Upper Ordovician Montoya Sequence Stratigraphy and Chert Porosity in Southeastern Delaware Basin*

By
David M. Thomas, III[1] And Huaibo Liu[1]

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[1]Tom Brown, Inc., Midland, TX (dthomas@tombrown.com)

Stratigraphic Framework

The Upper Ordovician (Cincinnatian) Montoya Group, of the southeastern Delaware Basin, was deposited approximately 450 Ma on a carbonate ramp in a shallow marine environment as a 2nd-order sequence. It is bounded by the unconformable Lower Silurian Fusselman Formation above and Middle Ordovician Simpson Group below. There are four formations; (Cable Canyon, Upham, Aleman, and Cutter) described in outcrop and correlated to the subsurface in the Delaware Basin. These formations consist of four unconformity-bounded 3rd-order sequences in the study area (Figures 1 and 2). Sequence I, which include both the Cable Canyon and Upham Formations, is composed of lowstand systems tract (LST) siliciclastics and carbonates, transgressive systems tract (TST) limestone/chert and a highstand systems tract (HST) limestone. Sequence II contains the Lower Aleman Formation, which is a TST limestone/chert and HST limestone. Sequence III is the Upper Aleman Formation and includes a TST limestone/chert and HST limestone. Sequence IV is the Cutter TST limestone/chert and HST carbonate (Figure 2). The LST and the HST are essentially chert-free and might have trace amounts (less than 1 percent) of silicified skeletons. The chert-bearing facies occurs in the TSTs and contains 20 to 60 percent chert by the rock volume (Figures 2 and 3).

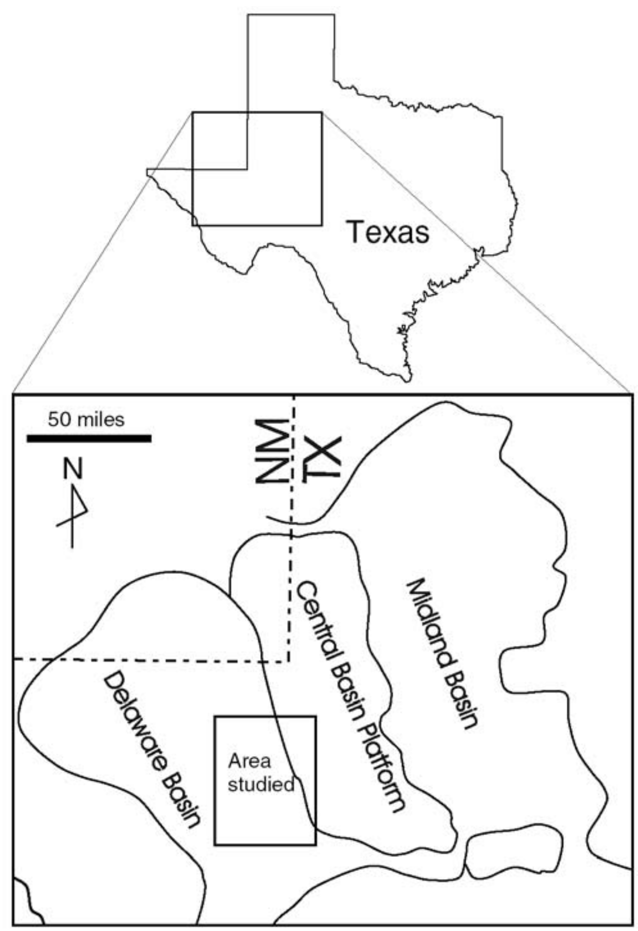

Figure 1. Locality map of study area.

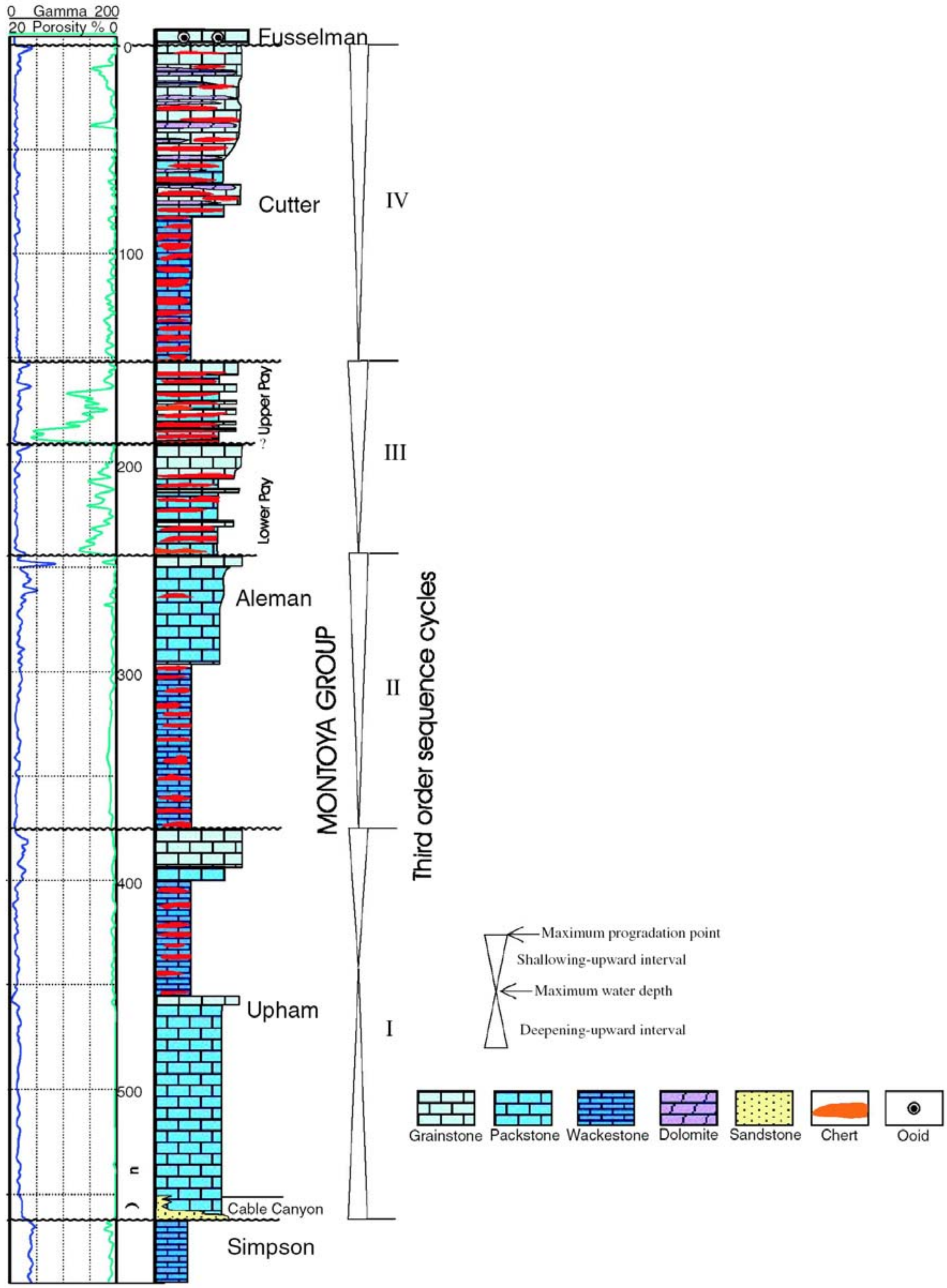

Figure 2. Type cross-section shows Montoya lithology and the 3rd-order sequence cycles. Lithology was interpreted from cores and samples.

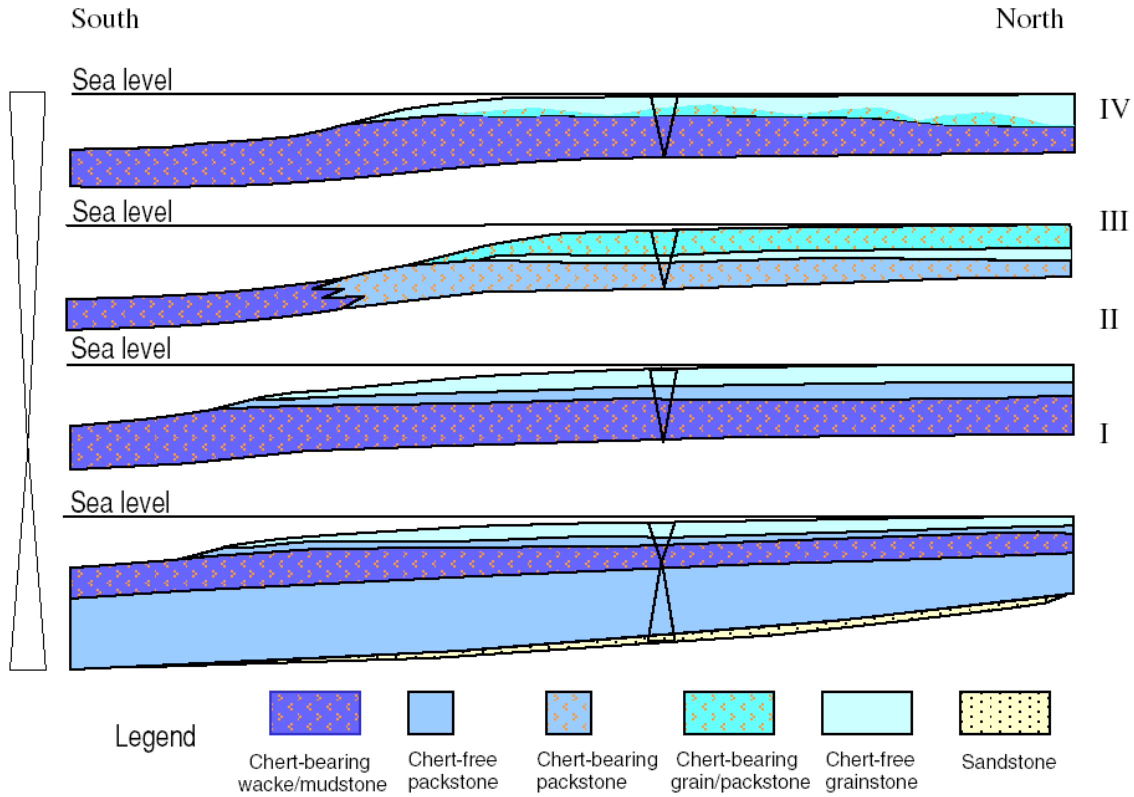

Figure 3. Cross-section from south to north showing depositional packages and their 3rd-order sequences. Stratigraphic interpretation developed from an integrated evaluation of the Ordovician Montoya shown in stages: Sequence I B Upham, Sequence II B early Aleman, Sequence III B later Aleman, and Sequence IV B Cutter. Triangles on the left indicate 2nd -order sequence water depth change (see Figure 2).

Facies

Chert-Free Facies

The chert-free facies includes three main lithologies: 1) sandstone and sandy skeletal packstone, 2) fine-to very coarse-grained skeletal packstone, and 3) fine- to very coarse-grained skeletal grainstone. The sandstone and sandy packstone of the Cable Canyon Formation, ranging from 2-20 feet thick, is a nearshore deposit characterized by well rounded, poorly sorted, and fine to very coarse quartz sands and skeletal fragments. The skeletal packstone of the Lower Upham is a dark-colored, poorly sorted, massively bedded shallow-marine deposit that accumulated rapidly; it consists of poorly sorted coarse-grained, diverse open-marine-fauna. The sandstone, sandy packstone, and skeletal packstone form the base of Sequence I's LST. The lighter colored chert-free packstones of the Upper Upham and Lower Aleman, characterized by a coarser-grained texture with diverse skeletons, are offshore bank deposits occurring as the lower section of the HSTs. The chert-free skeletal grainstone facies, especially the cross-bedded, coarse- to very coarse-grained skeletal grainstones (Figure 5 A) represent progressive shoal deposits that cap the HSTs. (Figures 2, 3, 4, and 6).

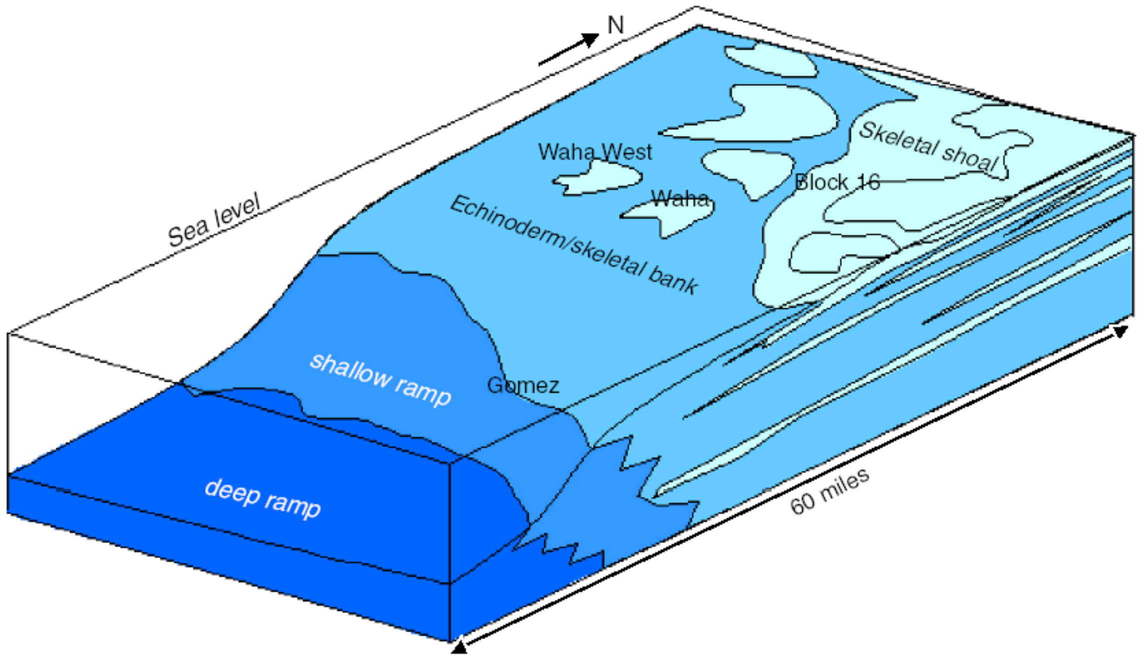

Figure 4. Block diagram showing depositional environments of the upper Aleman by the end of Aleman deposition.

Chert-Bearing Facies

The chert-bearing facies consist of host limestone and chert nodules, bands, and layers. The three primary lithologies are: 1) fine-grained skeletal grainstone (Figure 5 B), 2) fine-grained echinoderm packstone (Figure 5 C) and 3) lime wacke/mudstone; all are significant TST components. The wacke/mudstone found in the TSTs of the Upham, Lower Aleman, and Lower Cutter are dark in color and contain very fine spicules and spiculitic chert, representing deeper water, lower energy (deep-ramp) deposition with maximum water depth during the 3rd-order sequence sea-level rise (Figures 2 and 3).

The fine-grained skeletal grainstones and packstones deposited in the upper Aleman are characterized by an even lighter color and well-sorted skeletons (dominantly echinoderms and ostracods). This is interpreted to be a medium-energy bank deposit capping a TST high-frequency sequence (Figure 6). The remnant structures in the chert coincide with that of the surrounding host rock. The Upper Aleman’s lithological vertical assemblage and lateral distribution is interpreted as a shallow-marine skeletal bank deposited on a gentle ramp developed toward the south. The HST coarser grained skeletal grainstone capping each cycle could have been partially exposed to the northeast (Figure 4).

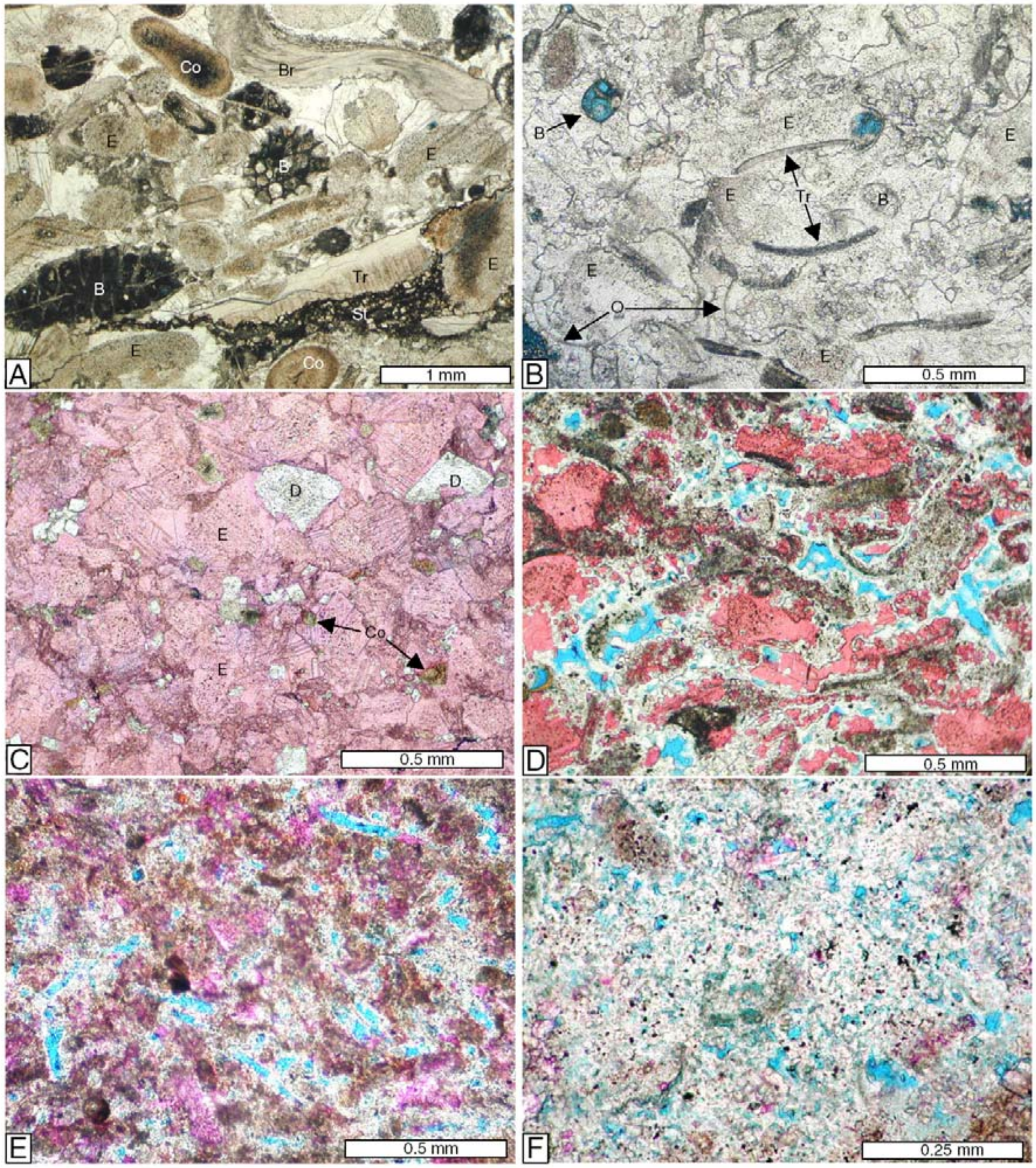

Figure 5. Photomicrographs show main lithologies and porosity types of the Montoya Aleman pay zone. A: Coarse-/very coarse-grained, skeletal grainstone, the main chert-free lithofacies of the Aleman Formation, with diverse skeletons including echinoderm (E), bryozoan (B), brachiopod (Br), and trilobite (Tr), some echinoderm having been collophane-replaced (Co), synaxial calcite cemented, fine dolomite occurring along muddy stylolite (St), thin-section from G. Lyda 1H, 15468 feet. B: Fine-grained, skeletal grainstone, one of the two most abundant host rocks of the pay chert, composed of well sorted skeletal fragments of echinoderm (E), ostracod (O), bryozoan (B), and trilobite and equant and synaxial calcite cements, with minor intraparticle pores (blue), thin-section from G. Lyda 1H, 15474 feet. C: Fine-grained, echinoderm (E) dominated, skeletal packstone, the other abundant host rock of the pay chert, well-sorted, slightly dolomitized (D), with minor collophane-replaced grains (Co), Stained thin-section from Rape 14-1H, 13626 feet. D: Reduced interparticle porosity in chert, remnant textures showing initially a skeletal grainstone with abundant echinoderms and ostracods, stained thin-section from Rape 14-1H, 13627 feet. E: Moldic porosity (blue) after dissolved spicules in spiculitic limy-chert, stained thin-section from Rape 14-1H, 13616 feet. F: Small pore system (bright blue) and micro-porosity in chert, resulted from continued precipitation of silica in the early interparticle spaces and remained intraparticle pores of silicified echinoderms, pore throats less than 0.05 mm, stained thin-section from Rape 14-1H, 13616 feet.

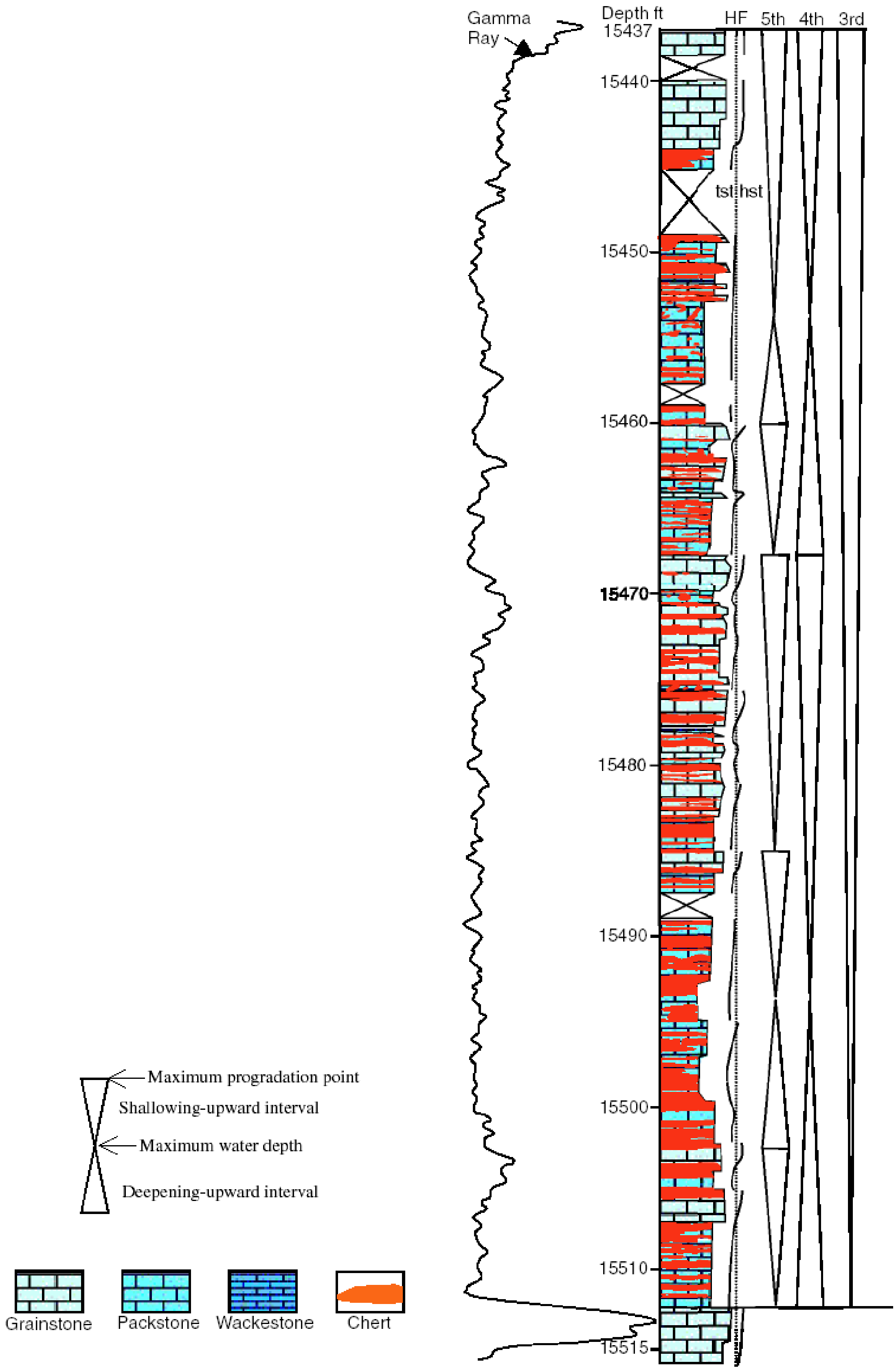

Figure 6. Sequence cycles of Aleman upper pay, G. Lyda 1H. HF: high frequency sequence.

Gas Reservoirs

Three gas-reservoir intervals, Cutter, Aleman and Upham, have been drilled and reportedly developed. The reservoir porosity in the Cutter Formation in the northern portion of the study area occurs primarily in the dolomite that developed within the HST skeletal grainstone with some minor contribution from porous and fractured chert. The Upham reservoir tested in the southern part of the study area included porosity at the top of the HST grainstone and fractures in the transgressive chert. The upper Aleman is the primary Montoya pay and contains a number of high-frequency sequences and high-frequency sequence sets of TST chert-bearing and HST chert-free limestones (Figures 2 and 6). The reservoir porosity is predominantly from the chert. Reduced interparticle (Figure 5 D), moldic (Figure 5 E), small pore and micro (Figure 5 F) porosities in the chert with some minor porosity developed in the dolostone and limestone provide the primary gas reservoir.

Sedimentary History and Porosity Development

During deposition of the Montoya, a vast deep siliceous ocean covered the area to the south. The movement of the silica-bearing upwelling water from south to north along the sea floor resulted in early silicification that was influenced by the environments of deposition, relative sea level, and sedimentary facies. The development of the chert and chert porosity was a direct result of the reaction rates and products of interstitial water and sediments. The LST sandstone and packstone of the Cable Canyon and Lower Upham were deposited in a relatively restrictive shallow-marine environment during a period of rapid sediment accumulation, which highly limited the upwelling activity, resulting in a chert-free facies. During the progressive HST grainstone deposition, high-energy waves, as well as storm and tidal currents forced the nearshore, higher-temperature, higher-salinity/lower-CO_2-content water deeper. The interstitial water of the shoal deposits was saturated with $CaCO_3$ but unsaturated with SiO_2, resulting in other chert-free facies of the Aleman and Upham. The transgressive packages of Upham, Aleman and Cutter were deposited on the ramp and skeletal bank during sea-level rise. The relatively lower energy and deeper water resulted in organic- and carbonate-mud-rich deposits. The relatively higher CO_2 partial pressure of the deeper water and organic acid from decomposition can decrease the pH value of the interstitial water in the sediments, enhancing silicification. The porosity development was strongly related to the texture of the precursor sediment along with the intensity and rate of silica diagenesis. The porous chert of the Montoya pay occurs only in the skeletal-bank facies. The reduced interparticle porosity, representing the dominant pore system has been created from silicification of original interparticle spaces in the grainstone and dissolution of interparticle matrix in the packstone. This initial silicification occurred during TST deposition and shallow burial (before compaction).

Three stages of silica diagenesis controlled the porosity evolution. The first stage was dissolution of metastable matrix and skeletal fragments as the siliceous, low-pH, upwelling water began to replace the primary interstitial water. The dissolution of this stage enlarged interparticle pore spaces and created moldic porosity. The second stage is silica precipitation on the pore walls to form a silica rim that partially replaced the metastable grains, such as echinoderms, ostracods, brachiopods, and bryozoans resulting in the main porous reservoir chert in the Aleman. The third stage was continuous silica precipitation and replacement that completely filled the porosity and replaced the calcite, forming a non-porous chert. The subsequent HST limestone deposition restricted further silicification and protected the porosity from further chert precipitation. In some areas the silicification was physically restricted in the second stage, resulting in reduced interparticle porosity. Elsewhere the chertification was almost completely prevented between stage 2 and stage 3, forming a small pore system.