PALEOKARST – AN ALTERNATIVE VIEW

by

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Abstract: The study of ancient karsts has always been a challenge for the karst scientist, especially for the one approaching the topic without a solid geological (especially sedimentological) training. From terminology to mineralogy and from sedimentology to geomorphology, interpretations keep shifting and changing according to the investigator's bias(es). This text provides some clues to a better understanding of syndepositional conditions and reviews some recent discoveries of seafloor processes that could generate paleokarst-like features.

Karst science ("karstology" in Europe where it was born) has a unique position in science: a lot of the field data it uses was built regionally and often by amateurs (spelunkers or cavers, according to location). This is why many of these terms are descriptive *par excellence* and often led to confusion. The epitome of this "scientific syncretism" is the concept of paleokarst. Although it appears to be a clear-cut term, paleokarst is assigned a broad array of meanings. Geographers tend to emphasise a landform; geologists a particular mineral paragenesis; karstologists hydrodynamic functioning and morphologies. It is significant that in one of the most comprehensive treatises on paleokarst published so far, Bosák *et al.* (1989) write about a 'terminological jungle'. Two terms, *paleokarst* and *fossil karst,* have been closely mingled from the early times of karst studies, as de Martonne (1910) pointed out. In different settings, these two terms have been used either as synonyms or with two different meanings. The following are just a few 'standard' definitions:

> Sweeting (1973): '***Fossil karst landforms*** *are of two main kinds. First, those formed in earlier geological periods and never covered by later rocks; these may be called* ***relict landforms****. And secondly, those formed in earlier geological periods, subsequently covered by non-limestone rocks and later re-exhumed; these are* ***exhumed*** or ***resurrected landforms***.'

> Ford and Cullingford (1976): *'**Fossil** or **paleokarst** … occurs beneath unconformities where solutional features of land surface have been covered by later deposits.'*

> Bosák *et al.* (1989):**Error! Bookmark not defined.** **paleokarst** : *'karst developed largely or entirely during past geological periods'*. It is divided into: * ***buried karst***: *'karst phenomena formed at the surface of the earth and then covered by later rocks*; ** ***intrastratal karst:*** *'karst formed within rocks already buried by younger strata'; **** ***relict karst***: *'…karst landforms that were created at the Earth's surface under one set of morphogenic conditions and which survive at the surface under a present, different set of conditions.'*

> Ford and Williams (1992): ***relict karsts***: *'karsts removed from the situation in which they were developed, although they remain exposed to and are modified by processes operating in the present system.'* **Paleokarst** or ***buried karst***: *'are completely de-coupled from the*

present hydrogeochemical system; they are fossilized. When stripped of their cover beds they reveal an **exhumed karst***.'*

Osborne (2000) thoroughly analyses the issue emphasizing the complexity and confusion that still lingers in the literature. The author then leans towards Ford & Williams' approach (paleokarst = buried karst = "completely decoupled from the present hydrogeochemical system").

Apart from the obvious confusion of terminology, another problem is that these definitions do not cover all reality. For example, the category of buried karst is ambiguous, since there are karsts with features that formed before the present morphogenic set of conditions. These karsts are covered by other rocks and yet they fully function as elements of the present day karst geosystem. Such an example is the Padiş karst plateau in the Apuseni Mountains of Romania, (Silvestru, 1997) where clastic sediments (tills) up to 85 m thick cover dolines that still act as punctual inlets for the runoff. The top of the till deposits is riddled with numerous suffusion dolines (each corresponding to a doline in the subjacent Triassic limestone). Phytochemical alteration of fines in the till has caused some of the suffusion dolines to be coated with clays sufficient to retain permanent ponds. (Fig. 1) The runoff infiltrating through the till feeds an active karst aquifer in the subjacent limestone, with drainages powerful-enough to break a drilling pipe! This aquifer (which includes some known caves) discharges through one major outlet.

Fig. 1 Suffosion dolines in the Padiş Plateau in Romania. Details in the text.

Obviously this example exhibits no 'paleo' features at all. In fact, it is practically impossible for any ancient karst feature to be completely de-coupled from some type of solution. Even when located deep under the surface, infiltrated water reaches them and consequently reshapes them. At greater depths, mineral waters and even hot, mineral-laden solutions of the hydrothermal, postmagmatic phase sometimes invade and even enlarge pre-existing karst features, depositing a wide array of minerals, including ores.(Silvestru, 1985) In extreme cases, such an invasion may occur in the pneumatolytic phase, with garnets depositing on top of calcite speleothems. (Mârza and Silvestru, 1988) The size and shape of such features are never truly frozen (or fossilized) since the karst system is usually within the range of one type of aqueous solution or another. There is also strong evidence that the thermo-mineral solutions actively create karst features deep inside limestones. Deposition in such environments would have occurred only after the aggressiveness of the solutions was neutralized by the limestones. (References 2, 3, 4, 16)

Relict karst (Bosák *et al.*, 1989) is also a misleading term since it is based on the undefined concept of 'survival'. What is it that survives of *'karst landforms that were created at the Earth's surface under one set of morphogenic conditions?'* Morphologies only? As we have already seen in the above examples, the presumed paleokarst can maintain its hydrogeological functions, so how can one effectively separate old morphologies from more recent ones? In most cases, hydrographic and geomorphic selection criteria are used, all based on how the researcher believes the hydrogeologic setting was functioning in the past. Ford and Williams (1992) draw attention to this problem but leave the issue open, by introducing the category of *true paleokarst* or *buried karst* while still using the term "*fossilized*" for it - obviously intending to link the category with the concept of 'extinct'. However, while an extinct, buried creature is literally 'de-coupled' from the present biosphere, no lithostructure, let alone a buried landform (which represents an important anisotropy inside a lithostructure) can be truly de-coupled from the present hydrogeochemical system, be it surficial or endogenous.

Finally, it is impossible to distinguish between an *exhumed karst* when 'stripped of its cover beds' (as defined by all authors) and a *relict karst*. Ultimately, it is at the researcher's discretion to decide which landform is what, **no matter which of the above-mentioned definitions is used**.

However, it is very difficult and impractical to interpret true paleokarst on the basis of its being a landform (i.e. geographic/geomorphic feature). It should be seen as a lithostructural (i.e. geologic) feature, hence it must have undergone one or several steps of diagenesis (compaction, cementation etc.) or/and orogeny. (Silvestru and Ghergari, 1994) In simpler words:

Paleokarst is a diagenized karst.

What is often referred to as "true paleokarst" can occur in a wide array of settings, ranging from voids (acting as secondary porosity), to intrastratal breccias, and to complex petrographic structures (including some ore deposits). Any other karst feature that is still a landform, i.e. is exposed to surface or/and subsurface processes, no matter its actual age or geomorphic setting, is just a karst feature which may be assigned to a stage of the history of a given karst geosystem. The term **fossil karst** best suits such a case, because it implies that it formed in a previous stage of karstification and diagenesis had not affected it. If a karst formed in a previous stage of karstification and is still active today, I would suggest the term **multi-stage karst**.

In the case of true paleokarst, diagenesis does not normally wipe away the difference, essential to karstification, between soluble and insoluble (or rather highly soluble and less soluble) rocks. On the other hand, seldom does paleokarst become buried beyond the reach of infiltrated water given the surprising results concerning free-moving water at 12 km in the ultra-deep drilling in Kola (Mitrofanov *et al.*, 2000) as well as a wide range of deep mines I have visited or/and worked in; that is, before the whole sedimentary sequence reaches metamorphism depth and therefore loses its original structure. Once unsaturated water (infiltrating or ascending) reaches the soluble/insoluble rock boundary, as would happen in the absolute majority of cases, it will exploit it and karsting would occur. Even if it may be argued that at some depth infiltrating water is saturated and therefore non-corrosive, erosion and uplift would eventually bring paleokarst to 'corrosive water depth'. Once there, clear neokarst features would be superimposed on the original paleokarst.

Under such circumstances it would be rather useful to avoid erroneous diagnosis of paleokarst in the first place and it is this author's purpose to provide some additional information on possible sources of misdiagnosis.

Sedimentary structures

To the karstologist, the sedimentary history of limestones can play a very important role in the understanding of the karsting history of a given lithostructural unit. It would of course help if the primary sedimentary information would be based on clearly understood criteria that were easy to apply in the field. Yet it seems that sedimentologists miss opportunities to ensure that have their contribution to knowledge is helpful to others… For example Selley (2000) writes about "primary inorganic sedimentary structures" grouping them into 4 categories:

1. Predepositional: channels, flute marks, groove marks, tool marks. Selley points out that geopedants would call these "interbed structures", though *they were formed before the deposition of the overlaying bed.* (emphasis mine)

2. Syndepositional (intrabed structures): massive bedding, flat-bedding, graded bedding, cross-bedding, ripples and cross-lamination.

3. Postdepositional: vertical plastic deformation structures, slumps and slides.

4. Miscellaneous: rain prints, salt pseudomorphs, desiccation cracks, synaeresis cracks, sand dykes, sedimentary volcanoes, pockmarks (see below).

The first 2 categories can be truly confusing to the non-sedimentologist as etymologically "predepositional" means "before the sediment was laid down" while "syndepositional" means "while the sediment was being laid down". Now how could a structure be preserved in a sediment before it was laid down? Well, yes, in this case "pre" means "before the overlaying bed was deposited. Yet "syndepositional" in the second category means "the same time with the deposition of the layer in which the structure is preserved". Please forgive my digression here, but it will bring (I hope) clarification later on…

A karstologist may ask at this time: where do then karst and paleokarst fit in this classification? Sedimentologists remain esoteric. For some unknown reason, in Selley's classification "primary sedimentary structures" are not followed by "secondary sedimentary structures". To him "primary" means in fact pre-diagenetic. To the sedimentologist, karst is a postdepostional and secondary i.e. post-diagenetic structure and (I suspect) is treated as a geomorphic feature, therefore outside the sedimentological domain. When buried by newer sediments, karst becomes paleokarst and categorized as a *secondary interbed geomorphic structure*.

When reconstructing the karstological history of a lithostructural unit, the ability to separate sedimentology from geomorphology is essential. Yet, given the above, the karstologist is more or less left on his/her own. If any of the following can help in this respect, this author will be truly happy!

Enter Cold Seeps

Cold seeps (subterranean movement of large volumes of gases and liquid, e.g. H_2S, CH_4, CO_2, at ambient temperatures) and the large array of signatures they leave in the geological record have entered the body of geological knowledge somewhat through the back door. They are differentiated from hydrothermal fluids, as they are unrelated to magmatic heat sources. Petroleum geologists discovered cold seep signatures (CSS) in the late 1970s and to this day they remain almost exclusively an 'internal topic' of what Miall (1997) ironically calls 'corporate science'. The reluctance of geological theorists to include CSS amongst standard geological features, especially as part of rock formations on continents, is unfortunate.

Selley (2000) considers one type of such signatures – pockmarks - to be exclusively present-day features. Yet, once covered by other sediments, pockmarks would move from the "miscellaneous structures" category to "postdepositional structures" but could easily be described as "syndepositional structures" as well!

Seep products

Once direct investigation of seep sites was possible and later, as new, more accurate remote sensing methods became available, it was discovered that quite similar to continental seeps, submarine ones left and continue leaving a geomorphic signature. Fluid-induced sea bottom geomorphic features include *seep precipitates (carbonates* and *hydrates), pockmarks, piping & rills*, while on the continents they create *brine pools*, *mud volcanoes* and other local features. As for their scale, it may range from meters to kilometers.

Pockmarks – crater-like sea floor depressions produced by sapping of unbound sediments during gas venting - are the most striking features and they are present on most continental platforms. Judd and Hovland (2007) have managed to gather a lot of very interesting information about CSS, including pockmarks. Present density can reach up to 200 per square kilometer, with diameters varying from several meters to hundreds of meters and depth up to 15 meters. The larger ones are almost always found in the finest (unbound) sediments. There are standard circular and elliptical pockmarks, composite pockmarks, asymmetric pockmarks, pockmark strings, elongated pockmarks and troughs. (Judd and Hovland, 2007). Fossil pockmarks have been also found, in which venting ceased and were subsequently covered by sediments. (idem)

Fig. 2 North Sea pockmarks (from Judd & Hovland, 2007, p.12)

Some of the most sedimentary-significant seep signatures are the carbonate bodies (irregular mounds, dykes, flat hardground-type surfaces), described by some authors as "authigenic carbonate" or "methane-derived authigenic carbonates" (MDAC) (Judd and Hovland, 2007) many aligned along fault lines. A frequent feature is various size columns dubbed "MDAC chimneys" (idem, p.299) which resemble stalagmites (Fig. 3) and have been recently identified at some locations on the ocean floor (the Black Sea, Kattegat, offshore Oregon, Nankai Trough, Gulf of Mexico, off New Zealand, Monterey Bay, California, Gulf of Cadiz (idem). When such features become diagenized they can very much resemble speleothems.

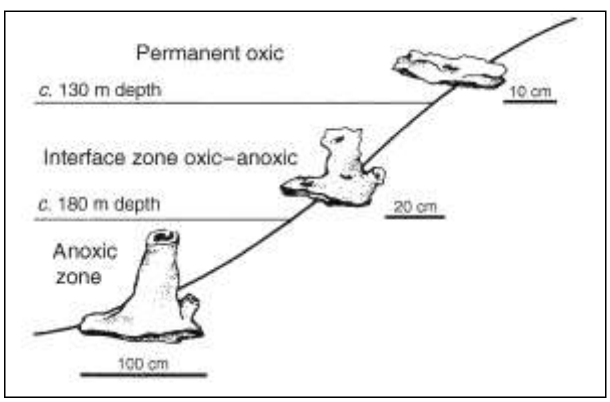

Fig. 3 MDAC chimneys on the shelf and slope of Black Sea (from Judd and Hovland, 2007, p.300)

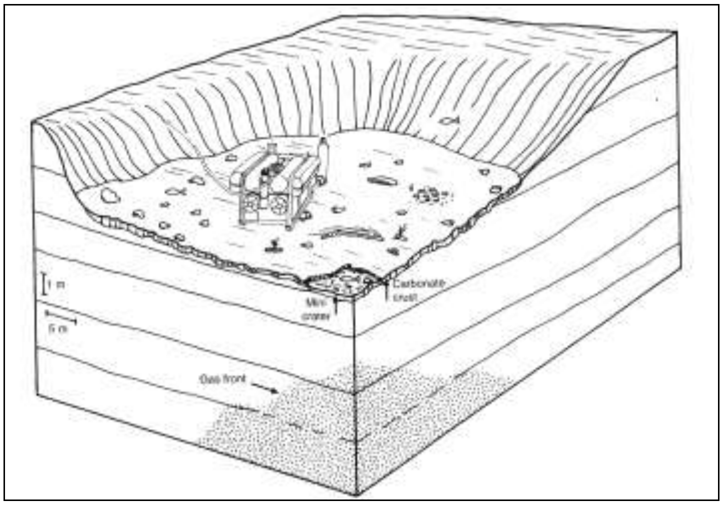

Fig. 4 North Sea pockmark paved with MDAC (from Judd and Hovland, 2007, p.34)

Many paleoseep carbonate bodies have already been revealed which are practically identical in structure with modern ones; they offer great hopes for paleoclimate, hydrological, chemical and biological reconstructions. Perhaps the largest of their kind appear to be the carbonate masses in terrigenous Miocene formations at Monferrato and cylindrical carbonate concretions in mud breccias at Verrua Savoia (both from Northern Italy)—interpreted as cold seep carbonates with strongly depleted $\delta^{13}C$ values.(Cavagna *et al.*, 2001) Other paleo-CSS have been reported in Silurian formations in Morocco (Barbieri *et al.*, 2002) and the Cretaceous formations of Tepee Buttes in Colorado.(Shapiro, 2003).

Paleoseeps seem to have a given life time, being buried by newer sediments after "death". About 17 macrofossil-rich hydrocarbon seep systems have been recognized in the Phanerozoic strata of Jurassic to Pliocene age, so far. There seems to be a gap in hydrothermal vent and cold seep deposits for the Permo-Triassic which is probably due to the Wilson cycle (the existence of Pangeea). Fossil cold seep deposystems appear to be concentrated in the Lower Cretaceous and Upper Eocene to Miocene, for reasons that remain unclear. The complex environments during the Alpine-Carpathian-Himalayan multiphase orogeny (which covers this period) may be the cause.

Terrestrial seeps have generated important local features like the famous tar pool at Rancho La Brea with its unique collection of fossil. There are also scores of travertine deposits around the world, especially on carbonate platforms.

Paleodolines or paleopockmarks?

One of the most characteristic markers of an ancient karst surface (paleokarst) are funnel-shaped depressions of all sizes, filled with allochthonous and sometime autochthonous sediments. They are interpreted as paleodolines and to my knowledge there has been no attempt to look at such features with a syndepositional alternative explanation in mind. Yet, pockmarks in the very marine environment where – according to traditional geological interpretation – most limestones formed i.e. carbonate platforms (Wright and Burchette, 2002) on continental shelves, are an alternative worth considering.

Extrapolating pockmarked environments into the geological past one can easily imagine that diagenesis could and should have preserved paleopockmarks as enclosed depressions on bedding planes with allochthonous or autochthonous sediment infill.

In the overwhelming majority of cases paleodolines are solitary features and are not associated with other visible elements of karst geosystems. Morphologically they are all bed-surface features rarely exceeding several meters in depth and are filled with newer sediments. One good example is provided by "dolines" in the Gonnesa Formation (Fig.5) exposed in the Santa Barbara Mine in Sardinia. (Bini *et al*., 1988) The funnel-shaped alleged paleokarst features exposed in the Santa Barbara are sculptured in Cambrian limestones and are filled by transgressive Triassic sandstones. (Fig. 5) The Triassic sandstones are at their turn carved out by another "doline" perfectly superimposed on the one in Cambrian limestones. The secondary doline is filled with terra rossa (Fig.6). This very particular setting is said to be the rule in this area. The way the section in the mine is presented by the authors reveals a peculiar sedimentological feature: the transgressive sandstones' bedding planes follow (mold) the geometry of the "doline" walls being far from the expected horizontal layering (present in the underlying Cambrian limestones). Such an unusual setting is very difficult to explain and if recurrent (as the authors claim) becomes an enigma. But, if instead of karstification processes, one considers pockmarks (and consequently seeps) as an explanation, such features make perfect sense. The paleoenvironmental as well as petrological consequences of such a diagnosis are major!

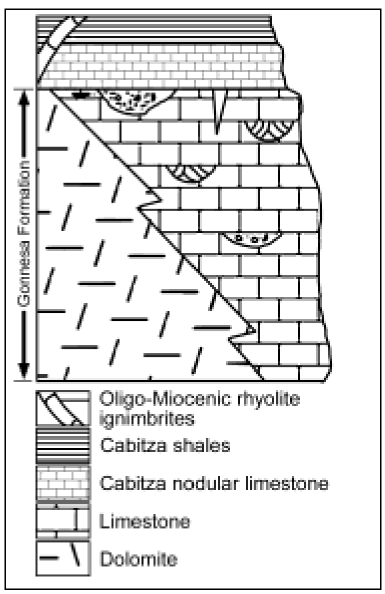

Fig. 5 The Gonnesa Formation (Sardinia) with recurrent doline-like depressions similar to the one in Figure 6. Note the 'paleorelief' on top of the Gonnesa Formation—conformably covered by the Cabitza nodular limestones. Also note the distribution of 'dolines' throughout the Gonnesa Formation. Such a setting is consistent with paleopockmarks (after Bini *et al*., 1988)

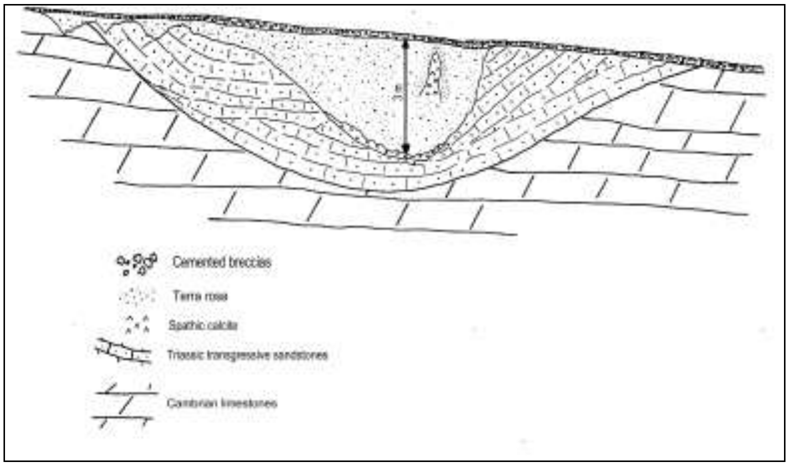

Fig. 6 Schematic section of an alleged 'doline' in the Santa Barbara mine, Mount Giovanni, Sardinia (from Bini *et al.* 1988)

Not only does this mean these features may not be paleokarst at all, but also that what has been described as terra rosa – a residual clay - may in fact be some type of marine sediment. Also the alleged speleothem can be a diagenized MDAC chimney.

Other paleokarst features homologous to CSS

The absolute majority of known paleokarst features are pit-shaped. Some resemble piping and rills. Lithologically, the most frequent feature is breccia-type formations. Judd and Hovland (2007, p.209) described "*sedimentary diatremes*", vertical pipes only a few meters in diameter and over 1,000 m long (deep), located in a pockmarked seafloor area offshore Nigeria. They contain clasts of surrounding rocks. In some cases such blowout pipes are plugged with clasts of overlaying rocks. Such syndepositional structures are the result of violent escape of fluids through unbound (pre-diagenetic) sediments. Once diagenized, they can easily be mistaken for paleokarst structures.

Carbonate sequences resembling hardgrounds are also present and so are rare "speleothems". These can also be alternatively interpreted as [diagenized] MDAC chimneys. There is a location in north-eastern Bulgaria where some of the most unusual naturally occurring carbonate features are found, over an area of 1 hectare. They consist of standing and lying columns (Fig.7), pipes and chimneys and are know as 'Pobiti Kamani' ('The Standing Stones'). They can reach over 5 m in height and over 1 m in diameter. Some have bulging 'caps' and in places the columns are in fact covered by a continuous layer of carbonate (a porous, sometimes fossil-rich limestone assigned a Sarmatian age (mid-Neogene). The underlying rock is fine sand believed to be of Sarmatian age as well.
Botz *et al.*, 1993 appear to be the first to have ever investigated these columns labeling them as "carbonate-cemented rocks". Based on stable isotope analysis, they suggested a polygenetic origin, from an initial marine origin to a late diagenetic under thick sediments. At that time of course, cold seep CSS were virtually inexistent in the scientific literature. Judd and Hovland (2007) reinterpreted the columns as originally MDAC with the addition of carbonate deposited from groundwater seepage.


Fig. 7 Pobiti Kamani, Bulgaria

There is a striking resemblance between these formations and the numerous carbonate pipes, chimneys, columns, mounds and crusts reported from many cold seeps on present continental margins making Pobiti Kamani excellent candidates for paleo-CSS linked to the large oil deposits of the Moesian Platform. There is in fact a significant oil reservoir located in their immediate vicinity, at Tiulenovo. (Feru, 1993) The same Sarmatian limestone continues north, into Romania's southern Dobrogea County, where numerous sulfurous springs emerge from it, discharging into the Black Sea. There are also numerous small ponds of sulfurous waters near Mangalia (Southern Dobrogea) called 'Obane'. (Constantinescu, 1995). These ponds are interconnected via karst conduits partially investigated by divers.

The Movile Cave

The ponds (obane) are located amongst gently sloping carbonate mounds, considered by some (Constantinescu, 1995) to be erosional features. It is however quite possible these mounds are also CSS features. The Movile Cave is located in such an area and is famous for its chemoautotrophic ecosystem based on sulfurous mesothermal waters rising from the deeper, confined karstic aquifer in Devonian formations. It is worth mentioning that the karsted Devonian limestone hosts large oil reserves as well, believed to be the source of sulfur. (Feru, 1993) The Movile Cave is interpreted as bathyphreatic acid karst whose inception predates the Messinian Crisis (5.1–5.5 Ma). (Summers, 1997) The lowering of the Black Sea level during the Messinian Crisis is believed to have generated three superimposed karstification levels, the deepest being located at about 150 m below the present sea level. (Lascu & Sârbu, 1996) As the level reached its present position, it is likely that sulfuric acid speleogenesis has reshaped and enlarged the pervious phreatic conduits and the sulfurous waters have provided the perfect habitat for a large bacterial population that constitutes the basis of the trophic chain in the cave. (Idem)

I first suggested the columns at Pobiti Kamani are CSS in 2004 (Silvestru, 2004). At the same location I noticed a feature that hints to a surprising possibility: that not only the Pobiti Kamani but the entire Sarmatian limestone on the western shore of the Black Sea, is in fact paleo-CSS, the mounds near Mangalia being a primary, syngenetic and not secondary feature. There are MDAC chimneys which support a layer of carbonate (like columns support the roof of an ancient Greek temple.) (Fig.8) This suggests the carbonate layer formed by carbonate solution fed through the chimneys and spreading out to form a layer, like, on a much smaller scale, the pockmark in Fig.4. Such features could be called "fluid-feeding pipes".

Fig. 8 Pobiti Kamani, Bulgaria. MDAC chimneys supporting a carbonate layer. Details in the text.

The fact that organic matter sampled in the Movile Cave yielded $\delta^{13}C$ between -47.5 and -37.5‰, (Sârbu & Popa, 1992; Sârbu *et al.*, 1995) very close to the ones measured in CSS in the Monterey Bay (49.88‰ avg.)(Stakes *et al.*, 1999) confirms the CSS nature of these features. I further contend that similar features must be present at other locations around the Black Sea and also in the proximity of the enormously-rich Caspian Sea oil fields, as well as in other similar geological settings around the world. It may also be possible that other, older platform carbonates formed as CSS, some incorporating reefal structures.

There are numerous other signatures of cold seeps like bacterial mediation in carbonate deposition, specific Ba/Ca ratios, high-Mg calcite (in fact presence of dolomite in chemical environments where it should not be present, except for bacterial mediation), carbonates with heavier $\delta^{18}O$ (> 3.5 ‰), drastically depleted $\delta^{13}C$ values to mention a few. No such sub-signatures have been studied thus far at the Bulgarian site and except for the Movile Cave, anywhere else on the western coast of the Black Sea. The presence of dolomites in the Gonnesa Formation (Fig.5), further confirms a possible cold seep origin. It may thus be worth using such signatures in assessing carbonate deposystems and their paleoenvironments.

Under such circumstances one can approach karsting processes and their history from a different perspective. Assuming that at least some carbonate deposits may have a cold seep origin, the older they are, the more diagenized they become and therefore CSS signatures are more difficult to recognize. But diagenesis could still leave some of the original features in place, like vertical, horizontal and sloping flow paths of fluids (in the shape of conduits), vugs and various size pores. When they become filled with penecontemporaneous sediments they could easily be assigned to paleokarst. And such inhomogeneities would undoubtedly increase karsting rates, especially when H_2S is also involved.

If this is true, than these "paleokarsts" may have nothing to do with subaerial conditions, as they all may have formed on the sea floor on unconsolidated sediments. Consequently, a more appropriate term for them should be *syndepositional pseudokarst*.

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