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Circular Sedimentary Figures of Anthropic Origin in a Sediment Stability Context

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ABSTRACT

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The French POSA project studies the seismic energy released by bomb and mine blasting. This project is based on seismological and acoustical measurements recording during blasting actions in order to study seismic wave propagation nucleated by controlled sources (location and explosive energy). These measurements are compared to numerical modeling of the acoustic and seismic wave propagation based on the most faithful 3D representation of the seabed sediments and underlying rocks. This project first focused on the 3D environment representation based on specific surveys and on two blasting experiments which consist in exploding bombs of different loads at two distinct environmental places. The in-situ measurements reveal several hundred circular figures with very specific characteristics which clearly differentiate them from other sedimentary, biological and geological figures encountered on the seabed. They are found within the whole studied area and their diameter is from 10 to 130 m. About 30 circles by kilometer square are observed without correlation with the depth which varies from 10 to 150m. These sedimentary structures indicate that they have been generated by the explosion of bombs, but at different periods. The oldest ones most probably result from bombs dropped in 1940 and 1944 during the landing of the Allied forces in the region of Toulon. These original anthropic sedimentary figures and their differences compared with other circular structures observed on the seabed are described.

ADDITIONAL INDEX WORDS: *Sediment marks, Blasting, Sediment dynamics.*

INTRODUCTION

World War II explosives, whose TNT equivalent varies from a few kilograms up to a few hundred kilograms, are found every week on the French coast by divers, fishermen, and by the services of the Mines Warfare. In a very short time after their discovery, these machines must be destroyed by the specialized services of the Navy. The risks related to the operations of destruction are well controlled by the deminers, but the consequences of the action of counter-mining on the environment are much more complex to evaluate. According to the surrounding geological configuration, the weight of the bomb or mine and their location, seismic waves are generated by these counter-mining can cause vibrations in homes or even some damage such as broken windows similar to what small earthquakes can produce. At sea, they could theoretically trigger submarine avalanches which could transform into turbidity currents and possibly breakage of submarine cables and / or local tsunamis; especially if the high-explosive device is on the edge of the continental slope. Even if the probability of such an occurrence is low, this risk should not be underestimated, especially in the case of narrow continental platforms.

The POSA project addresses the issue of risk management upstream of counter-mining operations. For this, the explosive charge / seabed / wave propagation relationship must be characterized and the environmental models developed to perform the seismo-acoustic simulation. The project began with sedimentological and bathymetric surveys. The analysis of sedimentary measurements and seismic data were carried out to build a 3D geological model of the area (Morio *et al.*, 2017) and allows propagation modeling (Wang *et al.*, 2017; Ambrois *et al.*, 2017). On the fringes of this work the discovery of circles of different sizes observed on backscatter imagery of Multibeam Echo Sounder data motivated a specific study.

The questions posed by the observed circles concern their characteristics and their origin. Before describing these observations, an analysis of the circles described on the seabed was made to evaluate the different possible origins of these structures.

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CIRCULAR STRUCTURES OF THE SEAFLOOR

Suggestions that seabed circle structures could have been formed from World War II bomb craters have been evoked in many cases. But all the papers about these historical explosions or on the more recent ones, when old bombs and mines are exploded by divers of mine warfare, concerne the acoustic propagation in the water or on the impact on marine life, but never the imprint of these explosions on the seabed. Having observed circular structures on seabed bombarded many times during the World War II, the attribution of these circles to these historical explosions appeared possible. But it is necessary to exclude other possibilities of formation of such sedimentary structures. Among the structures which cannot be excluded are those which form circles with a positive relief. This is the case of the salt domes, which also exist at the bottom of the nearby continental slope, as well as mud volcanoes and volcanoes. Neither these structures footprints nor the meteorites footprints are discussed here, because the depressions then created are isolated. This work of analysis of the different possibilities on the origin of these circles thus concerns the circular depressions found in high density on the continental shelf.

Circular structures from plant origin

On the seabed seaweeds repartition is restricted to the 0-50 m depth range ; the green ones from 0 to 5m, the browns up to 25m, and the red seaweeds in the deeper zone. The formation of circles by algae has not been found in the scientific literature, on the opposite two examples of circles were met for two species of seagrass. Formation of vegetation patch has been attributed to self-organization processes (Sheffer *et al.*, 2011). Most of these vegetation rings are in relief and therefore off topic for this study. The first case consists of narrow fringes of eelgrass (Zostera marina) growing at water depths from 1.5 to 2.5 m. The rings ranged in diameter from about 1 to 15 m, are 40 to 50 cm high, and consisted of narrow fringes of dense eelgrass shoots growing on sediment accumulated (Borum *et al.*, 2017). The second example comes from the Mediterranean endemic seagrass : Posidonia oceanica, which occupies between 20 and 50% of the coastal seabed. These meadows are particularly studied because they would host more than 20% of the Mediterranean biodiversity. The leaves of *Posidonia oceanica* are 40 to 140 cm long, 7 to 11 mm wide (Caye, 1989). This species is found on a wide variety of substrates: silt, fine, medium or coarse sands, rock, even if it prefers soft substrates rich in organic matter. The maximum bathymetric extension of *P. oceanica* meadows is between 30 and 40 m deep in clear waters such as in Greece (Gerakaris *et al.*, 2014). When water is particularly transparent, for example near the islands of Corsica and Malta, they can reach a depth of 45 m. Seagrass occupies the photic zone where light is sufficient for photosynthesis to occur. The majority of them, as *Zostera marina*, grow in the 1 to 3m depth area. The deepest one is Halophila decipiens which has been found up to 60m depth. The different sea grass are therefore candidates for the creation of circles on the seabed, but their range of distribution confines in the 1 to 60m depths area and only the *Posidonia* seems to present circular depressions with large diameter and metric depth.

For example a 13,3 km^2 hydrographic survey realized by the Shom along the coast of Corsica (France), at depths of 20-26 m presents a *Posidonia Oceanica* meadow with a series of 118 sub-circular holes from 3 to 96 m having a mean diameters around 25m (Figure 1). The Multibeam Echo-Sounder imagery (MBES) shows that all these circles have steep sides and flat bottom but, probably due to the accumulation of dead leaves by currents, the reflectivity is not homogeneous into the depressions.

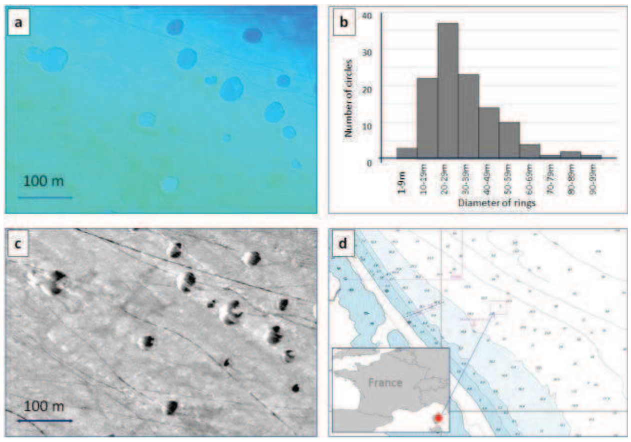

Figure 1. Circles in a posidonia meadow. a- circular depressions on the DTM, b- number of circles according to their diameter, c- visualization of circles by the MBES imagery, d- location.

Circular structures from the interstitial gas : Pockmarks

The expulsion of weakly buried gas in the sediment creates depressions on the seabed, called pockmarks. They were discovered on the close-to-Nova Scotia seabed (King and Mac Lean, 1970), and then in all the world's oceans thanks to the enhancement of the resolution of the seabed imaging systems. Such depressions are observed at depths up to 4800 m (Fader, 1991), but here we limit the next description to the depths comparable to the study area, that is to say between 0 and 500 m. Their shape is usually circular, but the pockmarks can be elliptical with elongation parallel to the direction of the bottom currents (Josenhans, 1978, Hovland, 1983). Their density can reach 1000 pockmarks per km^2 (Judd, 2003). These depressions are conical with mostly steep walls and a relatively flat bottom (Paull *et al.*, 1999). The diameter of these structures varies from a few meters to several hundred meters, with a depth generally comprised between 1 to few tens of meters. Some regions, such as the North Sea or the Gulf of Guinea present pockmarks several hundred meters in diameter which can come from fluid seapage or from the presence of gaz hydrates (Riboulot *et al.*, 2016). Pockmarks can be grouped, aligned, chained, or isolated. They are often associated with sedimentary or tectonics structures (channels, faults, diapirs, synclines-anticlines) and preferentially develop when the sedimentary layer is thin (Rise *et al.*, 1999, Jensen *et al.*, 2002). Their shape and size depend on their activity, the granularity of the sediments, the compaction, and the thickness of the sedimentary cover. The pockmarks are formed in clay or silty-clay seabed, but they can exist in the presence of sand; but only two, on about sixty papers describing pockmarks, indicate the presence of sand in muddy sediment. According to Hovland and Judd (1988), the depth has no influence on their size and spatial density, on the opposite for Cifçi *et al.* (2003) and Andrews *et al.*

(2010), a linear pockmark depth-to-diameter ratio exist for pockmarks field-wide. This relationship is also demonstrated by Brothers (2010) in a study based on 1767 pockmarks having the following characteristics: cover of 24% of the surveyed seafloor, 40% of these pockmarks occur in Holocene deposits less than 11.7m thick, the mean diameter is 84.8m (16 to 302m), there is a strong relation between depth and dimension of pockmarks, with larger pockmarks occurring in deeper water.

METHODS

During the analysis of the POSA data, carried out to characterize the geological environment of the Grande Rade de Toulon, circles were observed on the multibeam echo sounder (MBES) Kongsberg EM1002 imagery on two series of profiles. These observations motivated an analysis of previous surveys, previously acquired by the Shom in 2004 with the SMF Atlas Fansweep 20, then a new sedimentological survey was conducted on a sector restrained with Kongsberg EM2040C. The 4 sets of data present the same circular structures (Figure 2).

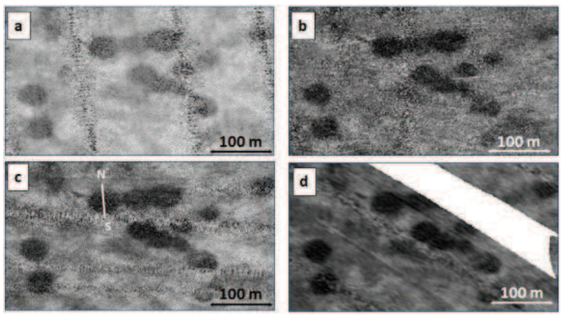

Figure 1. Circles on acoustic imagery from different MBES . a- Atlas Fansweep 2004, b- Kongsberg EM2040C 2016, c- Kongsberg EM1002 2015a, d- Kongsberg EM1002 2015b.

An analysis of the entirety of the bacscatter data acquired in the zone was then conducted and made it possible to count 661 circles whose diameter varies from 11 to 134m (Figure 3). The depths ranges from 32 to 256m and the size of these circles does not seem to correlate with depth as described in Table 1. It is nevertheless observed beyond 100m depth an absence of small structures and an increase of the average diameter.

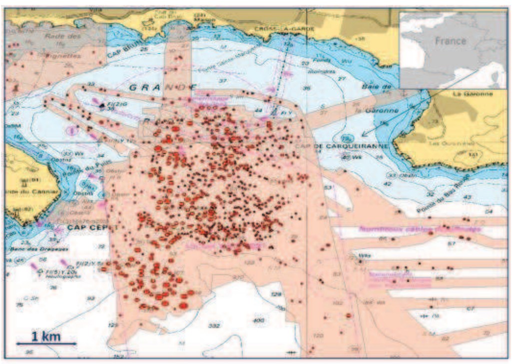

Figure 3. Studied area and the circles observed on MBES imagery

But this characteristic could come from the decrease of the bathymetric data accuracy when the depth increase, which generates the impossibility of observing small circles and therefore favors circles with large diameters. On the 71.45 square km area studied, the surface of the circles represents 3.4% of seabed. But the density is higher in the zone of 11.07 km^2, located in the center of the study area, where the area of the circles reaches 15.8%. What are these structures and which process is at their origin?

Table 1. *Numbers and diameters of the studied circles.*

Depth range (in m)	10-30	30-50	50-100	100-150
D. minimum	15	18	11	48
D. mean	26	43	46	79
D. maximum	47	124	103	134
Number of circles	19	144	464	34

RESULTS

Description of circular structures

Diameters are from 11 to 134m with a maximum of occurrences around 40 meters (Figure 4). They usually are well individualized but can sometimes partially overlap, they seem to be randomly arranged in terms of distribution and size, but sometimes they are organized in alignment; they are in this case series of circles with similar diameters and sharpness.

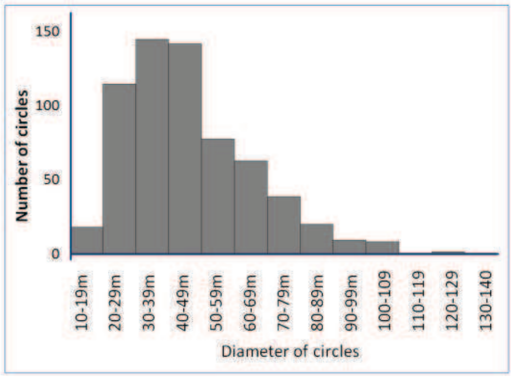

Figure 4. Variability of the diameter of circles.

This description firstly recalled the pockmarks, but some criterias go against this theory. First of all, the regional environment. The circles are all over the area without correlation with thickness of sediment which varies from 0.5 to 15m. They are distributed without correlation with the sedimentary bottoms which varies from gravelly cobles to muddy fine sands. All the sediments are heterogeneous and contain in different proportions gravel, sand, fine sand, silt and clay. The first centimeters or sometimes decimeters of seabed could contain up to 50% clays, but underlying layers are gravelly sands with a few percent of clay. The core realized in the center of a circle shows sandy sediment (70%), with some strata of 10 to 25% of sandy gravel. In this core of one meter long, the part of clay is from 5 to 22%, and this maximum is located on the first centimeter of the core. Thus sediments seem too coarse for development of pockmarks. A source of gas from the underlying geologic rocks is unlikely as it is metamorphosed Paleozoic rocks. This is confirmed by the absence of gas in the sediment cores. The gas is always observed in cores done in pockmarks by the fact that sound velocity in sediments become unmeasurable in the presence of gas.

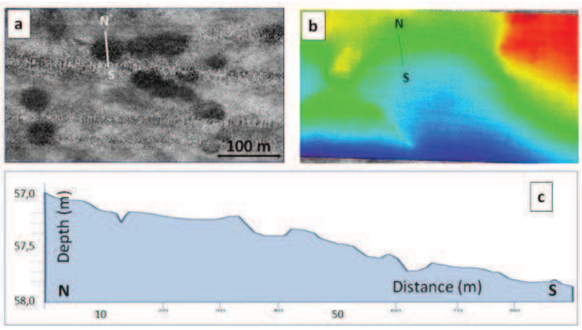

Figure 5. MBES imagery, DEM and bathymetric profile, showing the absence of relief in one circle

The most obvious criterion showing that it is not pockmarks is the absence of depressions in these circles. Some of them show a slight depression of a few decimetres, but most rings show no change of the morphology of the bottom. The seabed is flat and only the slope of the continental shelf is really observable (Figure 5). In summary, these circles are on a too great range of depths to be of biological origin and do not have the characteristics of the pockmarks.

Origin of circular structures : Blast marks ?

During the digitization of the circle marks it appeared that some circles were very sharp because their strong reflectivity was very different from the surrounding seabed. Others are less visible with a reflectivity close, in and out of the circle. The rule that was adopted was to take into account only structures whose perimeter was fully observable and could therefore be measured without difficulty. It is thus possible that the structures are more numerous than the 661 counted. The circles have been classified according to their sharpness (Figure 6).

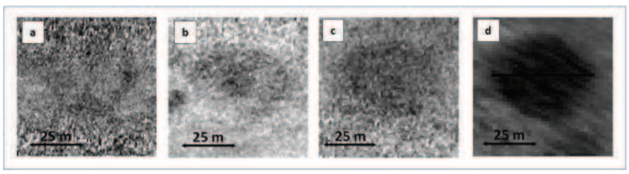

Figure 6. Classification of circles according to their visibility on MBES imagery: a-Blurred limit; b-Not very apparent; c-Net contours; d-Very clear

Table 2. *Sharpness in percentage of the circles studied.*

Depth range (in m)	10-30	30-50	50-100	100-150
Blurred limit	47	35	20	15
Not very apparent	37	47	40	26
Net contours	16	17	32	32
Very clear	0	1	7	26

Circles appear to present a relative increase in the visibility from the coast where the Blurred limit circles predominate, towards the deep sea where most of the very fair circles have been observed (Table 2).

Each year the counter-mining to destroy mines and bombs of the Second World War occurse about three times in this area. This number is nearly constant for several decades and this activity can not be at the origin of more than 250 circles. Furthermore these mine warfare operations are exceptional beyond 50m depth and are limited to depths of 80 m. As 81% of the circles are beyond 50 meters, it is impossible that the counter-mining is at the origin of these deep circles. Part of the 661 circles could come from counter-mining activities, but most of them belong to another origin. After the analysis of all the possible solutions it seems that the only remaining origin is the creation of these circles by the explosions due to the bombings of the World War II.

An analysis of the bombardments of this region during the World War II plead for this. Toulon as the main port of the French Navy was a target during the Second World War. This port was bombed on five occasions on June 12, 1940, November 24, 1943 and from August 13 to 20, 1944 during the Dragoon Operation. During this last period, 809 bombs for a total of 491.6 tons were launched on the Cape Cépet (W on Figure 3). They would be circles related to the blast of bombs, thus they should be named Blast marks. The process which gives the characteristics of these marks due to explosions of bombs on the seabed is not yet fully explained, but it is conceivable that the size of the marks would be related to the TNT equivalent weight, and that it gives rise to a modification of the internal structure of the sediment. The originality is the absence of the digging as it is the case in the aerial domain, as it was observed on Cape Cépet in 1944 (Figure 7). It is difficult to study the alignments because of the imbrication of circles of various sizes and of the masking of circles by subsequent explosions. In first analysis about twenty alignments of variable directions are observed. They are all composed of 4 circles of similar size. A comparison with photographs on a terrestrial area of sand must be done to see if similar series are observed.

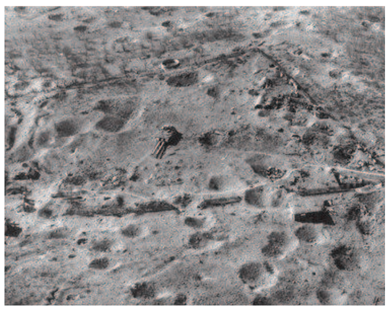

Figure 7. Aerial photo of craters of Cap Cépet in 1944 (Zaloga, 2015)

The presence and preservation of sedimentary structures of anthropic origin for several decades seems an exceptional case. On the French continental shelf, apart from this example, only five similar circles have been seen on the Normandy coast (Y. Ferret, personal communication). In our case, most of the blast marks originated from the 1944's bombardments. Since they do not show relief they are in theory easily erodible and it is necessary to have an absence of sedimentary reworking by the currents for these structures to be preserved. The increase in their sharpness with the depth is in this case a concordant criterion. The first circle appears at the depth of 15m, the first sharp contours circle is at -33m and the first circle with very sharp contours at the depth of 50m. This would be the imprint of an active reshuffle in the surf zone and then the decreasing of this process which becomes ineffective at a depth of 50m.

CONCLUSIONS

As part of the French POSA project a high resolution study of the marine sediment environment has been done for the subsequent modeling of wave propagation and earthquakes created by the destruction of bombs from the Second World War. This study in the vicinity of Toulon, which has been bombed during the World War II, has highlighted many circles whose surface can cover up to 15.8% of the seabed in the densest sector. These circles, whose diameter varies from 11 to 134m, have a high reflectivity in relation to the surrounding backgrounds but do not give rise to a change in the morphology of the seabed. These circles are not of biological origin, nor from the presence of gas in the sediments, they have not been described in the scientific literature. These circles are largely not attributable to the current activities of mine warfare and can only come from the action of bombs dropped during the bombings of this region in 1943 and even more in August 1944. To have been preserved until now, it has been necessary to benefit of an absence of sedimentary dynamics and of the trawling by the fishermen. New sedimentological surveys will be conducted in 2018 on some circles to characterize the origin of the changing of reflectivity. These sedimentary figures which we call Blast marks must exist in other places and it would be useful to be able to confront these observations to some others.

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