Shelf-edge reef and delta gas fields – highly unusual close association of thick Abenaki carbonate platform and major Sable delta, Mesozoic Nova Scotia Shelf Canada

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Summary with table and figures

"Rivers, not temperature, organisms or chemistry appear to control the distribution of carbonates" (Chave 1967). This is the key thought that often introduces cool-water carbonate discussions. But it speaks to the typical absence of carbonates near deltas anywhere, especially 'classical' warm-shallow-water carbonates and particularly if oolitic. In searching for exceptions to use as analogues to this long-standing observation very very few modern or ancient examples seem to exist. The mainly Late Jurassic Abenaki platform with its shelf-edge reefs and oolites with gas at Deep Panuke and the large gas-bearing Sable delta complex that at Venture includes shelf-edge deltas is a large but lonely example of an unusual association. Indeed there is a list of unusual features of this Nova Scotia-shelf association. Specifically: **1)** it is the north end of longest reef chain and platform trend (gigaplatform) with shelf margin reefs in the Phanerozoic geologic record (Poag 1991, Keissling 2001), **2)** it has all 3 typical Late Jurassic reef/mound types present even in one well – Demascota G-32 with sponge reef mounds, coral-stromatoporid shallow reefs and slope thrombolitic-microbial mud mounds (Eliuk 1978, Leinfelder et al 2002), **3)** it is the largest and continental-scale delta on North American (NA) Atlantic and Gulf of Mexico margin until the Mississippi delta but the Sable-Laurentian delta completely pre-dates the Mississippi at mid Cretaceous (arguably a possible example of mega "stream capture" though provenance studies by David Piper, Georgina Pe-Piper and associates make this highly unlikely but consider the modern St.Lawrence River carries the most Canadian water to the coastal oceans, cf. Milliman and Farnsworth 2011, yet it does not have a delta but uniquely does cut the Appalachians), **4)** it has the presence of both platform and ramp margin morphologies including prograding ramps associated with the Sable delta (Eliuk 1978, Wade and MacLean 1990, Kidston et al 2005, OETR 2011), **5)** it is only one of two areas with well control on the Late Jurassic NA Atlantic carbonate margin (Baltimore Canyon Trough off Delaware USA is other, Meyer 1989, Prather 1991), **6)** both Late Jurassic-earliest Cretaceous shelf margin deltas (Venture) and shelf margin reefs (Deep Panuke) are present and gas-bearing (Cummings and Arnott 2005, EnCana 2006, Weissenberger et al. 2006), **7)** worldwide Jurassic carbonate reservoirs contain huge hydrocarbon volumes (eg. Saudi Arabia) but only a rare few are in reefs at shelf margins, **8)** it has the only commercial gas field in carbonates on NA Atlantic offshore at Deep Panuke and finally **9)** it is a **unique(?) occurrence of a thick carbonate platform closely adjacent to very large delta over an extended period of time (circa 15MY)** (McIver 1972, Eliuk 1978). **Figure 1** illustrates the general setting and points 1 and 3.

Although the author's original intention was to study the presumed changes in Abenaki platform shelf-margin reefs and carbonate facies in a proximal-distal manner relative to the

Sable delta; there actually was an abrupt rather than gradual change. However at the top of the carbonates (particularly as shown by the lithistid sponge reef facies) and along the deeper slope there indeed appear to be recognizable gradual changes. But a secondary and maybe more significant problem to address is how did this very unusual ‘mega-scale’ mixed carbonate-siliciclastic association exist at all and why and how did it persist for so long. Both proverbial geological analytical techniques of analogy and application of general principles of mixed carbonate-siliciclastic studies were brought to bear (Wilson 1967, Mount 1984, Leinfelder 1997). Obviously where the two approaches reinforce one another there is greater confidence that some useful insight is being gained. Some principles, that may apply, include the following: 1) reciprocal sedimentation (in time/climate/locality – arid/monsoonal, delta lobe shifts), 2) slow sedimentation with vigorous adapted critters (heterotrophs, certain algae & corals), 3) appropriate ocean currents and perhaps most significant 4) isolate and separate by a) barriers = islands/ridges/salt walls-diapirs (eg. barrier islands = oyster reefs), b) isolated highs = offshore atolls, pinnacles, c) deep water = lagoons/gulf/basins (classic controls), and 4) bypass/sediment sinks = channels, salt withdrawal. Analogies are few but some of the better ones are tabulated below as Table 1. A study of that table will also remind us of some of the other controls especially changing ocean chemistries through the Phanerozoic that might be critical. This probably explains why sponges so important as limestone contributors in Lower Paleozoic and Jurassic reefs contribute very little Recent carbonate sediment in spite of being abundant in modern reefs. Before leaving analogies which attempted to find modern or at least Neogene analogues with limited success, it is surprising and intriguing to learn that the largest river in the world – the Amazon – may be underlain by a carbonate platform which may be the thickest Paleogene carbonate deposit in the world. Carozzi's (1981) Amapa Formation was considered by him to be "the largest coralgal-foraminiferal platform of the geological record" with a composite thickness of over 4km. Its’ being under the mouth of the world's largest river appears to make the Abenaki less unique even second rate. Subsequent studies on the Amazon drainage pattern (Latrubesse et al. 2010) and on the onset of the Amazon deep sea fan (Figueiredo et al. 2009) showed that in fact the Amazon for its early history was confined to interior drainage and the present continental scale drainage into the Atlantic only starts in mid Miocene. That is the time of the abrupt termination of carbonates. At best the Amapa platform and the Amazon River are a grand-scale single-event reciprocal sedimentation. There is nothing contemporaneous between the major delta and the thick platform. Such is the joy and danger of analogues.

The foregoing gives us insight to possible controls that allowed the Abenaki and Sable to co-exist. And going back to the opening quote, sometimes, albeit rarely, temperature (a warmer Mesozoic perhaps), organisms (heterotroph sponges and microbs in turbid waters) and chemistry (calcitic seas that allowed calcification of sponges and microbialites) can trump the killing effect of a big delta on carbonates. Indeed, sometimes the delta can give paleohighs for oolite and reef to armour prodeltaic ramps following delta-lobe shifting. For the Abenaki-Sable we will see that isolation shown by seismic and isopach thicks with by-pass channels, salt-withdrawal sediment sinks, hypothesized north-flowing paleo-Gulf Stream were some of the key factors that allowed the co-existence of this unusual sediment association and the eventual existence of shelf-edge delta and reef gas fields within about 60 km of one another. **Figure 2** is a work in progress illustrating some of these concepts that allowed clean thick Abenaki platform carbonates to co-exist with the Sable delta. Only in the deep slope as shown by interbedded shales and limestones at deeper levels southward in Penobscot L-30, Dominion J-14 and Queensland M-88 and at the top of the Abenaki with diachronous sponge reef mound facies in the Deep Panuke trend or in the interior further southwest does the influence of the deltaic siliciclastics become obvious. Near the delta, prodeltaic ramp morphologies are sometimes capped by variably thick oolitic and more rarely reefal limestones with quartz sandstone interbeds and down slope microbial-rich clinoforms. Thus following delta lobe shifts, the delta by basin-fill and shoaling by prodelta shales can allow re-establishment of carbonate sedimentation but of a different style involving obvious mixed sedimentation than the Abenaki platform proper.

EXAMPLES / CONTROLS	Nova Scotia Shelf ABENAKI PLATORM – SABLE DELTA Late Jurassic-early Neocomian	Baltimore Canyon Trough, USA 'ABENAKI EQUIVALENT' Late Jurassic-early Neocomian	Borneo (Indonesia) MAHAKAN DELTA Neogene (Miocene reef outcrops) to Recent	Gulf of Papua FLY RIVER DELTA –N. GREAT BARRIER REEF Neogene- with Miocene platform to Recent
LARGE DELTA SIMULTANEOUSLY - siliciclastic input	**YES**–Sable paleo-delta eventually buries carbonates	NO – several small later deltas therefore NOT ANALOGUE BUT USEFUL COMPARISON	NO – relatively small delta but in a petroleum -rich basin WELL STUDIED MIXED EXAMPLE	**YES** -Fly River drains high Papua-New Guinea mountain chain (in Miocene Borabi carbonate shelf drowned, progrades near delta)
SUBSIDENCE	Less than BCT	Greater than NS	Greater? (glacial effect)	Greater? (glacial effect)
PLATE TECTONIC DRIFT	North out of reef sub-tropic carbonate zone	North out of reefing but further south so delayed	North into reef zone of equatorial tropics??	North into reef zone of equatorial tropics
REGIONAL TECTONIC SETTING	Rifted blocks – passive margin. Thick salt affect delta (possible ponding slowed sediment supply periodically)	As left (NS) - Rifted blocks but regional clastic(?) wedge under carb' margin. Thin salt	Complex convergent margin with small basin being in-filled by active delta	Rifted blocks later collision change from passive to active margin (great influx sed')
EUSTACY	Important but not great fluctuations – mainly a rising trend (Base K tectonics?)	Same as Nova Scotia and many events equivalent	Major glacially controlled global fluctuations of late Neogene	Major glacially controlled global fluctuations of late Neogene
CLIMATE	Greenhouse time – equable subtropic humid	Greenhouse time – equable subtropic humid	Icehouse time. Humid equatorial	Icehouse time – major variations but in tropics (humid to monsoonal)
Oceanography – CHEMISTRY – SEAWATER TYPES	Calcitic seas so high saturation (oolites & biotically induced carbonate = sponges mud mounds)	Calcitic seas so high saturation	Aragonitic-hi Mg more corals (lack lithified sponges, no oolite), fresher water (brackish) input	Aragonitic-hi Mg more corals (lack lithified sponges, less oolite), fresh input. Phosphates – Early & Mid Miocene
Oceanography – WINDS & CURRENTS	Possible paleo -Gulf Stream with north flow	Possible paleo-Gulf Stream with north flow	Indonesian Through Flow Current south flow clears north delta lobes	East Australian Current with clockwise & north flow from Miocene (also cause prograded shelf?)
REFERENCES	Eliuk 1978, Wade & McLean 1990	Meyers 1989, Prather 1991, Eliuk & Prather 2005	Wilson 2005 Wilson & Lokier 2002	Davies et al. 1989, Tcherepanov 2008, Tcherepanov et al.2008,

Table 1 Analogue comparisons: Late Jurassic Abenaki (Nova Scotia) and Baltimore Canyon Trough (Delaware, USA) compared to some modern-Neogene mixed deltaic-carbonate platform analogues – Mahakan Delta (Borneo, Indonesia), Fly River Delta-Great Barrier Reef (Papua-New Guinea). But Shatt al Arab Delta-Kuwait Ramp carbonates (Arabian-Persian Gulf).is omitted to save space and because it is both arid and epeiric and thus less analogous

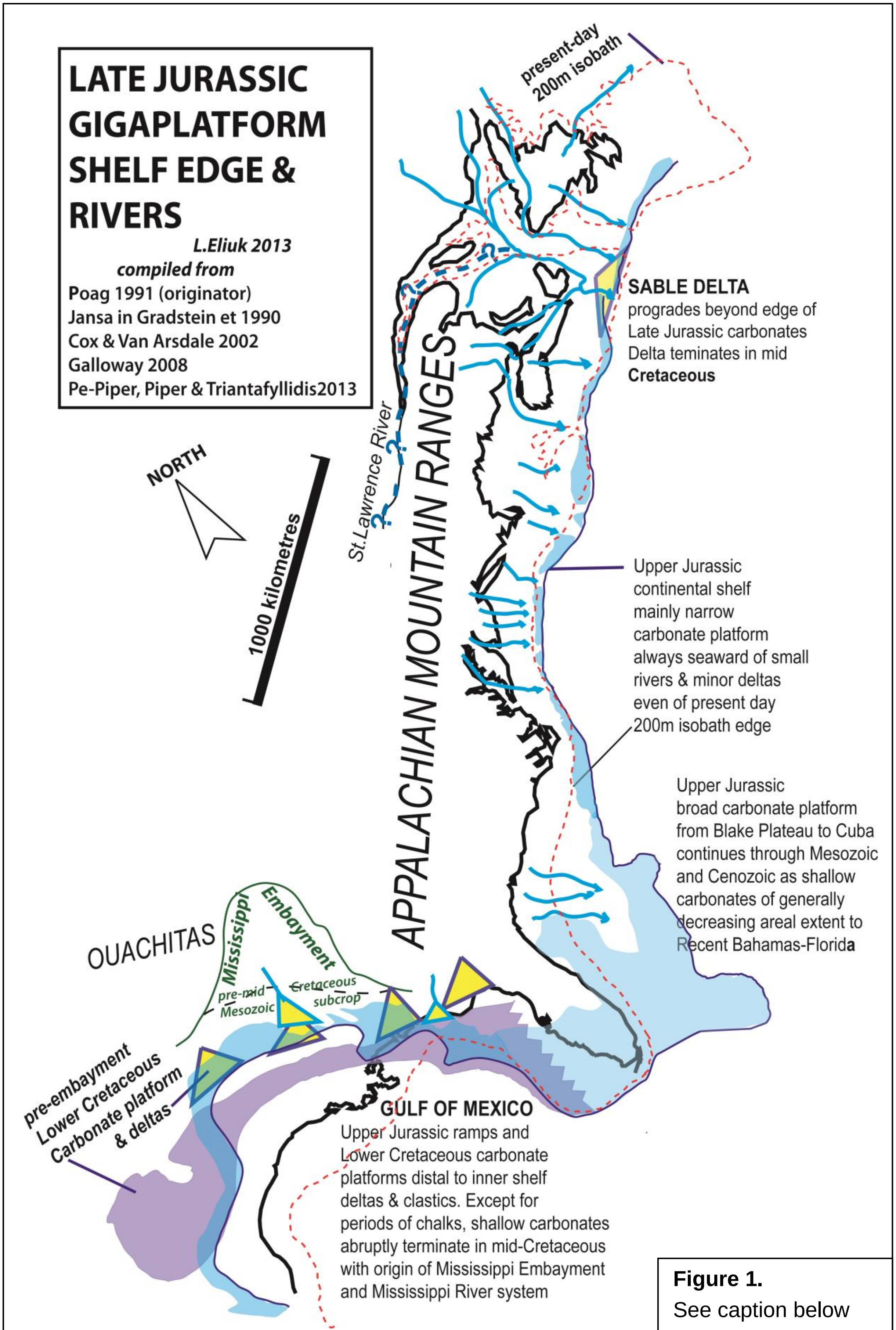

Figure 1.
See caption below

Figure 1. **Late Jurassic gigaplatform shelf edge and hypothetical rivers.** Poag (1991) first named this feature that is the largest Phanerozoic platform and coral reef trend (Kiessling 2001). Only the Sable-Laurentian delta as shown by the modern 200m isobath extends seaward of the Late Jurassic carbonate margin along the whole Atlantic-Gulf of Mexico seaboard until the Mississippi River delta area. But prior to Late Cretaceous all Gulf deltas were small with continuous carbonate shelves seaward (Galloway 2008; Late Jurassic = blue and Early Cretaceous = mauve). With the Late Cretaceous, Gulf shallow carbonates terminate Then the Mississippi delta progrades in a major degree due to breeching of the Ouachita-Appalachian barrier with the creation of the Mississippi embayment according to Cox & van Arsdale (2002).

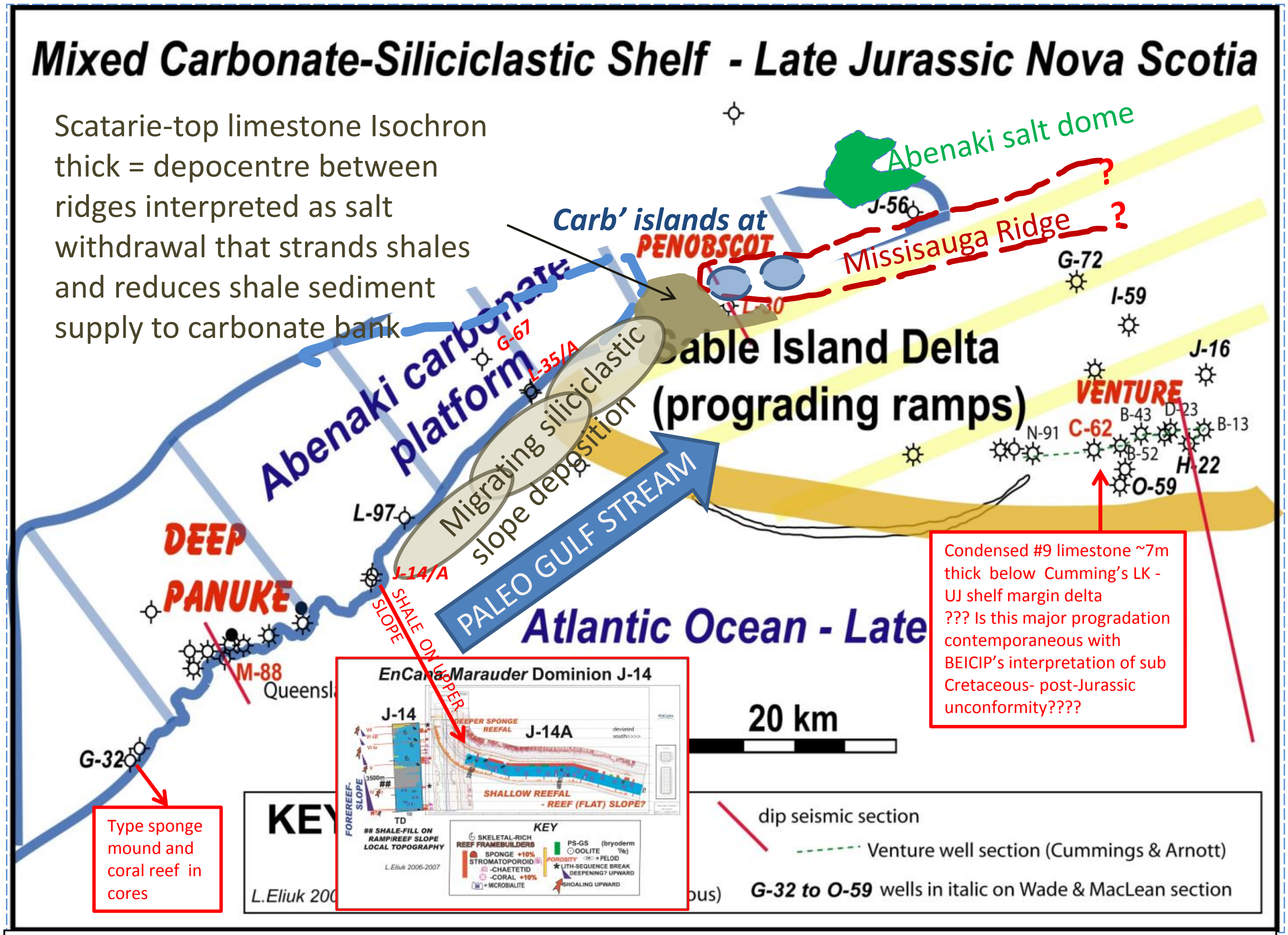

Figure 2. Preliminary cartoon of Abenaki platform-Sable delta association relationships. Except for capping shales and limestones rich in lithistid sponges southwest of L-35 and G-67, the Abenaki near its margin is thick and nearly pure carbonate. Isolation southwest of Penobscot as discussed on the figure is seen as the main contributing factor aided by postulated northerly paleo-currents. To the northeast and including those two wells the upper Abenaki has mixed oolitic limestone and quartz sandstone interbeds. L-30 and G-72 are respectively proximal and distal ramp carbonates-siliciclastics with capping shallow-water limestones and coarser sandstones built on prodeltaic shales and thinner microbial-thrombolitic limestones forming slope clinoforms (I-59 and J-16 seem similar but were not studied). The Venture area is interpreted as a shelf margin delta resulting from forced regression (Cummings and Arnott 2005). The thin #9 limestone in C-62 with a complex shoaling facies sequence can be interpreted to support their interpretation particularly since off-setting thin limestones have oolite. It may coincide with OETR (2011) base-Cretaceous unconformity though dating is lacking. The near margin trend of descending slope shale interbeds from L-30 to J-14 (illiustrated) to M-88 shows proximal-distal influx.

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