On natural gas venting and preliminary results on subsidence in Cartagena bay (Colombia)

Sobre emanaciones de gas natural y la evidencia preliminar de subsidencia en la bahía Cartagena de Indias (Colombia)

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Abstract

Mud and emissions are reported in the region. A multibeam survey carried out during 2015-2016 in the Bay of Cartagena showed numerous pockmarks (20m in diameter, 3m in depth) in the flat mud surrounding mud volcanoes in that area evidencing active natural gas venting in the south of the Bay. The observation of coastal land loss related to natural gas venting in the neighboring continental shelf and in situ high vertical resolution DGPS in the Bay confirm the existence of subsidence in the area.

KEYWORDS: Cartagena Bay, diapirism, pockmarks, subsidence.

Resumen

Se reportan actividad de emanaciones de lodo y gas en la región. El levantamiento batimétrico realizado con sonda multihaz en el sur de la bahía de Cartagena durante 2015-2016 permitió evidenciar actividad diapírica de lodos en el sector, con la presencia de numerosos manaderos de fluidos y gas y marcas circulares (pockmarks) de unos 20 m de diámetro y hasta 3 m de profundidad, localizados sobre el plano lodoso de fondo. La pérdida de zona costera y las emanaciones de lodo y gas presentes en zonas de la plataforma vecinas y mediciones con DGPS de alta resolución vertical en la bahía confirman la ocurrencia de subsidencia diferencial en la región.

PALABRAS CLAVES: *bahía de Cartagena, diapirismo, marcas de gas, subsidencia.*

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Introduction

Since the sea reached current levels, after having risen by about 120 m due to post-glacial melting 11700 years +-99 years (Walker *et al.,* 2009), the sea level has remained close to the current one, but has been having a net rising, as a result of the effect of several influential aspects, such as the warming of the water, the water that reaches the sea by melting ice and the movement of the earth's crust at the edges of the plates, rising or falling according to tectonic activity (IPCC, 2013). This report established that, in general, the sea was rising by about 1.8 mm/year between 1961 and 2003, being 2.8 mm/year between 1993-2003, which has been attributed mainly to global warming, melting glaciers, and the ice melting in Greenland and Antarctica.

The factors related to sea level are measured objectively with reference to the place where the level meters are located, which are positioned with precision, on the coasts of the world (GLOSS, 2016). In this sense, the factors not only directly related to the nature of the water mass are taken into account, but also those associated with the movement of the sensors due to tectonic dynamics of the plates where they are located. This implies observing consequences such as that the relative elevation of the sea level can be different from one place to another.

Analysis of relative sea level

Based on data taken from the tide gauge initially placed at the point of Castillogrande and later at the CIOH dock on Manzanillo Island, which have been collected by NOAA from 1951 to 2000, a calculation was made that resulted of 3.58 mm/year in a sea level rise in the Bay of Cartagena (Torres *et al.,* 2006). Subsequently, a new study with the same group of data established that in the Bay of Cartagena there was a tendency to a relative increase in sea level of 4.5 mm/year (Figure 1), while in the port of Cristóbal (Panama) the record only showed an increase of 1.6 mm/year (Andrade, 2008).

Recently, a deeper analysis showed that the relative level in Cartagena have risen at a higher speed (5.38 ± 0.5 mm/year) in the last 44 years compared to Cristóbal, who had a tendency of 2.0 ± 0.2 mm/year, Magueyes in Puerto Rico of 1.3 ± 0.6 mm/year, or Lime Tree in the Florida Keys of 2.9 ± 1.5 mm/year (Torres & Tsimplis, 2013), showing that the relative sea level is risen faster in Cartagena than in other neighboring seaports.

As can be seen, the measured over-elevation in the Bay of Cartagena, with respect to the rest of the Caribbean, seems to have been increasing in more than double compared with the data measured on both sides of the Caribbean Sea. It has been established that the free surface of the sea should be similar in relatively nearby parts. The fact that the sea level slopes measured in ports such as Cartagena and Cristobal, separated by only 300 miles is so different, indicates that in the Bay of Cartagena there is an additional effect to the sea level rise caused by climate change which, as already stated, makes the apparent sea level rise faster. The analysis of the movement of the continental mass in the area of Cartagena and the spatial characterization of the seabed in the south of the bay, was carried out as an essential task of the evaluation of the geomorphology of the Cartagena Bay through a review of the morphological variations in the coastal zone and thus understand the causes of these differences.

Methodology

In order to study the bathymetric characteristics of the seabed in the Bay of Cartagena (Figure 1), an assessment of its geomorphology was carried out by reviewing both the variations in coastlines and the depths measured at different times and the detailed visualization of the seabed with a multibeam echo sounder.

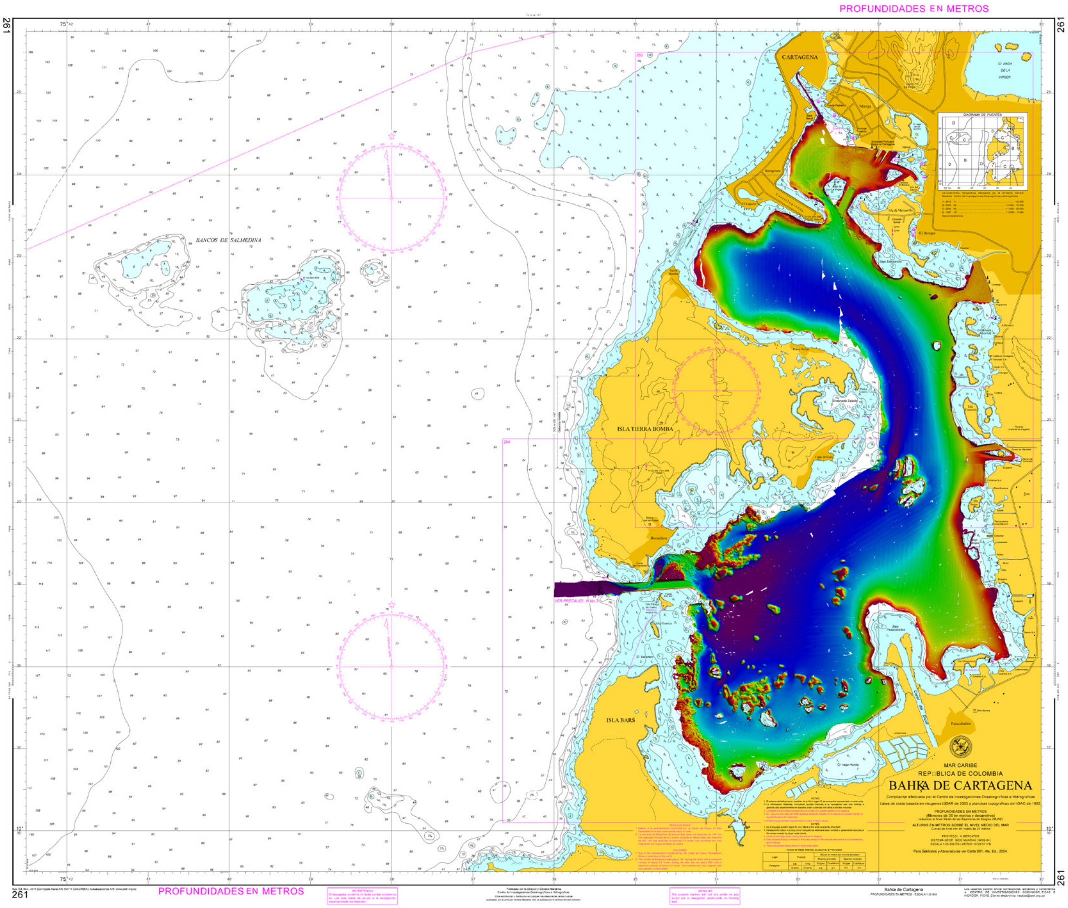

Figure 1. The bay of Cartagena, the bottoms and current form of the bay. On top of the nautical chart COL 261, CIOH 2011).

The subsurface structures were found and analyzed during the first-order bathymetric survey carried out with a Reson 7125 multibeam echo sounder in 200 and 400 khz 512 beams. This equipment was accompanied both by a Trimble differential positioning system and by Octans motion sensors, used during the investigations carried out by the CIOH in the bay of Cartagena, between 2015 and March 2016.

The multibeam survey in the southern Bay area showed very abrupt elevations emerging from a muddy, flat bottom and ending mostly in peaks that barely reach the sea surface (Figure 2). Many of these many structures have the appearance of small volcanoes and are shown as depressions of round and circular shapes like craters that are in some cases visible (Figure 3).

The bottom of the Bay in this sector is flat and is occupied by a number of circular marks in the mud of about 20-30 m in diameter and depths up to 3 m (Figure 3). These *"pockmarks"* are interpreted as an area of active recent emissions of natural gas. In many cases they are aligned, and dispersed in others but mostly locally grouped forming circular zones.

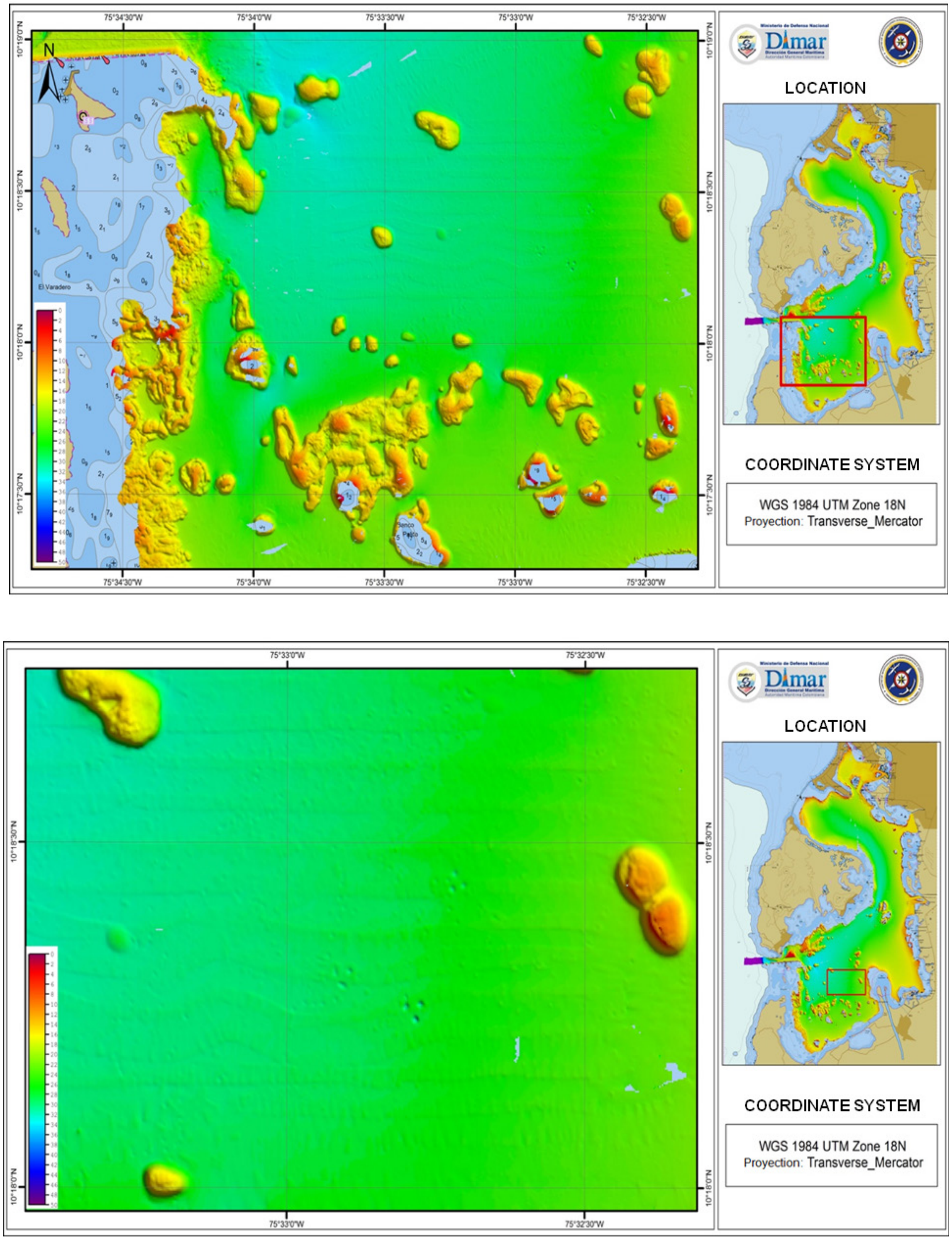

Figure 2. View of the multibeam survey in the southern area of the Bay of Cartagena. A relatively flat bottom (in green) is observed, dotted by elevations that rise abruptly almost to the surface, which is associated with old springs or mouths of mud volcanoes, several of which still conserve the upper crater.

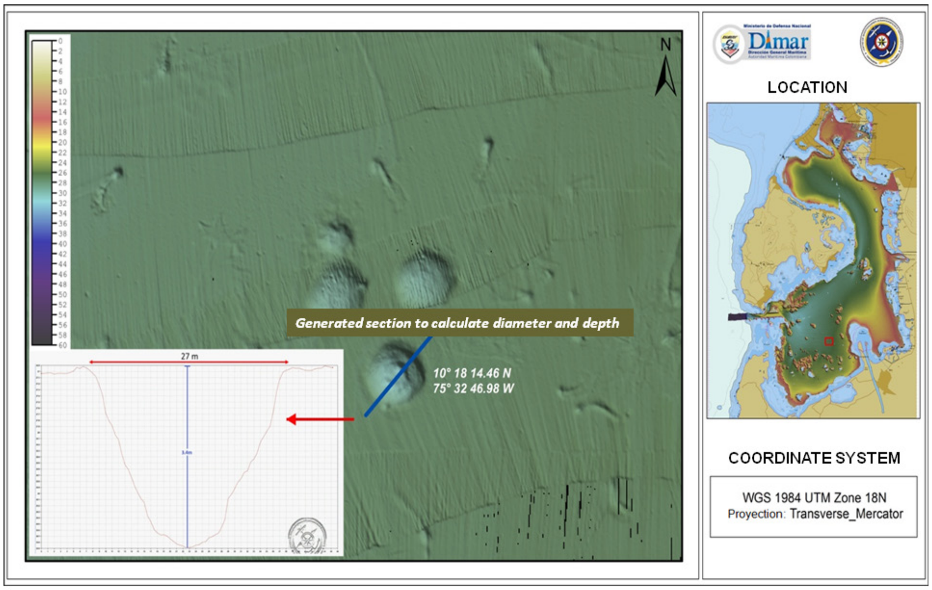

Figure 3. Details of the characteristics found in the muddy bottom of the southern area of the bay of Cartagena de Indias. Most of the these pockmarks are around 20 m in diameter and are grouped or aligned to 3 meters deep as possible product of structural control in depth.

The same round marks were also detected at the top of current coral zones and carbonated sands, such as in the shallow bank facing Bocachica entrance (Figure 4), which have the same appearance of round marks, with similar diameters and depths. Likewise, in front of the Varadero area, the presence of a dome with a crater was detected as a mud spring and numerous gas marks in the deeper muddy bottom (Figure 5).

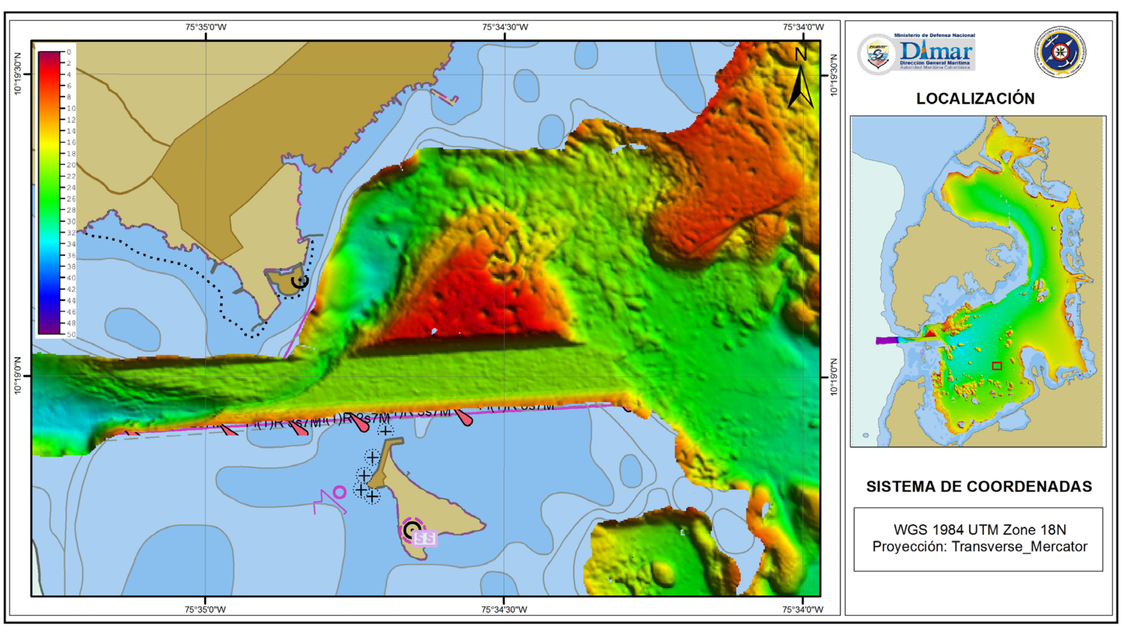

Figure 4. The mud and gas structures are also found in the vicinity of the current reef areas, as can be seen in the lower area in front of Bocachica.

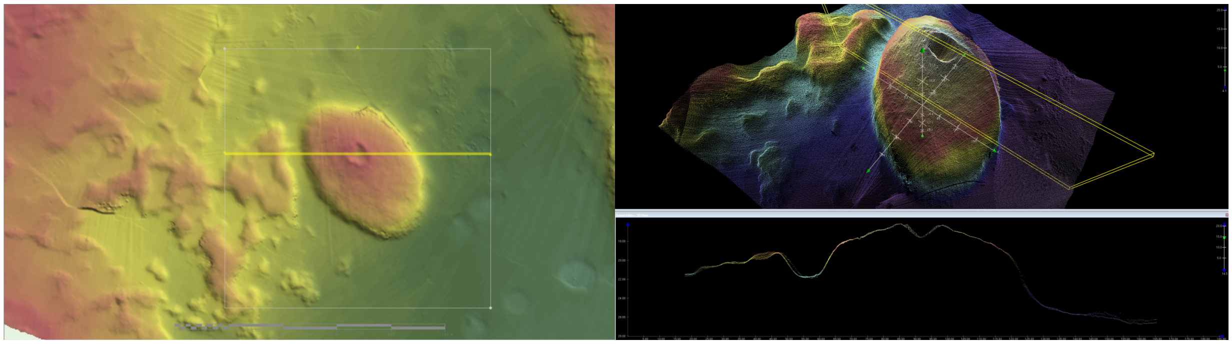

Figure 5. Mouths or mud springs found in the south of the bay with numerous gas marks around them, can be observed.

Analysis of DGPS data

On the grounds of the Oceanographic and Hydrographic Research Center in Cartagena, CIOH, in 2014 the permanent geodesic station of continuous operation, GNSS, was installed. The daily processing of this station data has allowed us to estimate the respective three-dimensional time series for this station.

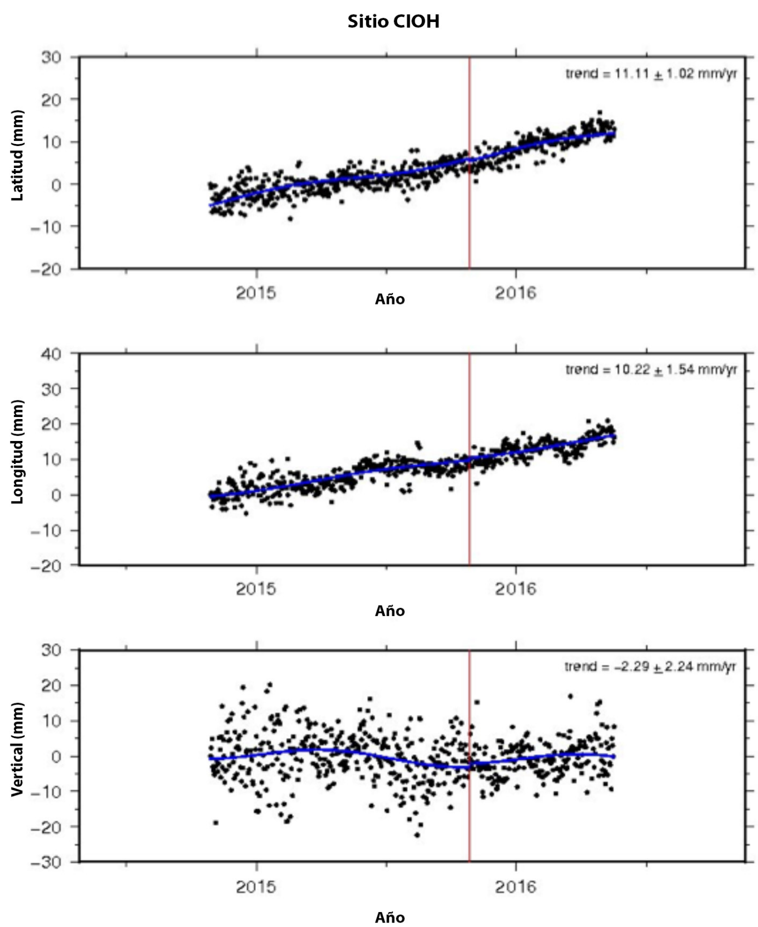

Figure 6. CIOH time series with seasonal signal.

In processing the data for almost two years, the seasonal signal has been considered; the trend line is adjusted to this signal, which yields an annual velocity of 11.11 mm for the north, 10.22 mm for the east, and a vertical drop of 2.29 mm per year.

The analysis of the vertical movement of the crust carried out with a high resolution vertical GPS of the SONEL network placed near the tide gauge of Manzanillo Island, shows that the zone descended around 31 mm between 2000 and 2014 (Figure 7) with a net decrease in 2.2 ± 0.5 mm/year which becomes an important factor .

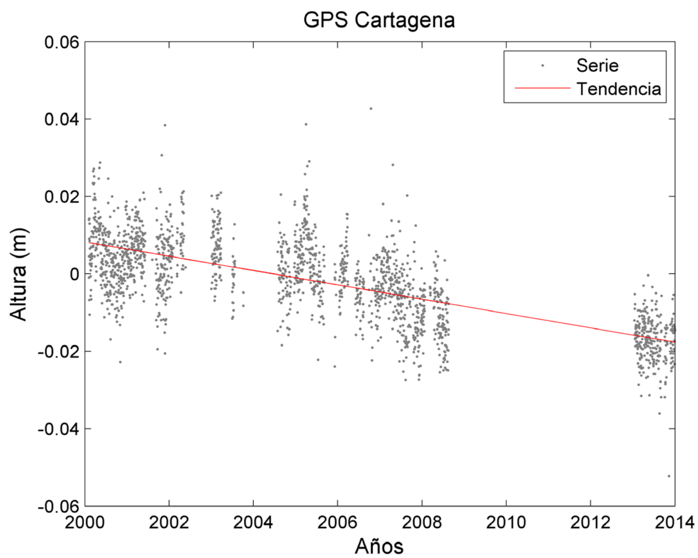

Figure 7. Vertical movement of the DGPS sensor placed in the CIOH (Manzanillo Island) The sensor shows a decrease of 2.2± 0.5 mm/year.

On the other hand, taking as reference the permanent GNSS station, the geodesic levelling was carried out between this station and a "witness" point associated to the tide gauge in the CIOH. Estimating if there are any differences that allow to observe the variations in vertical position of the tide gauge, it was used laser level with an Invar sight for most of the path, although it was not possible to be used this sight in the final part by the roof where the tide gauge is, the place where the reference point is located.

This final leg was carried out in a conventional way, which naturally was not the most convenient because the precision of the other part of the survey is lost. The difference that was found between two observations are of submillimeter order, which has allowed to estimate that the reading of the tide gauge should not be object of vertical correction different from that observed in the time series.

Finally, using the synthetic aperture radar interferometry technique, some interesting values have been found that also evidence a possible subsidence in Cartagena, but that must be confirmed with more data. Figure 8 shows the result of the interferogram for the period May 2015-March 2016, which is still a very short time.

The obtained data for this period have shown results considered as fluctuating with apparently subsident tendencies in sectors such as Membrillal, El Rodeo and Mamonal. Given the terrain characteristics and the environmental and meteorological conditions, the idea is to correlate these data with geological, geomorphological, geotechnical and rainfall studies of the region, in order to establish their incidence on the behavior of the terrain preliminarily. These values must be correlated with other GPS stations, for example the field in the Naval Club.

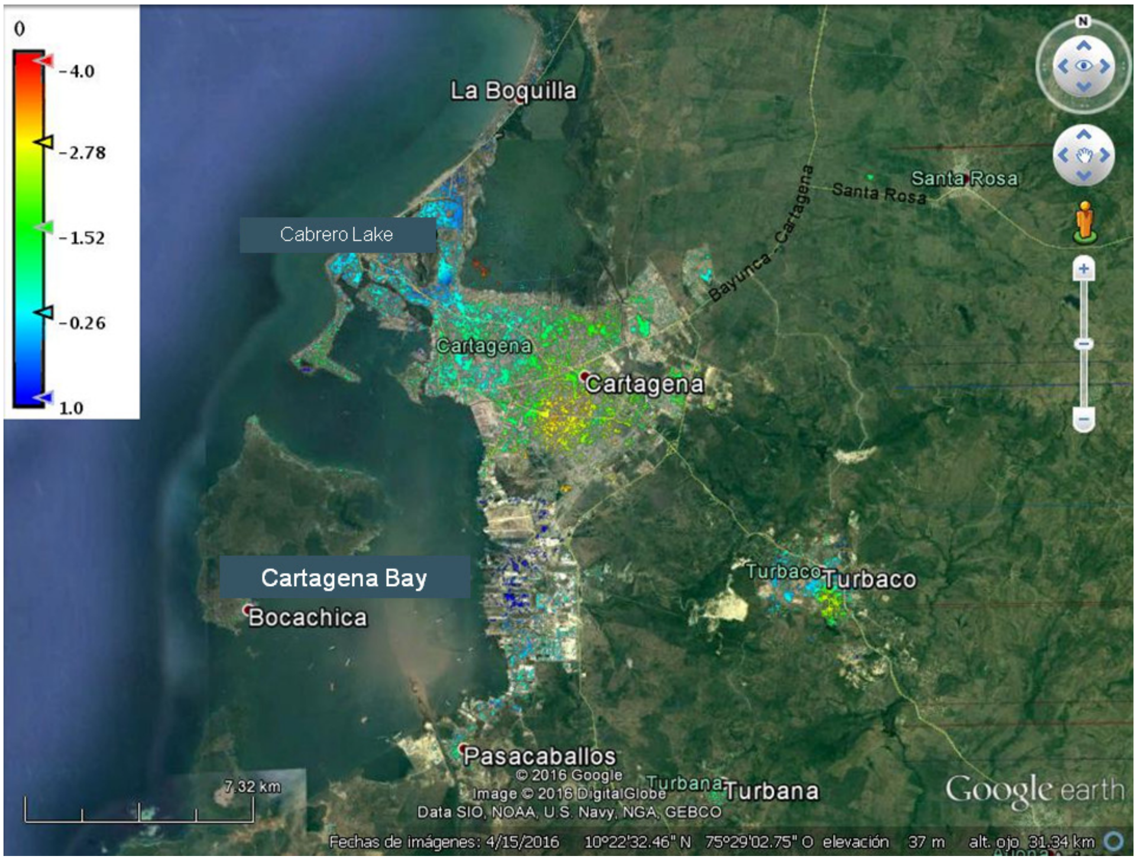

Figure 8. Interferogram for the period May 2015-March 2016 in the Cartagena area, the values (in millimeters) show the descend in the terrain in the year of observation.

For both groups of data, it is considered that more observation time is needed. It is important to look at how to avoid the problem of the sight, because the reading with the laser level and the Invar sight allows to read at scales of tenths of a millimeter. In the assimilation of these values for Cartagena, special caution must be observed and equally, its consequences must be subject to a longer time of observation and analysis.

DISCUSSION

The emanations of mud and gas are of common occurrence in the coastal zone of the Caribbean NW of Colombia between the Gulf of Urabá and Barranquilla including the continental and marine areas of near continental shelf. The most evident manifestations correspond to the so-called mud volcanoes that can be found locally aligned following the structural geological trend of the region and particularly in the Canal del Dique region to Galerazamba, where about 40 mud volcanic structures have been identified, many of which are located around the bay of Cartagena (Figure 9).

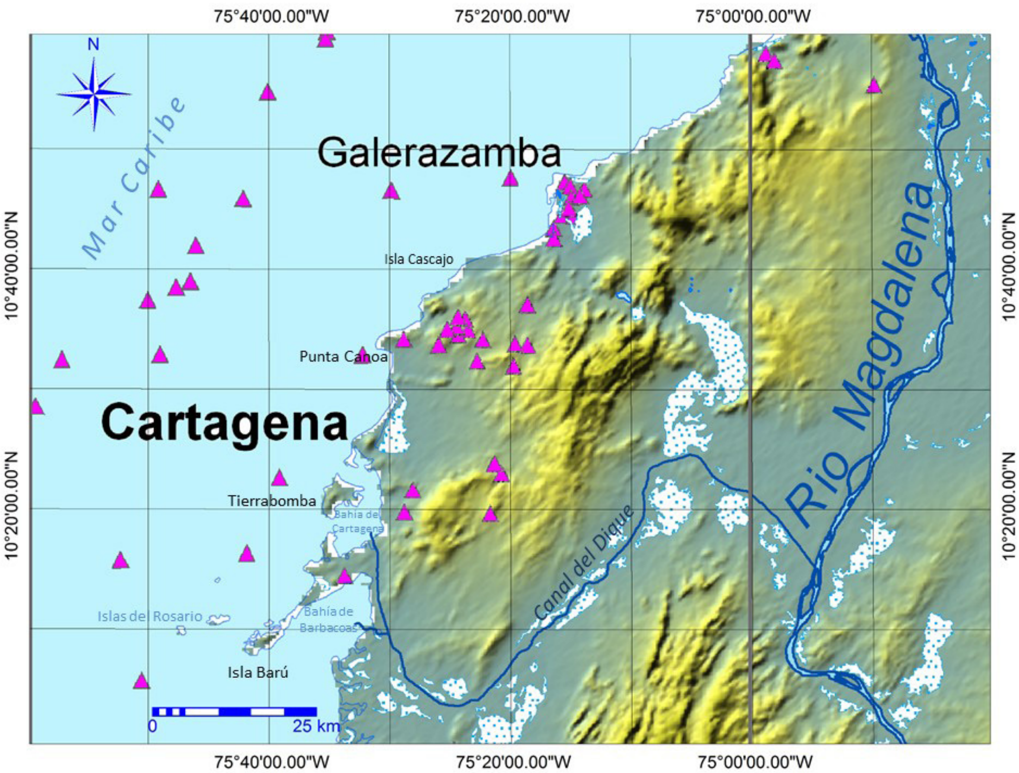

Figure 9. Location of the mud volcanoes present in the region of Cartagena de Indias. Note the concentration in the region of Galerazamba, Punta Canoas and SE of Cartagena (Carvajal, 2017 & Carvajal & Mendivelso, 2017).

Mud volcanoes are dome shaped hills with diameters between 0.6 and 6 km and variable heights between 40 and 100 m, whose origin is associated both to processes of vertical deformation of the terrain by the push of clayey materials and gases confined at depth, and to periodic eruptions of mud, which accumulates and moves laterally (Carvajal 2016 & 2017). These geological structures present in their upper part, both mouths or mud springs and gas venting that are also locally dispersed on the flanks of the "volcanic" structures. They have different shapes depending on the characteristics of viscosity and fluidity of the muds and can have shapes ranging from cones with diameters ranging from 1 - 20 m in diameter and heights of 0.5 - 20 m (Types A, B, and C), to craters of 1 - 50 m in diameter (Type D) or simple holes of venting gas of a few centimeters in diameter (Type O), (Carvajal 2016, Carvajal 2017, Carvajal & Mendivelso, 2017).

These types of mouths with the same characteristics can also be found isolated, dispersed or in groups in continental and submarine zones, but their occurrence is less common. Particularly in submarine zones, the presence of gas venters identified in the profiles as chimneys (Vernette *et al.,* 1992) and "pockmarks" are depressions of several cm to meters where fluids and gases are expelled through a conduit (Kopf, 2002).

In the south of the bay of Cartagena a number close to 200 mud and gas springs and dispersed *"pockmarks"* have been found, aligned or arranged in curved forms in the underwater flat bottom of the place, which indicates a structural control in depth (Figure 10). It is also evident the occurrence of shallow reefs locally colonized by mangroves, whose structures are considered to have been favored in their origin by the emanations of mud and gas as evidenced in islands such as Arena Island and shallow reefs such as Salmedina and in the south of the bay of Cartagena (Ricaurte *et al.,* 2004 - Andrade *et al.,* 2017 - Vernette *et al.,* 1990, Vernette *et al.*, 1992, Carvajal 2017).

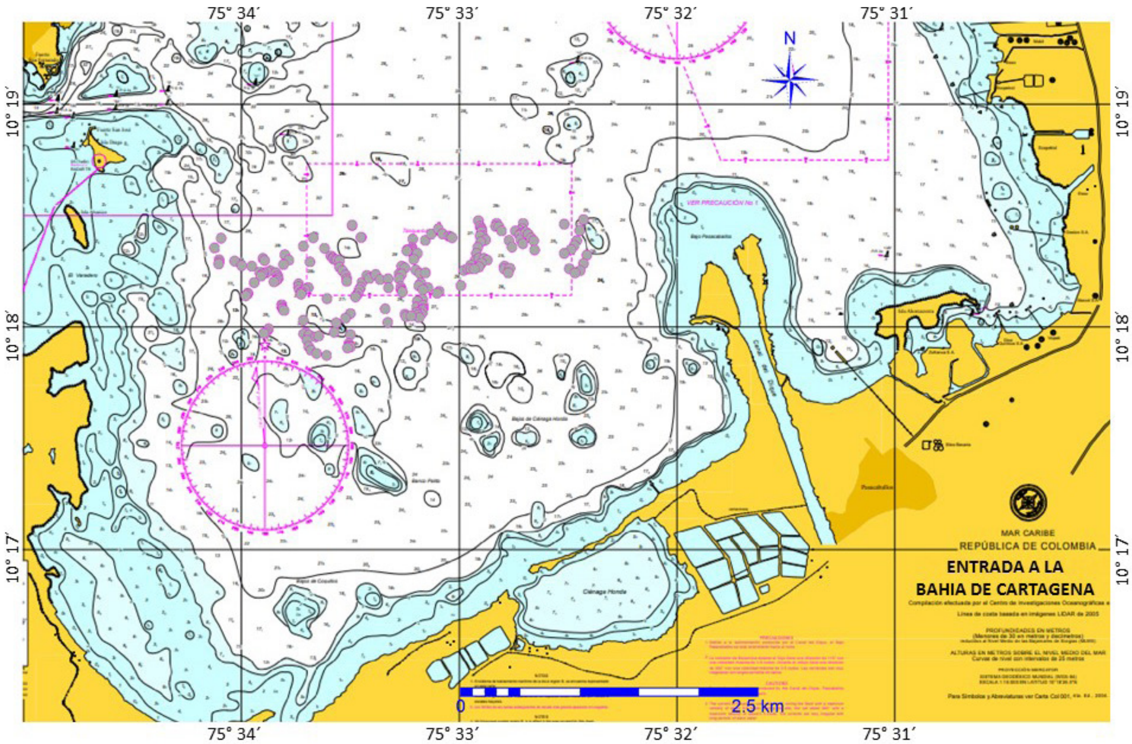

Figure 10. Bathymetry of the southern part of the Bay of Cartagena. Note both the distribution of the mud springs and *"pockmarks"* (grey circles) and the shallow reefs present in the sector, as well as the location of the mouth of canal del Dique by the SE sector (Taken and modified by CIOH 2011).

The Bay of Cartagena is considered by Gayet & Vernette (1989), as a coastal lagoon generated by tectonic control and this condition can be associated with the presence of a synclinal trough of SW-NE direction that nods towards the SW and sinks towards the bay partially bounded by a fault of the same direction of hatchet direction characteristics.

The presence of mud springs and pockmarks can be preliminarily considered as a neotectonic activity indicator associated with this fracture (Figure 11). It is also related to evidence of a diapiric structure, defined in depth with geophysical methods in the Mamonal region by Obando (2010) in Carvajal (2017), which should be the subject of future research in the Bay of Cartagena.

The history and geological and geomorphological evolution of the Colombian NW Caribbean has been associated with the tectonic interrelation of the Caribbean, Nazca and South American plates through geological time. Notwithstanding the above, based on the latest research carried out in the region, the phenomenon of mud diapirism has had and continues to have a great influence on the geomorphological and coastal conformation and dynamics between the Gulf of Urabá and Barranquilla, including both continental and submarine zones of the near continental platform (Carvajal 2016 & 2017-Carvajal & Mendivelso, 2017).

Diapirism, as a phenomenon, is associated with argilogenetic tectonics (clay tectonics), which has very regional characteristics and is generated by the lateral variation in depth of the thickness of the layers of clay constitution, as well as by the greater density of the materials of the upper cover, which determine a differential load that causes a lateral flow of clay material in depth, and a ductile takeoff zone from zones close to the distal ones. The mobility of the material over pressurized in depth is determined and favored by the relation of its porosity and permeability, thicknesses, the presence of gases (methane and CO2 type) and logically the oblique convergent effect of the Nazca and South American plates that still prevails according to the results of the GPS monitoring with geodynamic purposes developed by the Colombian Geological Service (Albertz *et al.,* 2010 in Carvajal & Carrillo, 2018 - Mora *et al.,* 2018).

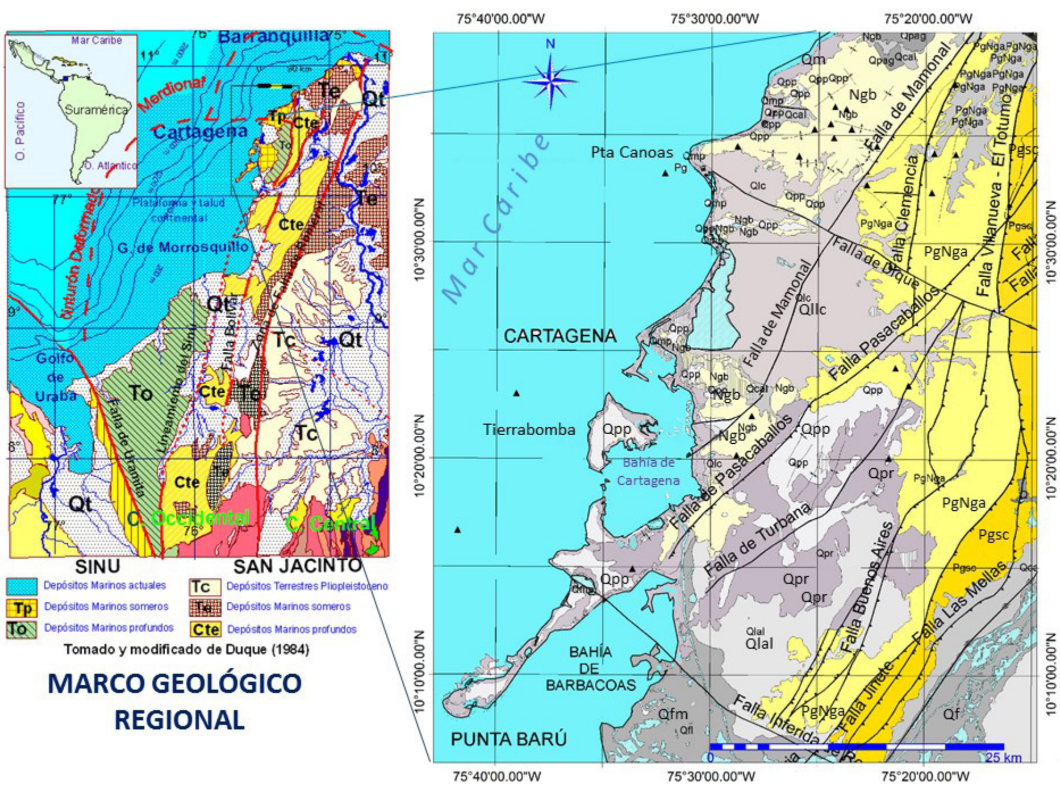

Figure 11. Structural and lithological geological framework of the surroundings of the bay of Cartagena. Note the faulting and alignment of the structures in SW - NE direction. Pgsc = F. San Cayetano, PgNga = F. Arjona, Ngb = F. Bayunca, Qpp = F. Popa, Qpr = F. Rotinet, Qfl = Fluvial deposits, Qmp = Littoral D., Qcal = Colluvioaluvial deposits, Qlc = D. Coastal, Qlal = Subactual alluvial deposits, Qllc = Subactual alluvial marine deposits Qfm = Fluvial-marine deltaicic deposits. Taken and modified from Duque (1984), Reyes *et al.*, (2001), Guzmán *et al.,* (1998), Reyes & Zapata (1996). Note the location of "volcanoes" in black triangles.

This tectonic dynamic has allowed through geological time from the Paleocene to the present time, the conformation of two stripes of folded rocks arranged in SW - NE direction, called from east to west, San Jacinto folded belt and Sinú folded belt (Duque, 1979 & 1984). Mud volcanoes are evident in these rocky strips, particularly in the Sinú belt, where manifestations of mud and gas emanation are abundant, both in continental zones and underwater zones, see figures 8 and 10.

The Sinú Belt, where Cartagena is located, is formed by a series of narrow NNE anticline folds that limit wide syncline gears, particularly in the Córdoba-Antioquia region; while in the region of

Galerazamba - Cartagena - Canal del Dique, the territory is characterized by the conformation of wide and curved synclines, minted and limited by narrow anticlines locally associated with inverse fractured faults with course component, in whose traces are the mud volcanoes (Carvajal 2017).

The general structural disposition of these folds in NNE-SSW and NEE-SWW direction, is interrupted and locally affected by sinistral heading faults (horizontal left displacement) of predominant NWW -SEE direction, among which El Dique and Rocha faults stand out in Cartagena, which define blocks and the conformation of isolated distension basins (Carvajal 2017- Vernette *et al.,* 1992).

The rocks that constitute the Sinú Belt in general correspond to a sequence of approximately 5000 m of deep marine sediments (pelagites hemipelagites, turbidites) of Upper Miocene-Pliocene age, folded and failed by diapirism and convergence of plates. On these rocks descend approximately 4000 m of claystones, sandstones and conglomerates of continental marine origin, being particularly notorious the occurrence of limestones of reef origin in the structural heights generated by the prevailing tectonics in the region (Duque 1979).

The quaternary deposits present in the region are clays and sands and classical and bioclastic gravel of alluvial and coastal marine origin. It is also very notorious, the presence of shallow and fringing reef bodies, locally colonized by mangrove, which is evidence of previous conditions conducive to the colonization of corals in the bay, which as previously indicated is favored by the expulsion of fluids and gases weak areas.

Although the characteristics of the materials expelled by the mouths and Pockmarks evidenced in this work are not known until now, they are considered to be very similar to those found in the materials expelled by the mud volcanoes around Cartagena. According to Carvajal & Mendivelso (2017), in the volcanoes present in the region, the expulsion of clays, the kaolinite and illite type predominates; and in the gases, the methane with lower quantities of CO2 predominats.

The materials expelled during the eruptions of the mud volcanoes have included blocks and disseminated fragments of rocks (claystones, sandstones and limestones) that are dragged from approximate depths between 1 and 4 km. In this sense, it is important to know the composition of the materials associated with the mouths and pockmarks found in the south of the Bay of Cartagena, because the diapiric activity evidenced may be associated at least in part with the programming of the materials brought by the Canal del Dique on the fine sediments of coastal lagoon marine origin.

In the Cartagena region, from the older to the newer, rocks upwelled from the Arjona (PgNga), Bayunca (Ngb) and Rotinet (Qpr) formations, and locally Popa (Qpp), partially covered by current and subactual fluvial eolian and colluvial sediments of marine origin, see Figure 11. The Arjona formation, present in the eastern part of Cartagena, is made up of an alternating sequence of sandy claystones, feldspathic sandstones and mudstone of turbiditic origin; (Reyes *et al.,* 2001, Guzmán *et al.,* 2004).

Discordantly or in failed contact, on the previous rocks, with a wide distribution between the urban zone of Cartagena and the limits with Turbaco, there is a sequence of transitional marine environment of mudstones in thin layers of dark gray color, with plaster disseminated and in thin layers, with gray sand levels of fine grain towards the middle part, arranged in thin layers interbedded with siltstones and gray-brown to brown mudstones towards the upper part, belonging to the Bayunca formation of Upper Miocene age (Carvajal, 2017) .

To the North of Cartagena de Indias, and to the SE of Turbaco is a sequence of gravels and sands of fluvial origin and locally with deltaic influence of the Rotinet formation, which were accumulated by the Magdalena River when it flowed into the Cartagena region. They correspond to an unconsolidated sequence of layers and thick lenses of gravels with variable size (1-3 cm) of quartz, black chert, volcanic rocks, neises and siltstones, with local intercalations of quartz sandstones of fine to medium grain, deleznables (Barrera, 2001, Reyes *et al.,* 2001, Guzmán *et al.,* 2004).

The structural highs, particularly are occupied by rocks of reef origin of the La Popa formation of Pleistocene - Holocene age. This formation is made up of two rocky assemblages constituted by banks of thin grained sandstone conglomerates and reef limestones (locally with abundant bioclasts of coral, algae and mollusks), separated towards the middle by an alternation of thin layers of siltstones, gray claystones clear and fine-grained sandstones to very fine, calcareous (Guzmán *et al.,* 2004; Carvajal, 2016).

The distribution and structural arrangement of the outcropping rocks in the Cartagena region indicates differential uplifts and subsidence of the order of several cm / year through the recent Quaternary. This situation has been recently evidenced, both with the monitoring of Gps-GNSS stations in the island sector of Manzanillo, and the analysis of the geomorphological evolution in the bay of Cartagena (Andrade *et al.,* 2017).

The argilogenetic tectonic dynamics associated with sludge diapirism, in addition to the manifestations of sludge volcanism, is manifested with terrain deformation processes. According to Carvajal 2016 & Carvajal 2017), among the morphostructural geoforms present in the surroundings of the bay of Cartagena, which owe their origin largely to the occurrence of this tectonic, the semi-paleoatoll associated with the hill of Albornoz, the Turbaco - Turbana arrecifal platform, the hill of La Popa itself, and the elevated abrasion platforms and marine terraces of 20 and 3 m in height stand out respectively of the island of Tierrabomba (Figure 12).

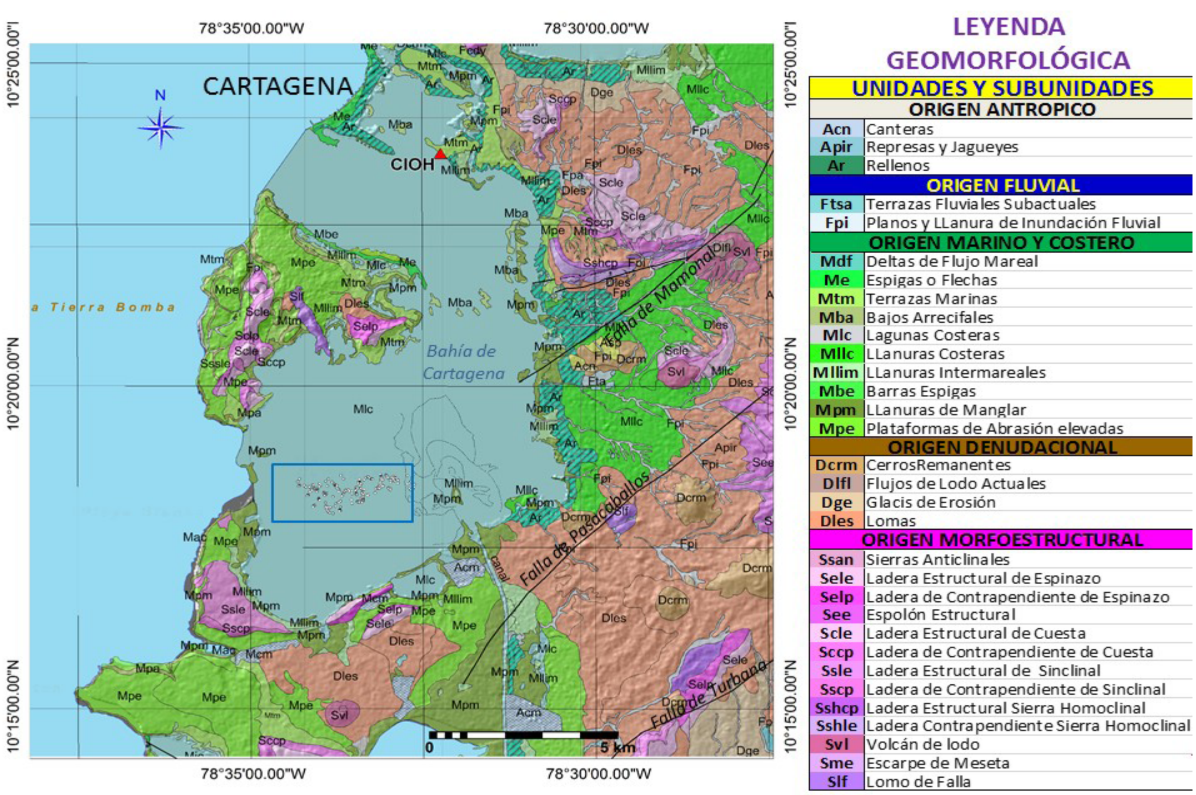

Figura 12. Geomorphological map of the bay of Cartagena surroundings. Note the blue box with the location of the submarine manifestations of mudholes and pockmarks and the plume of sediments brought to the bay through the Canal del Dique. Taken and modified by Carvajal (2017) & Andrade *et al.,* (2017).

The research made by Martínez *et al.,* (2010), based on analysis and paleontological studies of macrofossils and microfossils (mollusks, ostracods, corals and foraminifera) obtained at the low level of the marine terrace of Tierrabomba, determine surveys in the sector of the order 3.11 mm / year. Meanwhile, the first data obtained with GPS - GNSS in the island of Manzanillo located in the NE, on the other side of the Cartagena Bay, shows evidence of decreases of the order of -2.2 mm / year, which has been preliminarily confirmed with the first results. obtained with interferometry.

These results confirm the diapiric activity in the region manifested with differential movements of ascent and descent in the region of the bay of Cartagena. Such a situation is preliminarily associated with the tilting and sinking towards the NE of the sinclinal trough limited by SW - NE directional faults, which forms the southern sector of the Cartagena Bay, see figure 11.

The area around Cartagena is active in terms of the delivery of natural gas in the northern zone and in the southern areas, as is also documented in Vernette *et al.,* (2012). The presence of these marks of gas, diapirs and the loss of coastline in the interior of the bay supported by DGPS data, would indicate that there is subsidence in the sector.

Conclusions

In the south of the Bay (from the Dique canal to Varadero), the multibeam echo sounder data show manifestations of active mud diapirism in the area, in the forms of:

- Very steep cone-shaped elevations that rise from a muddy bottom.
- Presence of pockmarks or depressions of round and circular shapes as craters.
- Circular marks on these muddy bottoms that appear as a result of the escape of fluids and gas.

The spatial arrangement and its local conformation in curved forms are indicative of an in-depth structural control of the reported diapiric manifestations. It is also evident its location on the western flank of a sunken sinclinal structure of direction SW - NE, affected by fracture fault associated with the possible prolongation of the Mamonal fault towards the SW.

The abundant presence of shallows and reef bodies, both current and ancient in the bay of Cartagena, are associated at least in part to the presence of the emanations of fluids and gases that favor their growth.

Recent measurements with sub-millimeter error positioning systems and satellite image processing (interferometry) work, preliminarily show how the Cartagena area is differentially subsidizing, which explains the greater trends of relative sea level rise in the bay of Cartagena.

Current measurements indicate that the subsidence in the sector would be around 2 mm per year.

Recommendations

It is important in later phases of the investigation, to carry out the physical-chemical characterization of the materials emanated by the mouths (muds and gases) in order to define their deep or shallow origin. It is also essential to investigate in depth the entire bay of Cartagena in order to define the geological structures of the subsoil using geophysical research (3D seismic, gravimetry and magnetometry).

It is advisable to establish a monitoring network of permanent and field stations bordering the Bay of Cartagena in order to establish the dynamics of subsidence and local surveys of the Bay.

The evidences obtained in this work of in depth overpressedmaterials, it is advisable to avoid any anthropic intervention in the region, in order to avoid the deconfinement of these structures and to generate dangerous movements of material, at least while the origin of diapiric manifestations are known with greater detail.

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