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Non Marine Carbonates: Microbially Mediated vs. Abiotic Fabrics and Porosity

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Non marine carbonate buildups have recently been the object of renewed interests from the academia and industry following the discovery of the South Atlantic hydrocarbon reservoirs. Non-marine carbonate buildups and microbial bioherms are characterized by a wide range of geobody types, fabrics and flow unit architectures and distributions with complex depositional and secondary pore systems. Carbonate buildups accumulate in large spectrum of terrestrial settings ranging from sublacustrine to subaerial spring environments.

Precipitation can be the result of 1) abiotic processes (evaporation, degassing, mixing of water masses supersaturated with respect to carbonate minerals) as well as the product of 2) biologically induced and influenced (organomineralization s.l.) precipitation mechanisms in association with photosynthetic cyanobacteria and green algae, heterotrophic bacteria and their biofilms (extracellular polymeric substances). 3) Biologically controlled precipitation by organisms secreting a carbonate skeleton can be present (e.g., bivalves, gastropods, ostracods) but might also be very scarce or absent according to the water extreme chemical and physical properties (e.g. hypersalinity, high alkalinity or high temperature) that might exclude most of the biota. Silica fixation by diatoms and carbonate precipitation associated with insect larvae occur in some continental aquatic depositional settings.

In lakes, carbonate buildups accumulate in a wide spectrum of water chemistries but predominantly in hydrologically closed basins, with alkaline to hypersaline conditions, in arid climate and tectonically active settings. Carbonate buildups can be distinguished in: 1) decimetre to meter scale bioherms, subparallel to the shorelines forming continuous belts traceable for hundreds meters where microbially mediated processes seem to predominate (e.g., hypersaline Holocene Great Salt Lake, Utah; schizohaline Eocene Green River Formation of Utah and Wyoming; freshwater to alkaline Miocene Ries Crater, Germany), 2) isolated meter to decameter scale mounds located at sites of sublacustrine groundwater spring discharge where the mixing of groundwater and lake water is the trigger for abiotic and biologically induced/influenced carbonate precipitation (e.g., late Pleistocene-Holocene freshwater to alkaline Pyramid Lake in Nevada, highly alkaline Mono Lake in California), 3) decimeter to decameter sheet-like to mound-shaped deposits associated with sublacustrine hydrothermal vents (e.g., Pyramid and Mono Lake, Miocene Southern Tuscany, Italy). In the latter case, the location of carbonate accumulation is often controlled by extensional and strike-slip faults and both abiotic and organomineralic precipitation processes take place. In terms of potential reservoir architecture, shoreline microbial bioherms can cluster forming continuous belts hundred to thousand meters in lateral extension, whereas carbonate mounds associated with mixing of lake and groundwater at sublacustrine springs are generally isolated, separated by siliciclastic conglomerate, sandstone and mudstone.

In subaerial continental settings, flowing water issuing from punctual or linear springs precipitates wedge-, mound-, and pinnacle-shaped carbonate deposits of decimeter to several tens of meters in size, occasionally up to hundreds of meters. Within the subaerial spring deposits, two groups can be distinguished: 1) Travertines are precipitated from water issuing from hydrothermal hot-springs (temperature > 20°C) and can typically drape the antecedent topography, accrete and prograde building mounds, fissure ridges, fans with terraced and smooth slopes, and cascades (e.g., Pleistocene-Holocene Southern Tuscany, Italy). In these fast-flowing settings rapid CO_2 degassing, cooling and evaporation seem to be the predominant mechanisms inducing carbonate precipitation. In travertines, the dominantly abiotically precipitated crystalline fabrics reflect the extreme conditions of the depositional environment where most of the organisms are not able to develop. The lethal effect of temperature, sulphides and pH on the life of macrophytes (grasses and trees) and most of the microphytes (algae and bryophytes) generally prevent their presence. Nevertheless microbial contribution is significant, in particular in slow-flowing hot-spring pools and ponds, where biologically induced precipitation might occur associated with heat-tolerant bacteria and cyanobacteria biofilms acting as substrates for carbonate mineral nucleation. 2) Carbonate tufa are related to flowing ambient-temperature water from freshwater springs, rivers and streams and can form barrages, dams, and cascades (e.g., Late Pleistocene-Holocene streams and rivers in Central and Northern Italy). Although physico-chemical precipitation driven by CO_2 degassing is significantly responsible of the carbonate encrustation of the local vegetation (macrophytes, microphytes, bryophytes), tufa deposits are also associated with biologically induced precipitation by photosynthetic green algae and cyanobacteria. In fact, the interplay of microbial biofilms and abiotic processes results in complex carbonate precipitates, where variations of a single parameter can influence the resulting fabric.

The wide spectrum of carbonate microfabrics identified in non marine carbonate precipitates includes: 1) micritic and microsparitic laminae building domes, mounds and columns attributable to microbially mediated stromatolites, 2) clotted peloidal micrite and associated microspar forming bioherms interpreted as *in situ* precipitation associated with biologically induced and influenced processes, 3) millimeter to several centimeter thick crystalline crusts related to abiotic precipitation, more typical in settings of water masses mixing and/or fast flowing and degassing, 4) dendritic and branching clotted peloidal to crystalline fabrics of debated, possibly both abiotic and biologically influenced, origin, 5) coated grains ranging from inorganically precipitated high-energy ooids, pisoids and microbially mediated oncoids, 6) layers of massive calci-mudstone consisting of carbonate micrite deposited in supersaturated, stagnant environment of either detrital, abiotic or biologically induced origin.

Laminated and clotted peloidal micritic to microsparitic fabrics of inferred microbially mediated precipitation occur across the whole range of lacustrine water chemistry and subaerial spring environments. They are not diagnostic of a specific depositional environment and share texture similarities with marine microbialites common in the Paleozoic and Mesozoic geologic record. Carbonate crystalline crusts seem to predominated where abiotic precipitation plays a major role, such as in lakes where mixing with groundwater or thermal water occurs and in hot-spring travertine deposits.

In terms of depositional porosity 1) laminated stromatolitic fabrics range from tight to poorly porous with low, not connected inter-laminae porosity; 2) clotted peloidal micrite fabrics sustain a network of framework sub-millimeter to centimeter size porosity; 3) crystalline crusts might be tight but 4) when they form dendrites, inter-branching porosity can be high. 5) Coated grains are eventually associated with inter-particle porosity. Additional depositional porosity types are related to carbonate coated gas bubbles, encrusted vegetation stems and insect larval cases, and skeletal intraparticle and shelter pores.

Secondary porosity is firstly controlled by the stability/neomorphism of the primary mineralogy, which is in turn a function of the Mg/Ca ratio and temperature of the precipitating water. Meteoric dissolution, forming from millimiter size vugs to meter scale caves, is very common in travertine, tufa and in subaerially exposed lake deposits. Tectonic fractures can frequently affect hot-spring travertines and fault-controlled closed lacustrine basins. Biomoldic porosity derives from decay and dissolution of vegetation and skeletal biota.

Non marine carbonate buildups have the potential to constitute excellent subsurface hydrocarbon reservoirs. A key element with respect to the petroleum system potential is that in closed lacustrine systems, carbonate buildup reservoirs might occur in proximity to source rocks accumulated in the stratified anoxic lake bottom. However, the predictability of non marine carbonate reservoir properties is far from being understood as a consequence of the high variability and complexity of the carbonate fabrics and their spatial distribution and of the limited knowledge of early and late diagenetic processes (e.g., dolomitization, silicification and clay mineral authigenesis).