Why passive seismic in the Gulf of Mexico will benefit the oil industry, regulators and a concerned public

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Summary

This paper explores the potential role of continuous real-time seismic monitoring in enhancing future oil and gas developments in the US Gulf of Mexico. Passive seismic technology is already deployed in numerous shale gas projects onshore. It has proved a cost effective means of tracking the hydraulic fracturing process (fracing) used to produce the tight gas typical of shale plays. Not only does this accurate mapping of the subsurface help to maximize production from the reservoirs, it also provides a new level of environmental and safety monitoring able to meet regulatory and local community concerns.

In the post-Macondo era there is a clear imperative for the oil industry active in the Gulf of Mexico to provide transparency about the safety and sustainability of its drilling and production operations. This is destined to become more challenging as oil companies continue to push the technology boundaries in order to explore the big prizes waiting to be found in complex geological structures in the ultra-deep water of the Gulf of Mexico, for example in the Lower Tertiary/Paleogene Trend where some massive discoveries have already been made. With billions of investment dollars at stake to exploit these new opportunities, passive seismic monitoring could offer a valuable, real-time reservoir management decision-making tool. Just as important, the monitoring information can provide an early warning system for any safety or environmental hazard, and this applies not only to technologically challenging frontier areas, but effectively to all oil and gas operations being undertaken in the Gulf of Mexico.

Background: the credibility gap

‘We have a responsibility to unlock and deliver the new supplies of energy in a safe, secure, and environmentally responsible way .... We must focus relentlessly on our operational integrity and best practices — to protect our employees and the communities where we operate.’

Rex W. Tillerson, chairman and CEO, ExxonMobil at the 20th World Petroleum Congress, Doha, Qatar.
The oil industry is currently facing some key challenges which extend way beyond the confines of the Gulf of Mexico. They are not new, but have been brought into fresh focus as a result of the fatal explosion in April 2010 on board the *Deepwater Horizon* during drilling on the BP Macondo discovery. The incident not only took the lives of 11 rig workers but caused the worst oil spill in the history of offshore exploration and production worldwide.

The immediate US government reaction to the Macondo disaster was to suspend deep water exploration and issuing of new offshore drilling licenses pending a review. We do not need to be concerned here with all the details of the immediate fall-out, i.e., the length of the moratorium on offshore activities, the measures taken to mitigate the environmental/economic impact on shoreline states (largely made the responsibility of BP at a cost of billions of dollars), continuing litigation, etc.

More important is that the incident, widely reported worldwide, has created a depth of mistrust between the industry on the one hand and governments and local communities on the other. Oil company leaders have long fought an uphill battle to convince the public at large that oil prices are not the subject of profiteering. From a PR point of view, this is challenging when, for example in 2011, ExxonMobil reported profits of $41 billion which, according to *The Wall Street Journal*, were due to ‘high oil prices’. This was the same year that US consumers faced the highest average annual oil price since 1864.

In other words there has been a propensity to be suspicious of Big Oil. One example would be the well documented difficulty oil companies have experienced in the last decade in recruiting new talent because of the industry’s perceived ‘boom and bust mentality’ to employment and its attitude towards the environment. In the post-Macondo world, this suspicion of industry activities has intensified, which puts a huge onus on oil and gas companies. They have to convince a skeptical worldwide audience that current technology is reliable, safe and environmentally sensitive. This has been recognized by the International Association of Geophysical Contractors (IAGC), which has launched ‘Geophysics Rocks’, a web site designed to promote a positive image of the contribution of geoscience to the community aimed particularly at the younger generation.

As it happens the timing for the industry to wage a campaign to win public support is less than ideal. The problem is that oil and gas operations are entering a new phase in which the era of easy-to-find oil is over. The oil of the future to serve the world’s increasing energy needs are expected to come from challenging offshore exploration settings such as deepwater, the complex geological pre-salt plays of the Gulf of Mexico, offshore Brazil and West Africa, and the arctic region. Onshore, unconventional hydrocarbons such as shale sands, tight gas, and
carbonates are emerging as important new resources. All these hard-to-find and develop hydrocarbons have one thing in common: they all require the application of innovative technology, and that inevitably implies a heightened level of economic and environmental risk.

Ironically, until the Macondo disaster, the new technologies already being deployed to tap the deepwater resources had gone largely unnoticed by the public at large. That has of course now changed so that the conundrum is that as much as the world community wants to see these resources tapped, it has to be persuaded that it is safe to do so. Public perception of the industry’s track record in this regard – rightly or wrongly – is currently unfavorable, so there is a mountain to climb.

**Gulf of opportunity**

In the light of the Macondo disaster, it is clear that oil and gas companies operating in the Gulf of Mexico can in future expect extremely close scrutiny by regulators, environmentalists and those communities on the Gulf coast vulnerable to any offshore mishap. At the same time, the Gulf of Mexico is one of the world’s most mature and densely developed oil and gas provinces which continues to provide an important strategic resource for the United States. Over the 70 years of E&P operations in the Gulf, more than 40,000 wells have been drilled, and infrastructure inventory includes at least 4000 production platforms and thousands of miles of subsea pipelines and other installations. According to the US Energy Information Industry, the Gulf of Mexico’s offshore oil production accounts for 29% of total US crude oil production and 12% of natural gas production.

The Gulf of Mexico turns out to be the gift that keeps on giving. In the last two decades or so the major oil companies have been gradually pushing the technology frontiers in order to exploit the substantial oil and gas to be found at water depths now approaching 10,000 ft and deeper Lower Tertiary geological trend. In the 1990s Shell’s Mars and Auger field developments were in over 2500 ft of water, in 2012 the company’s Perdido installation has started operating in 8000 ft water depth and is the first commercial production from the Lower Tertiary of the Gulf of Mexico. BP began acquiring deepwater blocks in the 1980s, and today operates eight deepwater projects – Thunder Horse, Mad Dog, Atlantis, Holstein, Horn Mountain, Marlin, Na Kika plus the Mardi Gras pipeline. Daily production from these facilities and other deepwater projects in which it has an interest amounts to 250,000 barrels per day of oil.

Focus on Lower Tertiary E&P activity includes the emergence of the Paleogene trend. Early exploration in this deepwater, remote and geologically deep trend indicates it may contain more oil in place than has been discovered in all other Gulf of Mexico exploration and
production activities to date. Some of the prospects discovered in the Lower Tertiary include Trident, Great White, Cascade, Chinook, St Malo, Tobago, Silvertip, Tiger, Jack, Stones, Gotcha and Kaskida. Chevron operates six, BHP and BP operate two each and Shell and Total operate one each.

**Technology requirements**

The significance of the Paleogene trend is that discoveries commonly consist of 'tight' reservoir conditions. Liu et al. (SPE 115669, 2008) in ‘Water-flooding Incremental Oil Recovery Study in Middle Miocene to Paleocene Reservoirs, Deep-Water Gulf of Mexico’ provide as good a description as any of the geological setting and some of the recovery issues for reservoir production technology. ‘These middle Miocene to Paleocene reservoirs are characterized by high pressure and temperature, and low natural reservoir drive energy (due to compaction and cementation). In contrast, previous production experience in younger, Pleistocene through upper Miocene, reservoirs exhibit high primary oil recovery due to significant rock compressibility and aquifer influx. The requirement for water injection to supplement reservoir drive energy, improve oil rate, and maintain oil production rates is of primary consideration in development planning for the new, ultra-deep Gulf of Mexico discoveries. Unfortunately, there is limited production experience to use as guidance.’

The good news is that in the last five years plenty of experience has been accumulated onshore because the geological conditions are not dissimilar to those currently being developed in tight gas and related unconventional plays – the shale plays such as Marcellus, Bakken, Barnett, Haynesville, Eagle Ford, etc. The development of shale gas has been an extraordinary success story providing a major turnaround in US natural gas prospects from a net deficit position to potential exporter. This outcome has been made possible by improved technology, in particular, horizontal drilling and, more controversially, fracing.

There is little doubt that one of the improved oil recovery (IOR) methods likely to be considered by oil operators for Lower Tertiary/Paleocene reservoirs in the Gulf of Mexico will be fracing. In December 2010 ‘IOR for Deepwater Gulf of Mexico’ a study published by the Research Partnership to Secure Energy for America (RPSEA), authored by Joseph Lach of Houston-based Knowledge Reservoir, suggested that the tight reservoirs of the Walker Ridge and Keithley Canyon with an average permeability of 15 millidarcy (md) could hold about 85% of the estimated 25 billion barrels original oil in place (OOIP) for the whole Paleogene (Wilcox) trend in the Gulf of Mexico. In reviewing technologies likely to be used to optimize production, fracing was listed as a candidate, and the report estimated a 4% recovery factor which would translate into an additional billion dollars. The report recommends that ‘any IOR process considered for application offshore should already have a successful track record onshore’.
Fracing today is usually associated with the production of oil and gas from shale sands. However, petroleum engineers since the late 1940s have used the process to increasing well production from reservoirs located all around the world. It involves injecting large volumes of sand/proppants and water to create fractures in rocks and rock formations so that the fissures enable more oil and gas to flow out of the formation into the well bore. In the case of shale reservoirs onshore, the fracing is carried out in horizontal wells drilled thousands of feet below which release hydrocarbons into a parallel horizontal borehole.

In the shale play context, fracing has gained some notoriety (justly or not) because of environmental fears mainly around the possible contamination of aquifers (for human water supply) caused by leakage of chemicals through cracks created by the process. In addition there has been alarm expressed about earth tremors and potential damage to property. Fracing so far has been permitted in the US without any significant issue, but in many other countries around the world there is a moratorium in place pending further research. In the UK, a government-commissioned review of three seismic events caused by a fracing operations in the northeast of England in 2011 advised that the operator Cuadrilla Resources could resume operations on condition of following new guidelines (see UK Department of Energy and Climate Change website for report).

**Tracking the fracing**

One approach to assuring regulatory authorities and local communities that fracing operations are being carried out responsibly is to monitor what’s happening in the subsurface to map where the cracks are moving. This is also vital information for the operator who needs to track the impact of the fracing in order to plan the next step in the gas extraction process. Up until recently the only option has been to drill a separate monitoring well to record data from the well which is being stimulated. There are a number of limitations to this process. Such wells are invasive and expensive, costing some $2–4 million each, and there are temperature restrictions on the tools that can be placed in a well. Equally problematic is that the recording instruments can only map a relatively small area around the monitoring well. In other words, reservoir engineers do not have the full picture of where the fractures are occurring, and this hampers their ability to optimize completion and production strategies for the whole reservoir.

A better solution which is gaining wide adoption in US shale plays comes from MicroSeismic. The company has been pioneering a non-invasive solution for monitoring fracing, based on a large array of geophones recording microseismic events from, or near, the surface, in real-time.
As a result shale gas operators in North America are seeing more efficient and increased production, less drilling and a safer environment.

The key to the MicroSeismic approach is that it offers an alternative to using downhole monitoring tools for frac ing jobs. Developed from techniques used for detection of earthquakes, MSI's FracStar and BuriedArray services employ a series of passive recording devices (geophones) designed to record seismic events in the subsurface caused by the drilling and production operations: unlike conventional seismic acquisition, no surface source such as dynamite or vibrators is needed. Today the company is proving that multiple wells and simultaneous frac operations can be monitored in real-time from one installation over as much as 1300 km². MSI’s FracStar array design uses a hub and spoke pattern of geophones laid on the surface. The BuriedArray service uses hundreds or thousands of geophones placed at, or near, the surface and is capable of long-term, field-wide monitoring. Both methods, in effect create a large parabolic dish microphone that can detect multiple simultaneous microseismic events over an entire field, eliminating the need for monitoring wells.

MSI's Passive Seismic Emission Tomography (PSET) mapping and analysis technology links individual geophones together and serves as a focusing algorithm so that the location of microseismic events can be identified across a field with a high degree of accuracy. In the process it overcomes the issue of signal attenuation by the overburden which makes conventional seismological earthquake location techniques ineffective. With PSET it is possible to use the dense array of geophones to 'beam steer' or sum the output of the entire array to detect and locate the microseismic activity deep below the earth’s surface.

Currently the company offers both a temporary or life-of-field proprietary monitoring option. FracStar uses a removable surface-located array of geophones to monitor long laterals and pad drilling over a large area. The array's large 2D aperture and PSET-based microseismic monitoring images how the stimulation-induced fractures interact with a reservoir's natural fracture networks. MSI’s BuriedArray system, the more common option for oil companies, deploys an array of geophones permanently installed and buried at a depth of between 60–300 m for those operators who need to monitor multiple wells over a long period of time for strategic planning and development purposes.

Around 2009 Denver-based independent oil and gas company Whiting Petroleum was one of the early adopters of MicroSeismic’s hydraulic fracture monitoring system Whiting’s Sanish Field is MicroSeismic’s largest project to date. Some 298 permanent geophones have been installed across the field and enabled the company to gather microseismic data on every fracture stimulation (stage) it had pumped in the field. In its 2010 Annual Report Whiting concluded that the information had been ‘useful in determining the effectiveness of our
hydraulic stimulations along with assisting in developing the proper spacing of wellbores in the field’. In addition, James J. Volker, chairman and CEO of Whiting Petroleum, has stated that ‘MicroSeismic’s fracture monitoring process is one of the key technologies Whiting is using to optimize hydraulic fracturing’.

Adoption of the passive seismic monitoring technology introduced by MicroSeismic and of similar techniques which are likely to be developed by other service companies is accelerating because oil companies can expect two benefits from the investment: i) cost-effective mapping of fracturing which significantly improves optimal production and ultimately the bottom line and ii) an early warning system of any potential threat to human safety or the environment. As the technology matures, continuous real-time seismic monitoring will allow operators to see deeper into their reservoirs; be more sensitive to weaker microseismic events; measure pressure and stress changes; detect physical property changes in the reservoir as fluids move and are replaced; optimize depletion plans; find bypassed zones; and see changes in the overburden and under-burden. Meantime a number of regulators around the world are known to be considering the installation of passive monitoring as part of any future permitting of fracturing operations.

**Offshore translation**

The passive monitoring technique being developed by MicroSeismic is still in its infancy, but there is clearly scope for the development of a number of important offshore applications – for production, safety and environmental safety reasons. It is arguable that had some form of real-time monitoring been in place at the Macondo drilling site, there might have been some early indication of a major problem. US regulators are certainly beginning to consider the requirement of some form of monitoring for deepwater offshore operations. The HR 3534 ‘Consolidated Land, Energy, and Aquatic Resources Act of 2010’, passed by the House of Representatives in July 2012, includes in section 727 (Offshore Sensing and Monitoring Systems) the apparent requirement for a real-time monitoring system for operations in water depths greater than 500 ft capable of service for at least 25 years. It would be designed to provide alerts in the event of anomalous data, docking bases to accommodate spatial sensors for remote inspection and monitoring, and secure internet access.

To date the monitoring of oilfield reservoirs with the use of seismic recording equipment on the seabed has been limited, and focused entirely on providing reservoir management data to improve production. In the 1990s the concept of 3D seismic to image the subsurface to find prospective hydrocarbon locations ahead of drilling was extended to reservoir monitoring by the application of time-lapse 3D or 4D seismic. During production repeat seismic surveys over the same location could identify changes in the reservoir, e.g., movement of fluids, which could
help petroleum engineers in the planning of depletion strategies, for example, drilling of additional wells to optimize production.

Most time-lapse seismic to date has been achieved either by the use of towed streamers replicating the base survey by further monitoring surveys or by the use of retrievable cable or node recorders placed temporarily on the seabed. At least 80% of all 4D seismic in the last decade has been carried out with towed streamers mainly on the ground of cost. The disadvantage of towed streamers is that coverage of the target reservoir near production installation and other obstructions is limited. There is also an issue of accurately replicating previous surveys given the vagaries of marine conditions and constant advances in technology aboard seismic vessels. The other crucial issue, at least until recently, has been the limited resolution of the seismic imaging achievable by a towed streamer (dependent on hydrophone recorders) compared with ocean bottom survey (OBS) techniques that can make use of hydrophones and geophones (used in land seismic operations). Major contractors such as Petroleum Geo-Services, WesternGeco and CGGVeritas are now introducing improved broadband solutions for towed streamer surveys which greatly improve imaging resolution. As a result, there is unlikely to be a major shift toward the more expensive but better data that OBS can provide.

**Permanent solution**

For 4D seismic reservoir monitoring OBS is expected to remain a niche market commissioned by operators needing improved imaging that towed streamers cannot provide, especially around offshore facilities. But that is not the end of the story. Sensor technologies downhole, in sub-sea wellheads, collection stations, pipelines, and on surface facilities are being utilized more frequently and are commonly referred to as the ‘digital oilfield’. A number of major oil company operators have now begun to consider more seriously the value of permanent seismic reservoir monitoring systems for improved and cost effective management of production. The first so-called Life of Field Seismic (LoFS) system was installed by BP on the Norwegian offshore Valhall field nearly a decade ago in 2003, and is generally acknowledged to have been an extremely successful innovation. In essence there is a network of seabed recording cables buried across the reservoir, and every so often a vessel shoots seismic over the cable network with the results collected on board the platform. The major benefit is the quality of the data and the knowledge that the positioning of the records is precisely the same for each survey. To date there have been 13 LoFS monitor surveys over the Valhall field. BP has also implemented similar systems on its Clair field in the UK North Sea and offshore Azerbaijan. Recently ConocoPhillips on Ekofisk, offshore Norway, and Petrobras on Jubarte, offshore Brazil, have begun LoFS operations. The slow adoption of what appears to be a valid investment is generally put down
to the upfront cost of permanent systems, concern over the durability of the equipment on the seabed, and worry about the possible emergence of a better technology option.

Post-Macondo there could be a shift in sentiment regarding permanent monitoring systems in which the potential real-time 24/7 monitoring provided by passive seismic might play a significant role. Fracing is now being discussed as one of the techniques to improve oil recovery from deepwater Lower Tertiary/Paleogene geological settings in the Gulf of Mexico which means that oil operators will be under pressure or indeed subject to regulation to show that their operations meet new safety and environmental requirements. One logical step will be to install the passive seismic real-time recording systems already proven onshore. This meets both the companies’ need for improved oil recovery through the tracking of fracing operations and also compliance with regulatory requirements (upsets at or near the borehole, pipeline or other subsea equipment could potentially be mitigated before they developed into serious incidents). It also provides a valuable public statement of oil company concern for the environment.

In principle there is no reason why passive seismic technology will not be successful offshore, and MicroSeismic is actively working with operators on such applications. The BuriedArray system would have an analogue offshore using autonomous ocean bottom nodes that are deployed and retrieved via remotely operated vehicles (ROVs). Such systems cannot be supported by current communications and power supply technology so real-time applications would not be available. The FracStar system analogue offshore would consist of seismic cables laid out radially or in a fishbone or similar array pattern from a wellhead or other sub-sea installation where power and communications are available. The cabled array of this system could extend across entire fields or areas with infrastructure monitoring needs. This is exactly what current LoFS systems look like, and the seismic recording capability in the cables are suitable for recording passive seismic in real-time.

MicroSeismic has already been working with operators of LoFS to see how the data can be recorded and transmitted. The idea is that the passive seismic data available on a 24/7 basis would be an invaluable and cost effective addition to the digital oilfield. Operators active in the drilling of exploration and appraisal wells in the deepwater Lower Tertiary/Paleogene in the Gulf of Mexico have been planning and testing the use of fracing to complete wells and achieve production rates needed to sustain the tremendous exploration and development costs. It is a scenario which calls for the kind of passive seismic monitoring offered by MicroSeismic.

Other stakeholders of continuous, real-time seismic monitoring could include geoscience and bioscience academic and regulatory communities. The lack of local recording capability for natural seismicity in the Gulf of Mexico basin is acknowledged by the US Geological Survey
(USGS) and is becoming an increasing priority after serendipitous capture of earthquake activity in 2005 during industry seismic operations. Additionally the biosciences community has little to no data on deepwater cetacean and other important biological activity due to the lack of monitoring capability and installations. Cetacean activity is an ongoing focus for industry operations, and particularly seismic operations, and improved understanding of cetacean behavior will help the industry avoid impacts as well as assist research.

In the future, therefore, we could see the installation of permanent oil field monitoring systems (POM) as advocated by a leading seismic innovator Bjarte Fagerås of the Norwegian Octio Group (First Break, June 2012, pp. 81–84). Such systems call for a digital network deployed at the seabed incorporating the necessary sensors to measure all parameters of interest which are sufficiently configurable/scalable to add new functionalities as they become available. The extra cost of implementing additional sensors to monitor the overburden, the seabed, and the water column are minimal compared to the overall cost of installing a basic system for permanent reservoir monitoring (PRM).

Smaller semi-permanent oilfield monitoring systems can, according to Fagerås, be deployed before drilling for dense four component (hydrophone and geophone) acquisition to better image the overburden for drilling hazards. The system can continue to monitor during the drilling operation both for improved drillbit positioning as well as a surveillance system in case an unwanted incident happens during drilling. Finally the system can monitor either the production flow or the injection flow depending on the type of well. The size of the system can be extended as the requirements demand it, and new sensor types can be added depending on the purpose of the monitoring.

One of the implications of such POMs is that passive seismic monitoring systems could be applied to many offshore fields in the Gulf of Mexico, not just in deepwater, with safety and environmental considerations a key priority.

Conclusion
In the aftermath of the Macondo disaster, offshore operations in the Gulf of Mexico seem destined to change. Demands for regulation and surveillance to ensure safe and sustainable operations are bound to increase, especially in the deepwater environment where the reservoirs in the Lower Tertiary/Paleogene plays will require well stimulation techniques such as fracing. MicroSeismic has pioneered the use of frac monitoring in the US shale plays onshore, and is taking steps to adapt the technology for use offshore. As such it will provide oil companies with a valuable tool which not only can optimize the production from super-expensive deepwater developments in the Gulf of Mexico, but also anticipate any requirements from regulators for permanent seismic monitoring for safety and environmental reasons. The assurance provided by these monitoring steps could also be important in oil company’s efforts to mitigate their less than favorable public image. Significant development of offshore applications of MicroSeismic’s technology will, however, depend upon E&P companies embracing the need for some form of permanent oilfield surveillance. Assuming that this occurs, the market for technology will extend beyond the Gulf of Mexico to offshore hydrocarbon provinces worldwide, and not just in deepwater.
Water-flooding Incremental Oil Recovery Study in Middle Miocene to Paleocene Reservoirs, Deep-Water Gulf of Mexico

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