Submarine 'sinkholes': A review

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SINKHOLES: THEIR GEOLOGY, ENGINEERING AND ENVIRONMENTAL IMPACT

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Submarine 'sinkholes': A review

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ABSTRACT

The exploration of the submarine realm has led to the discovery that structures closely resembling subaerial dissolution karstic features are relatively frequent at great depth. Rounded, subcircular or oval depressions from a few meters up to 30 km in diameter have been reported from different basins (Mediterranean, North and Red Seas, Gulf of Mexico). The objective difficulty in making detailed studies of these depressions does not allow in most cases to inequivocally understand the nature of these structures and the mechanisms controlling their formation. The possibility of submarine karstification of carbonates leading to large scale structures seems unlikely but has not yet been investigated. The formation of sinkholes due to subsurface solution of salt does not necessarily require a subaerial environment. Important saline basins, such as the Gulf of Mexico, Mediterranean, Red and North Seas, display large depressions interpreted as salt collapse-structures due to the solution of underlying evaporites. The role that they play as mini-sedimentary basins appears to be important. In the Red Sea these depressions are likely to be connected to the formation and maintanance of hypersaline brines fundamental for the formation of metal-enriched precipitates of economic interest.

INTRODUCTION

The intense investigation of the deep-sea during the last decades has substantially advanced our knowledge of the morphology of the ocean bottom. Thus, morphological structures analogy to the better known structures of the subaerial environment have been discovered. A case in point is given by the detection of karst-like features in many basins of the world to depths as great as 2000 m. This paper will give a brief account on this attractive topic by discussing some of the theoretical and applied problems connected with it.

The first report of structures on the ocean bottom thought to be the product of large scale dissolution and collapse of soluble rocks is given by LOHMAN (1972) who provides convincing arguments of subsurface erosion (leaching) of the Permian (Zechstein) salt on the basis of seismograms recorded in the North Sea. Some of the circular to subcircular depressions (Chain, Discovery, Valdivia, Kebrit and Oceanographer Deeps) acoustically determined on the bottom of the Red Sea are suspected by SCHOELL et al. (1974: p.309) and BÄCKER et al. (1975: p.102-103 and 119) to be ultimately collapse structures due to removal of underlying salt. To support their view, BÄCKER et al. (1975) recall the morphological similarity between these structures and those shown by the diapirs at Gubbet Mus Nefit (Dahlak islands, southern Red Sea) reported by HOOPER in FRAZIER (1970). Salt collapse is also connected, according to TRABANT & PRESLEY (1977), to the formation of the Orca Basin, an elbow-shaped depression located in the Gulf of Mexico. Finally, ROSS & UCHUPI (1977), LORT (1977: p. 195), BELDERSON et al. (1978) and KASTENS & SPIESS (1984), independently argue that many depressions observed on seismograms, Gloria and Deep-Tow records from the eastern Mediterranean are due to collapse linked to salt leaching of underlying evaporites. It is noteworthy to record that HINZ (as quoted in SIGL et al., 1973) was the first to advance the hypothesis that "collapsing of underground caverns" due to chemical erosion of Miocene evaporites is one of the probable origin of the hummocky and rolling landscape of the Eastern Mediterranean.

Thus, it appears that karst-like structures are widespread phenomena in the oceans and not just local accidents.

It can be noted that the evidence available at present is limited to solution of salt. In the subaerial environment true karst is a phenomenon primarily linked to solution of carbonatic rocks (limestone, dolomite) through ground water circulation. Even if suspected (see for example, BIJU-DUVAL et al., 1982, 1983a, 1983b), the occurrence of deep ocean karstic dissolution of carbonatic rocks is yet to be proven. On the other hand, it is important to point out that dissolution of very soluble rocks such as Na,Mg,K salts need not take place only in subaerial conditions. Salt could be infact easily removed by seawater circulation when outcropping or within the subsurface (suberosion according to the German literature). This kind of leaching is therefore somewhat independent from the surrounding environment in the sense that the most important requirement seems to be water (either fresh or marine) circulation within the salt-bearing evaporites. Dissolution and collapse features in salty rocks are well known also on land (see references in KASTENS & SPIESS, 1984). As observed by LOHMAN (1972), who wisely discriminates between "true" karst and salt leaching the latter phenomenon can eventually evolve in collapse structures , the sinkholes, when salt leaching on the top of a diapir is faster than the flow of salt from downwards. Although the final result of the process may produce features resembling dolines, poljes and other subaerial karst morphologies, this does not strictly imply that they formed under subaerial karst conditions. If compared to the detailed morphological, lithological and structural analyses that can be carried out on the karst landscape on land, any approach to study the underwater environment still appears very primitive. Basically all the information we have about the underwater sinkholes derives from indirect, acoustic observations which supply little more than a rough morphology. LOHMAN (1972) has studied seismograms which give a vertical section of the sinkholes. The hypothesis that the Red Sea deeps are effectively collapse structures is not supported by any definitive direct observation but rather their peculiar morphology, detected by a traditional bathymetric survey. The same approach is shared by ROSS & UCHUPI (1977) and by TRABANT & PRESLEY (1978). Even the use of more sophisticated devices such as the GLORIA (BELDERSON et al., 1978) and Deep-Tow (KASTENS & SPIESS, 1984) systems provide only morphological information.

The morphological studies derived from the acoustic methods alone can not be considered diagnostically sufficient. The geological and structural setting of a given area must also be carefully analyzed. This factor is well understood by the above mentioned investigators which derive their final interpretation from a thorough analysis of all the geological and geophysical evidence at their disposal. In fact, circular or oval depressions on the ocean bottom can be associated with other mechanisms other than salt dissolution, for example, the collapse of the roof of pillow-lavas (SARTORI, pers. com.), subsidence related to methane escape from the sediment (Missisippi River Delta: PRIOR & COLEMAN, 1980), dynamic sedimentary processes (Malta-Siracusa escarpment: BIJU-DUVAL et al., 1983b) etc. Furthermore, karstic features originally produced under subaerial conditions can be encountered on rocks later subsided below the sea.

THE TERMINOLOGICAL PROBLEM

The use in marine geology of terms introduced to describe the subaerial karst is misleading when there is no definitive proof of the genesis of a given underwater "karstic" feature. In order to avoid confusion between a superficial, morphological appearance and the mechanism which originated it, it is prudent to use terms as "doline-like", "polje-like" or phrases as "resembing dolines" and so on. An uncorrect terminology can generate more than a wrong interpretation. For example, KASTENS & SPIESS (1984) use the terms doline and zanjones referring to some collapse and dissolution features present on the Eastern Mediterranean Ridge. However, from their paper it appears that their dolines (typically a karst structure of subaerial carbonate rocks) are collapse structures due to salt leaching and that their zanjones (originally described by MONROE, 1964, as a local karst feature of carbonates in Puerto Rico, and by the same author, 1976: p.4, defined as a local term for corridor) are solution features again in evaporites. Accordingly, it can be argued that the mechanisms known to produce those structures on land are also responsible for the origin of those discovered at sea. As a consequence, one can conclude that dolines and zanjones (an unnecessary term) may form also in evaporitic sequences (namely halite and/or K,Mg salts) exactly as they do in carbonate rocks; or, that the soluble bedrock was not made up by evaporites but by carbonates. Moreover, a zanjon is thought to form under special conditions through the action of "acidic waters derived largely from decay of forest vegetation" (Monroe, 1964). Similar conditions are highly unlikely in the deep ocean. It could be logically argued that the "karstic" morphology of the Eastern Mediterranean bottom is inherited by an ancient subaerial karst landscape. It is evident that the data at our disposal do not allow us to objectively recognize the mechanism (s) which formed these underwater structures and a less rigid use of the terminology would have generated less confusion between the observed morphology (the objective datum) and its interpretation (subjective).

In the present paper I shall use the informal term sinkhole when refering to the underwater morphological expressions recognizable as collapse structures due to subsurface dissolution of soluble rocks whatever (karst or salt leaching) is their likely origin.

SUBMARINE SINKHOLES: THEIR GEOLOGICAL ASPECTS

The submarine sinkholes buried in the North Sea subsurface (LOHMAN, 1972) range from a 1 m up to 5 km in diameter. Those of the Red Sea have a comparable magnitude (1-4 km about) as well as the collapse structures of the Eastern Mediterranean (1-6 km). The maximum diameter of the Orca Basin is about 30 km.. The vertical relief varies from a few tens to many hundreds of meters. It is immediately evident that these structures collect and preserve sediment acting as mini- sedimentary basins (LOHMAN, 1972) whose geological importance can be regional depending upon their size and setting.

The most common mechanism proposed by the authors implies that the collapse takes place at the top of a salt diapir; however, subsurface dissolution of the North Sea Permian evaporites is also thought (LOHMAN, 1982) to take place in the absence of diapirism.

Limiting our consideration to the first mechanism, we observe that sinkholes generated by salt-leaching pass through the following steps: 1) primary deposition of salt-bearing evaporites; 2) subsequent deposition of a sedimentary cover; 3) halokinesis and/or halotectonics (TRUSHEIM, 1960) due to the effects of sedimentary loading and/or tectonic activity leading to diapiric uplift; 4) subsurface removal of salt greater than its inward flow within a diapir with consequent formation of caverns; 5) formation of the sinkhole for the collapse of the cavern's roof.

In the Red Sea the widespread occurrence of a thick Miocene salt-bearing evaporitic sequence is well known from seismics and drilling (BONATTI et al., 1984, with references therein). Although the Plio-Quaternary sedimentary cover rarely exceeds the 100-200 m, extensive salt movement is favoured by active tectonic movements connected to the basin's oceanization. Furthermore the regional heat flow is high implying high subsurface temperature; high temperature is known (GUSSOW, 1968) to enhance the plasticity of salt which can, therefore, move also in absence of considerable loading. "Diapiric" subbottom configurations can be seen in many seismic reflection profiles of the Red Sea (ROSS & SCHLEE, 1973; BONATTI et al.,1984). BÄCKER et al. (1975) observe that the Red Sea deeps which they think to be collapse features, are connected with presumed transform faults. This observation seems to be correct since the Oceanographer Deep is situated in the area of the Brothers Fracture Zone (CRANE & BONATTI, in press), Valdivia, Discovery and Chain Deeps are situated in the Atlantis Fracture Zone (CRANE & BONATTI, in press) and Kebrit Deep can well be related to a transform parallel to the Dead Sea-Aqaba transform as suggested by some bathymetric alignments (see plate 5 of BÄCKER et al., 1975). Whether this connection is purely casually or directly connected to the sinkhole formation is still to be investigated.

Miocene (Messinian) evaporites are present also in the Mediterranean Sea where they form an extensive subsurface formation; the presence of Na,Mg,K salts within the evaporitic formation has been demonstrated by DSDP drills (RYAN, HSÜ et al., 1973). Diapiric structures have been extensively reported from the Eastern Mediterranean (LORT & GRAY, 1974; SMITH, 1976, 1977;), although not without criticism (e.g., GOGUEL, 1978; HIEKE, 1982). It is interesting to note that at present collapse features at the top of presumed diapirs are reported only from the Eastern Mediterranean while they are apparently absent from the Western basin where diapiric structures are far numerous (ERICKSON et al., 1977: p.270). This fact could be related to the different geologic and tectonic framework of the two basins. In the light of the previous discussion, it is interesting to re-examine the conclusion of HSÜ et al. (1973) which advance the hypothesis that the hummocky landscape of the Eastern Mediterranean largely derives from the karstification of the evaporitic deposits exposed to subaerial conditions when the basin completely dried up. They correctly reason that the solution of sulphates and carbonates, originating collapsing caverns, occurred as a result of ground water circulation. They also argue that the collapse of caverns formed during the subaerial phase may have continued also after marine conditions re-established in the Mediterranean. However, if the "karstic" morphology is due to dissolution of salt and not of less soluble products (as gypsum, anydrite and carbonates) there is no need of subaerial exposure. Lacking definitive information, none of the hypothesis can be ruled out with the possibility that both processes may have occurred.

The Gulf of Mexico, where the Orca Basin is situated, is an area of thick accumulation of salt which was deposited in Jurassic time in a geological/tectonical setting closely resembling the Miocene Red Sea (HUMPHRIS, 1977). Sediment loading triggered important halokinetic movements resulting in salt tectonics. TRABANT & PRESLEY (1977) argue that Orca Basin, the largest "sinkhole", until now, reported in the deep sea, is linked to massive collapse due to salt removal from an underlying salt mass or exposed salt diapir.

THE ECONOMIC IMPORTANCE

The disruption of salt-bearing evaporites in a tectonically active setting can facilitate intraevaporitic water circulation; salt within the evaporites can be easily dissolved forming brines which can eventually accumulate in nearby depressions. The sinkholes emplaced on saline formations, as those treated in the present paper, are an ideal place where brines can be formed and preserved from dissipation. The more or less prolonged stagnation of these brines could bring the bottom of the basin to anoxic conditions. The Red Sea Deeps and Orca Basin are two excellent examples of this phenomenon. The chlorinity (‰ Cl) of the Red Sea brines of the deeps reported in this paper ranges between 136.6 to 156 (BÄCKER & SCHOELL, 1972) comparable to that filling the bottom 200 m of Orca Basin that is 149.5 (TRABANT & PRESLEY, 1977). Anoxic conditions at bottom allow the preservation of organic matter; thus, under favorable geodynamic (low heat flow, absence of volcanism...) and hydrographic (especially high surface productivity) conditions, a sinkhole can become a source of hydrocarbons, as suggested by TRABANT & PRESLEY (1977). These geodynamic processes, active in the Red Sea since at least the time of the evaporite deposition (e.g., BONATTI et al., 1984), prevent the formation and preservation of this kind of hydrocarbons. However, in the Red Sea deeps metal-enriched sediments accumulate in relation to the intense hydrothermalism accompanying the separation of the Nubian and Arabian plates from each other (BÄCKER, 1982; THISSE et al., 1983). In this context, the sinkhole may have a two-folded importance: first, as a site where the brine (in which useful base metals are dissolved) can easily form through seawater circulation within the steep walls exposing evaporites, and second as a collector able to keep the brine itself which would otherwise be quickly dissipated.

Considering the striking geological, lithological and tectonic similarities between the Red Sea Miocene to Recent setting and the early phase of separation of the Atlantic margins, it is likely that fossil deeps which acted as sinkholes in the past (eventually enriched in base metals as the Red Sea ones) lay more or less deeply buried at places of the Eastern and western Atlantic margins where evaporites of that age has been reported.

CONCLUSIONS

1) Submarine collapse structures (sinkholes) probably due to leaching of underlying salt have been detected in many oceans where thick salt-bearing evaporites are present (Gulf of Mexico, North, Red and Mediterranean seas).

2) In order to avoid confusion between a simple morphological configuration of the ocean subbottom and the ultimate nature and genesis of these features, it is recommended to avoid as much as possible the use of a terminology strictly connected to subaerial geomorphologies.

3) Sinkholes form in a different sets of tectonic environments. The presence of diapirism seems to be an ideal pre-requisite, although exceptions to this rule have been reported.

4) The submarine sinkholes could act as mini-sedimentary basins and can be an important source for ore formation and/or preservation (young passive margin: Red Sea) as well as for hydrocarbons (mature passive margin, Gulf of Mexico).

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