Oilfield seismology in the 21st century: the marriage of reflection and earthquake seismology

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1.1 Introduction

Ever since the first oilfield experiments at the start of the 20th century, the use of seismology in the oil industry has been focussed on the use of reflection seismology with a minor interest in the refraction seismic technique and limited interest in earthquake seismology.

The difference between the oilfield seismologist and the earthquake seismologist lies with the nature of the source being used and the different objectives of each.

For the oilfield seismologist the nature and location of the source is known and engineered for its purpose. Although the source is clearly important, the focus of the work is in processing and interpreting what this source is able to say about the sub-surface. The objective of oilfield seismology is to better image hydrocarbon bearing and overlying formations in order to find such hydrocarbons and also to reduce the cost of producing such a resource or reduce the risk of exploitation.

For the earthquake seismologist the nature and location of the source is unknown. The objective of earthquake seismology has been to locate and define the nature of any unknown natural source, to attempt to understand the relationship between source generation and the local or regional stress regimes, to image the structure of the earth and to use this knowledge to mitigate against future potential earthquake hazard (The NTBT monitoring programme does rather extend this definition to include the location and definition of an unknown artificial source). Outside the oilfield, both earthquake and reflection seismology have always been seen as part of the broader subject of seismology.

Within the oilfield the subject of earthquake seismology has been of limited interest since it has offered no value in terms of understanding reservoir geometry or process. However over the past ten years this has been changing (Duncan, 2007).

The seismic community has known about the occurrence of induced seismic events in mines, under reservoirs and within oil reservoirs for decades (Rayleigh et al., 1976). Although seismic moments measured within oilfields tend to be many orders of magnitude smaller than those measured in the context of global seismic studies, the source mechanics of any macro-seismic and microseismic events are effectively the same, as are the seismic body waves that are generated.

In order for the application of earthquake seismology in the oil industry to really take off the coming together of several factors was required. These factors included (i) the improvement of downhole seismic tools (ii) the arrival of cheaper acquisition hardware and (iii) the rising importance of hydraulic fracturing and unconventional natural gas to the domestic gas supply in the USA. In 1995 unconventional gas supplied around 5% of US production. In 2009 it reached around 60%. Microseismic monitoring has been one of the key technologies in helping to optimise the stimulation of these unconventional reservoirs.

Hydraulic stimulation is expensive and by mapping the extent of the hydraulically stimulated zone corresponding to the locus of microseismic events, one can reduce the risk of bypassing reserves or unnecessarily stimulating the same volume twice.

The oilfield microseismic business now represents a substantial undertaking. From a limited pilot market worth a few hundred thousand dollars per year in the late 1990's, the oilfield microseismic[1] business has grown into a market worth over 100 M$ annually. This market continues to grow as improved methods are applied to better locate and define the nature of the natural seismic sources that are induced by oilfield operations. The delivery of microseismic event locations is now possible within a few seconds of their occurrence enabling the engineer to make decisions with an added value of several hundreds of thousands of dollars.

[1] Micro-earthquake and microseismic event are considered as synonyms in this paper

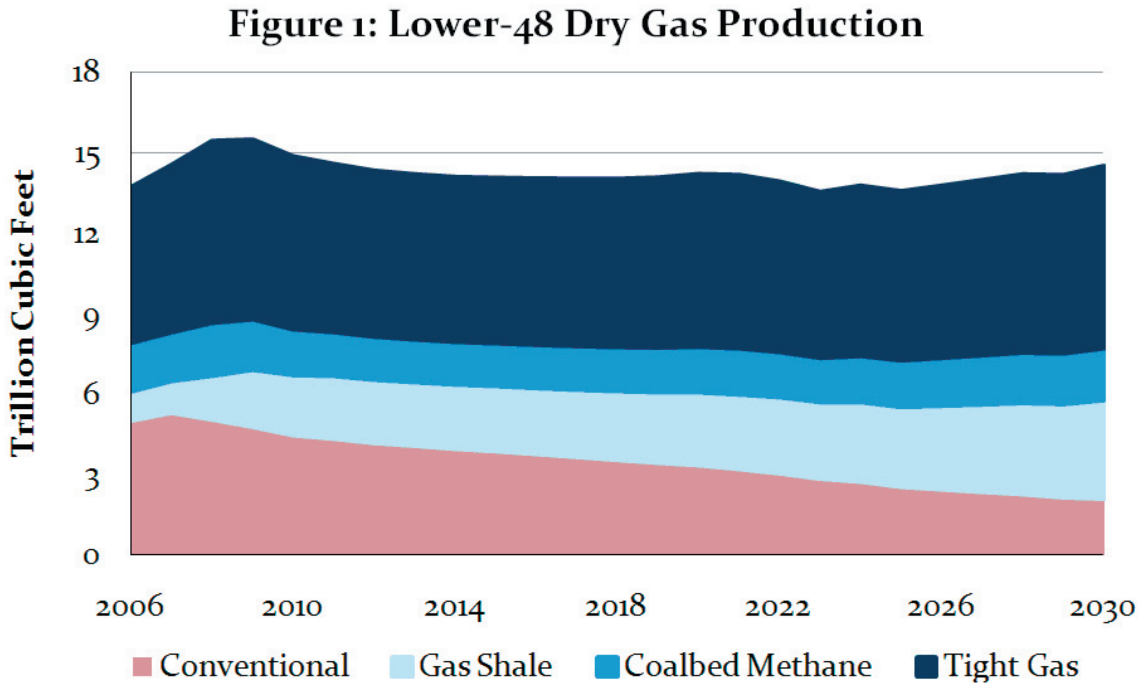

Figure 1: Rising proportion of unconventional gas production in USA

1.2 Earthquake seismology in the oil industry

1.2.1 The relevancy of earthquake seismology

As soon as a well is drilled the geomechanical state of the sub-surface is altered. If fluids are then injected or produced it is possible that some part of the sub-surface may exceed its failure criterion and in consequence seismic slip may occur. The slip vector of such an event may be only a few microns in dimension and the moment magnitude only minus 3. However the occurrence of this event tells the seismologist something about the state of the sub-surface that was not known before.

The understanding of the inter-well region within an oil reservoir is very limited. Any technique that can provide information about this region has potential value to a reservoir engineer. Microseismic monitoring and location is such a technology.

It can be used to map any stress changing process in the sub-surface caused by oilfield operations. Its most common use is to map the processes of hydraulic fracturing and steam injection for unconventional gas and heavy oil production.

Figure 2 shows a location plot for a population of microseismic events that took place during a series of hydraulic fracture stages. Such a plot provides the engineer with
(i) the direction of the frac
(ii) an estimate of the spatial extent of the frac

A movie of microseismic cloud development provides the engineer with an understanding of how the frac design is affecting the sub-surface during pumping and the ability to change the frac if the microseismic events show undesirable frac growth.

The acquisition geometry of the receivers used to locate the events shown in Figure 2 can be seen to the right of the figure. In this experiment two receiver arrays were used. Conventionally only a single, multi-level, 3C array is used to monitoring hydraulic frac operations. Such a configuration can result in uncertainty estimates of several hundred metres.
The availability of suitable monitor wells is a very significant constraint on the number of fracs that can be monitored. Globally several tens of thousands of frac operations take place each year. Of these perhaps only 1% are monitored microseismically. In consequence alternative, surface-based techniques have recently been developed that use the power of large surface arrays to stack potential energy sources in the sub-surface (Chambers et al., 2010). The principle behind the surface technique is a simple one whereby the recorded amplitudes corresponding to the modelled moveout of a notional event position, are stacked (Figure 3). If the signal energy across the array is coherent the summed amplitudes will create a high stack amplitude. If the signal energy across the array is incoherent the summed amplitudes will destructively interfere producing a low stack amplitude. This migration procedure is then repeated for all notional positions and all times.

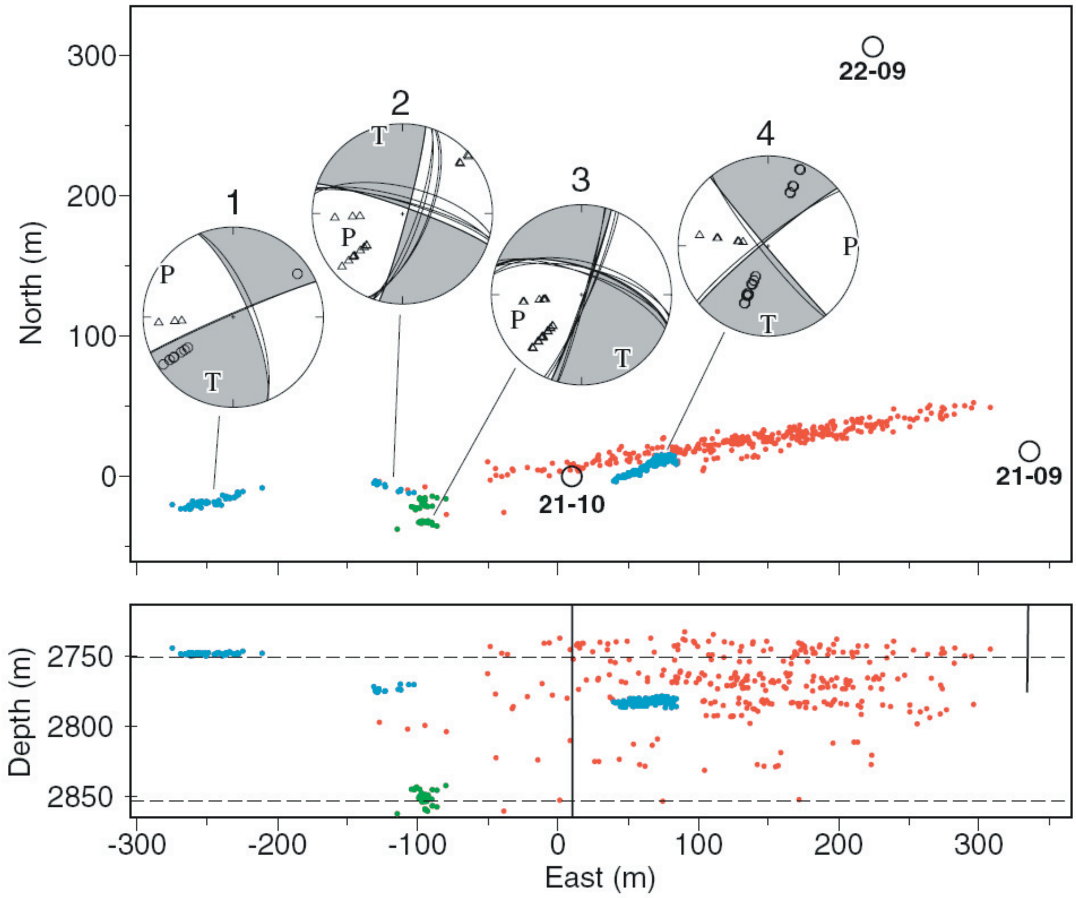

Figure 2 Example of a microseismic event population and associated fault plane solutions. The treatment well is labeled 21-10, the two monitor wells are labeled 22-09 and 21-09 (Rutledge et al., Faulting Induced by Forced Fluid Injection and Fluid Flow Forced by Faulting: An Interpretation of Hydraulic-Fracture Microseismicity, Carthage Cotton Valley Gas Field, Texas. BSSA, Vol. 94, No. 5, pp. 1817-1830, October 2004. © Seismological Society of America). Source locations and subcluster focal mechanism for gel-proppant treatment B at base of the UCV. The four subclusters shown in blue and green account for 65% of all events detected; cluster 4 alone accounts for 42%. Slip planes and event-trend orientations for the four subclusters strike off-angle from the overall treatment trend delineated by the red events.

Despite environmental noise and the very small signal amplitudes measured at surface it is currently possible to detect and locate microseismic events as small as magnitude -2. This is made possible with the use of arrays containing several hundred to several thousand channels.

The use of such arrays widens the potential market for frac monitoring since observation wells are no longer required. Such arrays also provide a much improved focal coverage of any event and provide an opportunity to better constrain the moment tensor.

In addition to the monitoring of hydraulic fracturing operations, the microseismic technique offers value in terms of better understanding any reservoir operation that causes geomechanical change in or above the reservoir. In particular microseismic monitoring has shown value in terms of identifying cap-rock breach, well-bore integrity failure, and the breakdown of fault seals.

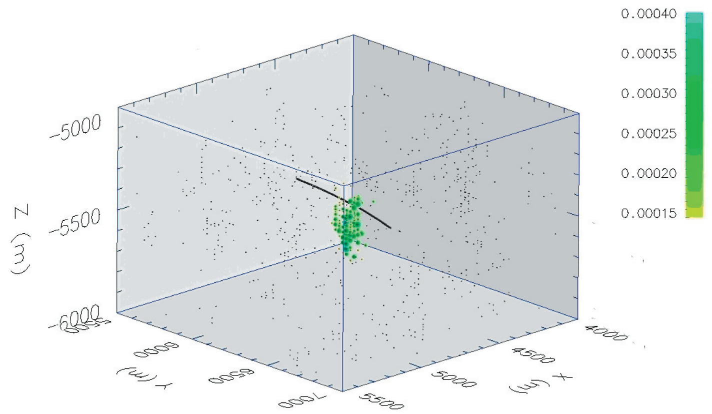

Figure 3 Microseismic event locations determined using a surface array. Those event locations with a high stack amplitude are shown in green together with the nearby well track

1.3 Reflection seismology in the oil industry

The objective of this short section is not to provide a summary of this discipline but more to identify the major directions that this subject is taking and some of the technical advances that are likely to increase the value of this technique within the oil industry.

The industry has delivered:
• Lower noise through better equipment, better configurations, better filtering, and better experiment design (P.Christie et al., 2001).
• Better sampling through improvements in array geometry (e.g. the use of wide azimuth acquisition: R. Sambell., 2010)
• Algorithms that better approximate the reality of seismic energy propagation in the subsurface and or analyse a larger portion of the seismic wavefield (e.g. the use of reverse time migration: Baysal et al., 1983).

The result has been:
• Imaging of interfaces with complex and/or steep topography.
• The use of more realistic velocity models incorporating 3D velocity heterogeneity and anisotropy
• Better resolution/sharper images, increased signal to noise and more accurate amplitude representation. Thus going beyond simple reflector location in order to analyse the variation in impedance contrast across boundaries.

These improvements now provide the oil industry with a tool capable of imaging sub-surface structure previously outside the reach of seismic technology. In the context of 4D seismic, travel time changes of a few milliseconds or less are detectable and actionable (Yu et al., 2009).

The obvious question is what next? The answer to this, in the author's opinion, probably lies within the following ultimate developments:
• The application of HPC technology to the problem of seismic inversion and the proximate application of computationally intensive methods previously considered unworkable
• The improved reliability and lower price of permanent systems
• Synergistic development and integration with other technologies, in particular that of earthquake seismology

There will be many proximate effects of these changes that rely upon the above developments for them to become realisable.

1.4 The value proposition for the integration of both reflection and earthquake seismology

Both reflection seismic and earthquake seismic technologies rely upon the measurement of vibration. Different applications may focus on different bandwidths and amplitude levels but in essence each technology is based on the measurement of the same phenomenon.

The man-made sources used in reflection seismology generate energy in a measurement bandwidth of a few Hz to a few hundred Hz.

If we define earthquake seismology as a discipline that relates to seismic slip at any scale then the bandwidth varies between a few thousandths of a Hz for long period teleseismic waves to tens of kHz for acoustic emissions emitted by stressed rock.

Fortunately the prime bandwidth of microseismic energy recorded in consequence of oilfield operations lies between a few tens of Hz to around 1 kHz when measured downhole. At the surface the top end of this spectrum drops to a few hundred Hz.

This means that for most purposes the requisite bandwidth for both reflection seismic and microseismic operations are coincident and the same sensing systems can be used for both.
This is an important fact to consider since it offers an opportunity to use the same measurement systems to determine two very different attributes of the subsurface (i) impedance and its change (ii) geomechanical change through the detection, location and characterisation of microseismic events.

Recent work using OBC sensing systems deployed for 4D seismic purposes, has shown that these devices can also be used to detect and locate microseismic activity (Chambers et al., 2010). The installation of shallow buried arrays in parts of the Middle East and the USA for steam injection and hydraulic fracture monitoring purposes represent the start of systematic installation of permanent equipment used for microseismic monitoring. These multi-level, multi-component arrays with channel counts generally between 20 and 100, are installed within multiple wells of a few hundred metres depth over an area of 10 to 20 km^2.

Over the past 10 years we have seen the rise of the microseismic technique within the oilfield seismic community. The author believes that we are now starting to see a search for the synergy between the two disciplines as the digital oilfield begins to take shape. The reasons and potential avenues of development of this synergy are listed below:
1. Both disciplines measure the same phenomenon of earth vibration
2. Within the oilfield the measurement bandwidths overlap
3. Oilfield seismology is widening its scope to include both permanent as well as temporary wireline installations
4. The automated determination of source location and source character is important to both disciplines.
5. Many of the techniques developed for exploration seismology can be adapted to the analysis of microseismic sources.
6. Reservoir imaging may be possible based on the use of microseismic events as sources
7. The joint inversion of synthetic source and natural source data to invert for reservoir properties

1.5 Conclusions

The value of microseismic monitoring to the reservoir stimulation business has demonstrated the potential of earthquake seismology to the reservoir engineers whose role is to understand and try to predict reservoir response to oilfield operations.

The widening scope of reflection seismology from an exploration tool to one for production monitoring brings it into alignment with the reservoir monitoring role played by microseismic technology.

New acquisition hardware in the form of permanent OBC and permanent downhole arrays together with parallel computing technology provide opportunities to develop the potential synergy between the two disciplines.

The outlook for seismology is an exciting mix of how best to apply the funding and knowledge from each side of the seismology fence to the intriguing problems and imaging concerns of our colleagues on the other.

1.6 References

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