Abstract
"Gas chimneys" and "gas plumes", poor seismic data zones above gas-bearing structures, are quite common and characteristic in hydrocarbon productive basins. Scattering of seismic energy causes poor data zones in the cap rock penetrated by leaked gas above a gas reservoir. This well-known effect is obviously relevant to hydrocarbon exploration but it is not the only leakage expression that can be observed on seismic. In fact, according to the active leakage process, a wide range of features can be generated (Eggland R., 1998). When gas diffusion through pore space or along fault planes and fractures is taking place, columnar bodies characterized by poor seismic response represent the effect on seismic data. These bodies are best named "gas plumes" or "gas clouds". When hydraulic fracturing is the main leakage process a variety of structures could develop after the deformation of the cap-rocks above overpressured reservoirs. The most impressive ones are collapse structures resembling volcanic calderas. Hydraulic fracturing and faulting could also trigger the intrusion of gas-saturated clay through the overburden sediments and sometimes mud volcanoes could be developed. Hydraulic fracturing usually occurs when overpressure in gas-bearing sediments exceeds the mechanical strength of the sealing rocks, a situation commonly observed in fast growing fluvial deltas.

For practical reasons, we reserve the name of "gas chimneys" to the observed volume of sediments that are not only characterized by the presence of diffuse gas but also show evidences of deformation related to hydraulic fracturing. The distinction has an obvious meaning for hydrocarbon exploration as the study of gas leakage features can provide information about hydrocarbon generation and regional occurrence, prediction in subsurface of overpressure conditions and seal integrity of traps.

Soon after the central part of the Nile Delta slope was covered by high quality 3D seismic, it was realized that leakage-related structures in the region were more than objects of mere curiosity. In fact, the two biggest gas fields (Ha'py and Scarab) over the twenty-one discovered within the Plio-Pleistocene succession of the Delta are associated to huge gas chimneys. Also the main charging-area feeding the long string of gas fields discovered in the Abu Madi Paleovalley is located at a region of the Delta slope highly populated by impressive gas chimneys. At present, a total of fifteen "gas chimneys" associated with pseudo-volcanic structures are documented through the IEOC seismic database. These structures include caldera-like depressions, up to 3-4 km in diameter (Fig. 1).

Multiple episodic activity of some gas chimneys is strongly supported by seismic data and seabed morphological interpretation. The process creating the main part of the Nile Delta gas chimneys is very recent as exhibited by the existence of deep morphological depressions at seabed surface, which are still not yet filled by the Delta sedimentary influx. Anyway, there are also other few cases of collapse structures that are buried by the last hundreds meters of Quaternary deposits.
In the caldera-like depressions observed on the seabed, a central uplift is generally present. The rims of these depressions are affected by extensional faults with a circular trace in the map view (Fig. 2). The downthrown of these faults is towards the depression center. A rollover component affecting the blocks bounded by these faults is evident in seismic section. Shallow gas trapped along the small structural closures associated to these rollover culminations has been detected by shallow seismic. Lateral side-scan images of two surveyed depressions are showing that the central zone is very irregular and highly reflective due to a rough seabed while in comparison the peripheral higher seabed is apparently flat and undisturbed. Gravity coring shows the most recent sediment of the seabed inside the craters is made of clay with intercalations of clay lumps and claystone while outside it is made of soft silty clays.

All the observed features are pointing to a collapse origin of the construction of the depression and the related rim faults. Volume-loss deformation probably took place at the origin of the observed collapse structures. It could occur through two processes that can act together at the same time:

- Dispersal of some amount of sediments from the gas chimney vent into the sea soon after the gas-burst originating the gas chimney had took place.
- Porosity-loss of the sediments into the gas chimney vent soon after the gas-burst. It is probably related to the mixing of differently sorted sediments (documented porosity values in the Plio-Pleistocene sands are commonly within the range of 30%).

As regard the origin of the central uplift no conclusive hypothesis can be made. They could be mud volcanoes related to gas-leakage or uplift related to mud diapirism. In one gas chimney, directly drilled in its first 800-m, a high background gas up to 40% has been tested. So, upward movement of buoyant gas-saturated mud could be really active inside the vent of the explored gas chimney.

Vertical migration of gas into the Plio-Pleistocene reservoirs from the pre-Messinian interval through gas chimneys related ring faults and fractures is evident in many cases from 3D seismic. As an example, the southern boundary of the gas field, present within the Pleistocene interval as shown by Fig. 3, is actually constituted by the ring fault of a gas chimney that shows also evidence of multiple activity.

The Akhen gas chimney offers another outstanding case of vertical migration from a Serravallian reservoir to a Pliocene one. Seismic and drilling have proved that the Pliocene sand reservoir of the Ha'py field forms a continuous body from the area of the field to the area of the gas chimney originated from the Akhen field (Serravallian reservoir). In addition, geochemical analysis point to a thermogenic origin of the gas trapped into the Pliocene sand of Ha'py (presence of hydrocarbons other than methane). This demonstrates that Ha'py does not belong to the family of the nearby gas fields filled by Pliocene biogenic gas. Of course it is difficult to imagine that a single burst of gas could have filled alone the Pliocene reservoir of the Ha'py field. A continuous slow-flow leakage was probably established along the gas chimney after hydraulic fracturing of the Tortonian and Pliocene sequence overlying the Akhen field.

Gas chimney distribution inside the Nile Delta basin is not casual. They have been observed only in the present slope region. The largest ones are just located on the culmination area of the NE-SW trending regional rollover anticline associated to the downthrown block of the Rosetta Fault. The gas-chimneys present in the central area of the slope are clearly originated from the culmination of pre-Messinian structures as demonstrated by high resolution 3D seismic. Geochemical modeling proved that hydrocarbon generation in the Nile Delta pre-Messinian source rocks (Qantara Fm and Tineh Fm) peaked during the Pleistocene, shortly after the maximum burial conditions were reached in the area of the present slope.

As clearly known from wells drilled by IEOC, overpressure conditions are found in the pre-Messinian sequence of the Nile Delta offshore. In the slope region very high overpressure is present below the basal Pliocene in the Rosetta Fm. (Late Messinian) and Sidi Salim Fm.
(Tortonian-Serravallian). At Late Oligocene sediments depth, the pore pressure approach the hydraulic fracture gradient (Nashaat, 1998) and hydrocarbon expulsion is favored. Migration toward the upper sequence, through breaking of the sealing layers has probably been active during very recent time in the Nile Delta. So there is no surprise in finding gas chimney with its associated pseudo-volcanic structures in the region of the Nile Delta where they were actually seen, i.e. an area lacking a thick evaporitic seal, characterized below the basal Messinian unconformity by overpressured unconsolidated sediments and gas-prone source rocks undergoing maturation and hydrocarbon expulsion.

Conclusions
In addition to direct hydrocarbon indicators (bright spots and flat spots), gas chimneys presence has been used in defining the most promising areas inside the IEOC-operated exploratory blocks. This approach has been mainly tested in the exploration of the Plio-Pleistocene interval. Areas populated by gas chimneys are obviously indicating and securing the presence of an efficient hydrocarbon generating system. Geological and seismic evidences of hydraulic fracturing at depth represented by pseudo-volcanic structures and mud diapirism pose the problem of seal integrity in over-pressurized intervals. Therefore careful prediction of pressure regimes is not only necessary to perform safe drilling operations but also in order to reduce exploratory risk in the many basins characterized by overpressure conditions.

References


Nashaat M. (1998) - Abnormally high Formation pressure and seal impacts on hydrocarbon accumulations in the Nile Delta and North Sinai basins, Egypt —AAPG Memoir 70, p.161-180

Fig. 1- Caldera-like depressions are observed on the seabed in correspondence of some gas chimneys. A central uplift resembling a mud-volcano is generally present.
Fig. 2 - Side scan sonar image. Rollover faults with a circular trace in map view affect the rim of gas chimney depressions and the seabed morphology.

Fig. 3 - The "A" gas chimney shows evidence of recurrent activity. A gas field into the Pliocene is strictly associated to this gas chimney.