New depositional model (lake-shelf hyperpycnites) for enigmatic Brushy, Cherry and Bell Canyon Formations, Permian, Delaware Basin, USA: importance for local and global petroleum exploration and development

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Abstract

Many oil companies use a popular deep-sea-fan model for exploration and development in the Brushy, Cherry and Bell Canyon ('BCB') formations, despite the Brushy's previous shallow-water interpretation. Moreover, the Brushy is popular as an outcrop analog for worldwide passive-margin, deep-sea-turbidite reservoirs (fans and leveed sinuous channels; e.g., offshore GoM, Brazil, Africa), where economic losses from using incorrect analogs can potentially reach billions of dollars. A new BCB depositional model is offered here, river-fed turbidites (hyperpycnites) on a lake shelf, based on (1) a literature survey, (2) the author's outcrop observations, and (3) his intimacy with the Brushy-lookalike Bude Formation (UK). Evidence for a low-salinity "Lake Brushy" includes: (A) lack of reported marine fossils other than abraded (reworked) ones; (B) lack of exclusively marine ichnogenera; and (C) distinctive "premature amalgamation", whereby sand sheets are up to 10 m thick yet comprise only thin (< 40 cm) beds, reflecting easy resuspension (weak cohesion) of fresh-water bottom muds. Shallow water is indicated by numerous BCB event beds with evidence for storm waves (HCS; near-symmetrical ripples; mud-draped scours), interpretable as wave-influenced hyperpycnites. An inner-Brushy belt of "deep-sea slope" muds with "slope channels" is reinterpreted here as a stack of delta-slope clinothems, each < 15 m thick, separated by ravinement sequence boundaries and fluvially incised valleys with low sinuosity and non-estuarine hyperpycnite fill. Delta progradation at highstand alternated with lowstand deposition of hyperpycnites on an outer-Brushy shelf, fed by incised rivers. Shelf emergence was prevented by storm erosion that maintained an equilibrium profile. The shelf was on an inherited passive margin, facing a SE-subducting remnant ocean cut off from the world ocean by the Marathon salient (of Gondwana) colliding early against Euramerica, raising a sill (Diablo Platform), isolating the Brushy 'oceanic lake', freshened by river inflow. The new shelf model is vital for BCB exploration and production, since predicted sand distribution, geometry and architecture differ strongly from those forecast by the popular model of deep-sea fans fed by slope channels. The BCB formations are unsuitable global outcrop analogs for passive-margin deep-sea-turbidite reservoirs.

Introduction

This contribution is based on a thorough literature review and three days studying roadcuts of the Brushy Canyon and overlying Cherry Canyon and Bell Canyon (BCB) formations (Permian, Delaware Basin) in Guadalupe Mountains National Park, reinforced by the author's intimacy with one of the few Brushy lookalikes worldwide (Bude Fm, Pennsylvanian, UK; Higgs, 1991, 2004, 2008). The BCB paleo-water depth is controversial (10s v. 100s m; Harms and Brady, 1996), yet many oil companies apply a deep-sea-fan model (after Jacka et al., 1968) to exploration and development in all three formations, with vital implications for predicting sand distribution, geometry and architecture, essential for: (1) optimum borehole placement (producers, injectors; vertical, horizontal); (2) positioning of perforations; (3) choice of reservoir-model input parameters; and (4) economic evaluations (predicting reserves and production rates). The Brushy is also widely used globally as an outcrop analog for passive-margin, deep-sea-turbidite reservoirs (fans and leveed sinuous channels; e.g., Gulf of Mexico, Brazil, Africa) where, due to high operating costs, the use of improper analogs risks billions of dollars in (A) non-optimum well placement and (B) unrealistic production- and reserves forecasts, causing unwarranted field development or non-development (Higgs, 2009a).

Evidence for Brushy deposition on a lake shelf

Diverse marine fossils occur in many Brushy sandstone beds but are abraded (King, 1948; Newell et al., 1953), suggesting reworking from older strata. Lack of reported *in situ* marine fossils or unequivocally marine trace fossils suggests deposition in a lake (Higgs, 2009b), here named "Lake Brushy". Nevertheless, thin (cm-dm) bands with indigenous marine fossils would be unsurprising, reflecting eustatic rises high above the lake sill (see below; cf. Quaternary Black Sea; Higgs 1991). The lake's low salinity (humid paleoclimate; see below), hence low density, favored hyperpycnal flows (river-fed turbidity currents), especially during catastrophic floods. Dominance, in Brushy turbidites, of Bouma A divisions without clear grading suggests steady depletive flows too slow for traction. The water depth was within storm wavebase (probably < 100 m, due to limited lake fetch), based on four observations: (1) numerous event beds with symmetrical or near-symmetrical ripples (King, 1948; Newell et al., 1953), suggesting deposition involving waves. Harms (1969, fig. 17) attributed Brushy quasi-symmetrical ripples to wave-dominated combined flow. Both King (1948) and Newell et al. (1953) interpreted the Brushy as shallow-water deposits; (2) presence of hummocky- and swaley cross stratification (HCS, SCS; author's observations), previously described as "low-angle lamination", "lenticular sandstone", "cross bedding", "trough cross stratification" and "Helmholtz waves" (Zelt and Rossen, 1995; Beauboeuf et al., 1999; Gardner and Borer, 2000), and as "plow-and-fill ... (that has) ... been misinterpreted as ... hummocky to swaley cross-stratification" (Gardner and Sonnenfeld, 1996, p. 31). Oversteepened "plow and fill" (Gardner and Borer, 2000) may reflect *in situ* foundering due to earthquake-induced liquefaction; (3) common undulatory mud-draped scours, characteristic of storm beds (Walker et al., 1983, fig. 1 ideal bed); Brushy examples are concave-up or undulatory, with low relief (cm-dm); and (4) basin-fill architecture, i.e. inner-Brushy mudstones (mainly laminated silt) with sandy "channels" are supposedly deep-sea-slope deposits but, unlike those of the Exxon slug diagram, they (A) interfinger basinward with outer-Brushy sandy "fans" (instead of downlapping onto them) and (B) onlap an unconformity, in the opposite direction (Beauboeuf et al., 1999, fig. 4). The "channels" are incised, narrow (10s-100s m) and shallow (individually <10 m but can be amalgamated; Beauboeuf et al., 1999; Gardner et al., 2003). Sinuosity is low (Pyles et al., 2010) and there is no unequivocal evidence for levees (Harms, 1974).

Consistent with the above features, an alternative interpretation of Brushy architecture is proposed: (A) inner-Brushy stacked, muddy, delta-slope clinothems (foreset dip < 0.5°, undetected at outcrop), individually < 15 m thick, formed by progradation during successive highstands (glacioeustatic; see below), separated by ravinement sequence boundaries (delta-plain facies, including paleosoils, eroded) and by incised valleys containing hyperpycnites (including wave-influenced ones) and background mud (silt). The concept of hyperpycnite-filled incised valleys, in contrast to the usual estuary model, is new (Higgs, 2014); and (B) shelfal outer-Brushy lowstand sand sheets (0.5-10 m thick) made of amalgamated hyperpycnites and wave-influenced hyperpycnites, both fed via the incised valleys, alternating with highstand heterolith (mud with thinner [0-30 cm] hyperpycnites and wave-influenced hyperpycnites). Oddly, even in the thickest (5-10 m) amalgamated-sand sheets, the constituent beds are only thin (< 40 cm) and seldom coarser than fine sand. Higgs (1991) attributed such "advanced amalgamation" to fresh-water bottom mud (low cohesion), easily resuspended by the next sand-delivering event. These over-amalgamated sand sheets can deamalgamate laterally (cf. "frayed" sheets of Higgs, 1991), i.e., each component sand bed occupies and overspills a shallow (0-30 cm), steep-walled, flat-floored channel cut in mud. Successive mud pinchouts (channel walls) may occupy a surprisingly narrow belt (< 10 m; e.g., Beauboeuf et al., 1999, fig. 5.2), indicating that flows followed the same track and had similar velocity structure. These flat-floored microchannels are of unknown flow-transverse width, inferred here to widen away from the feeder-valley mouth, perhaps reaching 5-10 km width. The alternation between amalgamated and non-amalgamated "packets", differing sharply in average event-bed thickness, defines a cyclicity attributed (Higgs, 2014) to glacioeustatic sea-level rises and falls of short duration (0.1-1 ka solar cycles, convolved with Milankovitch?), great rapidity (c. 2 cm/year; cf. Pleistocene), and low amplitude (2-20 m?). During high- and lowstands alike, shelf shallowing by deposition of hyperpycnites and fair-weather mud was limited by storm-wave erosion that maintained an equilibrium profile (intrinsic to shelves worldwide unless exposed by extreme eustatic fall; Higgs 1987, 2004, 2010).

Paleoclimate

During Brushy deposition the Delaware Basin lay within 10° of the equator (Scotese and McKerrow, 1990). Evaporites, signalling aridity, occur stratigraphically close below and above the Brushy (Yeso and upper San Andres Formations; Kerans et al., 1994). For the Brushy, a humid climate is suggested by: (A) terrestrial organic matter in background carbonaceous siltstones (see below; Harms and Williamson, 1988; Sageman et al. 1998); (B) coeval karstification of the adjacent NW land area (Kerans et al., 1994; Stoudt and Raines, 2004); and (C) fossil leaves (Hill, 1999) in Brushy-equivalent strata near the southern basin margin. Interpretation of Brushy event beds as hyperpycnites is consistent with a humid climate.

Lake Brushy tectonic origin, physiography and hydrology

Due to the great length (1000s km) of the Euramerica-Gondwana collision belt (Scotese and McKerrow, 1990), of which the Marathon-Ouachita segment is just a part, early collision of continental salients against the opposing continent would have pinched off sectors of the shrinking (subducting) Phoibic-Rheic Ocean, severing them from the world ocean by raising a tectonic sill, limiting entry of ocean water, forming “oceanic lakes” (Higgs, 2014; cf. Black Sea) diluted by river inflow, such as Lake Brushy. Lake Brushy contained a northwestern “Brushy shelf”, dipping SE (paleocurrent direction; e.g., Beauboeuf et al., 1999), facing an inferred southeastern tract of remnant-ocean floor (hence lack of Brushy paleoflows from SE), subducting southeastward at the Marathon subduction zone. Thus, the Delaware Basin was not then a foreland basin, but a remnant-ocean basin, with Brushy deposition on an inherited “passive” margin, although probably with earthquakes and relatively rapid subsidence (and adjacent forebulge uplift?; see below) due to the approaching subduction accretionary prism (load).

The Brushy onlaps NW onto a carbonate-siliciclastic ramp comprising the Cutoff Formation and, proximally, the lower San Andres Formation (Janson et al., 2007). In the Brushy outcrop area, the ramp underwent pre-Brushy differential (forebulge?) uplift, based on three observations: (1) karstification of the inner ramp (Kerans et al., 1994), indicating subaerial exposure; (2) a mid-ramp structural steepening, the Bone Spring Flexure (King, 1948), inferred to have become subaerial too; and (3) a thick (c. 100 m) interval of slide deposits forming the basinward upper Cutoff (Amerman et al., 2006), interpreted here as sliding off the rising, steepening flexure, consistent with the Cutoff’s local absence (King, 1948). Besides shallowing by slide aggradation, the former outer ramp may have risen tectonically, but it remained submerged. The Diablo Platform is also inferred to have undergone uplift then, by early collision of the Marathon salient, forming Lake Brushy’s sill, restricting the western connection to the paleo-Pacific Ocean. Either the Hovey or the Diablo Channel (Hill, 1999) was the lake spillpoint, crossing the Diablo sill. River inflow lowered Lake Brushy’s salinity, consistent with the Cutoff upper contact being "commonly littered with ammonites" (Carr and Gardner, 2000), suggesting mass mortality. The base of the (Brushy) Pipeline Shale Member is interpreted here as a sequence boundary, comprising a subaqueous conformity passing NW into a subaerial unconformity (proximal, sub-Brushy karst; Gardner and Sonnenfeld, 1996). Whenever global sea level fell below the spill point, Lake Brushy remained perched at this level, topped up by river inflow and potentially turning fresh (Higgs, 1991, fig. 20). When rising sea level overtopped the sill sufficiently, a wedge of ocean water intruded up the outlet channel, increasing the lake salinity (cf. modern Black Sea and Bosporus Strait). Extreme rises (if any) may have turned Lake Brushy into a marine gulf.

Brushy background sediment

The background siltstone comprises alternating laminae (mm/sub-mm) of silt and carbonaceous matter (Harms, 1974), interpretable as seasonal couplets. Wet-season silt from river-fed hypo- or mesopycnal plumes was spread shelf-wide by wind-driven circulation of the oceanic lake’s epilimnion (including entire shelf water column), flowing too fast for clay fallout. Thus, attributing clay scarcity to provenance or eolian transport (Newell et al., 1953) is unnecessary; besides, sand angularity (Newell et al., 1953) and inferred humidity (above) negate the eolian model. Lack of carbonate laminae, whose photosynthetically induced precipitation is common in lakes (Kelts and Hsü, 1978), suggests limited phytoplankton, possibly reflecting suspended clay cutting light penetration, or evolutionary failure related to the unusual salinity (brackishness) or the global Late Paleozoic marine "phytoplankton blackout" (Riegel, 2008). Organically richer siltstone marker beds (10 to > 200 cm thick) interpreted as condensed sections (Sageman et al., 1998) are further interpretable as maximum flooding intervals (MFIs); some of their organic matter is reportedly marine (Sageman et al., 1998; Beauboeuf et al., 1999; see also Harms and Williamson, 1988), compatible with Lake Brushy temporarily becoming a marine gulf during exceptionally high eustatic rises over the sill (see above). These MFIs can drape “channel” floors (Harms and Williamson, 1988; Beauboeuf et al., 1999), supporting the incised-valley interpretation, and indicating that the valleys filled during early highstand.

Role of caves in Brushy sediment supply

If the climate was indeed humid, the scarcity or absence of macroscopic (cm size or larger) plant fragments in the Brushy requires explanation. One possibility is that sediment-supplying rivers traversed the exposed, former inner-ramp carbonates (lower San Andres Formation) in caves, trapping leaves and branches in log-jams at narrowings, where they bio-fragmented (Simon and Benfield, 2001) to sand- and mud-size ‘coffee grounds’ that reached Lake Brushy via cave mouths or drowned gorges (rias; fronted during lowstands by incised valleys). Paleocaves are indeed known in (and below and above) the lower San Andres (Kosa et al., 2003), and "collapsed solution cavities (paleo-caverns?)" underlie proximal Brushy strata (Gardner and Sonnenfeld, 1996). Between cave mouths (point sources of Brushy sediment), a receding limestone cliff left a wave-cut platform, onlapped by inner Brushy silts (starting with Pipeline Shale). Proximal, basal-Brushy carbonate conglomerates in the "Bone submarine canyon" (Beauboeuf et al., 1999) can be interpreted instead as ria fill of wall-derived debrites and rockfall deposits, interbedded with hyperpycnites. The abraded marine fossils in the Brushy are interpreted here as reworked from San Andres limestone exposures in cave- and ria walls. Brushy sand fineness (mainly fine and very fine) reflects the caves (A) trapping bedload, dropped into potholes and fissures, and (B) "choking" the peak river velocity, limiting the suspended grain size arriving at the lake.

Cherry and Bell Canyon Formations

The Bone Spring Flexure incline was eventually buried by onlapping Brushy strata. The succeeding Cherry and Bell Canyon silciciclastic facies differ little from the Brushy (Jacka et al., 1968; Harms and Williamson, 1988), and are thus interpreted here as lake-shelf deposits too, consistent with most Cherry ripples being symmetrical (King, 1948). Moreover, a possible alga in the Bell Canyon, thought to have lived benthically, suggests photic water depths less than 30 m (McMillan, 1993). Landward the Cherry and Bell interdigitate with Goat Seep-Capitan carbonates, interpretable as interfingering of lowstand, cave-fed, lake-shelf clastics and highstand, arid, marine ramp carbonates, implying that highstands drowned the lake sill deeply enough to turn the lake marine. Capitan "forereef" clinoforms, steepened by differential compaction (Silver and Todd, 1969), are interpreted here as artifacts of high compactability of Bell silt (especially the organic half-couplets), dominant in the upper Bell (Harms and Williamson, 1988). The anomalous fineness of the "forereef" sediment (Melim and Scholle, 1995) fits a ramp model better than a platform-edge "reef" (cf. Fagerstrom and Weidlich, 1999). Rudstone tongues in the Capitan "forereef", with clasts larger than 5 m and (curiously) “probably more large (> 3 m) blocks in the middle forereef than in the upper forereef” (Melim and Scholle, 1995, p. 110), may, rather than “forereef” debrites, reflect collapse of ria walls or caves. A shelf origin for the Bell supports a shallow-water (largely less than 40 m) reinterpretation of the suprajacent Castile evaporites (Leslie et al., 1996). Early compaction of the Bell by c. 100% can account for Castile accommodation and the false "forereef" dip.

Utility as outcrop analogs

The Brushy is popular as an analog for truly marine, deep-water (100s-1000s m), turbidite reservoirs, i.e., base-of-slope fans and sinuous leveed slope channels. However, among other factors bound to cause fundamental contrasts in sand-body distribution, geometries and architecture: (1) the Brushy “channels” are incised valleys, with low sinuosity and no proven levees, implying intra-/extra-channel sand distribution and geometry very different from those of deep-sea channels; (2) Brushy-type lacustrine “premature amalgamation” is inapplicable in the deep sea; (3) mud-draped storm scours (permeability baffles/barriers) cannot form in the deep sea; (4) hyperpycnal flows would be fewer and briefer in the sea, due to the greater density of sea water; (5) slump-generated turbidity currents are more likely on continental slopes (tall, facilitating acceleration to ignition velocity) than on Lake Brushy's low delta slopes. These currents would have different duration and velocity from hyperpycnal flows, hence different runout distance, competence, capacity, and susceptibility to Coriolis deflection, all affecting sand-body shape, dimensions and depositional poro-permeability; and (6) mass transport deposits are voluminous on continental-slopes. On the other hand, the Brushy, Cherry and Bell are excellent outcrop analogs ("self-analogs") for BCB exploration and development. The new shelf model is vital in this respect, since predicted sand-body distribution, geometries and architecture differ significantly from those forecast by the popular model of deep-sea fans fed by slope channels. An excellent subsidiary analog for the Brushy is the Bude Formation, three times thicker, with 50 years of published sedimentological debate, a 15 km cliff line with intermittent wave-cut platforms offering exquisite wave-polished detail, on public land, just 4 hours by car from London.

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