon reservoirs. Most of the hydrocarbon production has been from siliciclastic-dominated units in the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations, with secondary production from associated detrital carbonate strata (fig. 1). More than 262.2 million barrels (MMbbl) of 39° gravity (production-weighted average) oil has been produced from approximately 267 reservoirs, within which 65 percent of the 2,103 total wells were producing in 2003. The section has also produced 280,517,264 thousand cubic feet (Mcf) of gas from approximately 95 reservoirs, within which 63 percent of the 183 total wells were producing in 2003. Production depths range from 900 to 9,820 ft (274–2,993 m) (Railroad Commission of Texas, 2003). Despite the economic significance of the DMG, most published technical information regarding its stratigraphy, lithology, and reservoir character is derived from geographically severely limited outcrop exposures and a few field locations.

The Ochoan Series is also present in the Delaware Basin and includes, from older to younger, the Castile, Salado, Rustler, and Dewey Lake Formations. However, only the Castile Formation is restricted to the basin; therefore, stratigraphy and sedimentology of the Salado, Rustler, and Dewey Lake Formations are discussed in the section of this report that deals with the Guadalupian and Ochoan shelf section. The Ochoan in the Delaware Basin hosts a few small reservoirs in the Castile and Rustler intervals. More than 186,403 bbl of 36.26^{o} (production-weighted average) oil has been produced from approximately eight reservoirs, within which no wells were producing in 2003. The section has also produced 429,348 Mcf of gas from approximately six reservoirs. Only three wells were producing from one Rustler reservoir in 2003. Production depths that include all historical reservoirs range from 380 to 3,704 ft (Railroad Commission of Texas, 2003). The importance of the Ochoan to hydrocarbon issues in the Permian Basin is related to its generally low permeability and in its role as a regional top seal for the Delaware Mountain Group in the Delaware Basin. It has also been known to guide hydrocarbon migration from basinal source beds into reservoirs located on the Central Basin Platform and Northwest Shelf (Hills, 1972).

This report summarizes published information on the DMG, whose literature spans nearly 100 years—from initial reconnaissance expeditions early in the 20th century through definitive geologic formational characterizations in the 1940's, development of modern depositional and sequence stratigraphic models in the 1990's and early 2000's, and ongoing investigations of DMG petroleum systems. The DMG, a significant producer of hydrocarbons, still contains abundant resources, although its depositional and diagenetic characteristics are complex. The objective in this report is to provide a basis from which to advance our understanding of the geologic succession and to stimulate continued and more efficient exploitation of the resources of the DMG.

PREVIOUS WORK

The Delaware Mountain Group succession was first described by Richardson (1904), who described it as a formation that included the Bone Spring Limestone. He noted the lateral geometric variability in sandstone strata, which later were recognized as variations among depositional facies. Beede (1924) recognized a lithologic tripartite character in the Delaware Mountain sandstone interval, which formed the basis of its subsequent subdivision into three formations. King (1942) raised the classification of the section to group status and named the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations. King (1942) raised the Bone Spring to formation rank, although its Leonardian age had been recognized previously (King and King, 1929), at which time it was also suggested that the Bone Spring be divided from the Delaware Mountain Formation because the two formations were obviously separated by a pronounced unconformity and were dissimilar lithologically. King (1948) produced several excellent cross sections in the Guadalupe Mountains that are accepted as largely accurate, even after 6 decades of additional investigation by many workers.

Hull (1957) discussed the petrogenesis of the Delaware Mountain sandstones, pointed out the generally finer grained character of the Delaware sands compared with mineralogically similar, coeval sandstones on the surrounding shelves (also recognized by King, 1942), interpreted the carbonate members as including reef detritus, and suggested a turbidite model for Delaware Basin deposition. Jacka and others (1968) summarized previous investigations of Delaware Mountain sedimentation that largely concluded that the section recorded deep-sea fan deposition with submarine-canyon feeder systems, a conclusion reinforced by Meissner (1972). Payne (1976) described and interpreted siliciclastic subfacies from the Bell Canyon and proposed sand-transport directions from shelf areas and estimated relative importance of different source areas. Fischer and Sarnthein (1988) suggested an eolian source on the shelf for Delaware Mountain basinal siliciclastics. Harms and Brady (1996) summarized the several hypotheses historically suggested for deposition of the deep-water succession that, most importantly, contrast turbidite mechanisms with saline density-current mechanisms. Hills (1984) produced west-east cross sections for the Delaware Basin, suggested that the paleogeographically closed character of the Delaware Basin promoted accumulation of organic material that eventually generated hydrocarbons, and that the Castile evaporites overlying the Delaware Mountain effectively preserved hydrocarbons and guided hydrocarbon migration into reservoirs in the surrounding shelves. Facies models were developed from outcrop, core, and well log analyses by Gardner (1992, 1997a), Gardner and Sonnenfeld (1996), Barton (1997), Barton and Dutton (1999), Beaubouef and others (1999), Dutton and others (1999), Carr and Gardner (2000), and Gardner and Borer (2000). Sequence stratigraphic relationships in the Delaware Mountains were investigated and described by Gardner (1992, 1997b) and Kerans and Kempter (2002). Particularly useful discussions of hydrocarbon generation, source rocks, and reservoirs that were developed in Delaware Mountain strata include Payne (1976), Jacka (1979), Hayes and Tieh (1992a), Hamilton and Hunt (1996), May (1996), Gardner (1997b), Dutton and others (1999, 2000, 2003), Montgomery and others (1999, 2000), and Justman and Broadhead (2000). Impact of Delaware Mountain clay authigenesis on reservoir development was discussed by Walling and others (1992). Enhanced oil recovery (EOR) in certain Delaware Mountain Group fields was discussed by Kirkpatrick and others (1985), Pittaway and Rosato (1991), Dutton and others (1999, 2003).

REGIONAL SETTING

The Delaware Basin during deposition of the Delaware Mountain Group was a deep-water basin bounded by carbonate-ramp (San Andres and Grayburg) and carbonate-rim (Goat Seep and Capitan) margins that developed on the western edge of the Central Basin Platform, the Northwest Shelf, and the Diablo Platform. The primary connection between the Delaware Basin intracratonic sea and the open ocean was through the Hovey Channel (fig. 2). Most deposition in the area during sea-level highstands was on the shelves and consisted of the mixed carbonate-siliciclastic San Andres Formation and Artesia Group (Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations). The Delaware Mountain Group shelf-derived siliciclastics and shelf-margin-derived detrital carbonates were deposited during intermittent sea-level lowstands (for example, Silver and Todd, 1969; Meissner, 1972). Basin subsidence outpaced sediment supply such that deep-water conditions were maintained until the close of the Guadalupian, after which Ochoan evaporites filled the basin and eventually blanketed the entire greater Permian Basin area. Onset of basin evaporite accumulation corresponded with demise of the Capitan Reef system and is hypothesized to mark closing of the Hovey Channel, which promoted progressive restriction of the basin from marine influx (King, 1948).

FACIES AND SEDIMENTOLOGY OF THE DELAWARE MOUNTAIN GROUP

Distribution and Age

The Delaware Mountain Group (DMG) is Guadalupian in age, according to fauna described by Girty (1908). The DMG includes the uppermost occurrences of Guadalupian fauna in the Delaware Basin (Lang, 1937) and the three formations of the Delaware Mountain Group were defined to represent the early, middle, and late subdivisions, respectively, of Guadalupian time (King, 1948).

The DMG is formally divided into three formations. From base to top they are the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations. These names, assigned by King (1942), reflect the names of canyons in the Delaware Mountains. The formations are lithologically similar except that the Brushy Canyon contains abundant medium-grained channelized sandstone beds. The other formations are significantly finer grained and dominated by laminated bedding in the outcrop area, although these differences may mark a shifting toward the east and southeast of shelf-edge siliciclastic storage areas that sourced Cherry Canyon and Bell Canyon deposition. The boundary in outcrop between the Brushy Canyon and the Cherry Canyon was placed at the top of the uppermost medium-grained sandstone bed in the Brushy (King, 1942). The contact with the overlying Cherry Canyon is unconformable (fig. 3), and the lower part of the Cherry Canyon composes the Cherry Canyon (sandstone) Tongue. Whereas the Brushy Canyon, most of the Cherry Canyon, and the Bell Canyon are restricted to the Delaware Basin, the Cherry Canyon Tongue extends well onto the shelf and pinches out approximately 6 mi shelfward of the stratigraphically superjacent Goat Seep shelf margin (Kerans and Kempter, 2002). Goat Seep and Capitan shelf-margin carbonates form the updip limits of subsequently deposited Delaware Mountain successions.

The Brushy also lacks the prominent carbonate members that are characteristic of the Cherry Canyon and Bell Canyon intervals. Carbonate members were named by King (1942) for minor geographic features such as small canyons, hills, springs, or houses, where the correspondingly named strata were described. The Hegler (limestone) Member of the Bell Canyon is used to divide the Bell Canyon from the underlying Cherry Canyon. Other carbonate members are used to subdivide the Cherry Canyon (South Wells, Getaway, and Manzanita) and the Bell Canyon (Hegler, Pinery, Rader, McCombs, and Lamar) (fig. 1). South Wells and Getaway members of the Cherry Canyon are lenticular, whereas the Manzanita is more laterally persistent. Hegler, Pinery, Rader, McCombs, and Lamar carbonate members of the Bell Canyon are thinner overall and more laterally persistent than are Cherry Canyon carbonate members. All carbonate members thin basinward from their updip pinch-outs near the shelf margin. All three DMG formations are recognized throughout the Delaware Basin, although they may be more problematic to distinguish in parts of the basin where carbonate interbeds are thin or absent.

It was recognized early (for example, Cartwright, 1930) that the Delaware Mountain Group is a sea-level-lowstand wedge of sedimentary rock that is restricted to the Delaware Basin. Todd (1976) considered the Spraberry basinal sandstones (presumably the upper Spraberry of later usage; for example, Handford, 1981) of the Midland Basin to be Brushy Canyon equivalents and Guadalupian in age. Jeary (1978) and Handford (1981) concluded a Leonardian age for the Spraberry. If Jeary (1978) and Handford (1981) are correct, there may be no deep-water equivalents for the Delaware Mountain Group elsewhere in the Permian Basin. However, Ruppel and Park (2002) demonstrated the existence of Brushy-Canyon-equivalent lowstand-wedge deposits in the Midland Basin, as have other authors.

Facies

The Brushy Canyon was deposited upon an unconformity that developed on Leonardian-age (King, 1942, 1948) Bone Spring carbonates. The unconformity is locally marked on the

Western Escarpment of the Guadalupes, where the Cutoff and Victorio Peak Formations are truncated beneath the Brushy Canyon. On the flanks of the Bone Spring Flexure, an area between El Capitan and Shummard Peak in the Guadalupe Mountains where the top of the Bone Spring rises more than 1,000 ft, the outcropping basal 100 ft of the Brushy Canyon consists of conglomerates as much as 10 ft thick, with interbedded sandstone, limestone, and thinly to thickly bedded sandstone. Conglomerates are composed of gravel, cobbles, and boulders as much as 4 ft in diameter. Conglomerates include limestone material from the Bone Spring and Victorio Peak Formations. Conglomerate bodies are lenticular (channelized) and absent from higher areas of the flexure where Brushy Canyon sandstones onlap (King, 1948). Conglomerates are not reported from Brushy Canyon intervals in the hydrocarbon-productive areas, which are largely located a minimum of several miles from Delaware Basin shelf margins (figs. 2, 4).

Dominant facies in the Delaware Mountain Group are arkosic to subarkosic sandstones and siltstones (for example, Hull, 1957; Kane, 1992; Thomerson and Asquith, 1992) (fig. 5). Sediment texture ranges mainly between coarse silt and very fine grained sand, although fine-grained sand is found in the Brushy Canyon. Shales are rare. Finer grained intervals, even those that contain several percent organic carbon, are properly classified as siltstone (Thomerson and Asquith, 1992). Siltstones compose organic-rich (up to 46 percent total organic content [TOC]; average 2.36 percent TOC) and organic-poor subfacies (average 0.52 percent TOC) (Sageman and others, 1998; Wegner and others, 1998; Dutton and others, 1999) (fig. 6) Clay content is dominantly authigenic illite and chlorite (fig. 5) rather than detrital and is not abundant (for example, 11.6 percent average in the Brushy Canyon, Lea County) (Green and others, 1996).

Siliciclastic sources are updip of and on the surrounding shelves, given the lithologic similarities between the DMG and Guadalupian clastic strata on the shelves (King, 1948; Hull, 1957). Carbonates are volumetrically of secondary importance and increase in prominence shelfward. Limestone is most common; however, some diagenetic dolomite is present. Carbonates are dominantly detrital and derived from the lower San Andres/Victorio Peak ramp margin (Brushy Canyon), Grayburg ramp-margin (lower Cherry Canyon), and Goat Seep (upper Cherry Canyon) and Capitan (Bell Canyon) rimmed shelf-margin complexes (Beaubouef and others, 1999; Kerans and Kempter, 2002).

Depositional Setting and Facies Architecture

DMG facies successions are typical of those found in deep basins in areas relatively proximal to carbonate-shelf margins. Sandstones compose channel, levee, overbank-splay, and lobe subfacies (for example, Galloway and Hobday, 1996; Gardner and Sonnenfeld, 1996; Beaubouef and others, 1999; Dutton and others, 1999, 2003) (figs. 7–10) that were deposited as sea-level-lowstand submarine fans basinward of the shelf-margin break and as lowstand wedges shelfward of ramp margins (Beaubouef and others, 1999). Turbidity flow appears to be the primary transport mechanism for coarser sediment (sand and shelf-margin carbonate debris) (for example, Hull, 1957; Jacka and others, 1968; Silver and Todd, 1969; Meissner, 1972; Zeldt and Rosen, 1995), whereas suspension settling may be an important mechanism for silt-sized sediment, especially the organic content (Payne, 1976). Eolian transport of silt has been proposed as a mechanism for conveyance of silt to the basin margins (for example, Fischer and Sarnthein, 1988; Gardner, 1992). Margins of the Guadalupian platform are well defined by the change from Lower Guadalupian (San Andres Formation) ramp and Upper Guadalupian (Goat Seep/Capitan) reef facies to slope, carbonate-debris-rich facies of the carbonate members of the Delaware Mountain Group (figs. 1, 11). Because of the limited availability of cores through these slope and basin-floor complexes, understanding of their paleoenvironmental setting and facies geometries is greatly facilitated by analyses of the well-exposed Delaware Mountain Group outcrops in the Delaware Mountains (figs. 12, 13).

Facies architecture is controlled by relative sea level and position along the shelf-margin to basin-floor profile. During falling sea level the slope is incised by submarine erosion. Incised channels are (1) barren as long as all throughgoing sediment bypasses the location, (2) containers of laterally discontinuous conglomerates as lag, or (3) blanketed by thin accumulations of silt or sand that mark the waning stages of throughgoing turbidity-current deposition (Beaubouef and others, 1999). Potential for net deposition of sandstone soon following incision increases for basinward locations. Incised channels that are initially bypassed by sediment are eventually back filled.

Channel-levee-complex sandstone deposits are variably sinuous (figs. 14, 15) and asymmetrical in cross section normal to flow direction. Channel sinuosity generally increases downslope, marking decrease in flow velocity attendant upon decreasing topographic gradients.

Channel-facies geometries and stacking patterns systematically vary according to position along the slope-to-basin-floor profile. On the upper slope, which is constructed largely of laminated siltstone intervals that are deposited during sea-level rise, deep incised channels are less numerous than are shallower channels farther down slope. Upper-slope channel deposits are generally isolated and vertically stacked. Channel fills compose multiple, onlapping strata, thus recording backfilling of incised channels. At the toe of slope, avulsion (channel abandonment) promotes development of laterally offset complexes of amalgamated channel deposits (for example, fig. 16a). In progressively downslope locations on the basin floor, avulsion-prone channel systems bifurcate into channel-levee complexes, and overbank sediments (splays) increase in prominence (fig. 8). Along the basin-floor profile, proximal channelized-fan sedimentation transitions to sheet deposition on lobes. Although approximately sheetlike, sandstone packages in distal positions are still deposited in compensatory fashion (Beaubouef and others, 1999) (fig. 8). The overall thickness distribution of individual Delaware sandstone intervals (that is, bounded top and bottom by laterally extensive siltstone sheets) is marked by dominance of channel facies along the axes of maximum thickness (fig. 16b).

Thin, laterally discontinuous siltstones are interlaminated with sandstones in overbank-splay deposits. In many cases siltstones blanket the sandstone deposits that remain after channel abandonment. However, the more important siltstones, in terms of reservoir development, are laterally extensive sheetlike organic-rich and organ-poor accumulations that stratigraphically separate successions of channelized sandstone deposits on the lowstand fan complex. Brushy Canyon correlative siltstone units have been mapped over distances exceeding 50 mi in southern New Mexico (Broadhead and Justman, 2000). In some places, siltstones compose nearly 80 percent of the Delaware Mountain Group (Hayes and Tieh, 1992b). Particularly thick siltstone accumulations (lowstand wedge) occurred during the latest stages of lowstand deposition, when relative sea level rose onto the shelf edge and sand transport to the basin largely ceased (Beaubouef and others, 1999).

DMG carbonate units are constructed largely of allochthonous debris derived from the outer shelf and shelf margins (King, 1948). Rock types range from lutite to boulder conglomerates. Conglomerates from Brushy Canyon carbonate units occur mainly as lag on the bedrock floors of incised channels at the shelf margin and generally do not compose a significant fraction of the formation in more basinward areas (King, 1948; Beaubouef and others, 1999). No carbonate members are formally recognized in the Brushy Canyon or Cherry Canyon sandstone tongue. In the basin-restricted Cherry Canyon and Bell Canyon Formations, however, widespread carbonate-bearing intervals are present and are formally recognized as members (King, 1948). The geometry of carbonate members ranges from lenticular in older units to more sheetlike forms in the younger units (King, 1948). Although conspicuous for their carbonate content, these units comprise cyclic interbeds of carbonate and siliciclastic sandstone and siltstone; carbonate-dominated beds may represent less than half of the thickness of the member (fig. 17).

Diagenesis

The most economically important diagenetic processes in the Delaware Mountain Group are (1) feldspar dissolution, (2) feldspar and quartz authigenesis, (3) clay authigenesis, and (4) calcite cementation. Similar to processes observed in Guadalupian shelf siliciclastics, DMG siliciclastics show evidence of K-feldspar dissolution, which imparts a component of secondary porosity to reservoir facies, although initial porosity enhancement may be destroyed by subsequent collapse of remaining crystal elements. Dissolution of feldspar and quartz (the latter evidenced by sutured contacts between detrital quartz grains) created fluids that resulted in feldspar and quartz overgrowths elsewhere in DMG sandstones, reducing already impoverished permeability (Behnken, 1996). Clay authigenesis (chlorite and illite) probably had the greatest single effect on reservoir quality in DMG sandstones (Green and others, 1996; Thomerson and Asquith, 1992). Whisker- and weblike clays dissect pore space, illite/smectite species may swell when contacted by drilling fluids, and chlorites may decompose in the presence of acidic solutions to form pore-clogging, insoluble, Fe-hydroxide gels if the acids are left in the formation long enough for the pH to rise above 2.2 (Spain, 1992; Behnken, 1996; Green and others, 1996). No stratigraphic or lateral systematic variations in clay mineralogy have been defined in the DMG, although Thompkins (1981, cited in Walling and others, 1992) noted changes in chlorite fabric with depth. Calcite cements occur in thin stratiform accumulations that impart a component vertical porosity and permeability heterogeneity to DMG facies (Dutton and others, 1999) (fig. 18). Calcite cement appears to be most abundant in finer grained siliciclastics that are outside of channel-sandstone subfacies (Spain, 1992; Dutton and others, 1999) (fig. 19).

Hayes and Tieh (1992a) recognized a four-phase sequence of diagenesis in Delaware Mountain sandstones from Reeves and Eddy Counties: (1) early cementation by carbonate, sulfate, and halite that preserved significant intergranular porosity during early burial; (2) dissolution of cements and detrital minerals to produce secondary porosity; (3) chlorite authigenesis that dissected porosity; and (4) authigenesis of dolomite, feldspar, Ti-oxides, and illite. Although Hayes and Tieh (1992a) did not recognize illite/smectite as being as prominent in their studies from Waha field and Big Eddy Unit (Reeves and Eddy Counties), Thomerson and Asquith (1992) in their study of Hat Mesa field (Lea County) and Behnken (1996) in his study of Nash Draw field (Eddy County) did. Walling and others (1992) proposed that chlorite evolved from smectitic precursors and that chlorite may revert to expansive and migratory forms in the presence of some fluids used in well development and completion.

SUBSURFACE RECOGNITION AND CORRELATION

Identification of DMG formation boundaries in the subsurface is based largely on relationships between the formations observed in Guadalupe Mountain outcrops that were described by King (1948). One of the most useful subsurface cross sections based on well log correlations is found in Meissner (1972). Boundary correlations are lithostratigraphic. The Delaware Mountain Group is overlain by the evaporite-dominated Castile Formation, which produces a relatively low gamma-ray response and high acoustic velocity compared with those of the feldspathic siliciclastics of the DMG (Payne, 1976; Dutton and others, 1997, 1999) (fig. 20). The Castile is characterized by bed thickness that is distinctively greater than that of any of the beds in the underlying Delaware Mountain Group (fig. 10).

The base of the Delaware Mountain Group (base of Brushy Canyon Formation) is defined at the base of the lowermost siliciclastic interval that overlies the thick carbonate interval assigned to the Bone Spring limestone. This relationship appears to be basinwide. The Bone Spring typically has a gamma-ray signature that is distinctively lower than that of the siliciclastic-dominated DMG and has comparatively greater resistivity, density, and acoustic velocity. The Bone Spring strata also exhibit greater carbonate-bed thickness than do DMG strata.

The boundary between Cherry and Bell Canyons is extrapolated into the subsurface from relationships observed in the Guadalupe and Delaware Mountain outcrops. The Cherry Canyon/Bell Canyon boundary is between the Manzanita and Hegler Limestone Members in outcrop. These strata have been interpreted into nearby wells (for example King, 1948; Tyrrell and others, 2004) (figs. 17, 21) and form the link between outcrop-defined formation boundaries and the subsurface. In particular, a volcanic ash mapped in the outcropping Manzanita succession by King (1948) has been interpreted as regionally widespread and correlated extensively into the subsurface (BCB marker of Tyrrell and others, 2004) (figs. 17, 21).

The boundary between Brushy and Cherry Canyons was defined by Gardner and Sonnenfeld (1996) to be an organic-rich siltstone (lutite) similar to that observed between the Brushy Canyon and the Bone Spring. Most workers place the boundary at the base of the organic siltstone interval (for example, May, 1996) (fig. 22), which is consistent with King's (1948) original pick at the top of the uppermost sandstone on the Brushy Canyon outcrop. Gamma-ray-log responses for this facies are typically high (fig. 22). These units record transgressive and highstand basin starvation where deposition of windblown silt and marine plankton dominated. The organic-rich siltstones and interbedded carbonate probably record the transgressive leg of late Brushy Canyon deposition and, in light of sequence stratigraphic analysis, might better be placed in the Brushy Canyon Formation.

Most DMG carbonates also have gamma-ray values that are lower than those of most DMG siliciclastics, the exceptions being thinly bedded examples that are interbedded with siliciclastics. A more reliable log for carbonate identification is the density log, however, which indicates much higher densities for the carbonate-dominated strata (figs. 17, 20) than for the more porous siliciclastics. Siltstones have significantly higher gamma-ray values than do sandstones, and organic-rich siltstones (which often include a fraction of volcanic ash) show the highest gamma-ray values of all (for example, fig. 10a).

Sandbodies can be discriminated by their overall lower radioactivity compared with that of the siltstones that envelop them. Widespread siltstones, especially those that are organic rich, are useful for correlation and allow confident mapping of correlative sandstones. Discrimination of DMG sandstone subfacies is more problematic and attempts to define log facies for channel, splay, levee, and lobe deposits that have been largely model driven (for example, Dutton and others, 1999). Interpreted channel subfacies tend to show little gamma-ray variation, such as might be expected in less massive subfacies. Levee deposits have been interpreted where log responses suggest some interbedding of coarser and finer grained siliciclastics, the finer grained of which contain marginally more clay and feldspar and, thus, are slightly more radioactive. Outcrops indicate that levees are most common where sandbodies thin laterally, and this criterion is useful for interpreting the probability of levee development.

The Brushy Canyon/Cherry Canyon boundary in outcrop is picked at the top of the uppermost medium-grained sandstone interpreted to be in the Brushy Canyon (for example, fig. 6). However, the textural fineness of Cherry Canyon compared with that of Brushy Canyon is probably somewhat a function of evolving paleogeography. By Cherry Canyon deposition, sand depocenters had begun to shift toward the east from positions that were prominent during Brushy Canyon deposition (fig. 4). In the north part of the Delaware Basin the Brushy contains no significant carbonate except at the bases of incised channels on the Bone Spring shelf margin. Along the Central Basin Platform margin prominent Brushy Canyon carbonate intervals are evident within the lower part of the section, although they are subordinate in thickness to those in the Cherry Canyon and Bell Canyon.

The Cherry Canyon/Bell Canyon boundary is defined in outcrop at the base of the Hegler limestone member, a pick that King (1948) considered to be correlative to the lowermost part of the Capitan shelf margin. Acceptance of this boundary places the Getaway, South Wells, and Manzanita carbonate members entirely within the Cherry Canyon. Further, the Manzanita was correlated by King (1948) into the Shattuck sandstone member of the Queen. This correlation places the Manzanita stratigraphically between the Goat Seep and Capitan shelf-margin successions. Some subsequent writers agreed with King’s correlation (for example, Newell and others, 1953), although some placed the Manzanita at the top of Cherry Canyon (for example, Kerans and Kempter, 2002; Tyrrell and others, 2004) (fig. 11). Others suggested that the Manzanita correlates at least partly into the Capitan (for example, McRae, 1995a; Beaubouef and others, 1999).

There is some uncertainty concerning the stratigraphic equivalence of the Manzanita to either the Goat Seep or Capitan margins. Tyrrell and others (2004) correctly pointed out the potential ambiguities inherent in using only well log criteria for correlations of the Manzanita, which can lead to its correlation into the Capitan in some areas in the north part of the basin, and into the Goat Seep in other areas (fig. 21). The root of the problem may well be that carbonate members and the shelf-margin carbonates are significantly diachronous; thus, lithostratigraphic correlations are not always justified. Carbonate intervals identified as Manzanita may be equivalent to the Goat Seep in some locations and to the Capitan in others.

The top of the DMG (Bell Canyon Formation) is a relatively straightforward pick on the base of the Castile evaporites (anhydrite and calcite), the latter of which is expressed by a regionally extensive, thick interval of very low radioactivity on a gamma-ray log and generally high sonic velocity on an acoustic log (figs. 10, 20).

DEPOSITIONAL MODELS FOR THE DELAWARE MOUNTAIN GROUP

Water Depth

The presence in outcrops of texturally coarse, rippled and cross-laminated, channelized sandstone with current-oriented fossils prompted King (1942, 1948) to interpret the Brushy Canyon as having been deposited under "agitated" conditions and, thus, was an overall shallow-water deposit. King recognized alterations between high-energy and low-energy deposits; however, he did not think that this sedimentary cyclicity indicated significantly varying water depths. He drew similar conclusions for the lower half of the Cherry Canyon, including the carbonate-bearing intervals. However, he interpreted the largely unchannelized upper part of the Cherry Canyon as recording overall deepening of the depositional environment.

It is important to appreciate that King was describing data compiled near the shelf margin of the basin, where water depths were shallower than those anticipated toward the basin center. Even so, King (1948) calculated water depths to be more than 1,000 ft (>305 m) in the area on the basis of the difference in altitudes between updip and downdip extents of the outcropping Lamar limestone member at the top of the Bell Canyon.

Based on differences between updip and downdip altitudes of correlative stratigraphic horizons, King's cross sections (1948) suggest an overall deepening of the Delaware Basin sea during DMG accumulation. One explanation is that development of shelf-margin barriers over time more efficiently attenuated continental sediment influx while the basin continued to subside at historically comparable rates, such that sediment influx was increasingly unable to match basin subsidence. Alternatively, or concurrently with barrier development, siliciclastic source areas may have become exhausted or buried (King, 1948). Siliciclastic influx into the basin eventually ceased, as evidenced by post-DMG deposition of the virtually clastic-free Castile Formation that filled the basin to its rim.

Sediment Sources and Depositional Processes

Areas to the northwest, north, and northeast of the Delaware Basin were siliciclastic depocenters during sea-level lowstands throughout the Permian and probable sources to the basin for DMG siliciclastics. The Queen and Yates Formations of the Artesia Group (Tait and others, 1962) are especially notable for their abundant siliciclastic content. Broadhead and Justman (2000) interpreted the source of Brushy Canyon sand to be entirely from the Northwest Shelf. This interpretation is supported by the preferred location of Brushy oilfields in the north part of the basin (fig. 4). DMG depocenters shifted toward the east side of the basin during Cherry and Bell Canyon deposition (figs. 4, 23). The dominant original source of DMG siliciclastics was probably granitic rock in the ancestral Front Range in Colorado, given the high feldspar content of siliciclastic facies (Basham, 1996).

Carbonate sediments appear to have been mainly allochthonous and derived from erosion of carbonate shelf margins. Additional carbonate material was swept from outer-shelf back-reef environments, which bounded the Delaware Basin.

Adams (1936) was one of the first to suggest that the very fine siliciclastics found in the Delaware Mountain Group may have been wind borne (see also Fischer and Sarnthein, 1988; Gardner, 1992). Requirements for eolian sedimentation include (1) the presence of winds of adequate power to entrain significant quantities of sediment and (2) proximity to the basin margin of a large sediment reservoir having textural and pedogenic properties amenable to wind transport. Prevailing wind directions during Guadalupian time have been suggested to be northeasterly, northerly, or northwesterly (present azimuths) on the basis of crossbedding measurement across the southwestern U.S. (Peterson, 1988). These directions are mirrored in the orientations of Delaware Mountain submarine-channel systems.

Most depositional models for the Delaware Mountain Group, including and since the early work of Richardson (1904) and King (1934, 1942, 1948), have recognized that patterns of siliciclastic and carbonated sedimentation record the systematic effects of sea-level changes. However, details of this process are debated. For example, sandstones have been interpreted by many to have been transported into the basin during sea-level lowstand from eolian-dominated ergs near the emergent shelf margin. In this mode, sand was transported to the upper slope by wind and then distributed by waves. Upper-slope sand stores grew until a critical mass was reached and sediment began to slump or avalanche into deeper water and eventually be carried farther into the basin by turbidity currents (for example, Gardner, 1992) or saline-density currents (for example, Harms, 1974). By contrast, Loftin (1996) thought that most of the sand that had accumulated during lowstand was "cannibalized" during transgressions and transported into the basin from shelf-margin ergs that had been stabilized by a rising coastal water table.

Similarly, there has been disagreement regarding the timing of carbonate transported to the basin. Some (for example, Gardner, 1992) concluded that carbonates were shed from platforms during highstand when primary carbonate production was optimal. Others (for example, Loftin, 1996) suggested that carbonate was mobilized by erosive wave energy that impinged on an exposed carbonate-shelf margin during the transgressive leg of sea-level change. Both propositions may be correct. During early stages of transgression, shore lines were probably near the shelf margin and wave base probably impinged on parts of the antecedent carbonate margin.

Most carbonate members of the DMG contain gravels, cobbles, and even boulders, with maximum grain size and interval thickness increasing toward the shelves. These deposits are lenticular and have been suggested to be turbidites. Regardless of the sea level, it appears likely that a steepened carbonate margin facilitated carbonate deposition. This conclusion follows from the observation that the carbonate-poor Brushy Canyon and Cherry Canyon tongues lap onto low-angle lower San Andres and Grayburg ramp margins, whereas the carbonate-"rich" Cherry Canyon and Bell Canyon lap onto higher angle forereef deposits of Goat Seep and Capitan rimmed margins.

DMG sandstones have been interpreted by most to compose channel, levee, overbank splay, and lobe subfacies (Galloway and Hobday, 1996; Beaubouef and others, 1999; Dutton and others, 1999, 2003) deposited by turbidity currents (Hull, 1957; Jacka and others, 1968; Silver and Todd, 1969; Meissner, 1972; Zeldt and Rosen, 1995). The alternate theory of hypersaline density current flow proposed by Harms (1974) has recently been challenged by Kerans and Fitchen (1996) and others. These workers contended that the evaporative hypersaline lagoons invoked by Harms (1974) and Harms and Brady (1996) to generate high-density transport fluids could not have existed on the emergent lower San Andres shelf during mid-San Andres time Brushy Canyon sea-level lowstand.

Siltstones include organic-poor and organic-rich subfacies (Sageman and others, 1998) and have been interpreted to occur in three modes: (1) discontinuous drapes and lenses associated with channel sandstones during turbidity-current deposition, (2) laterally continuous intervals deposited by hemipelagic suspension during channel abandonment, and (3) laterally continuous sandstones interbedded with organic-rich siltstones deposited during basin starvation associated with transgressions (Wegner and others, 1998). Organic-rich siltstones are laterally continuous. Organic content varies generally between 0.5- and 4-percent TOC in Brushy Canyon (Sageman and others, 1998) but is as high as 46 percent in uppermost Bell Canyon (Dutton and others, 1999). Organic material, interpreted as being largely hemipelagic, probably accumulated during highstand periods of reduced sand transport to the basin (Gardner, 1992).

Most workers have generally agreed on the sequence of depositional phases that are recorded in DMG successions (fig. 24). During highstand, deposition in the basin consisted of hemipelagic silts that settled from suspension under conditions of basin-sediment starvation (Gardner, 1992; Beaubouef and others, 1999) (figs. 6, 10a, 25a). Organic matter, which is dominantly of algal (Sageman and others, 1998; Wegner and others, 1998) or bacterial (Sageman and others, 1998) origin, occurs in all DMG siltstone. Organic-rich siltstone records relatively high rates of organic production relative to silt deposition and may indicate either an absolute increase in organic productivity or a decrease in silt influx to the basin. High hydrogen-index values, an indicator of marine organic carbon, is correlated approximately with relative organic-carbon abundance in Brushy Canyon siltstones (Sageman and others, 1998). Assuming that organic carbon deposition over the long term occurred at an approximately continuous rate, higher organic-carbon content implies reduced rates of silt deposition. Reduced silt influxes probably occurred when silt sources were at greater distances from the location of deposition. Thus, more organic-rich siltstones were probably deposited during sea-level highstands.

During lowstand, siliciclastics prograde into the basin as channel, levee, splay, and lobe architectural elements of a basin-fan system. Several pulses of deposition are common and show laterally offset (compensatory) depositional axes (figs. 13, 16, 24). Silt deposition commences in areas of channel abandonment. Intermittent splay deposition may also occur in areas near active channels. As sediment supply from the shelf slows, commonly during sea-level rise, sand depocenters backstep onto the slope until widespread silt deposition dominates.

CYCLICITY AND SEQUENCE STRATIGRAPHY OF THE DELAWARE MOUNTAIN GROUP

Cyclicity

Core and outcrop studies demonstrate that the Delaware Mountain Group in the Permian basin is cyclic at several scales. As discussed earlier, DMG successions include alternating sandstone, siltstone, and organic-rich siltstone on the slopes and on the basin floor and interbedding with basinward-thinning, carbonate-debris-bearing intervals along basin slopes. The largest-scale cycles are the three formations that each exhibit overall upward fining that records third-order sea-level rise. Highest frequency cycles consist of channel-levee-splay-lobe complex, sandstone-dominated intervals that alternate with generally widespread sheets of siltstone. These cycles record updip avulsion and channel abandonment (lobe shifting) or shorter term sea-level rises, during which sandstone-depositional environments migrate upslope. Within lobe deposits, sandstone intervals alternate with siltstone intervals, a characteristic that may record episodic deposition of sand and silt under waning current energy or episodes of density-driven sand deposition followed by relatively quiescent periods, when silt entered the basin either by wind or in hypopycnal plumes. Finally, within the siltstone-dominated intervals, organic-rich beds alternate with organic-poor beds—a pattern that records alternating periods of lower and higher siliciclastic sedimentation, respectively (for example, Sageman and others, 1998).

Sequence Stratigraphy

The sequence stratigraphic approach applied to the Guadalupe Mountain DMG succession by recent workers is based essentially on the "Exxon model" (Mitchem and others, 1977). This model was applied to the Guadalupian shelf carbonate succession in the Permian Basin outcrop by Kerans and Kempter (2002) and to the DMG outcrop slope/basin succession by Gardner (1992), Gardner and Sonnenfeld (1996), and Gardner (1997b). The outcrop-based sequence stratigraphic framework was extended into the subsurface of the Delaware Basin by Kerans and Kempter (2002) and Tyrrell and others (2004).

Delaware Mountain Group Sequences in Outcrop

Although the Delaware Mountain Group has historically been subdivided into three formations (Brushy Canyon, Cherry Canyon, and Bell Canyon), it has been interpreted to comprise the basinal components of at least 21 high-frequency depositional sequences recognized on the shelf. Three additional sequences are recognized in the basin that are not present on the shelf. Equivalences between shelf and basin strata are difficult or impossible to establish because shelf-equivalent strata are either not coupled with basinal strata or are so thin as to be below resolution. A possible exception is the Shattuck sandstone of the uppermost Queen Formation, which can be traced convincingly onto a surface that separates the Goat Seep from the Capitan shelf-margin complex, the latter of which can be correlated into the Manzanita Limestone Member of the uppermost Cherry Canyon Formation (King, 1948).

On the basis of studies in the Guadalupe Mountains Kerans and Kempter (2002) defined a sequence stratigraphic framework for the Guadalupian succession that comprised all or part of 6 composite sequences and a total of 28 high-frequency sequences (HFS’s). The six composite sequences each record a third-order sea-level cycle. Twenty-five Guadalupian HFS’s are recognized on the shelf and in the basin, whereas three HFS’s are recognized only in the basin, all of which compose approximately the lower 95 percent of the Brushy Canyon. The Brushy Canyon is interpreted to onlap the upper surface that is developed on the lowermost of the six composite sequences; therefore, the DMG is contained in the younger five of six composite sequences. The DMG includes 24 of the 28 Guadalupian HFS’s. Because a complete review of this framework is beyond the scope of this paper, the reader is directed to Kerans and Kempter (2002) for a complete treatment of terminology, concepts, and interpretations. Figure 11 delineates high-frequency and composite sequence boundaries mapped by Kerans, Gardner, and others. However, only composite sequences are labeled. A horizontally extended, more completely labeled version is found in Kerans and Kempter (2002).

RESERVOIR DEVELOPMENT

Delaware Mountain Group reservoirs were assigned to the Delaware Mountain Basinal Sandstone Play by Dutton and others (2003). All of these reservoirs are productive from mainly subarkosic sandstones of the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations.

According to Dutton and others (2005), 78 reservoirs produced more than 1 MMbbl from this play through 2002. Total production from the play, as of 2003, stood at 262.2 MMbbl of oil from 267 reservoirs and 280.5 Mcf of gas from 95 reservoirs (Railroad Commission of Texas, 2003). As of 2003 2,103 oil wells and 183 gas wells were producing.

Controls on Reservoir Distribution

The primary control on reservoir distribution is the geometry of channel-lobe complexes in the context of local structure. A major component of reservoir geometry is the pinch-out of permeable sandstone facies into adjacent low-permeability siltstone. Levee, splay, and lobe subfacies have, to varying degrees, contact with sinuous, depositional-dip-trending channel-sandstone facies. All these stratigraphic elements pinch out laterally into siltstone baffles. However, the overall dip-aligned channel facies provides a potential pathway for fluid migration out of the reservoir system (fig. 26).

Structural elements that affect Delaware Mountain reservoir development are of four types. Regional-scale structures include (1) regional Laramide-induced tilting of the Delaware Basin to the east (figs. 26, 27) and (2) shelfward structural rise near shelf margins that is inherited from original depositional topography (figs. 11, 26). Reservoir-scale structures include (1) local compactional structures developed over subjacent sandstone bodies (fig. 28) and (2) slumps at the updip margin of channel-lobe complexes (fig. 25). Most reservoirs are developed where permeable facies are draped over or pinch out against local structural highs. Highs formed by differential compaction over reservoir-subjacent channel-lobe complexes. A common type of DMG reservoir occurs where a channel meander bend is in an updip position (figs. 26, 27) such that fluids cannot escape into the rest of the channel belt. More regional-scale hydrocarbon migration toward reservoir traps is controlled by the eastward dip imparted to the Delaware Basin by Laramide deformation. Many Bell Canyon reservoirs are located in the basinward extents of channel-lobe complexes rather than toward the Central Basin Platform shelf edge, from which the Bell Canyon feeder channels originate (figs. 4, 26), probably in response to structural tilting to the east. The paucity of basin-margin reservoirs probably reflects the structural rise toward the shelf edge that is inherited from original depositional topography and that may allow hydrocarbons to escape into reservoirs located on the shelf (fig. 26). Although basin and shelf reservoirs are not well connected in the sense that a basin reservoir interval can be traced directly into a shelf reservoir, fluid migration into shelf strata could occur along surfaces where basin strata onlap the slope or through the dip-aligned incised valleys that directed shelf-derived sediment into the basin.

Development of reservoirs in the DMG depends on the location of development of favorable facies, which is a function of the shifting of deep-water sandstone depocenters through the Guadalupian. King (1948) suggested that development of a post-Brushy rimmed margin comprising Goat Seep and Capitan carbonates may have obstructed formerly active clastic-transport fairways across the Guadalupe Mountains region during later DMG deposition. Consequently, early Guadalupian Brushy Canyon reservoirs are most abundant in the northern part of the basin in southeastern New Mexico (Lea and Eddy Counties). Several middle Guadalupian Cherry Canyon reservoirs are also located in the north part of the basin, although some also occur along the margin of the Central Basin Platform in Texas (Loving, Reeves, and Ward Counties) (fig. 4). Late Guadalupian Bell Canyon reservoirs are developed mainly in the northeast and east parts of the basin.

DMG reservoirs are not developed extensively to the west of the basin midline axis (figs. 2, 4), even though channel-lobe complexes occur in the west part of the basin. Channel-lobe complexes are especially evident in the Brushy Canyon outcrops that provide data for the facies models that have been developed (for example, Gardner and Sonnenfeld, 1992; Barton and Dutton, 1999). Absence of reservoirs in the western Delaware Basin partly reflects the absence of a top seal for the Delaware Mountain Group in the west such as the Castile and Salado provide in the subsurface. Channel-lobe complexes on the west side of the basin are sourced from the west and, in the absence of a top seal, dip-aligned channel systems provide a ready conduit for escape to the west of fluids generated in the subsurface.

Porosity and Permeability Development

The present state of DMG reservoir sandstone porosity development reflects the complexities of primary depositional and secondary diagenetic processes. Typical reservoir porosity values range from 10 to 26 percent; permeability values range from 0.1 to 155 md (Spain, 1992; Dutton and others, 1999; Broadhead and Justman, 2000). In spite of overall textural differences between the overall coarser grained Brushy Canyon and very fine grained Bell Canyon intervals, however, productive reservoir intervals from both formations show similar porosity/permeability relationships (fig. 29). Further, there appear to be no significant differences in the porosity/permeability relationships among various sandstone depositional facies (Dutton and others, 1999).

Two of the best single summaries of DMG porosity development and its effects on reservoir performance and well-log-based calculations of fluid saturation come from studies of the Brushy Canyon in Nash Draw field (Eddy County, NM) by Behnken (1996), who used XRD and SEM in his analyses of sidewall cores and cuttings, and by Thomerson and Asquith (1992), who used petrographic analyses coupled with well-log analyses on Brushy core from Mesa Hat field (Lea County, NM). Behnken (1996) recognized that very fine grained texture, grain angularity, and poor sorting caused vertically extended oil/water transition zones and high irreducible oil saturations in subarkosic clastics at Nash Draw. Thomerson and Asquith (1992) interpreted moderate to good sorting of subarkoses in Mesa Hat samples but recognized reduced permeability and enhanced irreducible fluid saturations accompanying very fine grained textures.

Diagenesis in DMG siliciclastics has produced secondary porosity due to feldspar dissolution. Pore throats have been further reduced by pressure solution of quartz grains, which produced a slitlike geometry. Authigenesis of feldspar, quartz, and clay minerals, which occurred in pores, was caused by the presence of organic fluids that were probably sourced from DMG organic-rich siltstones (Hayes and Tieh, 1992 a). However, the most common cements are carbonate (Thomerson and Asquith, 1992; Dutton and others, 1999). Predictably, total cements are the main control on porosity and permeability (Dutton and others, 1999).

Authigenic clay minerals present a particularly troublesome set of complications. Fibrous illite and chlorite, in particular, have developed bridges across pore throats and dissected porosity. Weblike growths of illite/smectite may swell 15 to 20 percent when contacted by drilling fluids, thus occluding even more pore space. Chlorite, as well as other iron-bearing authigenic minerals, can promote precipitation of pore-occluding, insoluble, Fe-hydroxide gels when contacted by acids.

Reservoir Quality Determination from Well Logs

Several critical issues must be dealt with when well log data are used to identify and evaluate DMG reservoirs. First, DMG siliciclastics are subarkosic to arkosic and produce elevated gamma-ray-log responses in shale-free sandstones. Shale is rare in the Delaware

Mountain Group, probably owing to sand storage in an eolian environment prior to basinal deposition.

Second, authigenesis of clays provided abundant microporosity, which is detected by neutron logging because of the presence of bound water. The effect is an overestimate of effective porosity and calculation of high water saturations (Thomerson and Asquith, 1992; Behnkin, 1996). The pessimism generated from calculations of high water saturations may be mitigated by the insight that much of the water bound in the clay fraction is irreducible (Behnken, 1996).

Third, resistivity contrasts between oil- and water-productive intervals are low because of high residual oil saturations in the invaded zone, as well as high irreducible water saturations (Thomerson and Asquith, 1992).

Calculation of effective porosity requires corrections of total porosity for included microporosity. Thus, determination of clay content is required, which cannot be performed using gamma-ray data alone because of the abundance of K-feldspar. In Hat Mesa field (Brushy Canyon), Thomerson and Asquith (1992) used neutron-porosity (ϕ_N) and density-porosity (ϕ_D) data to calculate the clay volume (V_{clay}):

$$V_{clay} = (\phi_N \text{ shaly sand} - \phi_D \text{ shaly sand}) / (\phi_N \text{ shale} - \phi_D \text{ shale}),$$

where all porosities were corrected to a sandstone matrix. Complications arising from borehole rugosity (observed in caliper logs) and gas (observed in gas/oil data) were minimal in Hat Mesa field. Thereafter, Thomerson and Asquith (1992) generated a series of petrophysical crossplots that were interpreted to differentiate permeable water-productive from permeable oil-productive zones.

Integration of the results from crossplot analyses produced cutoff values for productive intervals in Hat Mesa (Brushy Canyon) reservoir: ϕ = 12 percent at 0.1 md. Very similar cutoff values were determined by Dutton and others (1999) for hydrocarbon-productive Ramsey sandstone at Ford Geraldine (Bell Canyon) reservoir in Reeves and Culberson Counties, Texas.

Identification of widespread organic-rich siltstone intervals is important because they act both as local source beds for hydrocarbons and as part of the reservoir seal. Organic-rich beds correspond to some of the most radioactive units observed in gamma-ray logs. Only volcanic-ash deposits show similarly elevated gamma-ray responses.

Older resistivity logs often show an increase in resistivity beginning within the upper part of the Bell Canyon several feet below the contact with the Castile. This effect, called the "Delaware Effect," is a function of electrode spacing of the resistivity tool (Laterolog). The result can be a misinterpretation that hydrocarbons are trapped below the Castile, when, in reality, the interval may be water bearing. Improvements were eventually made in electrode spacing and tool design (Asquith and others, 1997a).

Traps, Seals, and Sources

DMG reservoirs reflect both stratigraphic and structural controls on hydrocarbon migration and trapping. Stratigraphic controls include lateral pinch-outs of permeable, laterally discontinuous, channel-levee-complex, overbank-splay, and lobe sandstone- and coarse-siltstone facies into much lower permeability, laterally more extensive siltstone facies. Further, the laterally extensive siltstones provide reservoir-scale top seals (for example, Kane, 1992). Gardner (1992) recognized that deposition of regionally extensive fine-grained sediments during third-order sea-level rise recorded progressive basin starvation and produced top seals that genetically and hydraulically separate the three DMG formations. Carbonate strata in DMG carbonate members, which also contain siliciclastics reservoirs, may also form lateral and top seals on siliciclastic reservoirs contained within or below such members (for example, in Avalon reservoir, described by Kane, 1992) (fig. 17). Locally, stratiform calcite-cemented intervals provide additional controls over vertical flow (for example, Dutton and others, 1999) (figs. 18, 19).

Hydrocarbon sources are thought be organic-carbon-bearing siltstone strata that are interbedded with, and laterally adjacent to, reservoir facies (fig. 6). DMG organic carbon in siltstones and in most of the oil accumulations has similar sulfur and carbon isotopic composition (Hayes and Tieh, 1992a). Evolution of organic fluids appears to have controlled much of DMG diagenesis, including development of dissolution-produced secondary porosity and subsequent mineral authigenesis (Hayes and Tieh, 1992a). Some siltstones are remarkably organic rich. Dutton and others (1999) reported a Bell Canyon coarse-grained siltstone (average grain size of 4.94 phi, with an organic-carbon content of 46 percent by weight. Most so-called organic-rich siltstones are not so carboniferous, however, averaging less than 4 percent by weight (Sageman and others, 1998).

Structural controls on reservoir development include a Laramide-induced, regional monoclinal dip down to the east (fig. 26); local compactional antiformal and synformal structures over subjacent sandstone bodies (for example, fig. 28); and syndepositional slumps that bound the up-depositional-dip ends of channel systems (for example, Gardner and Sonnenfeld, 1996) (fig. 25).

Production Characteristics and Completion Challenges

Primary oil production is typically only about 50,000 to 100,000 bbl per well (10 percent of OOIP) in DMG fields. (Montgomery and others, 1999). Production decline rates are initially high as solution gas, the predominant drive mechanism, is depleted. Production characteristics vary significantly over short distances (fig. 30), probably reflecting the laterally restricted extent of productive channel-levee-lobe complex sandbodies.

Porosity and permeability attributes in DMG reservoir facies are modest. Reservoir porosity ranges typically from 12 to 25 percent; permeability ranges from 1 to 5 md, with exceptional occurrences of 200 md in thin, laterally restricted units (Montgomery and others, 1999). Although detrital clay (kaolinite) composes less than 1 percent of the rock, the already impoverished permeability would be further diminished by clogging of pore throats by Fe-hydroxide gels precipitated through the contact of iron-bearing minerals (for example, chlorite) with acidic borehole fluids (Behnken, 1996). Walling and others (1992) warned that chlorites could de-evolve to water-expandable forms in the presence of some anthropogenic borehole fluids and become migratory. Behnken suggested that addition of as little as 2 percent KCl will mitigate potential clay deflocculation and clay-particle migration. Other additives are available to prevent precipitation of Fe-hydroxides, including acetic or citric acid (Green and others, 1996).

Because DMG permeability is marginal, fracture stimulation with sand propping is commonly used in the final stages of well completion. However, reservoirs characteristically comprise numerous thin hydrocarbon-productive intervals that are interbedded with thin water-productive intervals. Further, control of fracture propagation is problematic because of the microlaminated, lithologic variability of reservoir intervals and lack of shaly, stratal, fracture barriers. The danger of connecting water-bearing and hydrocarbon-bearing intervals with induced fractures (“treating out of zone”) is always present, and it can result in excessive water production or “watered-out” hydrocarbon reservoirs (Scott and Carrasco, 1996). Fracture-stimulation jobs are customized for local geologic conditions by varying pump rates, pad-stage volumes (amount of fluid used to create fractures), fluid viscosities, sand concentrations, and fluid-loss additives (Scott and Carrasco, 1996). Success of fracture treatments has traditionally been tested by posttreatment injection of radio tracers (for example, iridium and scandium) and gamma-ray relogging of the well. Posttreatment assessment of the success of the treatment may potentially be performed after formation damage has occurred, a problem whose recognition has prompted the design of real-time fracture-treatment monitoring techniques that allow timely discontinuance of treatments (Scott and Carrasco, 1996). Increased productivity is an obvious indicator of success. Design criteria for fracture stimulation in relatively lower permeability units are different than those for higher permeability units. After successful fracture stimulation, ultimate recoveries in lower permeability units are increased over what might otherwise be expected, whereas they are not increased for higher permeability units (Scott and Carrasco, 1996).

The primary drive for DMG sandstone reservoirs is solution-gas and water drive (Spain, 1992). Per-well initial production may exceed 80 bbl/d (13.25 m^3/d) but will decline to less than 12 bbl/d (<2 m^3/d) after 4 years as solution gas is depleted (fig. 31). Injection of water for pressure maintenance has yielded significant improvement in some cases (for example, Dutton and others, 2005; after Broadhead and others, 1998) (fig. 32). Injection of CO_2 has also proven successful, for example, in Ford Geraldine field (Bell Canyon) (Dutton and others, 2003) (figs. 33, 34).

Limited lateral continuity of productive facies presents a challenge for economic development of DMG reservoirs. The geographic limitation of reservoir continuity is demonstrated by differences in production characteristics in closely spaced wells. Drainage areas for wells at Nash Draw (lower Brushy Canyon) range from 19 to 66 acres, with an average of 34 acres (Montgomery and others, 1999). The effects of limited reservoir are shown by comparing production characteristics in closely spaced wells. Figure 30 shows oil, gas, and water production in three wells that are 0.25 to 0.5 mi (0.4 to 0.8 km) apart. Dutton and others (1999) pointed out that pinch-outs of channel, levee, and lobe sandstone into siltstone are the primary control on lateral reservoir heterogeneity. Additional complications include the pinch-out of splay reservoir sandstone onto topographically elevated levee complexes. Vertical heterogeneities are produced by deposition of both laterally extensive and discontinuous siltstones between stacked channel sandbodies (fig. 8). As discussed earlier, laterally discontinuous distribution of stratiform calcite cements also imparts interwell heterogeneity to reservoirs.

SUMMARY AND CONCLUSIONS

The Guadalupian-age Delaware Mountain Group contains the rock record from deep-water deposition in the Delaware Basin. Rock types include shelf-derived, fine-grained, feldspar-bearing siliciclastics and limestone-dominated carbonates derived from the outer-shelf and shelf margin. Sandstones were deposited mainly by density flow during lowstand and early transgressive sea-level stages, whereas regionally extensive siltstone intervals were deposited from suspension most abundantly during sea-level highstands. Carbonates were probably deposited during periods when the greatest amount of energy was imposed on shelf-margin source areas, which may have been during transgressions or when early highstand shorelines were near the shelf margin. Calcite cement is common and is most often associated with finer grained sandstone and coarse-grained siltstones in areas dominated by overbank deposits. Detrital clay is not abundant, and most clays comprise authigenic chlorite or illite. Clay content decreases sandstone permeability without significantly affecting porosity and increases irreducible water content.

The DMG succession has been formally divided into 3 formations (Brushy Canyon, Cherry Canyon, and Bell Canyon), 5 composite sequences, and 24 high-frequency sequences. The Brushy Canyon, the coarsest grained formation in the outcrop area, contains little carbonate compared with that of the others. Correlations between wells generally depend on recognition of the carbonate members and widespread siltstone intervals. Recognition of the prominence of organic-rich siltstone in the upper parts of the Brushy Canyon and Cherry Canyon facilitates correlations between wells of the Brushy Canyon/Cherry Canyon and Cherry Canyon/Bell Canyon boundaries, respectively. Interpretation of siliciclastic and carbonate end-member rock types from gamma-ray and porosity well logs is relatively straightforward, in most cases. High irreducible water content associated with the clay fraction produces lower-than-expected resistivities in hydrocarbon-productive strata.

Hydrocarbon reservoirs have both stratigraphic and structural elements. Lateral pinch-outs of sandstone porosity into low-permeability siltstones and superposition of siltstones over sandbodies compose the stratigraphic elements. The structural components may include (1) anticline formation caused by differential compaction over and around subjacent sandbodies and (2) regional dip arising either from Laramide deformation or (3) depositional topography on slopes approaching shelf margins. Reservoir traps are preferentially developed where porosity-pinch-out areas are in updip positions. Hydrocarbons may escape to shelf reservoirs where porous and permeable facies are positioned on slopes that rise toward shelf areas.

The DMG is an underexploited reservoir succession; estimated typical primary recovery efficiency is only 10 percent of OOIP. Most enhanced recovery efforts recover an addition of less than 20 percent of OOIP, with some notable exceptions. This modest performance arises largely from laterally restricted distribution of reservoir sandbodies, generally low permeability, and characteristic interbedding of thin hydrocarbon- and water-productive intervals. Economically acceptable production requires fracture stimulation that risks interconnecting water- and hydrocarbon-productive reservoirs and acid stimulation that risks production of formation-damaging Fe-hydroxide gels from decomposing Fe-bearing minerals such as chlorite. Successful application of enhanced recovery techniques depends on accurate knowledge of the interconnectedness of permeable facies between injection and production wells. For example, productive lobe and channel sandbodies may be well connected, whereas productive overbank-splay sandbodies may be isolated from the others. High-resolution 3-D seismic imaging may facilitate mapping of laterally and stratigraphically heterogeneous sandstone distribution. Horizontal drilling may intercept and facilitate production from laterally disconnected sandbodies, although maintaining stratigraphic separation of hydrocarbon- from water-productive intervals may be more complicated than with vertical completions.

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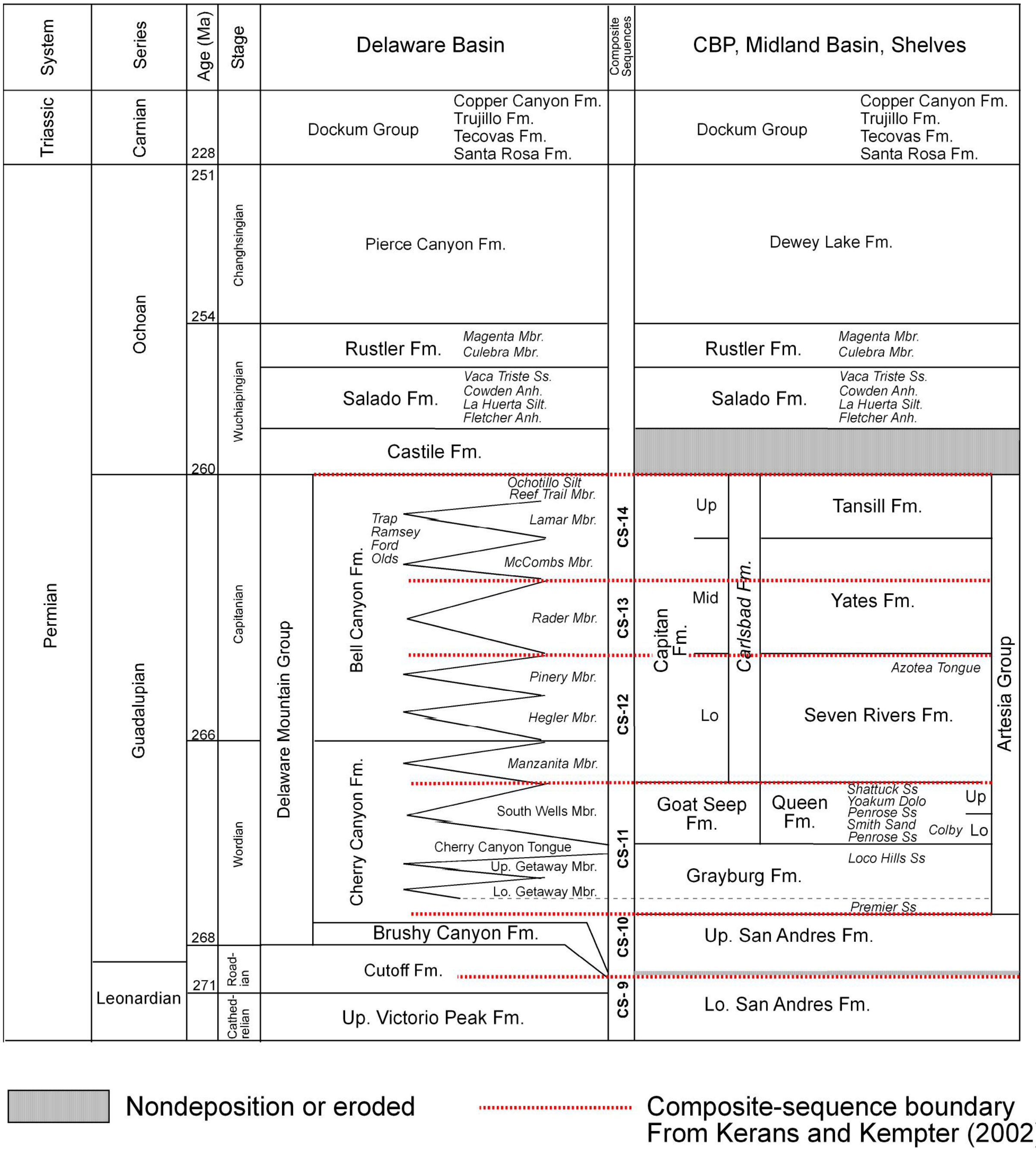


Figure 1. Correlation chart for uppermost Leonardian and Guadalupian strata in the Permian Basin.

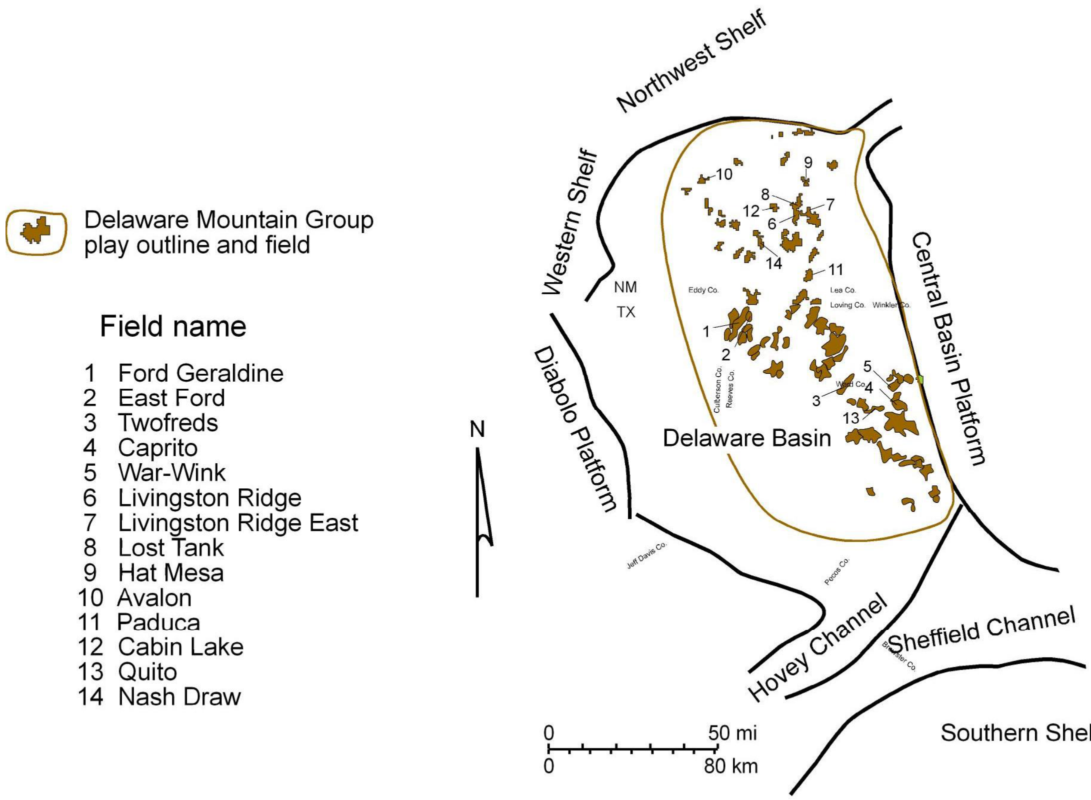
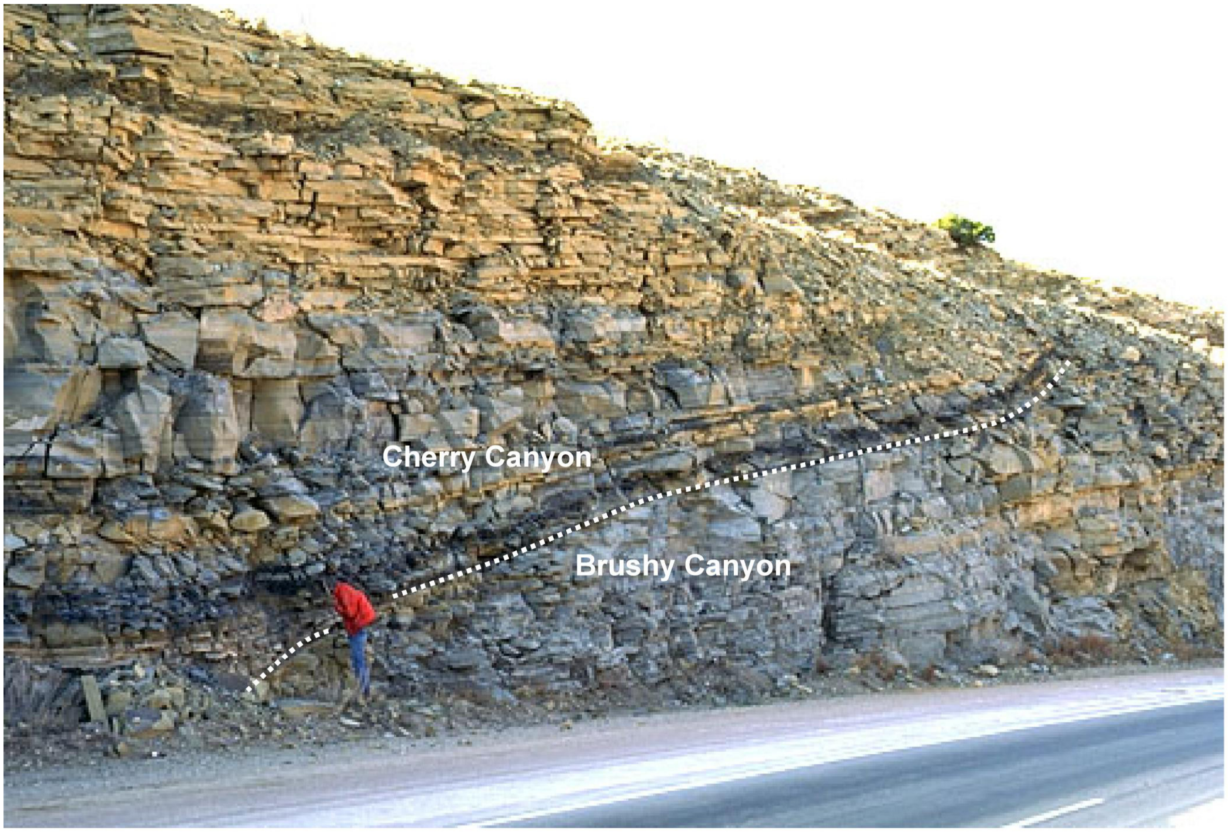


Figure 2. Map showing locations of reservoirs (cumulative production > 1MMbbl) within the Delaware Mountain Group play. Also shown are approximate positions of major tectonic elements and suggested boundaries of plays. Reservoirs specifically discussed in this report are indicated.



Modified from Scholle (1999)

Figure 3. Unconformable contact between the Cherry Canyon and underlying Brushy Canyon Formations. Outcrop is on Hwy 62-180, south of Guadalupe Pass and north of El Capitan scenic turnout, Guadalupe Mountains. Strata are composed of subarkosic sandstone and siltstone.

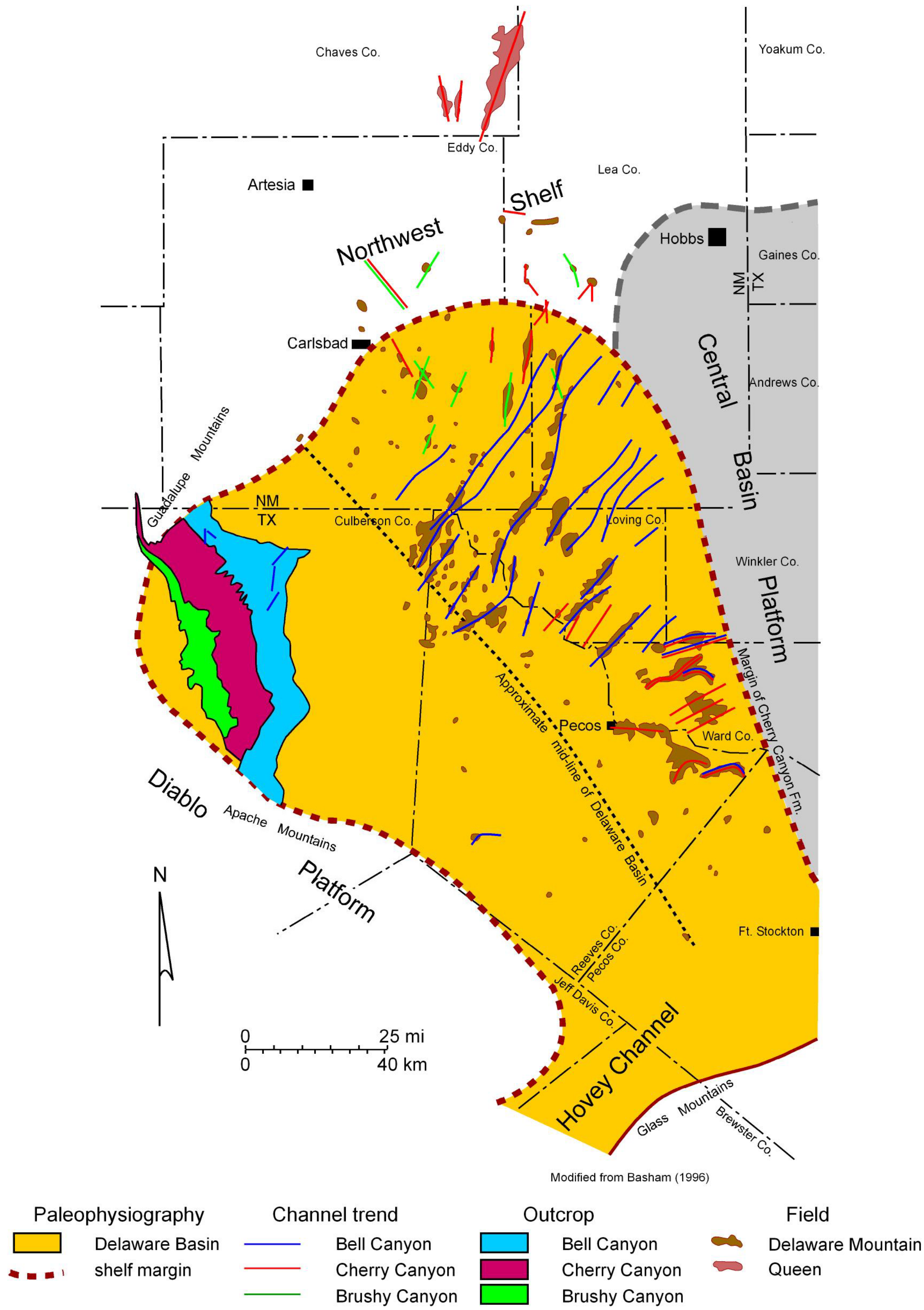


Figure 4. Map of Delaware Mountain Group reservoirs. Also shown are inferred submarine channel trends that are color coded to indicate primary reservoir intervals. Note that Brushy sandstone fairways trend preferentially north to south, Bell Canyon fairways trend northeast to southwest, and Cherry Canyon fairways trend from the north and from the east.

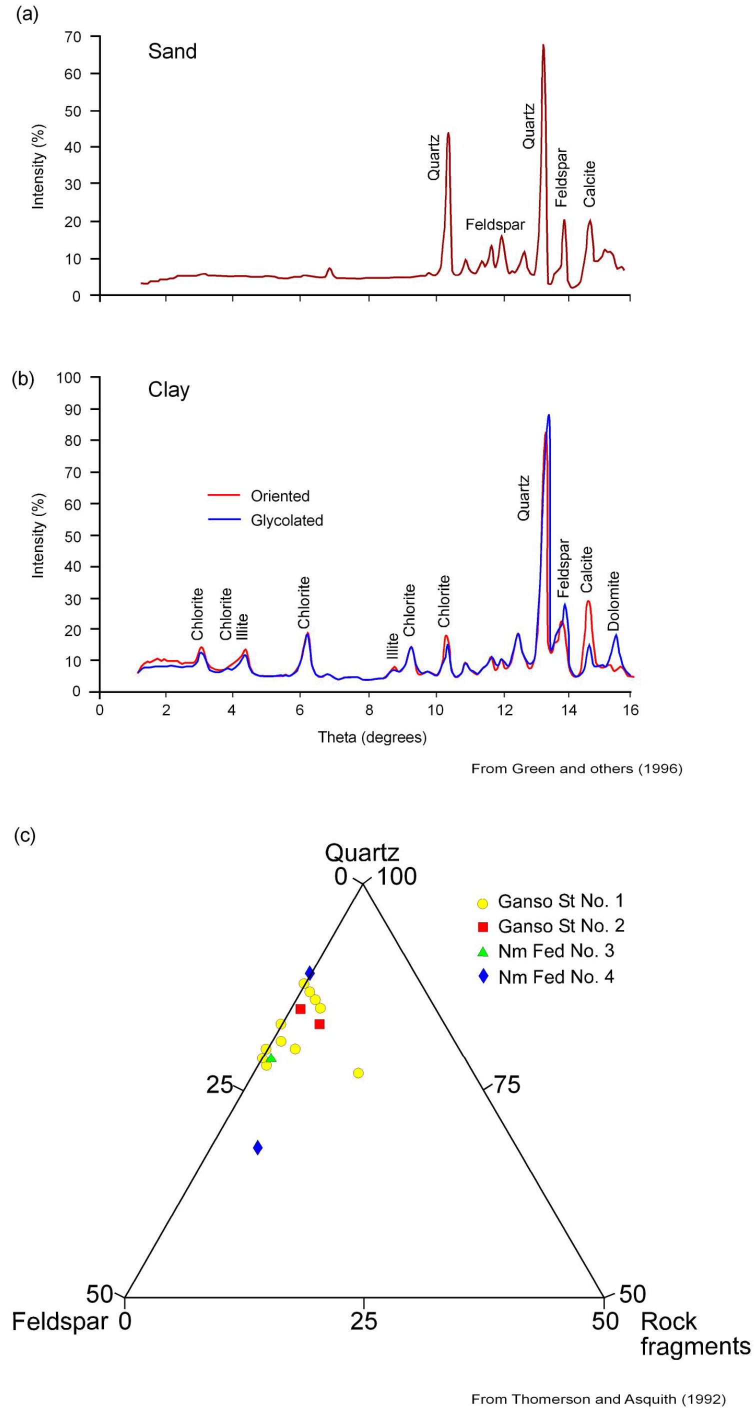


Figure 5. Mineralogy of Delaware Mountain Group siliciclastics: (a) x-radiogram of typical fine- to very fine grained Brushy Canyon sandstone showing prominence of quartz, feldspar, and calcite (cement); (b) x-radiogram of typical, mainly authigenic clay fraction composed of illite, chlorite, feldspar, calcite, and dolomite; (c) ternary compositional diagram of sand fraction from four Brushy Canyon wells showing subarkosic to arkosic character of DMG reservoir facies.

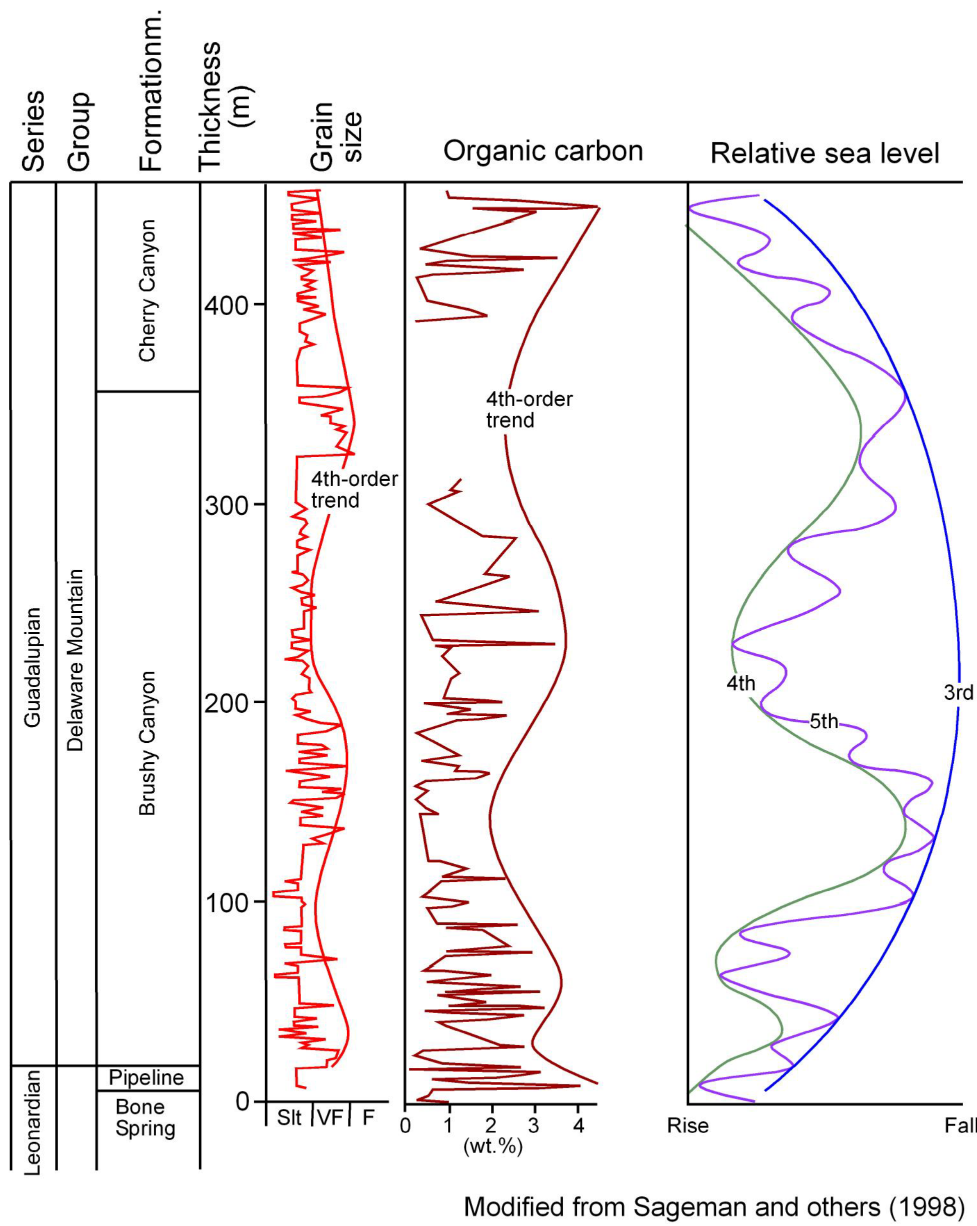


Figure 6. Graphs showing correspondences of grain size, organic carbon content, and interpreted relative sea-level stages for the Brushy Canyon and lowermost Cherry Canyon Formations. Samples are from outcrops in the Guadalupe and Delaware Mountains. Peaks in deposition of silt and organic matter tend to be associated with interpreted rises and highstands of sea level. Modified from Sageman and others (1998).

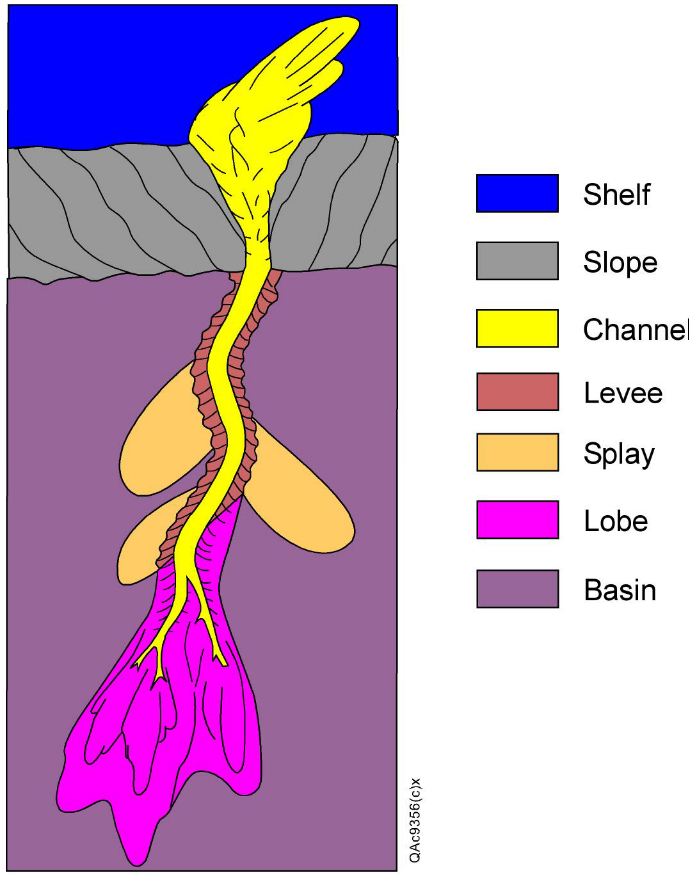


Figure 7. Simplified model of generalized shelf-margin paleogeographic and depositional elements of Delaware Mountain Group deep-water sandstone facies. From Dutton and others (2005); modified from Galloway and Hobday (1996).

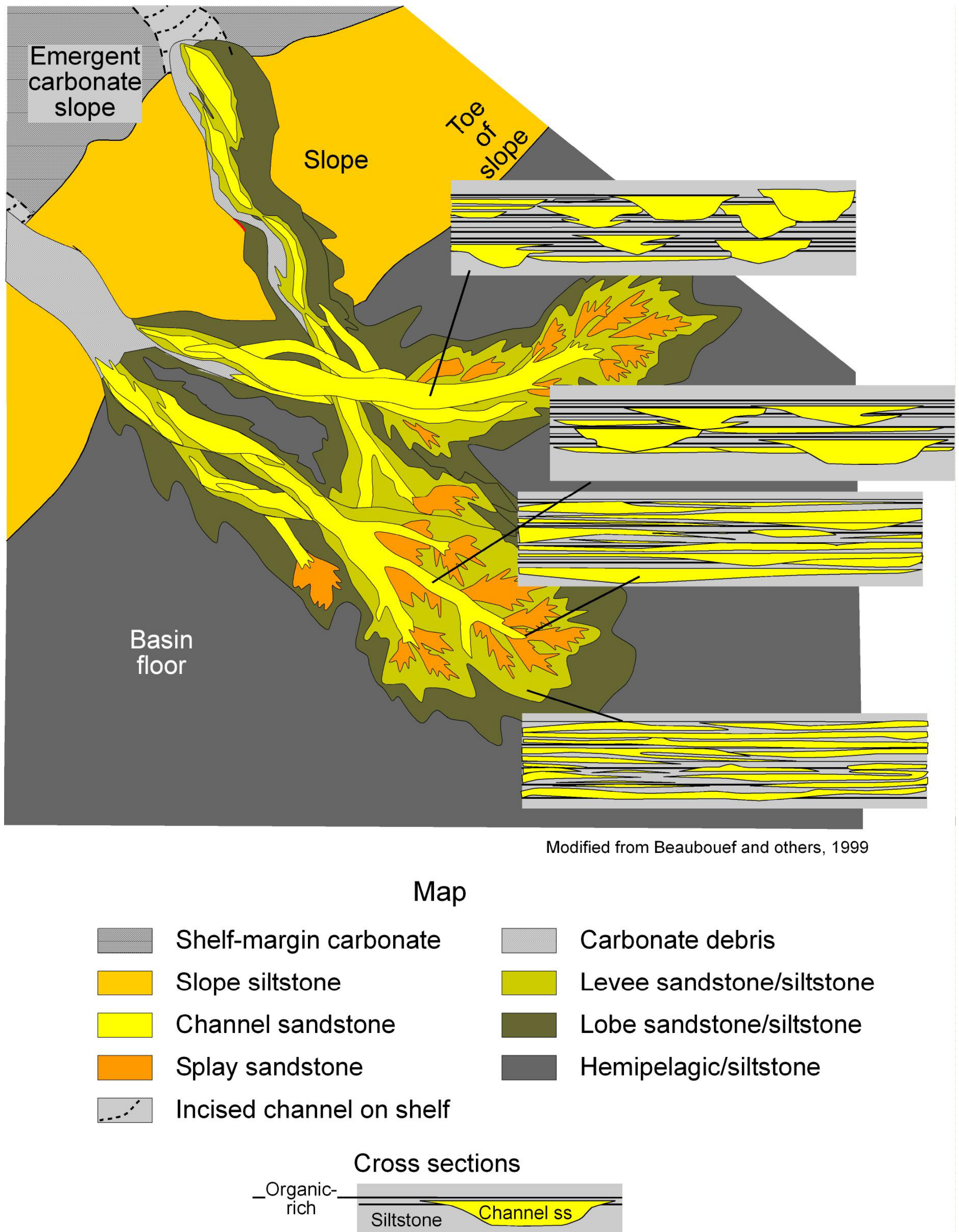


Figure 8. Schematic model of principal reservoir facies of the Delaware Mountain Group showing idealized cross sections of sandbody development along depositional dip. Sandbodies tend to become laterally more extensive with less vertical incision downdip, although compensatory stacking of sandstone units is a characteristic process along the slope profile. Modified from Beaubouef and others (1999).

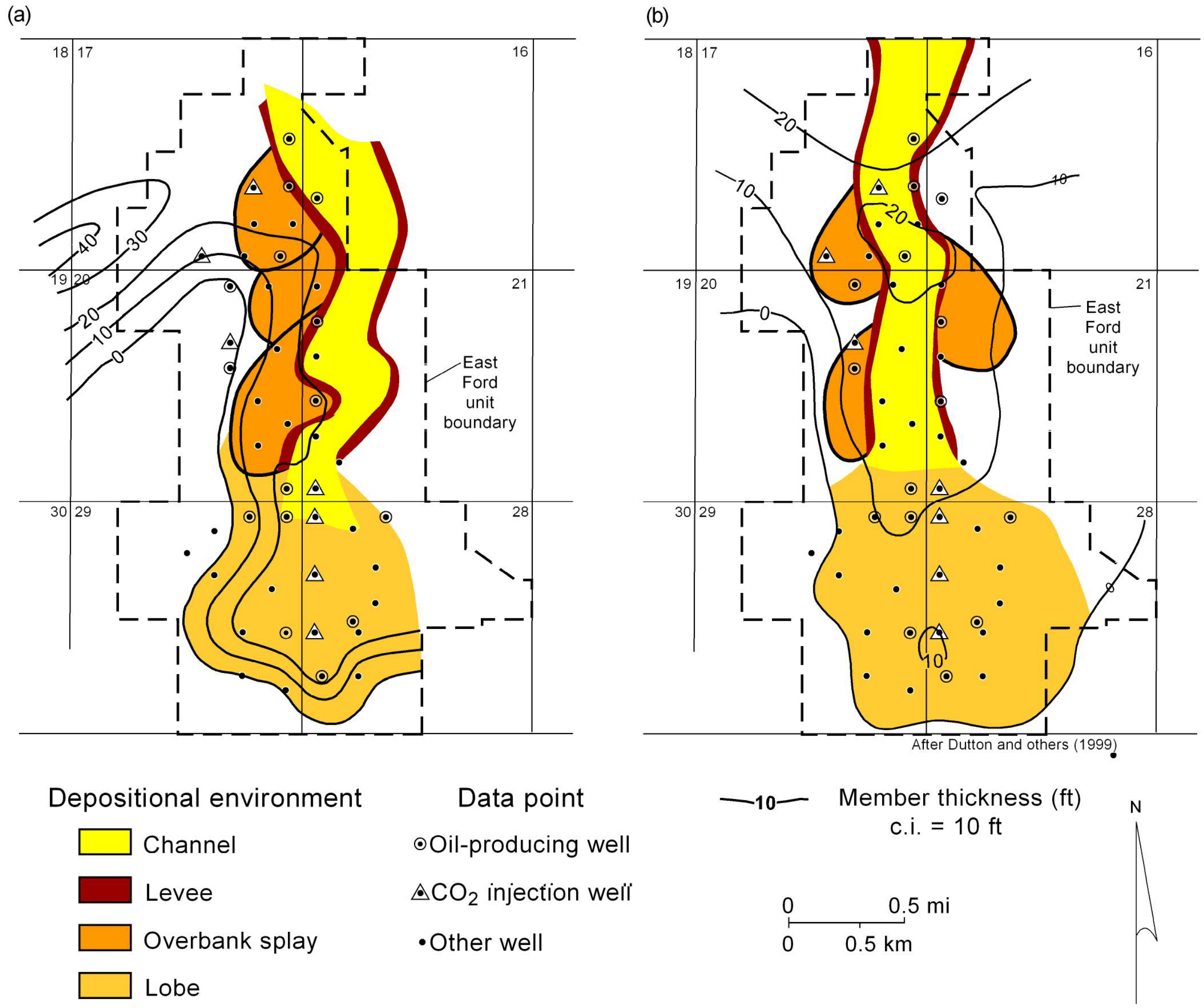
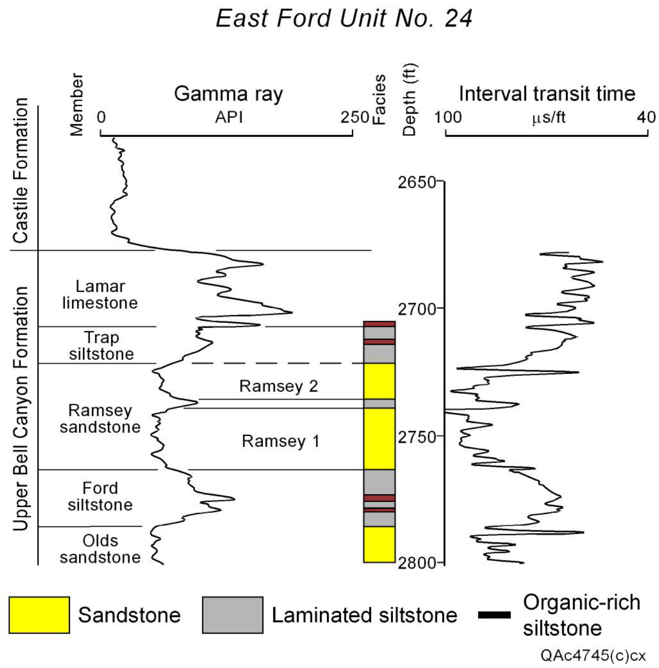
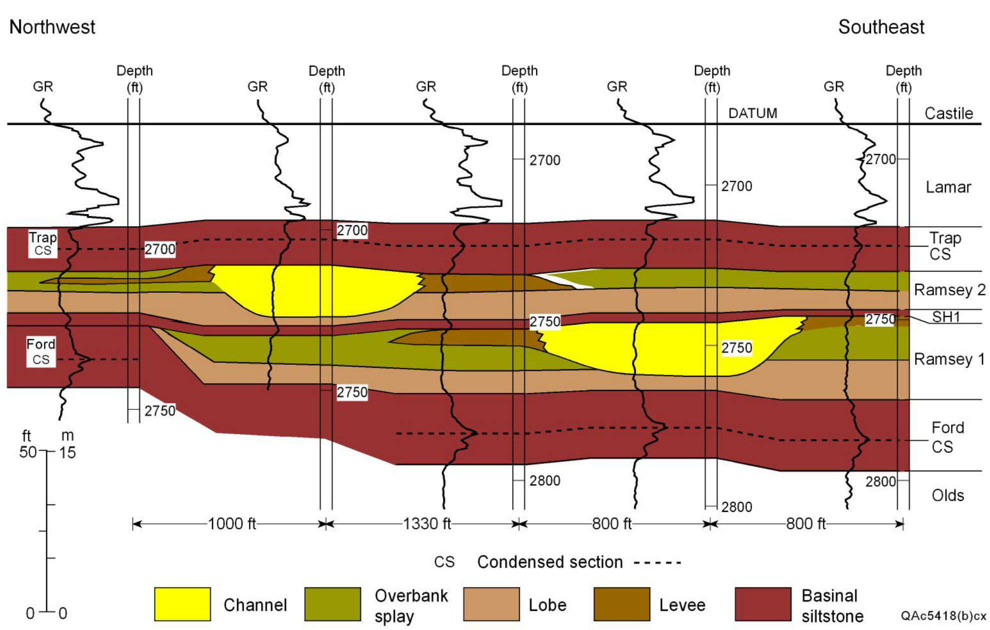


Figure 9. Isopach and interpreted facies maps of (a) Ramsey 1 and (b) Ramsey 2 sandstone, East Ford Unit (Bell Canyon). Facies are based on classification scheme illustrated in figure 7. Field location shown in figure 2.

(a)



(b)



From Dutton and others (2003)

Figure 10. Stratigraphy of Bell Canyon Formation at East Ford unit. (a) Type log showing representative gamma-ray and acoustic logs for the upper part of the formation; Ramsey primary sandstone reservoir intervals are highlighted; (b) Northwest-to-southeast stratigraphic cross section showing compensatory stacking of sandbodies and laterally extensive siltstone seals. Field location shown in figure 2.

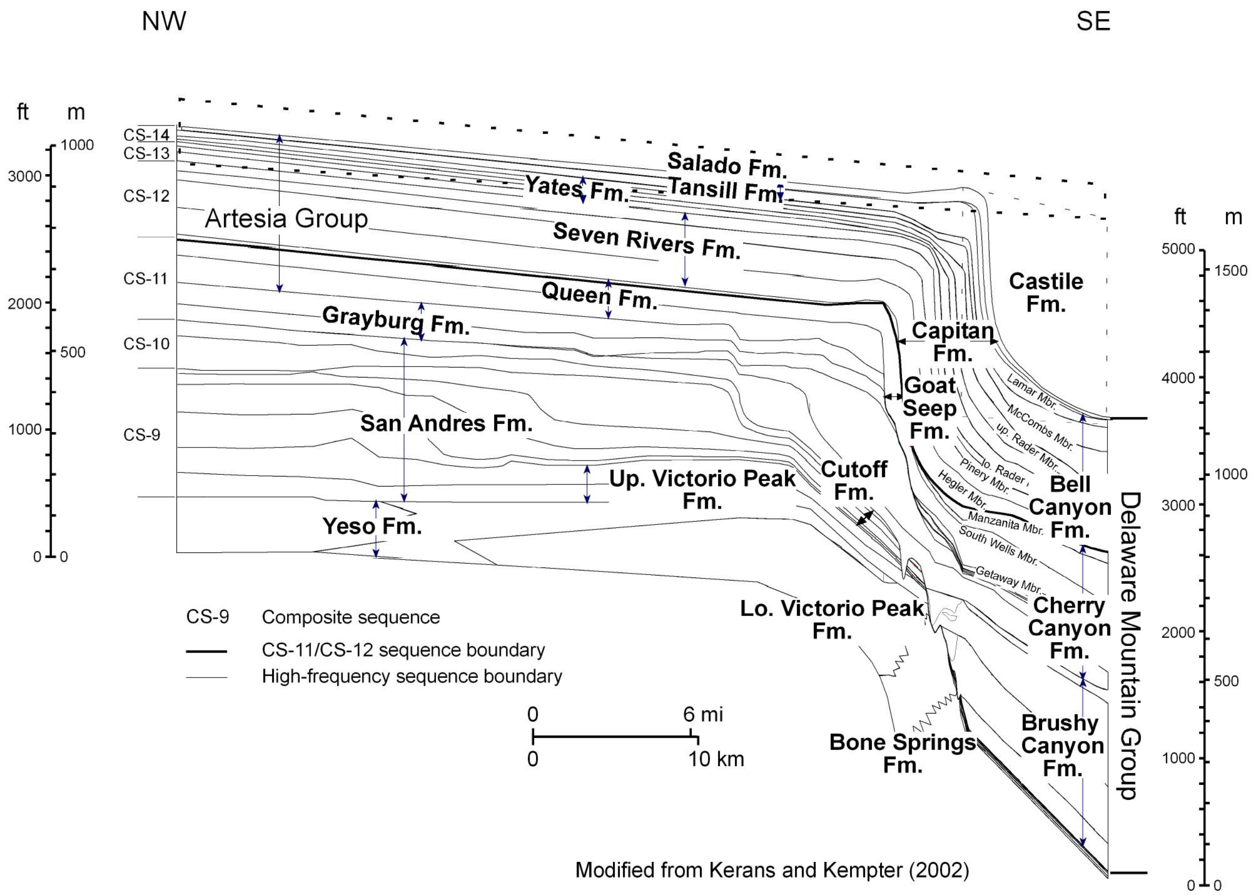
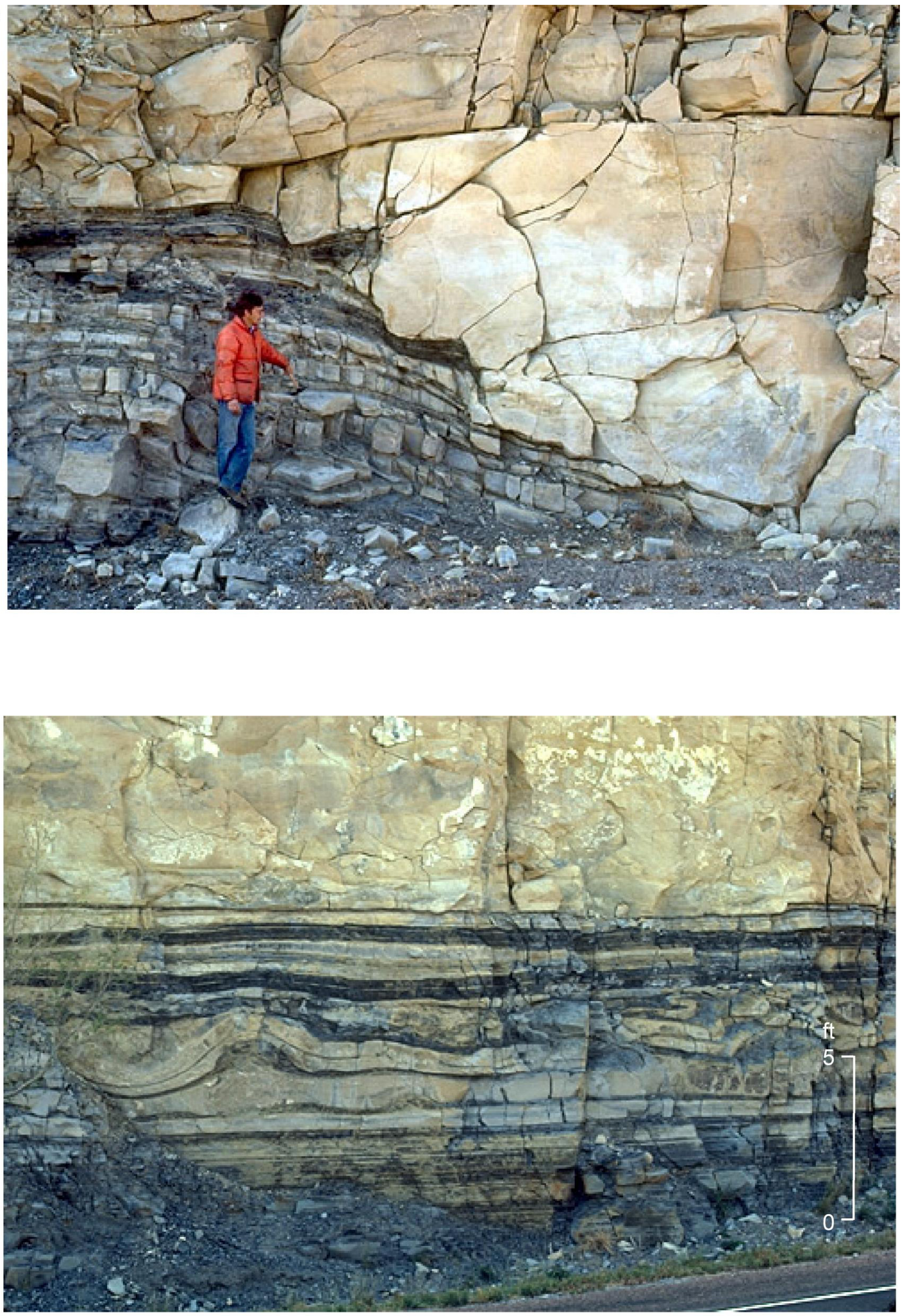


Figure 11. Composite structure dip section of the uppermost Leonardian, Guadalupian, and lower part of the Ochoan in the Guadalupe and Delaware Mountains area showing formation and member names. Also shown are sequence stratigraphic subdivisions, including composite sequences (CS), and high-frequency sequences (not labeled). Sequence boundary that separates the sequences associated with the Capitan shelf margin (Bell Canyon in the basin) from the underlying sequences (Brushy Canyon and Cherry Canyon in the basin) is indicated by the bold line. Modified from Kerans and Kempter (2002).

(a)

(b)



From Scholle (1999)

Figure 12. Channel and overbank facies, Brushy Canyon Formation, Guadalupe Mountains. (a) Incised valley in overbank deposits with channelized sandstone fill and (b) overbank sandstones and siltstones overlain by channel sandstone. Dark strata are organic-rich siltstones similar to those that act as hydrocarbon source beds for reservoir sandstones. Outcrops are on Hwy 62-180, south of Guadalupe Pass and north of El Capitan scenic turnout, Guadalupe Mountains.

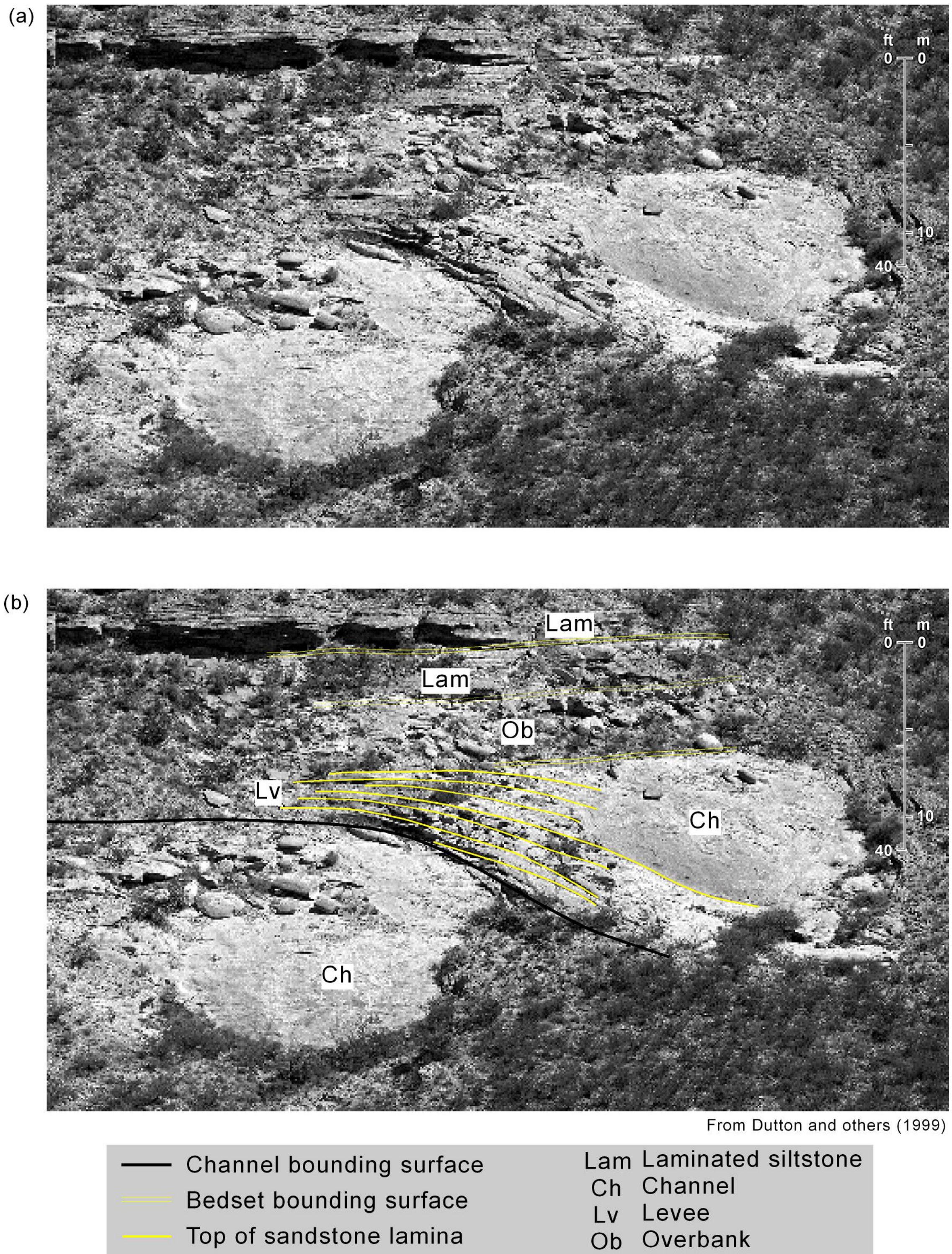


Figure 13. Outcropping channel-levee complexes, overbank deposits, and laminated siltstone deposits at Willow Mountain outcrop area, Delaware Mountains, Bell Canyon Formation: (a) outcrop photo and (b) annotated outcrop photo. Note compensatory stacking of channel sandbodies. From Dutton and others (1999).

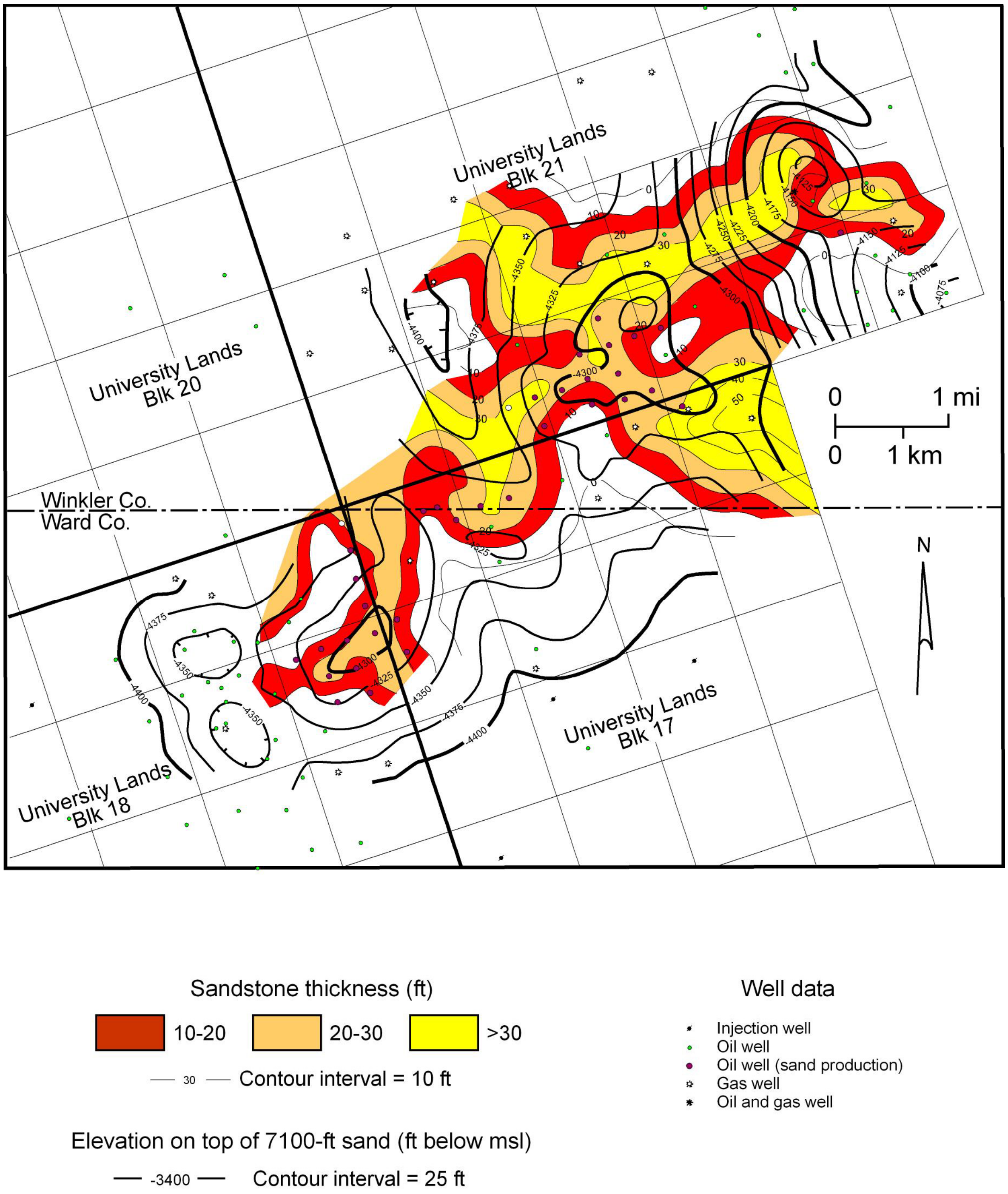


Figure 14. Isopach and structure maps of 7100-ft sand in the War-Wink field area. Porous sandstone facies record deposition in submarine channels. Note that sand-reservoir production is concentrated near anticlinal crests or where sandstone porosity pinches out onto anticline flanks. Field location shown in figure 2.

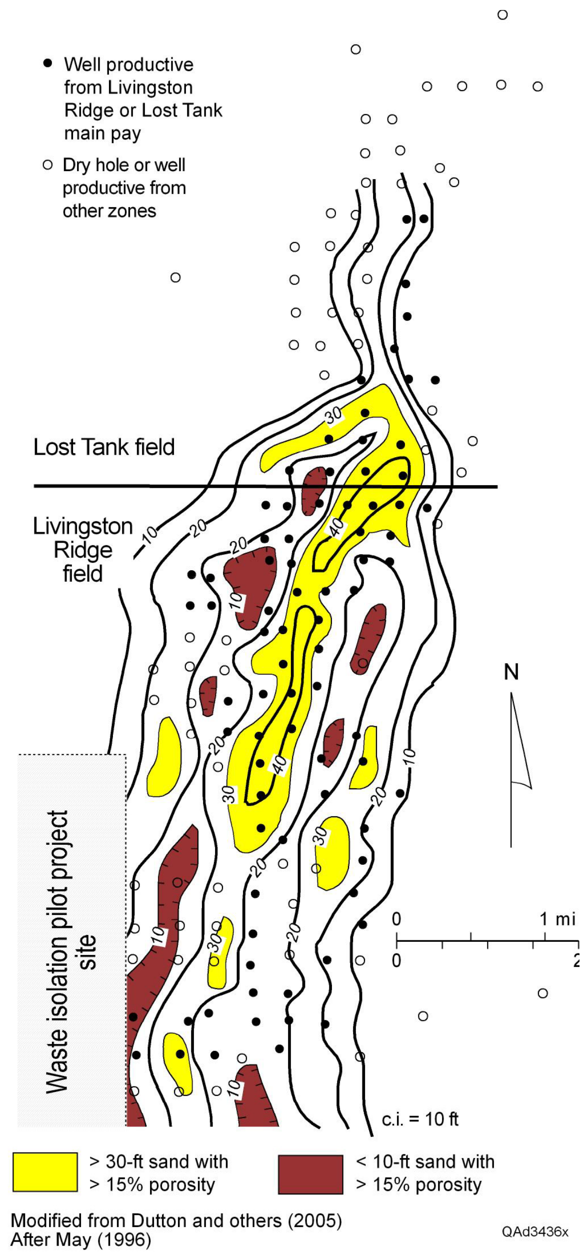


Figure 15. Thickness map of the main pay (porosity >15%) in the Brushy Canyon Formation, Livingston Ridge and Lost Tank fields. Thicknesses greater than 20 ft correspond to main channel complexes. Note that production is not limited to thicker intervals. Field location shown in figure 2.

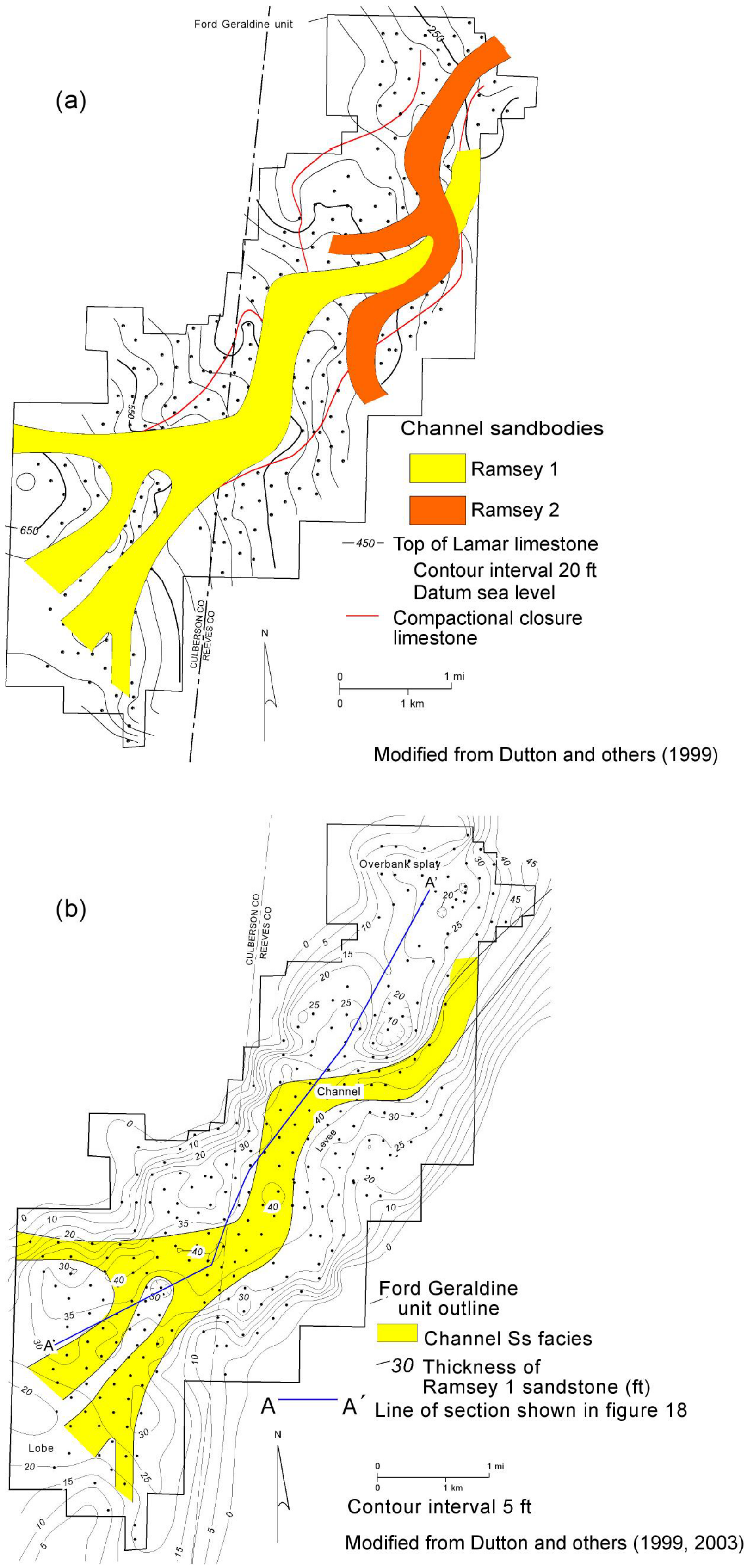


Figure 16. Ramsey Sandstone and Lamar Limestone (Bell Canyon) maps, Ford Geraldine field. (a) Thickness of Ramsey 1 sandstone interval. Thickest accumulations correspond to locations of channel and splay facies development. Note compensatory stacking of channel sandstone facies. (b) Structure on the top of the Lamar Limestone Member of the Bell Canyon Formation showing compactional anticline development over trend of dominant Ramsey Sandstone channel system. Note correspondence with isopach thickness trend shown in a. Field location shown in figure 2.

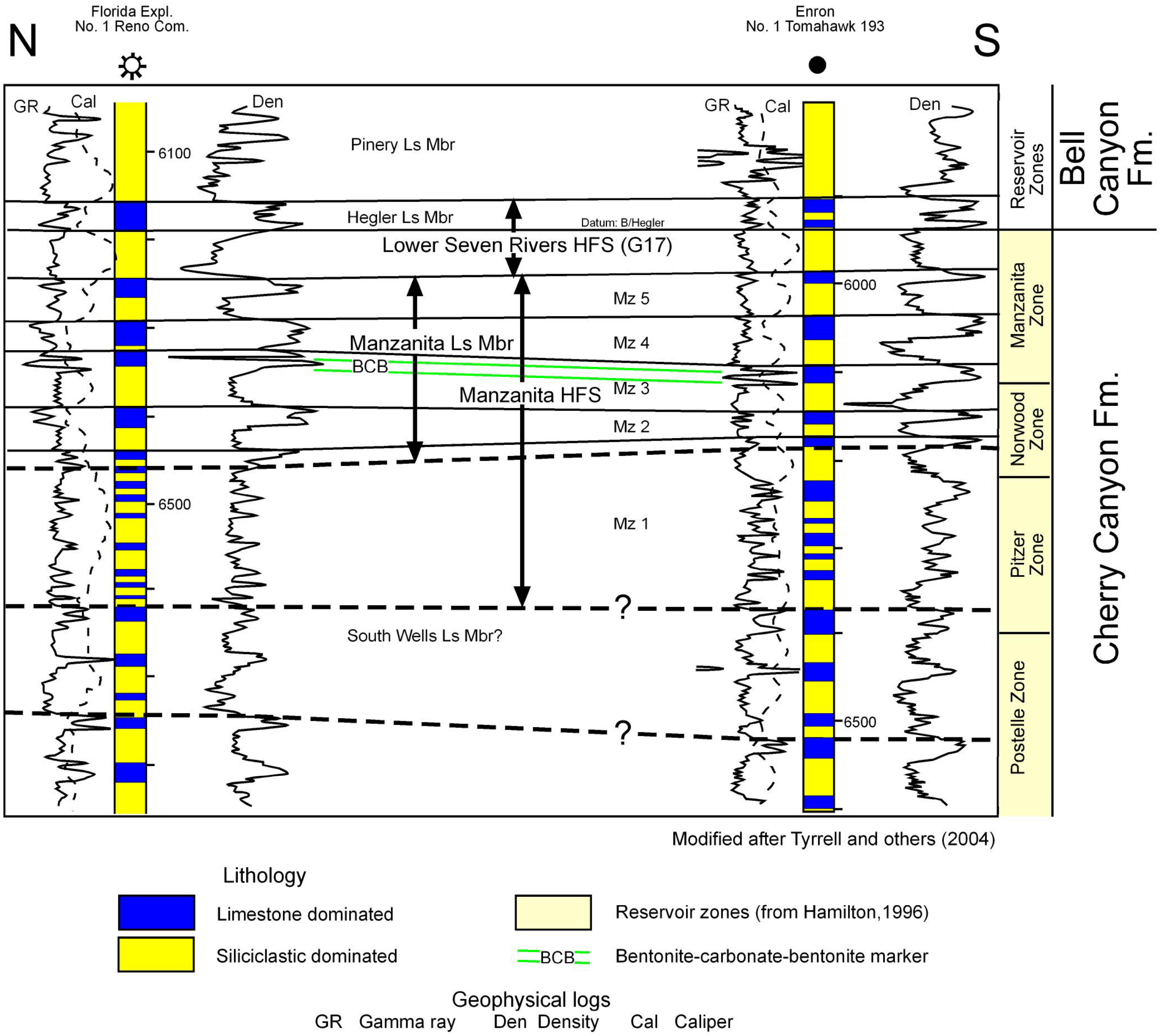


Figure 17. North-south correlation section in Quito field area showing upper Cherry Canyon and lowermost Bell Canyon limestone and siliciclastic intervals and sequence stratigraphy. Reservoir zones designated by Hamilton (1986). Quito field area shown in figure 2.

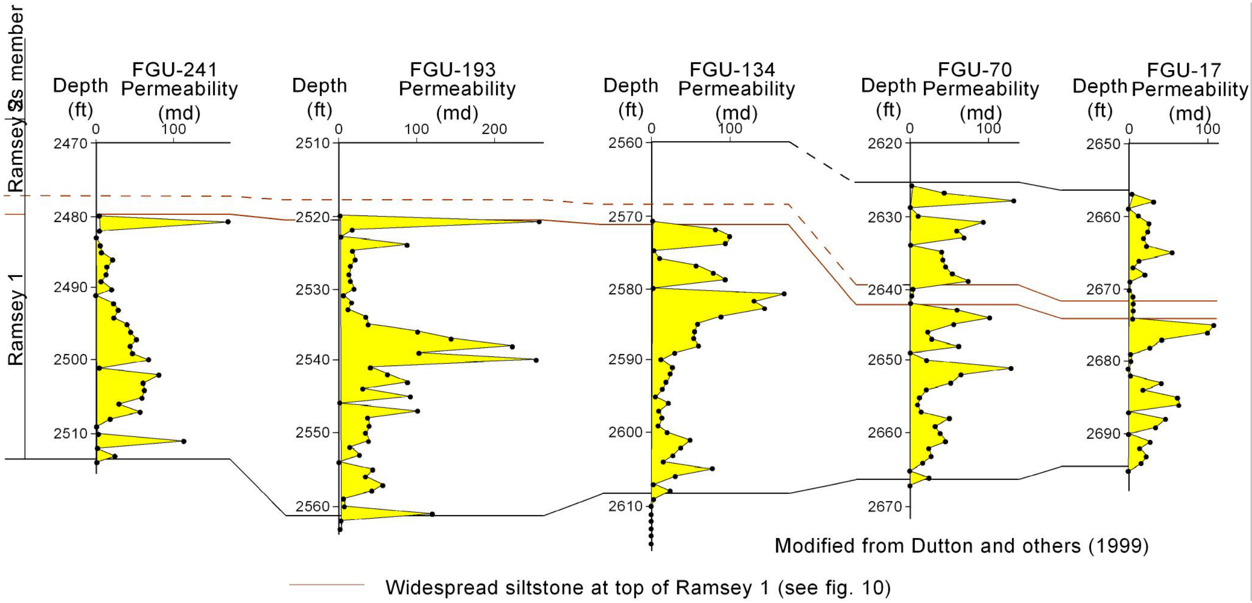


Figure 18. Vertical profiles of permeability distribution for five wells from core analyses. Significant permeability variations are tied more to presence of cement than to grain-size variation. High-permeability zones underlain by calcite-cemented low-permeability zones are common at the top of Ramsey 1 and Ramsey 2 intervals. High permeability at the tops may record calcite dissolution. Location of wells shown in figure 20. Map of calcite cement distribution shown in figure 20. Field location shown in figure 2.

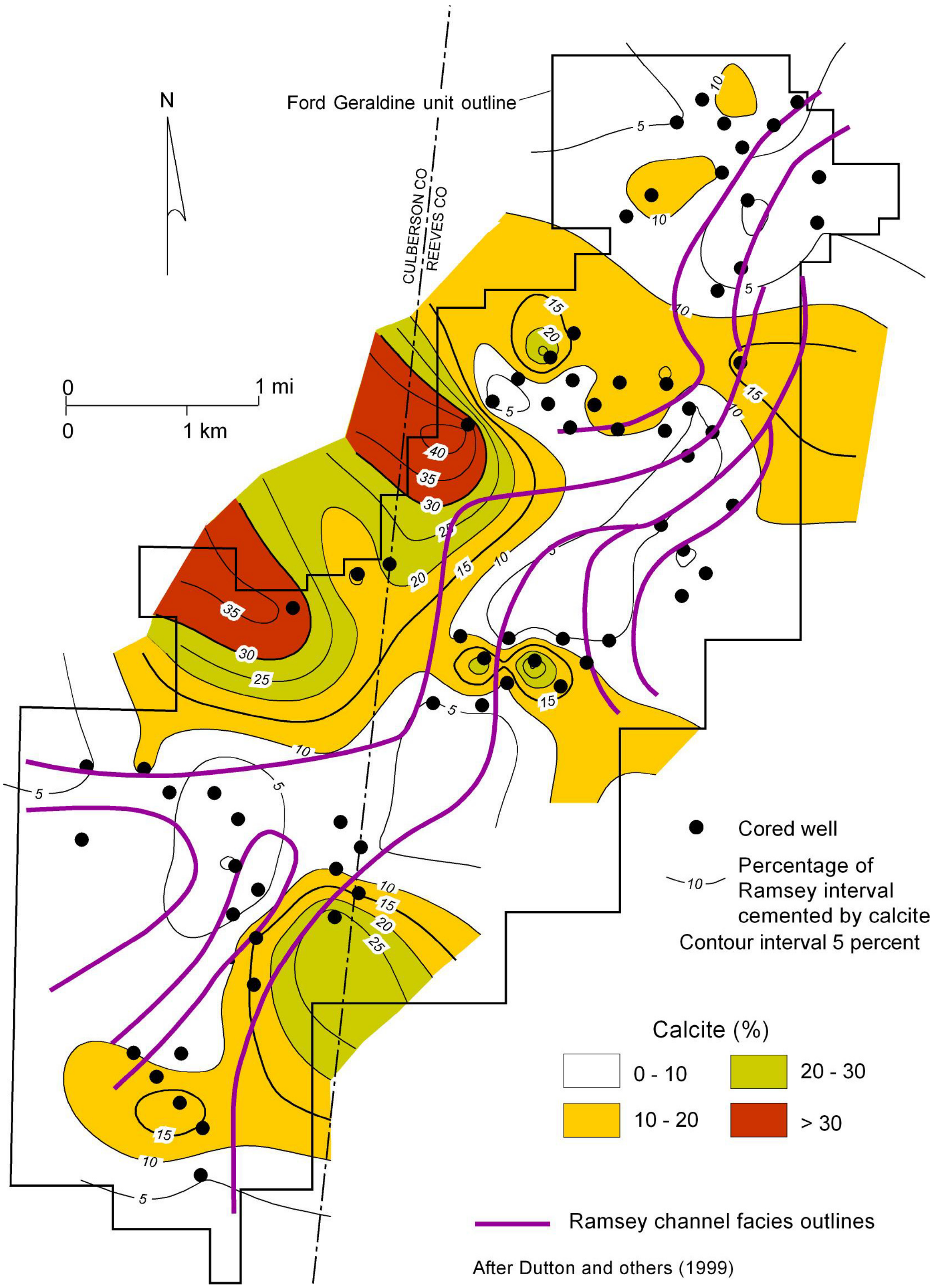


Figure 19. Map of interpreted calcite cement distribution in Ramsey sandstone based on core analyses. Also shown is the outline of combined Ramsey 1 and Ramsey 2 channel sandstone facies. It is possible to recontour the cement map to show a correlation between cement distribution and facies outside the channel complexes. Field location shown in figure 2.

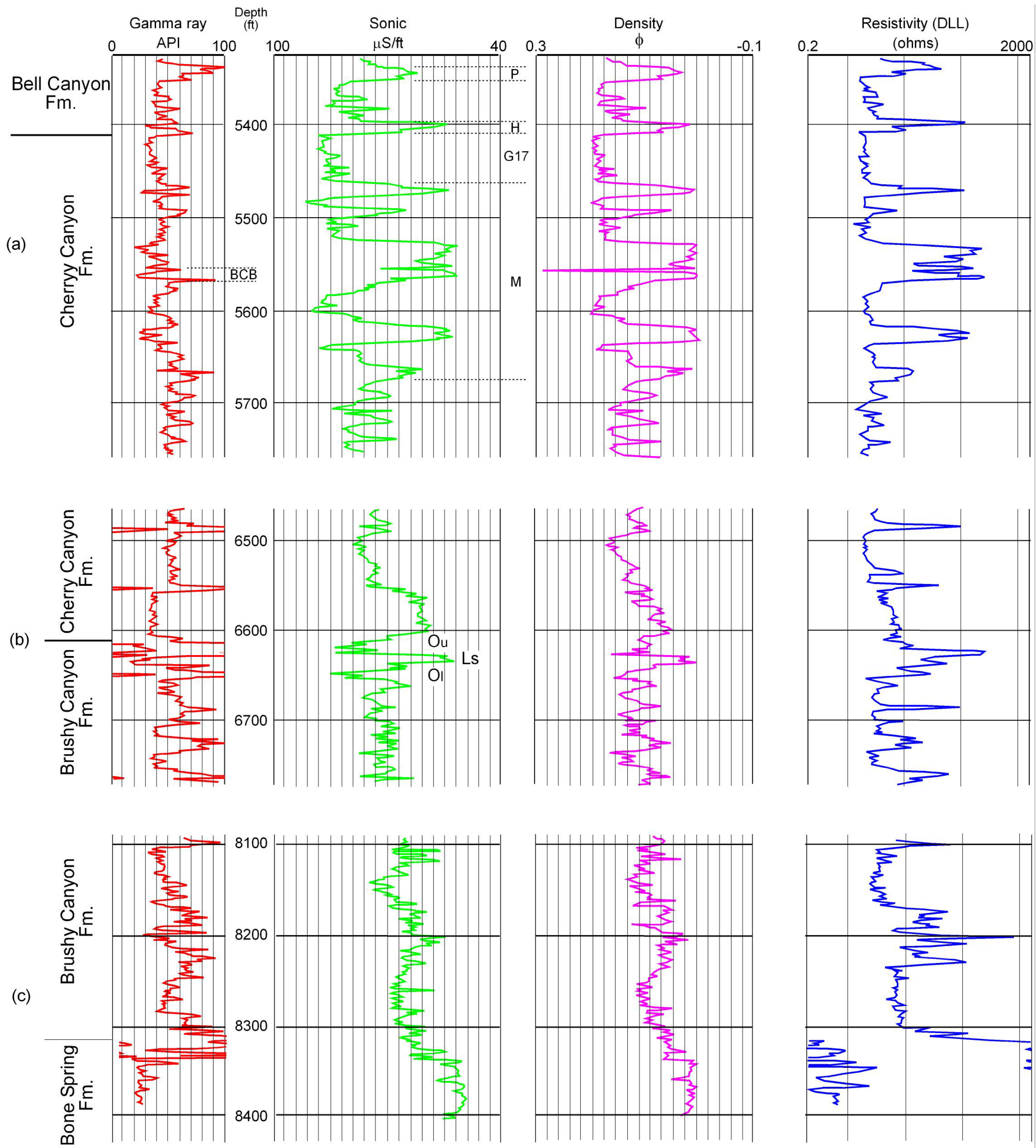


Figure 20. Well log responses in Eddy County Yates Petroleum No. 5 Martha "AK" Federal well (Livingston Ridge field) showing typical stratigraphic boundaries of formations in the Delaware Mountain Group, including (a) top of the Bell Canyon Formation, (c) Cherry Canyon and Brushy Canyon Formations, and (c) base of the Brushy Canyon Formation. Castile and Bone Spring strata at the top and base of the DMG, respectively, are distinguished by distinctively lower gamma-ray values, higher acoustic velocities, lower density porosities, and higher resistivities than those that characterize Delaware Mountain strata. Field location shown in figure 2.

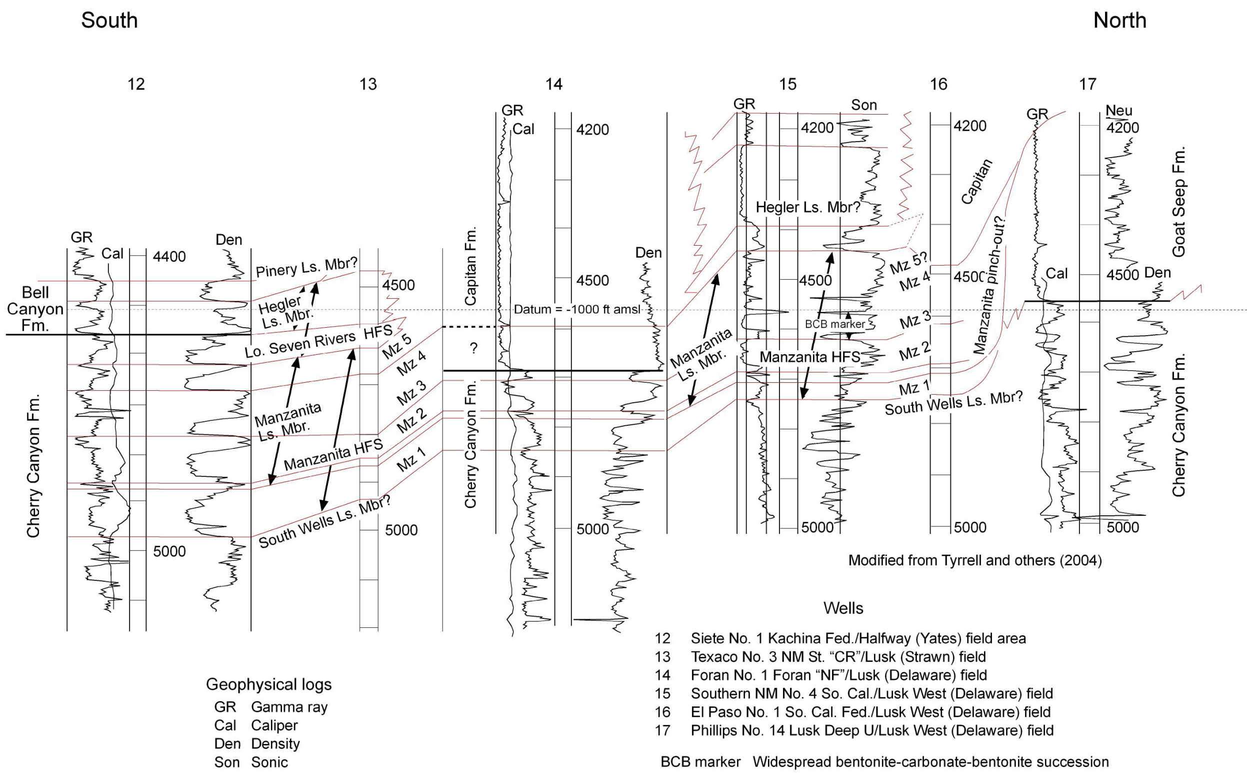


Figure 21. South-north stratigraphic cross section from Halfway field to Lusk West field, northern Delaware Basin, showing correlations within the uppermost Cherry Canyon interval to the Guadalupe shelf margin.

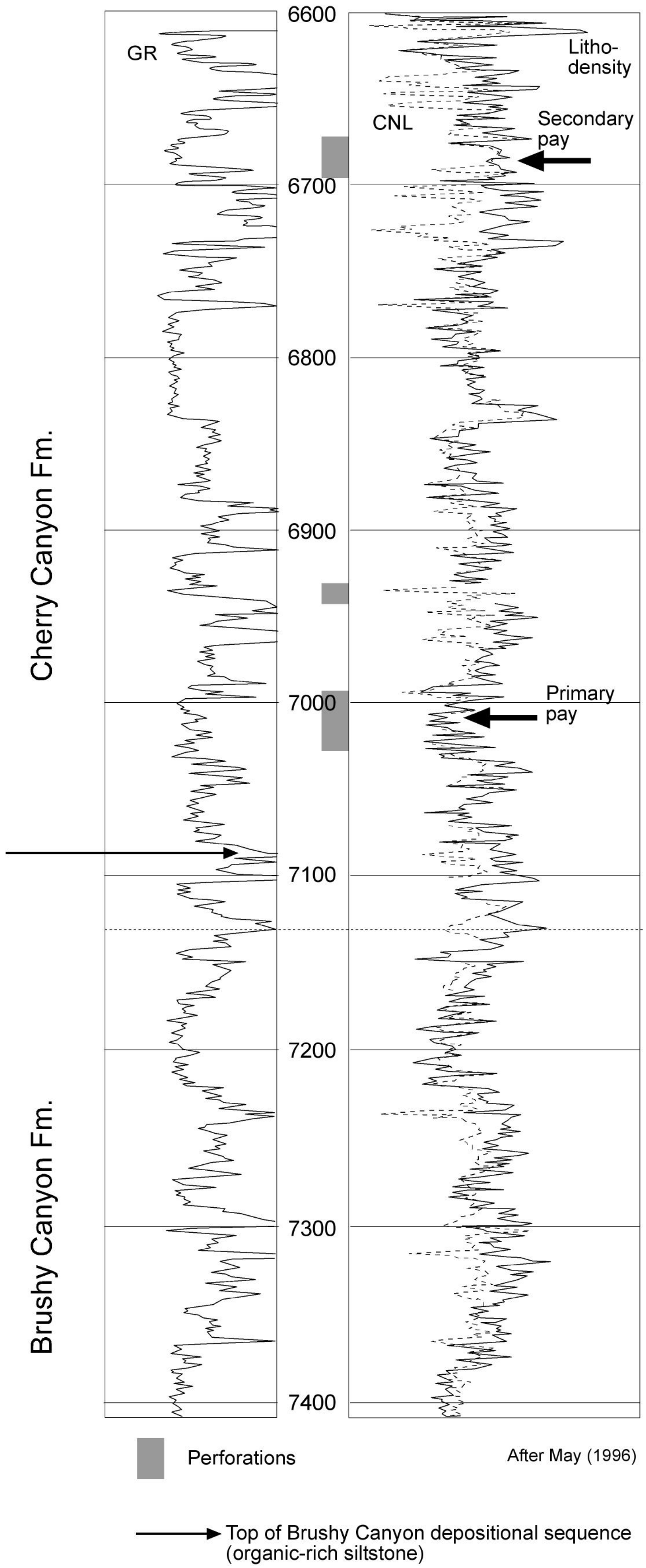


Figure 22. Type log from Livingston Ridge field. Shown are responses for organic-rich siltstone at the Brushy Canyon/Cherry Canyon boundary. The top of the Brushy Canyon depositional sequence is designated to be at the top of the organic-rich siltstone at approximately 7,090 ft, interpreted to record maximum flooding of the shelf. Field location shown in figure 2.

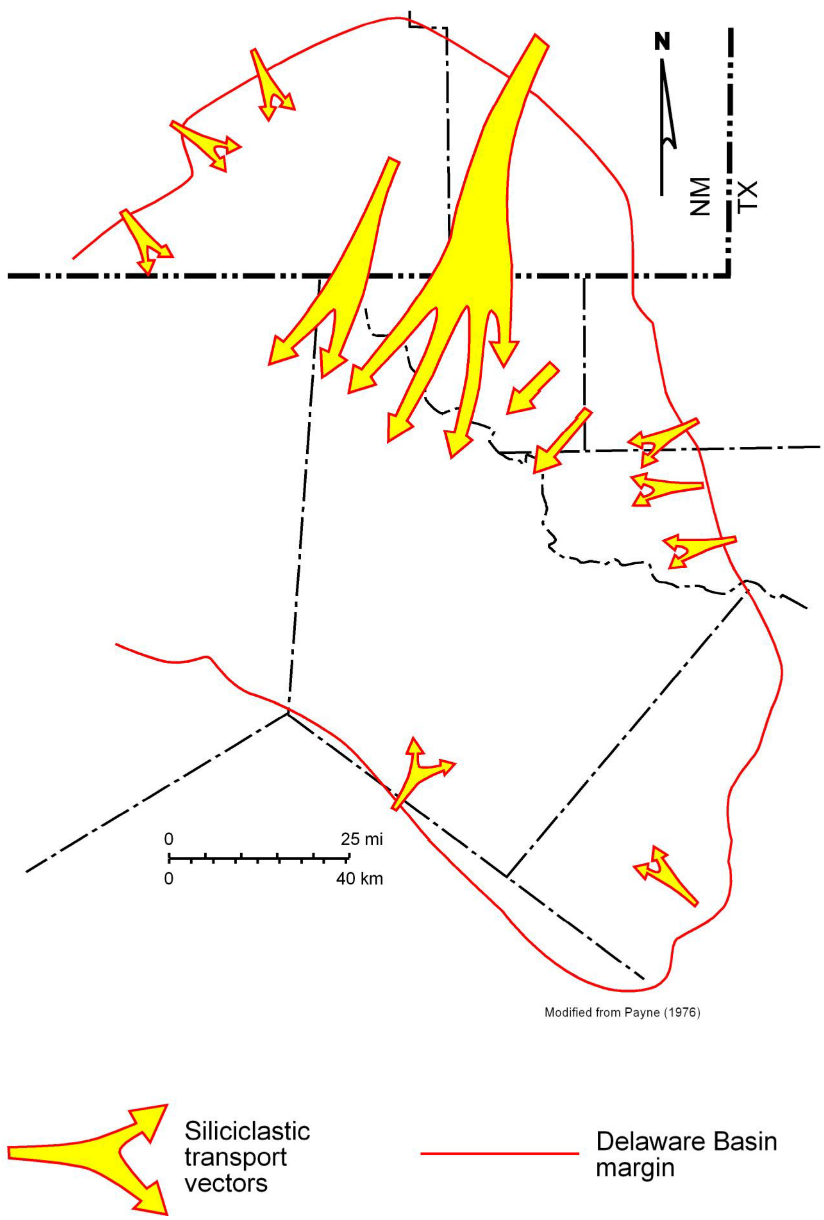


Figure 23. Interpreted Bell Canyon sand depositional fairways based on relative incidence of channel-complex facies. Size of arrows indicates relative importance of fairway.

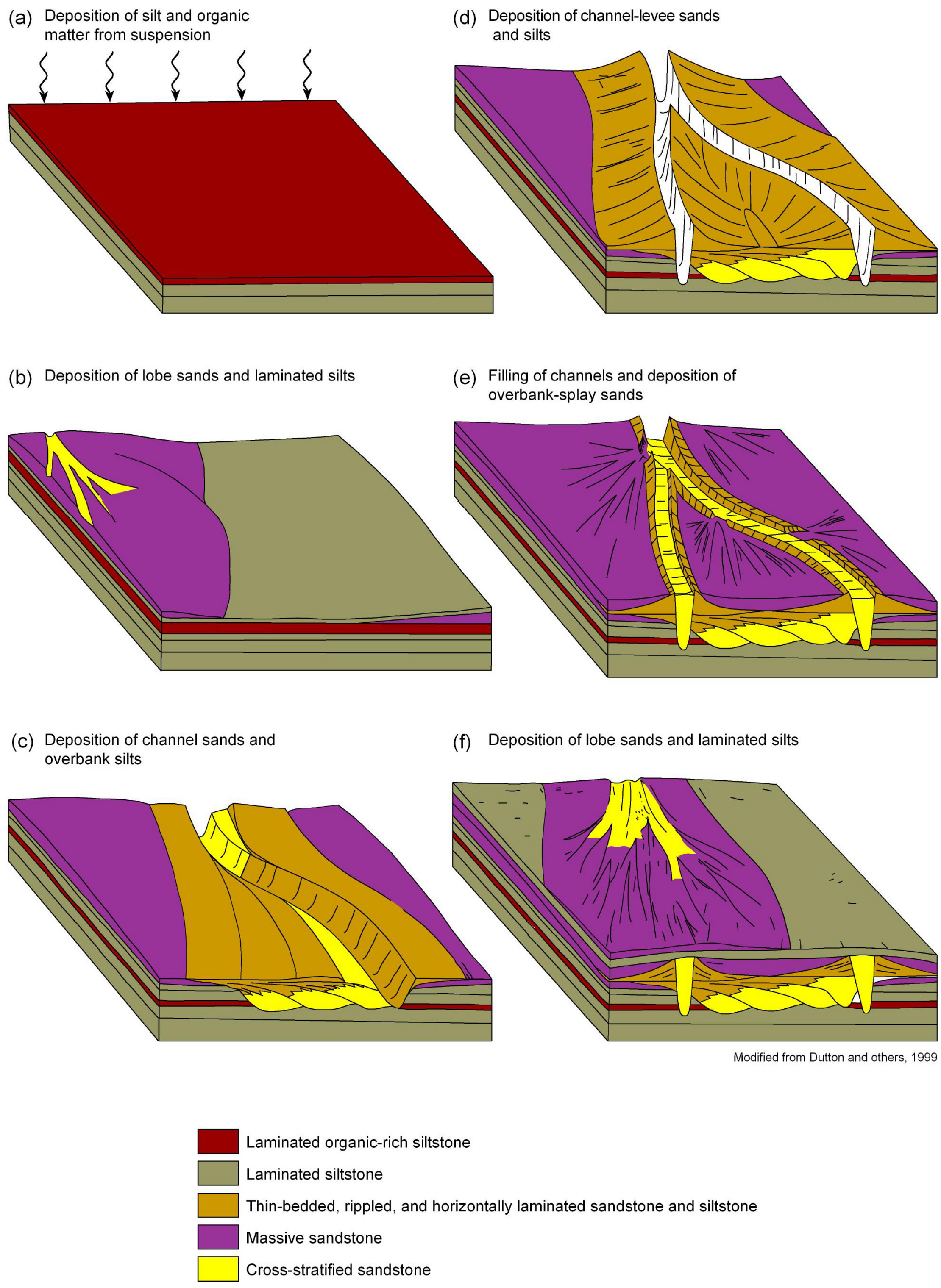
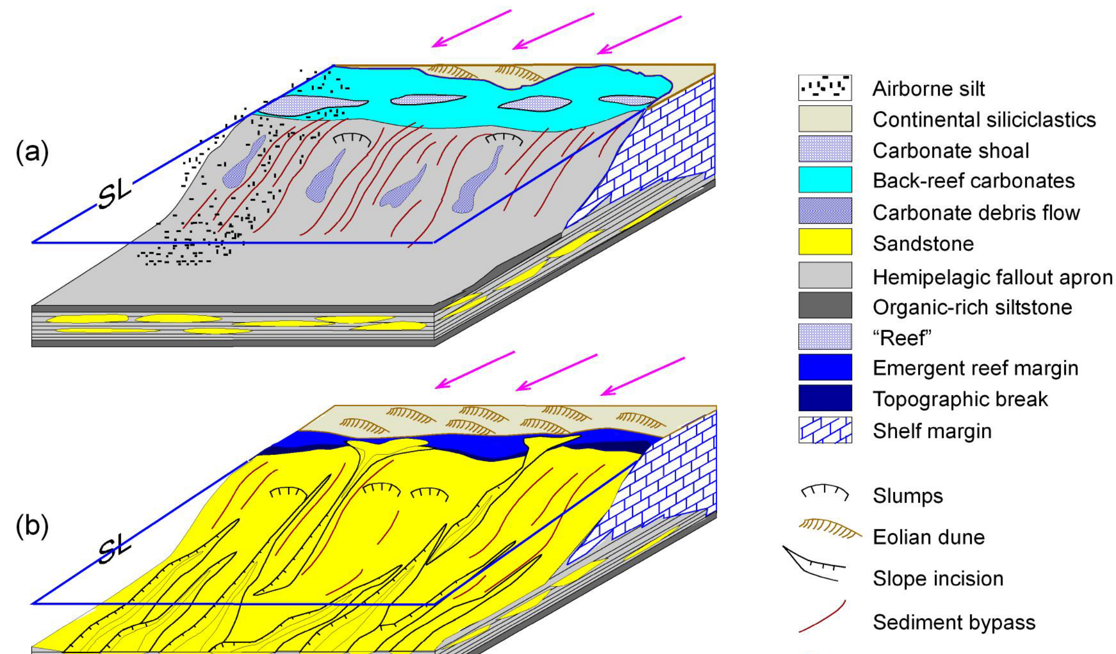


Figure 24. Models of facies development for Delaware Mountain Group depositional units. Organic rich siltstones depicted in a are probable hydrocarbon sources for adjacent sandstone reservoir intervals (see fig. 30). Silt-rich units form top seals. Lateral boundaries for reservoirs are pinch-outs of permeable sandstone facies.



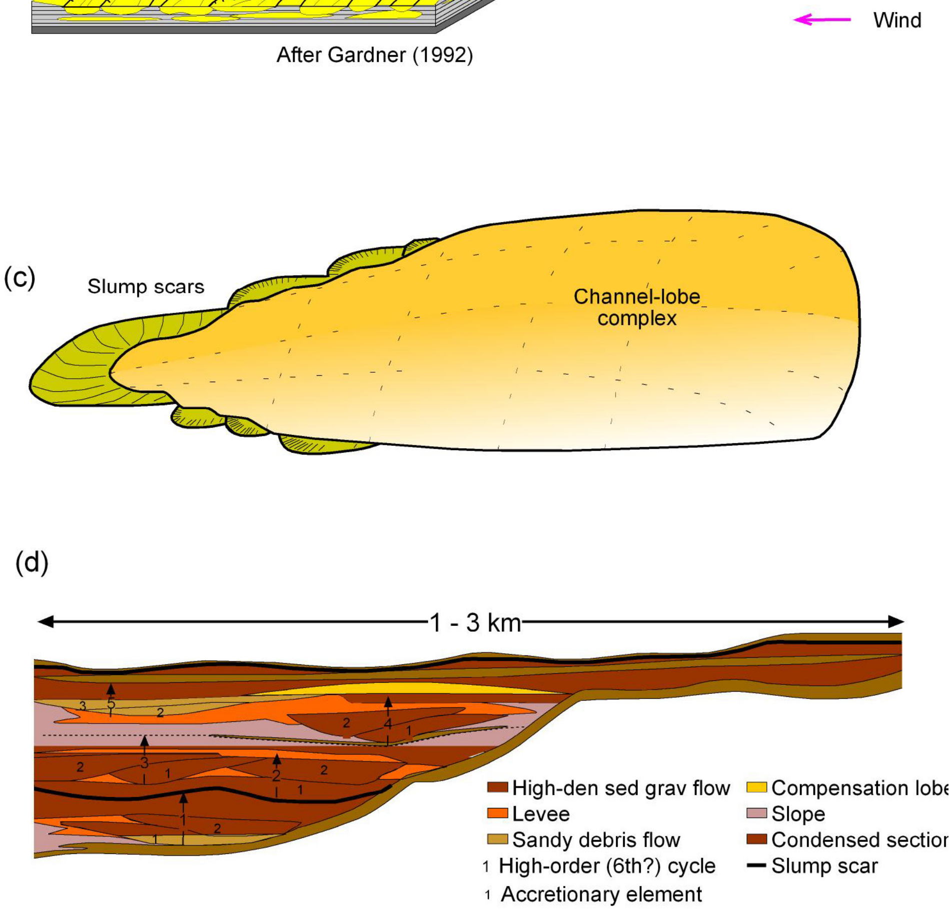


Figure 25. Brushy Canyon depositional cycle models of Gardner (1992): (a) processes during sea-level highstand include restriction of continental siliciclastic depositional environments well shelfward of shelf margin, deposition in basin of windblown silt, and gravity transport of shelf-margin carbonate debris; (b) processes during sea-level lowstand include encroachment of prominently eolian depositional environments on shelf margin, accumulation of siliciclastics on upper slope, slumping of accumulated siliciclastics, and downslope transport of siliciclastics by turbidity flow; (c) idealized model of relationship of channel-lobe complex to slump scar; and (d) idealized strike section showing depositional environments, slump scars, and depositional elements of high-order cycles. Slumping may place updip margins of reservoir facies in contact with low-permeability slope siltstones, thus providing updip lateral seal to some reservoirs.

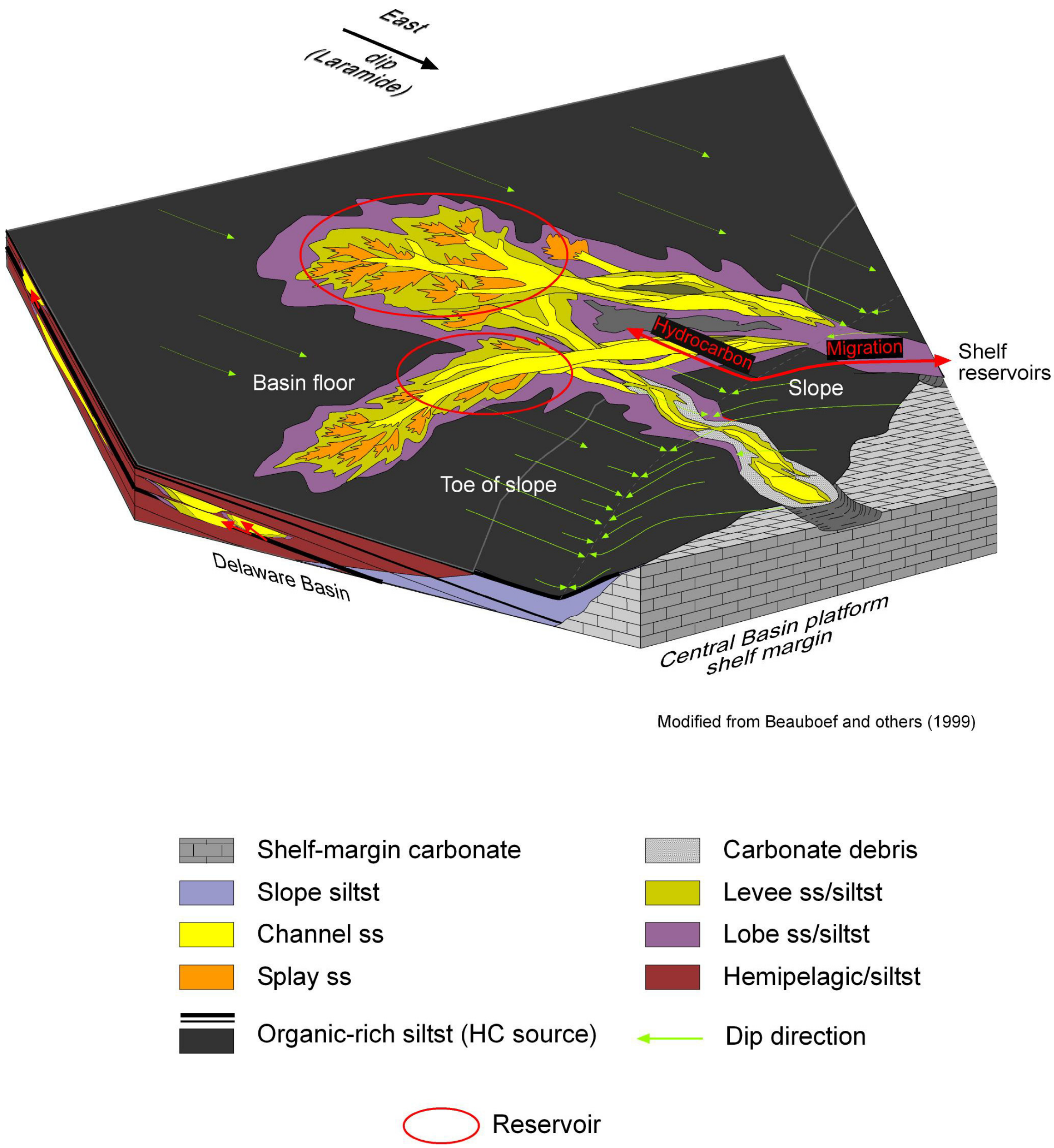


Figure 26. Model of Delaware Mountain Group reservoirs showing paleogeographic elements, principal reservoir and hydrocarbon source facies, regional structural components, and generalized hydrocarbon migration directions. Hydrocarbon reservoirs are preferentially developed in favorable facies, where porous sandstone facies laterally pinch out into low-permeability siltstones. Depending on location, hydrocarbon migration is directed toward the west by easterly dip imparted by Laramide epeirogeny or toward the east into shelf reservoirs by residual, depositionally controlled structural rise on the slope toward the shelf margin.

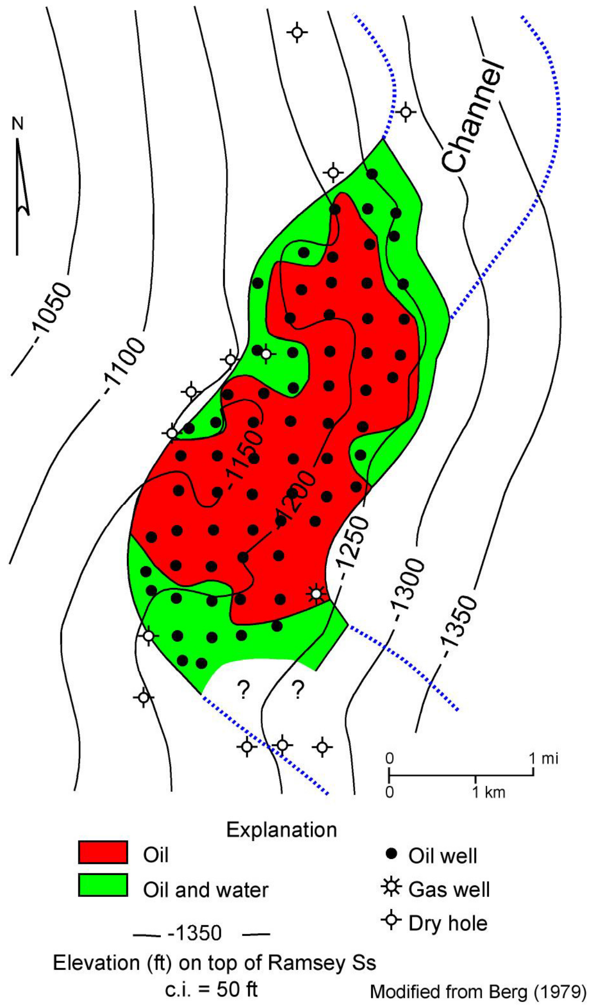


Figure 27. Simplified model of Ramsey sandstone reservoir (Bell Canyon) configuration in Paduca field. Hydrocarbons accumulated in channel-complex meander bend in updip location on regional eastward-dipping structure produced by Laramide epeirogeny. Field location shown in figure 2.

(a)

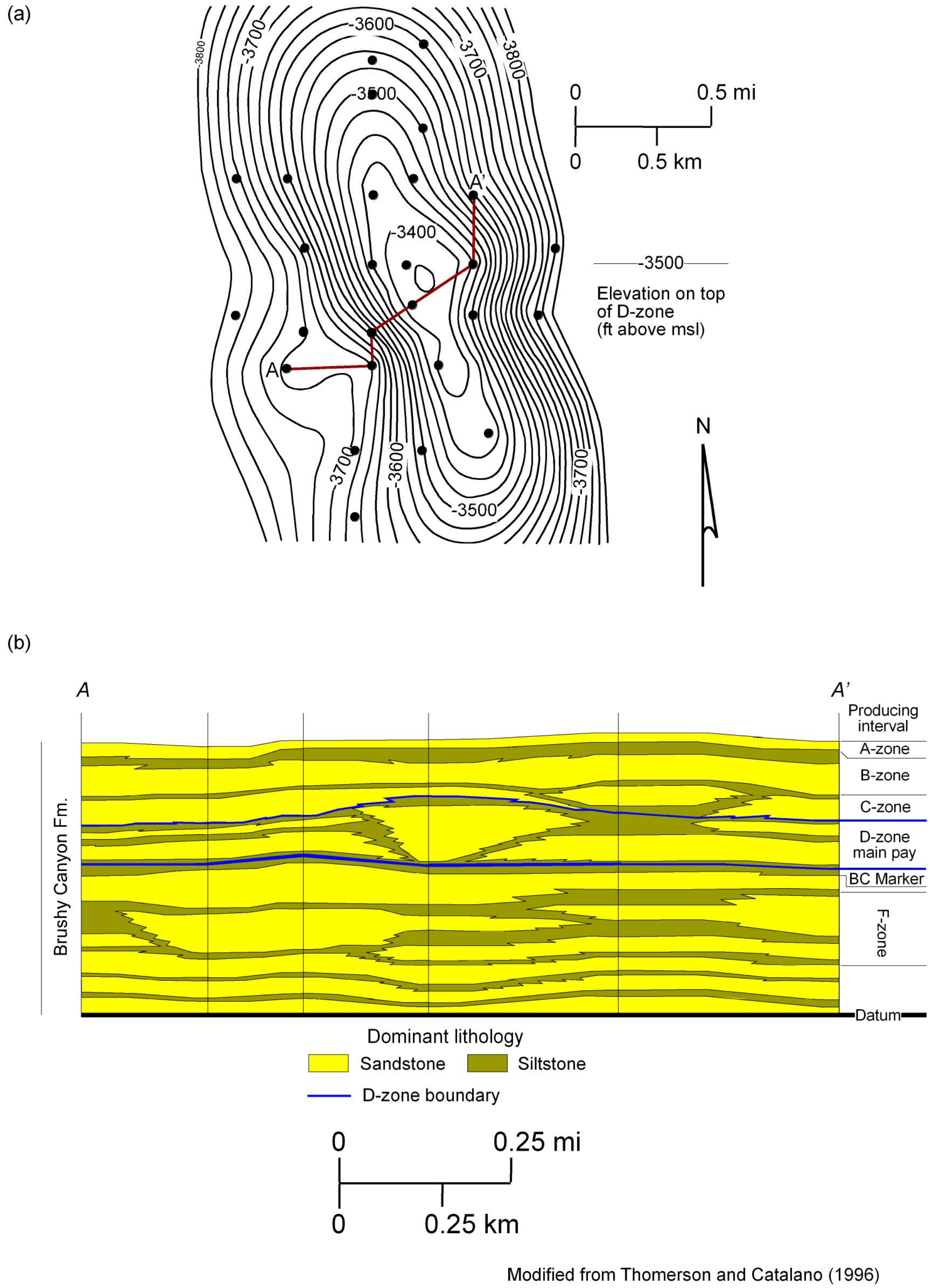


Figure 28. Sandbody architecture, East Livingston Ridge field, Upper Brushy Canyon Formation. (a) Structure map on top of D-zone (primary reservoir) and (b) southwest-northeast stratigraphic cross section of productive intervals. Cross section shows compactional anticlinal structures over thicker parts of sandbodies, especially over D-zone channel sandbody and compensatory offsets of stratigraphically sequential sandbodies. Field location shown in figure 2.

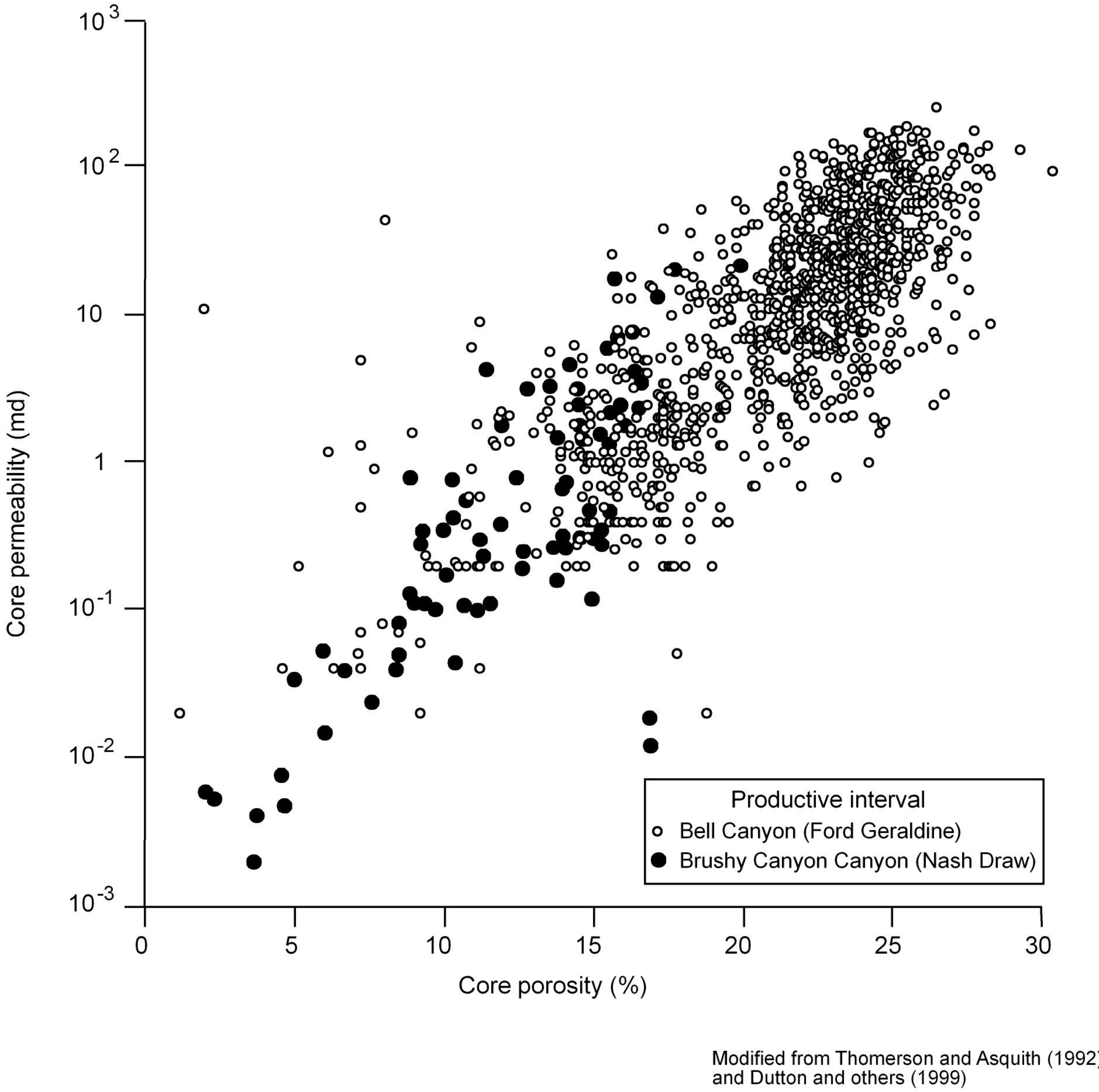


Figure 29. Plot of core-derived porosity and permeability measurements of productive sandstones from Ford Geraldine (Bell Canyon) and Nash Draw (Brushy Canyon) fields. Although Brushy Canyon porosity and permeability values are overall less than Bell Canyon values, the linear relationship between the parameters is similar in both reservoirs.

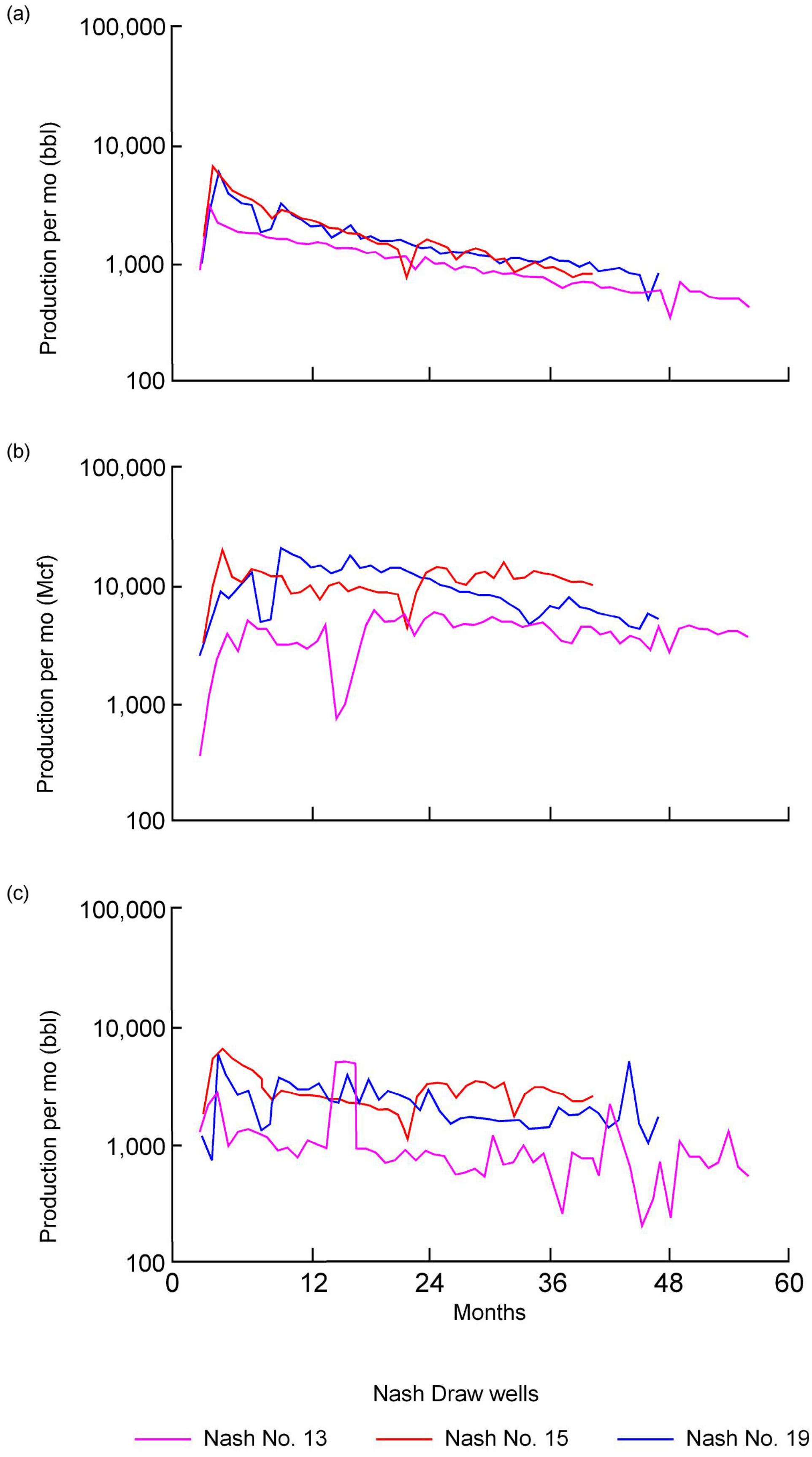


Figure 30. Graphs showing monthly production rates for (a) oil, (b) gas, and (c) water from three closely spaced wells in Nash Draw field. Dissimilarity of production responses in closely spaced (0.25–0.5 mi) may reflect lateral petrophysical variability in channel-levee-lobe complex facies. Note rates of oil-production decline similar to those seen at Livingston Ridge/Lost Tank fields (fig. 31). Field location shown in figure 2. Modified from Montgomery and others (1999).

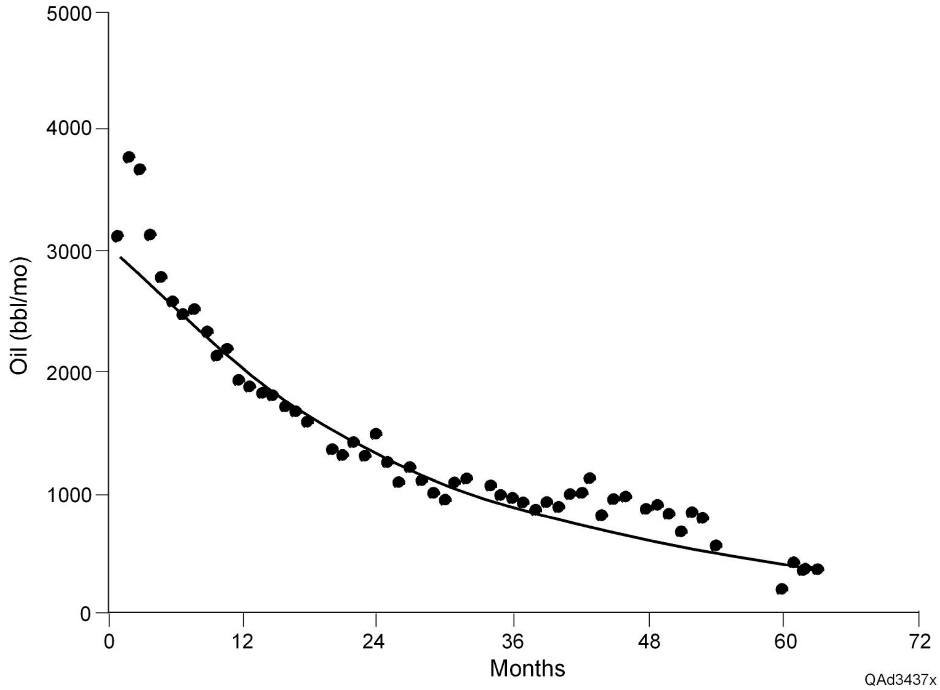


Figure 31. Average production-decline curve for wells in Livingston Ridge/Lost Tank field. Average production is reduced to approximately 10 percent of initial rates after 5 years. Modified from Broadhead and others (1998). Field location shown in figure 2.

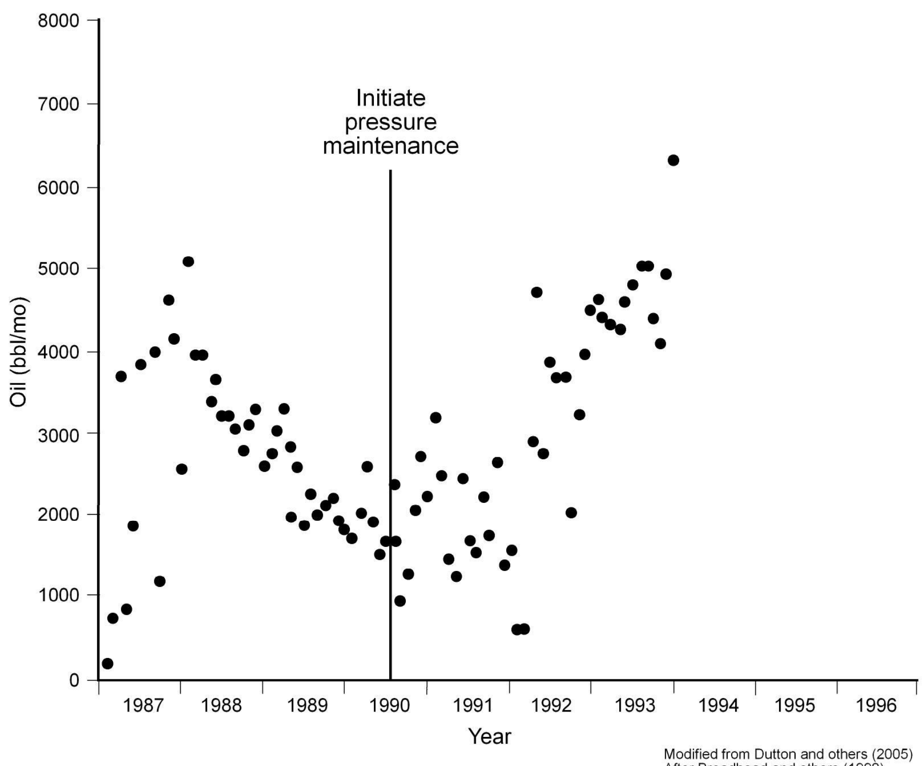


Figure 32. Monthly oil production from Phillips No. 2 James A well, Cabin Lake field, showing production increase after water injection for pressure maintenance. Field location shown in figure 2.

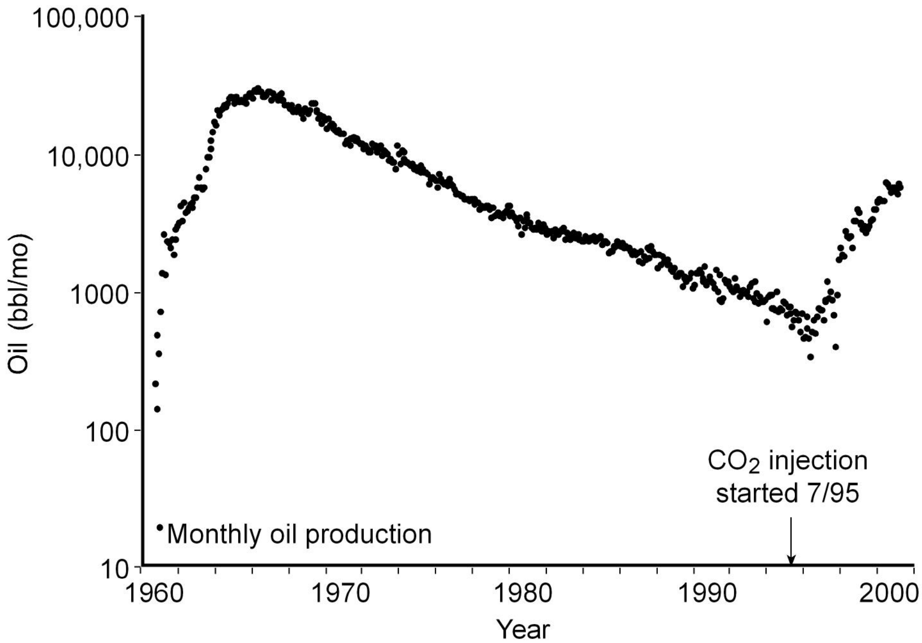


Figure 33. Monthly oil production from East Ford Unit (Bell Canyon), showing production improvement after change from primary to secondary production with initiation of CO_2 injection in 1995. Field location shown in figure 2. From Dutton and others (2003).

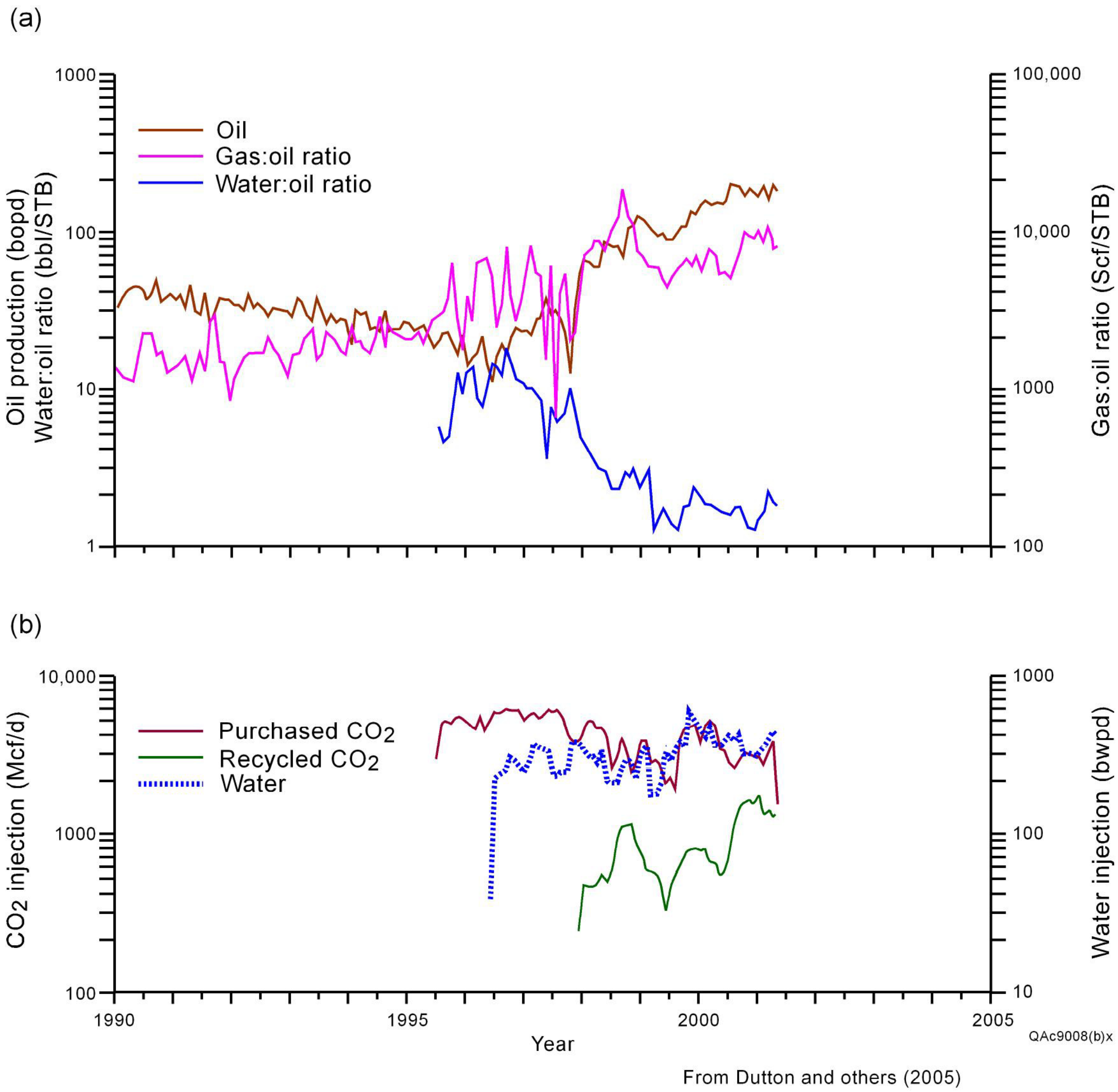


Figure 34. Graphs showing (a) values of oil production, gas/oil, and water/oil for a typical well in the East Ford unit, Reeves County, for 1990 through first half of 2002 and (b) injected volumes of CO_2 and water. Gas injection began in 1995, and water injection began in 1998. Note that production shows an overall increase soon after initiation of water injection. However, water:oil values decrease while gas:oil values increase, suggesting that overall production increases more probably reflect success of CO_2 injection. Field location shown in figure 2.