

PS Origin and Significance of Thick Carbonate Grainstone Packages in Non-Marine Successions: A Case Study from the Barra Velha Formation, Santos Basin*

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Abstract

Potential reservoir facies represented by lacustrine shoreline grainstones and rudstones are typically relatively thin compared to those from marine basins because of limited fetch, reducing wave action and producing a shallow wave base. This is especially the case in low gradient endorheic lakes, in which rapid lake level oscillations preclude the development of a stable shoreline. However, the closed lake deposits from the Cretaceous Barra Velha Formation, Santos Basin, locally have thick (decametre-scale), continuous packages of grainstone and rudstone comprising fragments of crystal shubs, spherulites, intraclasts and, in some cases, peloids and volcanic fragments.

Grainstones and rudstones of this type occur in two distinct settings: (1) the escarpment and dip slopes of tilted fault blocks along which a marked thinning of the Barra Velha Fm is evident, (2) apparent debris aprons adjacent to seismically resolvable mounds that developed on narrow elongate fault blocks. Grainstones and rudstones of the former are sharp-based packages, with fining-upwards trends, of well sorted and well-rounded grains, with mainly planar and low-angle stratification, but cross-lamination and planar cross-bedding is locally present. Paleocurrents are normal to paleoslope. These are interpreted as most likely carbonate fan delta shoreline deposits with wave reworked sheet flood or terminal splay deposits of alluvial fans. Those associated with dip slopes of half grabens are generally finer than those associated with scarp slopes which are also less mature in texture. Core plug measurements indicate porosities of up to 25% but moderate permeability ranging from 1 mD to *ca.* 100 mD. The grainstones associated with mound-like features are more coarsely textured, less mature and likely represent colluvial wedges as a result of the sub-aerial disaggregation of mounds formed largely of crystal shubs. Core plug measurements indicate good reservoir quality with up to 25% porosity within predominantly intergranular pore space and permeabilities ranging from 10 mD to several Darcies. While much effort has focused on the origin of the *in-situ* constituents of the Barra Velha Formation, such as crystal shub facies, numerous reservoirs are dominantly composed of more conventional re-worked, detrital deposits and constitute significant potential targets.

Origin and significance of thick carbonate grainstone packages in non-marine successions: a case study from the Barra Velha Formation, Santos Basin



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Introduction and Geological Setting

The Barra Velha Formation of the Santos Basin is Aptian in age and lies within the Brazilian Alagoas Stage (Fig. 1; Moreira *et al.* 2007). It is bounded at its base by the Pre-Alagoas unconformity that separates the Alagoas from the underlying Jiquia Stage and the distinctive “microbialite” lake system from the older, lithologically more varied mollusc coquina-bearing lakes. It is overlain by the evaporites of the Ariri Formation, which marks the initial influx of marine waters into the Santos Basin (Davison *et al.* 2012). The Barra Velha Formation is also internally divisible by the Intra-Alagoas unconformity, which separates the informally defined “Rift microbialite” below from the “Sag microbialite” above. The thickness of the Barra Velha Formation varies significantly across the basin from > 500 metres to < 25 metres on fault block highs along which it may be locally absent.

Evidence acquired to date supports a non-marine origin for the Barra Velha Formation (Wright & Barnett, 2015):

1. Marine fossils are absent, including typical restricted marine indicators such as miliolid foraminifera.
2. Ostracods are locally present but are forms that have a wide salinity tolerance and appear to be non-marine.
3. Early sulphate minerals such as gypsum and anhydrite are absent, suggesting that the carbonates were not sourced from marine waters.
4. $^{87}\text{Sr}/^{86}\text{Sr}$ values are significantly more radiogenic than those for Cretaceous seawater (Fig. 2).

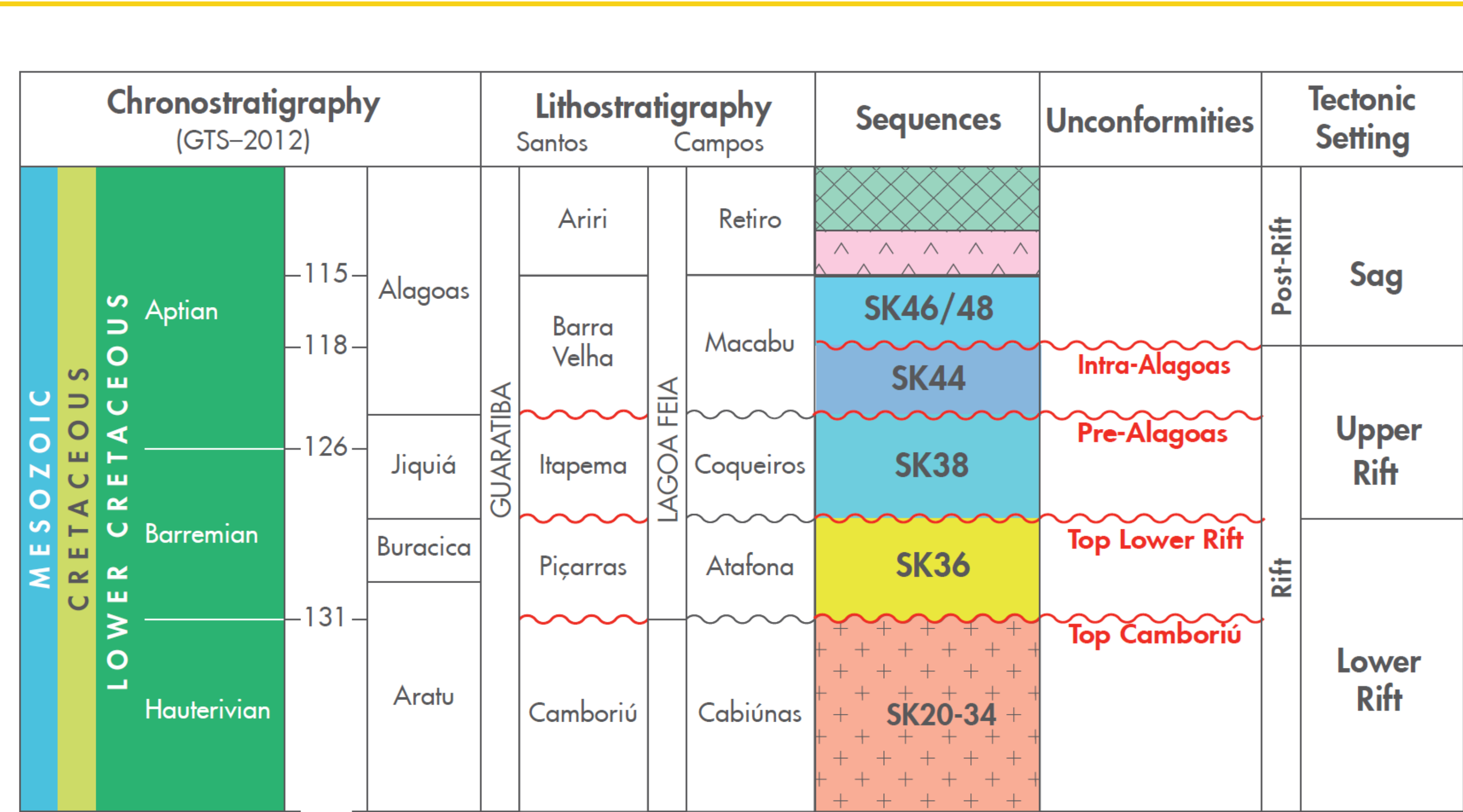


Fig. 1 – Stratigraphic chart for the Lower Cretaceous of the Santos Basin.

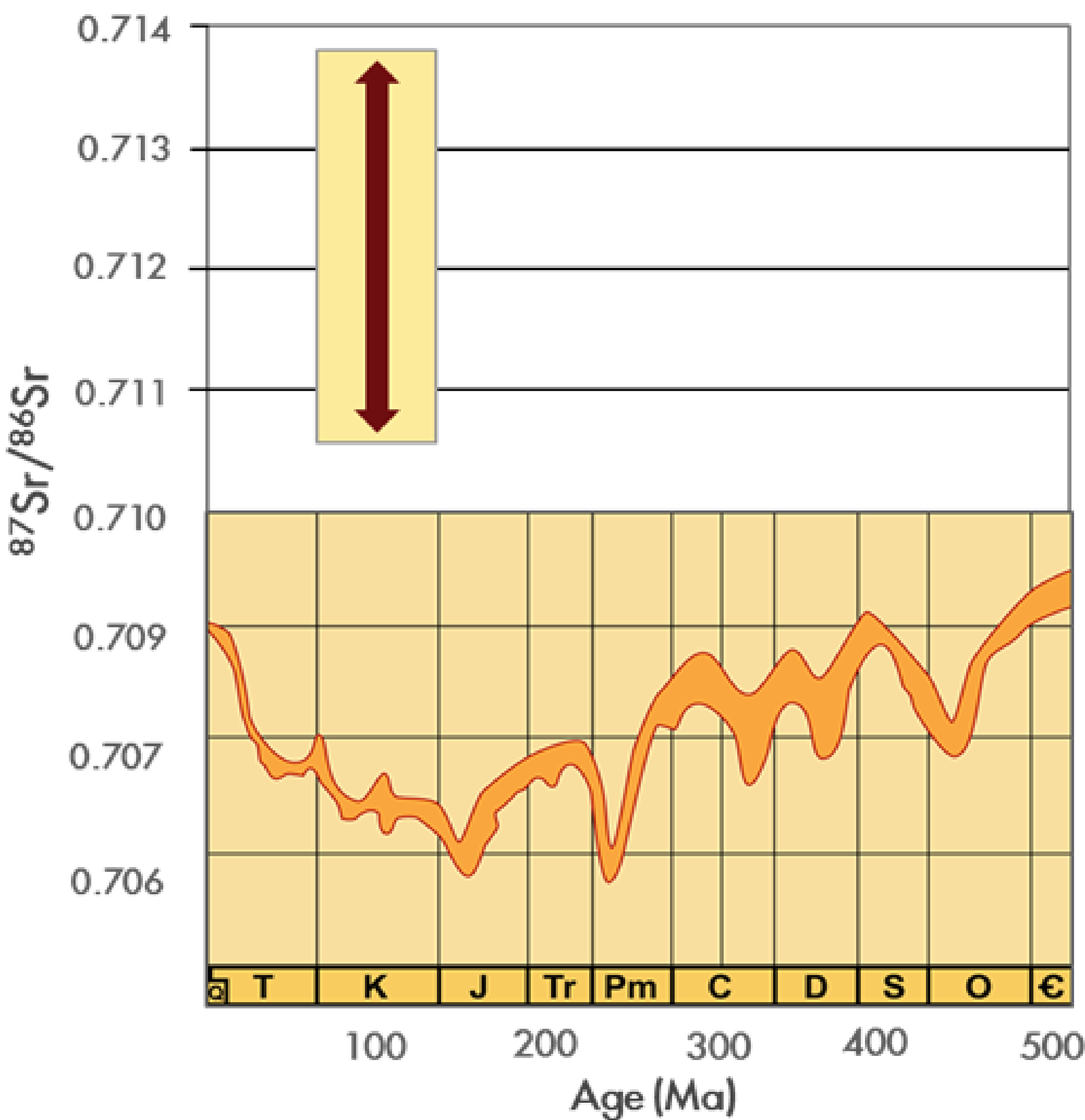


Fig. 2– $^{87}\text{Sr}/^{86}\text{Sr}$ curve for Cretaceous seawater and average $^{87}\text{Sr}/^{86}\text{Sr}$ values from the Barra Velha Formation.

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Lithofacies and Cycles

An examination and statistical analysis of >3 km of cored section shows that the basic components and facies described opposite (Fig. 3) are arranged into decimeter- to metre-scale cycles (cf. Wright & Barnett, 2014, 2015; Fig. 4). The basal portions of the cycles are composed of laminated calcimudstones with demonstrably early silica nodules and common vertebrate remains, including locally well-preserved fish. This facies association is interpreted to represent a flooding (pluvial) event and a resulting increase in lake level. This is supported by the matrix-supported texture of the facies, suggesting low energy conditions below both fair-weather and storm wave base. A freshening of lake waters is indicated by the presence of pre-compaction silica nodules (silica precipitation is favoured by a lowering of alkalinity) and an abundance of fish remains, including well-preserved whole fossils. Alkalinity of pH 9-10 is harmful to many extant freshwater fish and values >10 are typically lethal (Alabaster & Lloyd, 1980; compare conditions for precipitation of Mg-silicate clay below).

The middle parts of the cycles are composed of spherulite-dominated facies: *in-situ* pseudo “boundstones” lacking Mg-silicate clay or floatstones with Mg-silicate clays (for a discussion of the terminological problems associated with these textures see Wright & Barnett, 2017a,b) and/or re-worked grainstones/rudstones. Re-worked carbonate spherules also occur in wackestone/packstone textures but are comparatively rare. The up-section transition from laminated calcimudstones to spherulite-dominated lithologies is transitional and is marked by rare laminae of carbonate spherules within the calcimudstones which become progressively more abundant, eventually forming the spherulite-dominated facies described above. This facies association is interpreted to represent evaporation of the lake water body and a concomitant decrease in lake level. This is suggested by the widespread presence of stevensite and other Mg-silicate clay minerals in this facies association. In fact, available evidence suggests that a Mg-silicate matrix was originally ubiquitous and was subsequently removed by dissolution (Wright & Barnett, 2015, 2017a,b).

The abiotic precipitation of stevensite would require elevated pH conditions of at least 9 or above in palaeo-lake water (Jones, 1986; Khoury *et al.* 1982; Wilson 2013). Tutulo & Tosca (2018) suggest that spherulitic carbonates and Mg-silicate clays like those observed in the Barra Velha Formation were likely precipitation from elevated pH (ca. 10-10.5) waters based on their real-time observations of *in-situ* fluid chemistry, post-experiment analysis of precipitated solids and geochemical modelling. That the spherulite-dominated facies association represents less hospitable, higher pH conditions is supported by the paucity of well-preserved vertebrates and their stratigraphic restriction to the lower parts of individual beds near or at the laminite-spherulite transition. Progressive evaporation of a common water body is also suggested by carbon and oxygen stable isotope data. The isotopic composition of primary carbonates moves along a covariant trend in response to changes in hydrological balance and water residence times. Carbonates precipitated during periods of high lake level will in general plot towards the negative end of the trend, those precipitated during lake level lows towards the positive end (Talbot, 1990). This is exactly the trend shown by micro-sampled laminites and calcite spherules in the Barra Velha Formation.

The upper parts of the cycles are composed of shrub-dominated facies: *in-situ* framestones (or cementstones *sensu* Wright, 1992), with or without Mg-silicate clay, and/or re-worked grainstones/rudstones. Re-worked shrubs also occur in wackestone/packstone textures but, as with the spherulite-dominated facies, are comparatively rare. The up-section transition from spherulite- to shrub-dominated facies is transitional and in some occurrences the two components are interlaminated giving a mixed shrub-spherulite facies. The transitional nature of this transition is also apparent at the pore-scale at which spherules are observed to become increasingly asymmetric representing a transitional spherule-shrub grain-type. The palaeo-environmental conditions that tend to favour shrub precipitation over that of spherules are unclear.

An additional facies forms the uppermost parts of the cycles but is only well-developed where the Barra Velha Formation shows marked thinning, in the up-dip areas of tilted fault blocks for example.

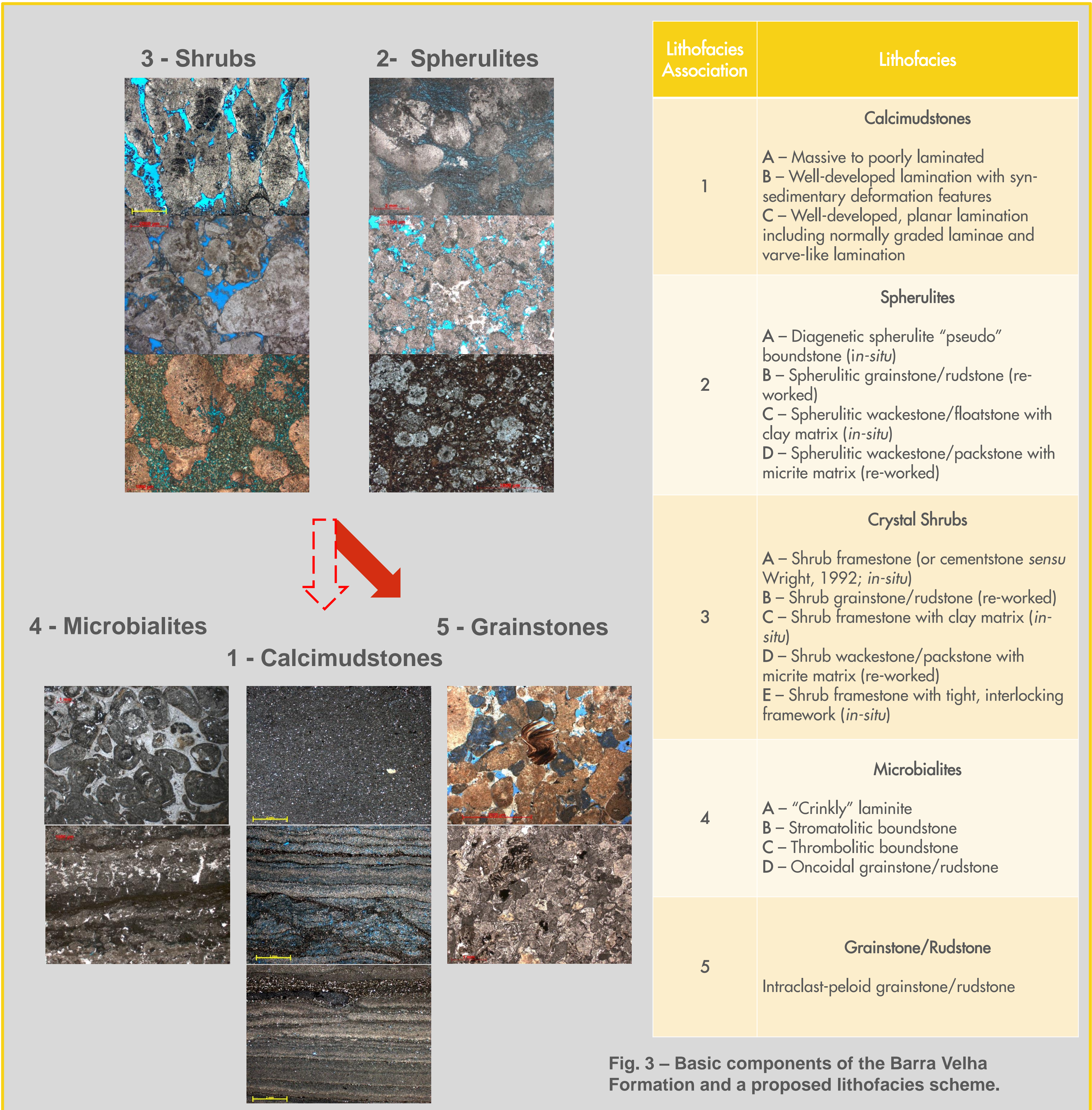


Fig. 3 – Basic components of the Barra Velha Formation and a proposed lithofacies scheme.

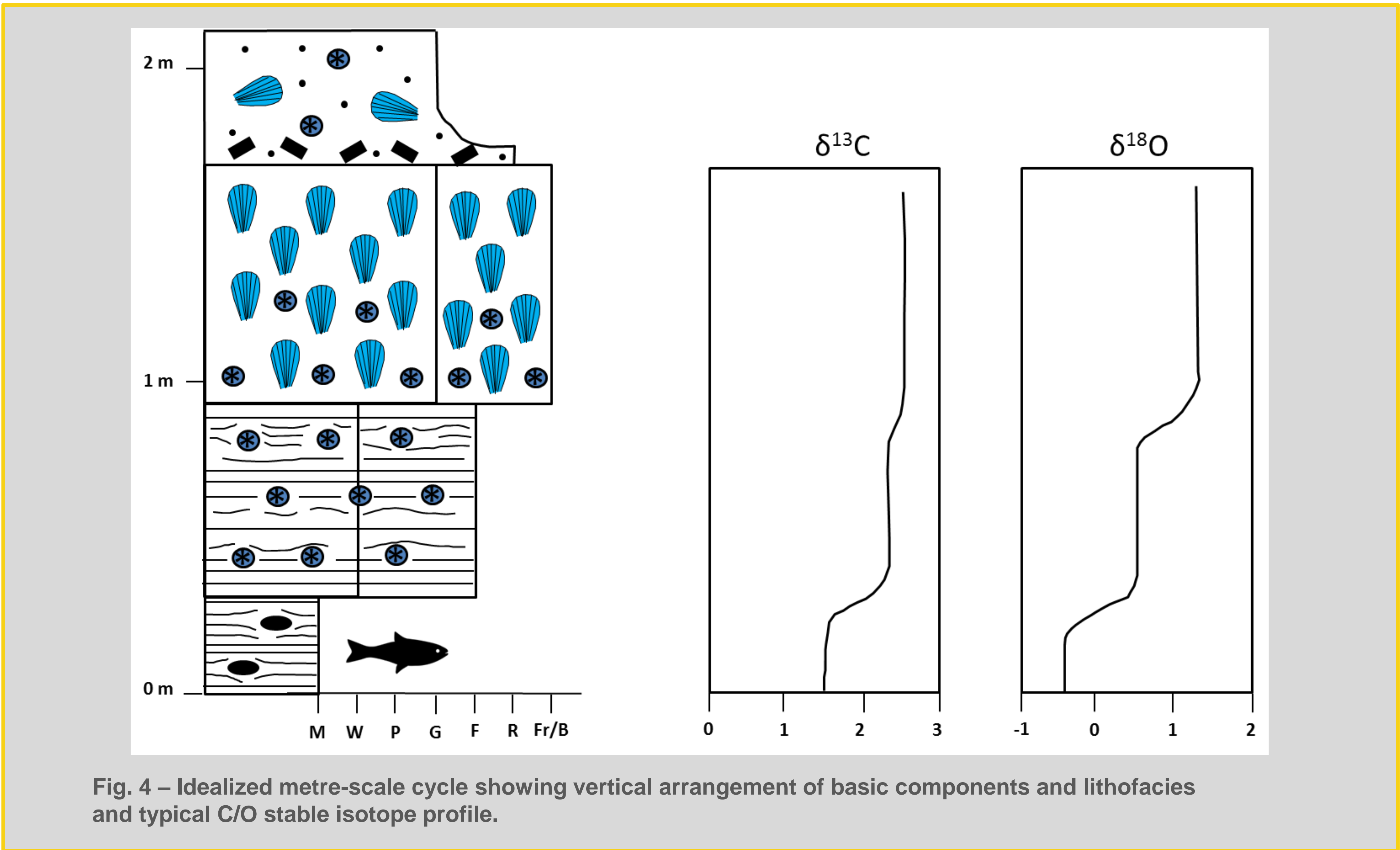


Fig. 4 – Idealized metre-scale cycle showing vertical arrangement of basic components and lithofacies and typical C/O stable isotope profile.

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Thick Carbonate Grainstones

While much of the Barra Velha Formation can be interpreted in terms of the cycle model opposite, locally thick (decametre-scale), continuous packages of grainstone and rudstone occur comprising fragments of crystal shrubs, spherulites, intraclasts and, in some cases, peloids and volcanic fragments. These cannot be readily explained by the cycle model because lacustrine shoreline grainstones and rudstones tend to be relatively thin compared to those from marine basins due to limited fetch reducing wave action and producing a shallow wave base. This effect is especially marked in low gradient endorheic lakes, in which rapid lake level oscillations preclude the development of a stable shoreline.

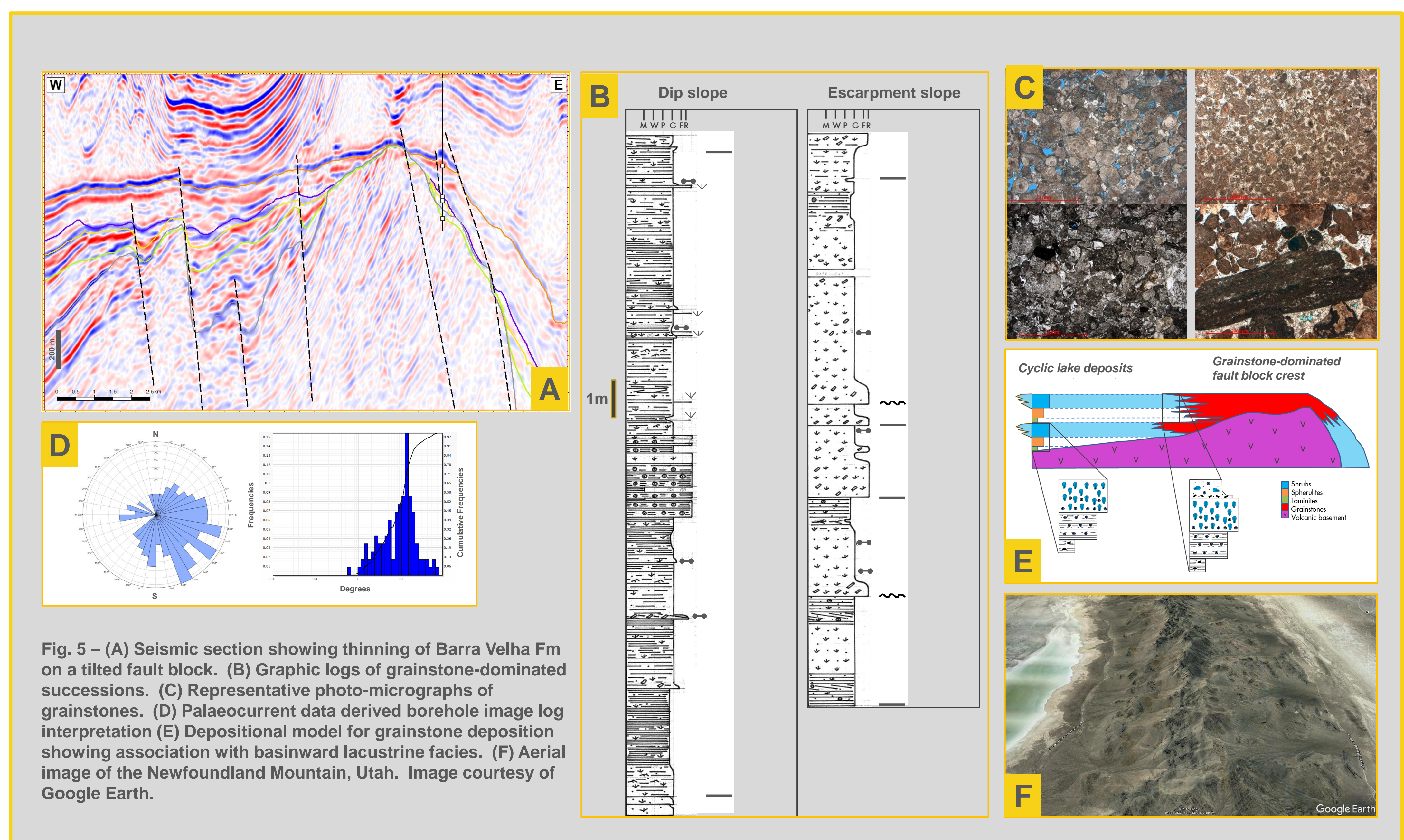
Grainstones and rudstones of this type occur in two distinct settings: (1) associated with unconformities on the escarpment and dip slopes of tilted fault blocks along which a marked thinning of the Barra Velha Fm is evident; (2) apparent debris aprons adjacent to seismically resolvable mounds that developed on narrow elongate fault blocks.

(1) Grainstones Associated with Unconformities and Stratal Thinning

Grainstones and rudstones associated with unconformities and thinning of the Barra Velha Formation form sharp-based packages mostly showing fining-upwards trends. Grain-size is mainly medium- to coarse-grained but is locally up to granule- to pebble size in the rudstone textures at the base of fining-upwards packages. Grain-size also shows a relationship to structural setting with grainstones deposited on steeper escarpment slopes being coarser than those on gentler dip slopes. Component grains are generally well sorted and well-rounded. The dominant physical sedimentary structures are planar and low-angle stratification, but cross-lamination and planar cross-bedding is locally present. Palaeocurrents are normal to palaeoslope and show a radial pattern. Core plug measurements indicate porosities of up to 25% but moderate permeability ranging from 1 mD to ca. 100 mD.

Grainstones of this type are interpreted as carbonate fan delta shorelines with wave reworked sheet flood or terminal splay deposits. This is consistent with the radial, palaeoslope-normal palaeocurrent patterns, the degree of grain abrasion and the thickness of the grainstone successions which would be more difficult to explain in a wholly lacustrine environment. The escarpment slope vs. dip slope grain-size variations are analogous to those observed in siliciclastic alluvial fan environments in which steeper depositional gradients are generally associated with coarser grain-size.

A partial analogue could be the Newfoundland Mountains of Utah where a tilted fault block sources alluvial fans that debouche into the Great Salt Lake.

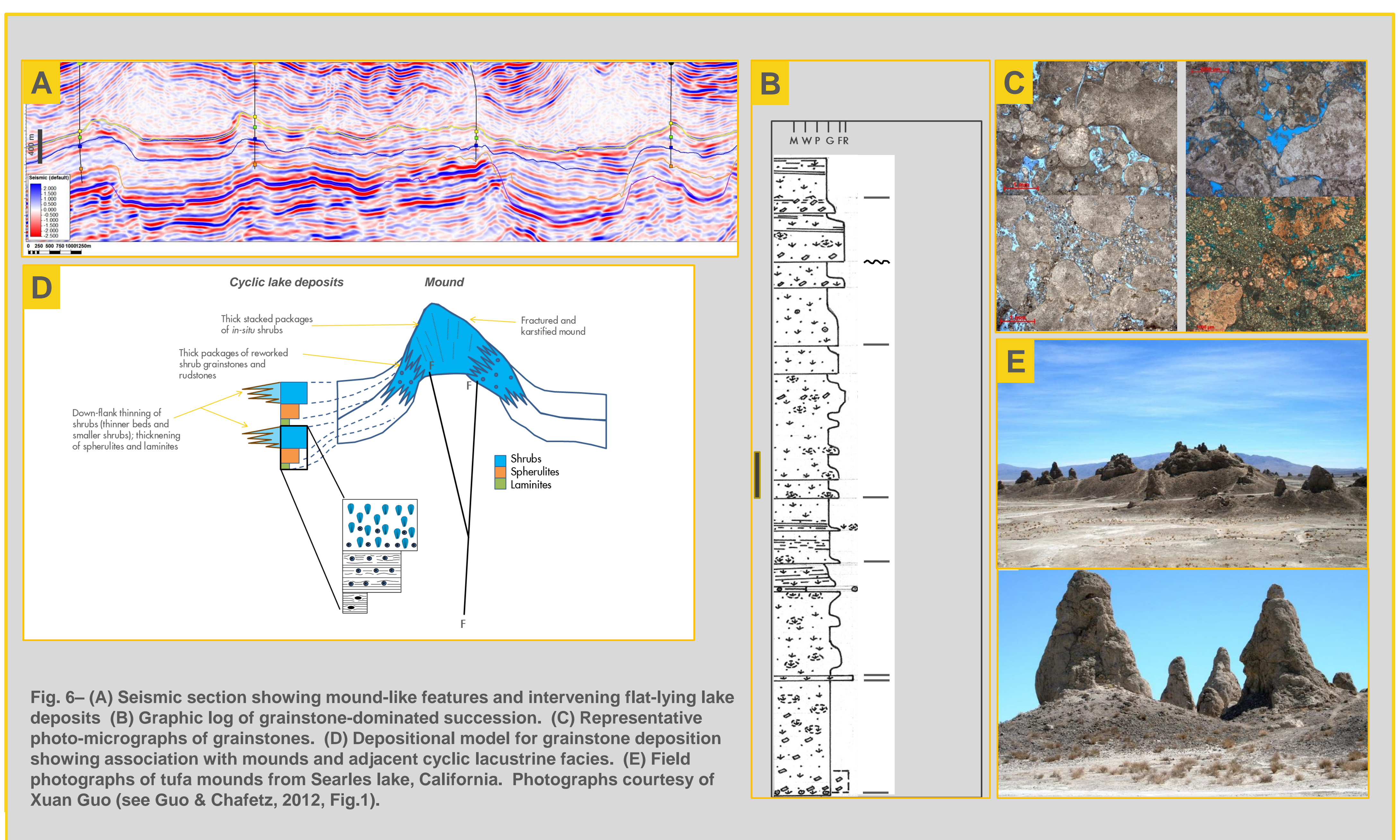


(2) Grainstones Associated with Seismically-Resolvable Mounds

Deposits associated with seismically resolvable mound-like features comprise grainstones, rudstones and, less commonly, packstones and floatstones. The dominant grain-types are re-worked shrubs, with platy, angular and well-rounded intraclasts mainly comprising cm- to dm-scale fragments of *in-situ* shrub framestones. Re-worked spherulites occur but are distinctly less common than shrubs. Grain-size is mainly coarse- to very coarse-grained but up to granule- to pebble-grade and greater in rudstone textures. Sorting is poor to moderate with sub-rounded to rounded grains. Beds are normally graded but mainly lack internal stratification. Planar to low-angle lamination and, very rarely, cross-lamination are locally developed. Bed contacts are sharp and planar or irregular, commonly with cm-scale relief. Packages of beds commonly show elevated dips of ca. 20-40°. Core plug measurements indicate good reservoir quality with up to 25% porosity within predominantly intergranular pore space and permeabilities ranging from 10 mD to several Darcies.

Grainstones and rudstones of this type are interpreted as colluvial wedges or debris aprons formed as a result of the sub-aerial disaggregation of mounds formed largely of crystal shrubs. This is supported by their relative textural immaturity, predominantly monomictic grain composition, steep depositional dips and their association with seismically-resolvable mound-like features.

A partial analogue could be the tufa mounds of Searles Lake (cf. Guo & Chafetz, 2012) which are flanked by prominent debris aprons produced by the weathering of tufa deposits.



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