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Contents

Chapter 1

Beyond microseismicity: an overview of geophysical monitoring in hydrocarbon reservoirs

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Summary

Extraction of hydrocarbons from unconventional reservoirs demands ever-increasing technological effort, and there is need for better understanding phenomena occurring within the reservoir. The focus of the petroleum industry has shifted from exploration to monitoring production, and it is essential to monitor the processes in the subsurface (4). Significant deformation processes happen when man-made stimulation is performed, in combination with effects deriving from the existing natural conditions such as stress regime in situ or pre-existing fracturing. Temporal changes from an initial (unaltered) state of the reservoir can be associated to alterations in the rock properties, temperature and pressure or fluid flow.
Keeping track of such changes in reservoir is important, on one hand for improving recovery of hydrocarbons, and on the other hand to assure safe and proper mode operation. Monitoring becomes particularly important when hydraulic fracturing (HF) is used, especially in the form of the much-discussed “fracking”. Monitoring hydrocarbon reservoirs has essentially two purposes. First it allows geoscientists and engineers to understand how the reservoir reacts to external or internal perturbation of its state; secondly, monitoring is one of the first steps in preventing and addressing environmental issues (e.g., gas leakage in a close by aquifer). Monitoring contributes to reducing the uncertainty in the reservoir’s dynamics. A combination of monitoring procedures and good operational practice is necessary for exploiting natural reserves in reservoirs, while minimizing the environmental impact.

1.1 Introduction

Hydraulic-Fracturing (HF) is a sophisticated technique which is widely applied in low-permeability geological formations to enhance the production of natural hydrocarbons. In principle, similar HF techniques have been applied in Europe for a long time in conventional reservoirs, and are likely to be intensified in the near future. When HF is used, especially in the form of the much-discussed "fracking", knowledge of the state of the reservoir becomes important, both for optimizing operations, and also to safeguard against potential hazards. This suggests an increasing demand in technological development, including updating and adapting existing techniques in applied geophysics.

The first attempts of tracking temporal changes (monitoring) in hydrocarbon reservoir are dated 40-50 years ago. These surveys were mainly focused on characterizing the subsurface using probes, such as seismic and electric, deployed in boreholes or at the surface. Reservoirs are nowadays monitored during exploration and exploitation of the hydrocarbons by using different monitoring techniques, according to the geological conditions. Techniques have been developed and are still in usage in offshore plays, with different design from the on-shore case. Some of these techniques aim at constructing images of the reservoir compartments; others can estimate important parameters directly in-situ. Nevertheless, the output of geophysical surveys needs robust interpretation and may not exhaustively explain the cause of changes in reservoir.

In this work we review currently available geophysical techniques for reservoir monitoring.
First, we describe basic characteristics of geophysical monitoring, and we identify properties and the associated monitored quantities in a hydrocarbon reservoir, according to the different fields of analysis in reservoir.
Second, we present an overview of current monitoring techniques associating them to monitored quantities.

This work has been carried out as part of the FracRisk consortium (www.fracrisk.eu); this project is funded by the Horizon2020 European Union (EU) research programme, and it aims at developing a knowledge base for helping minimize the environmental footprint of shale-gas exploration and exploitation.

1.2 Monitoring a hydrocarbon reservoir

Hydrocarbon reservoirs are composed substantially by rocks containing different minerals, fluids (water) and hydrocarbons (oil or natural gas). Natural reserves can be trapped in geological formations at variable depth depending on the geological conditions in reservoir. Each reservoir is characterized by its natural conditions, such as faulting and folding that contributed to the formation of an existing network of natural fractures. Unconventional reservoirs are characterized by very low-permeability geological formations bearing hydrocarbons, as opposed to conventional reservoirs, where rock permeability is higher by many orders of magnitude. Hydrocarbons are usually extracted from unconventional reservoirs by artificial stimulation, which generates significant changes in the reservoir.

Geophysical monitoring implies keeping track of temporal changes of characteristics (later called "properties") of a reservoir that are imposed by external or internal perturbation of the reservoir state; such changes may not only allow inferences to be made on the reaction of the reservoir to the perturbation (e.g., in terms of deformation, fluid flow or temperature changes), but also give information on reservoir properties that were previously hidden (e.g., 4). Monitoring can be achieved by implementing probes in-situ (directly into the reservoir), or outside of the reservoir, where the non-invasive nature of the method prevents any further perturbation of the reservoir

Let us assume that a hydrocarbon reservoir is analyzed in-situ at time t_0. If no external stimulation is applied, the reservoir is unaltered, and remains in its *initial state*. Natural variations can be due to the background stress in the underground rocks, forces of tectonic, volcanic, or tidal origin, presence of faulting/folding, fracturing, or presence of fluids, such as water and hydrocarbons. At time t_1 an artificial stimulation starts to be applied and it is terminated at time t_2. The time interval between t_1 and t_2 refers to the stimulation; much of its effects should occur within this time interval, on top of any occurring natural variations. After t_2 the stimulation is stopped, however significant effects may still occur. After the stimulation, the reservoir will unlikely return to its exact initial condition at t_0. After a certain time, changes may not be detected anymore; however the reservoir characteristics will usually differ from those at t_1.
Monitoring refers to tracking the temporal changes of the reservoir, starting from its initial state at time t_0, to a possibly long time after t_2. A baseline study of the hydrocarbon reservoir should be conducted before the stimulation (e.g., fracking) to obtain the background state, which provides an objective point of comparison for the reservoir state as measured during and after the stimulation. In this way, both the natural and artificial deformation processes can be tracked; where possible, these two contributions should be distinguished.

Geophysical monitoring requires a detection geometry, which can be adapted to the type of reservoir. A number of detection geometries are shown in Figure 1 and listed hereafter:

- Surface
- Borehole
- Shallow borehole
- Satellite
- Suspended in air/water

The specific design may include sensors suspended in air or water, such as in the monitoring of off-shore reservoirs, where instrumentation can be deployed in the water and/or towed by a ship, or in airborne surveys.

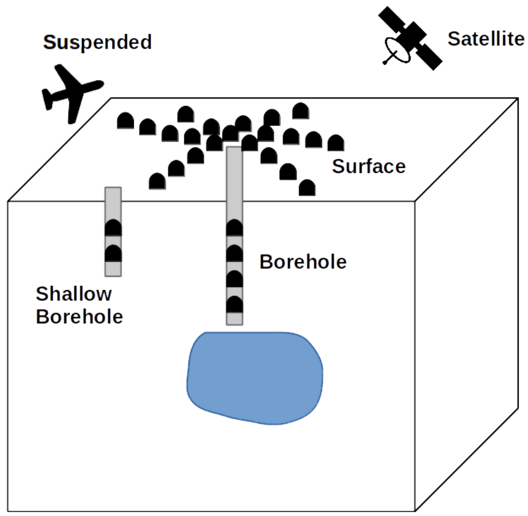

Figure 1: Basic elements of a geophysical monitoring in a hydrocarbon reservoir.

Limiting factors in reservoir monitoring are specific for the different types of reservoir, and may include: available capital, time, current technology level, geometry, feasibility, etc.
Geophysical methods can be used to create images of a reservoir at different times, constituting snapshots at the time of data acquisition (4). Such imaging is one of the most powerful tools and can be used to visualize temporal changes in a reservoir. Changes can be tracked by inspecting the variations of a measured variable after time t_0 on a Cartesian plot, where one of the axes is time or a different variable to monitor.

1.3 Properties and Monitored Quantities

In this section, the term *property* will refer to a specific feature which characterizes a certain object. Applying this concept to a hydrocarbon reservoir, a reservoir property refers to a specific characteristic of the reservoir. In the following we will assume that the property can in principle be quantified, unlike "beauty" for instance. The property will be associated with one or more quantities, each of which carries a physical unit, at least in principle.
A *monitored quantity* can be measured by using a specific measurement tool or monitoring technique. We will not make a distinction between directly measured quantities and inferred ones (e.g., by some inversion procedures such as seismic tomography, or derived by empirical relationships). Tracking changes of a property means measuring temporal changes of its associated monitored quantities.

We deal in principle with three overlapping groups of characteristics, which can be identified as:

1. Quantifiable in principle (these are the "properties" according to our definition)
2. Measureable by some specific techniques (these are the Monitored Quantities (MQ))
3. Monitorable (implying that repeated measurements are possible and useful for a reservoir monitoring)

For the purpose of our study ("monitoring"), we are most interested in the third group, which is a subset of the second group; however, we will also discuss quantities that pertain only to the second group.

We identify Geophysical Properties (GPs), and distinguish them from Non-Geophysical Properties (NGPs) which we do not cover in this work.
According to the different fields of analysis in a hydrocarbon reservoir, we categorize the properties in the following way:

- **Geophysical Properties**
  - Physical Properties (Ph)
  - Structural Properties (St)
  - Geological Properties (Ge)
  - Thermodynamic Properties (Th)
  - Hydrological Properties (Hy)
- **Non-Geophysical Properties**
  - Chemical Properties
  - Biological Properties

The comprehensive list of the GPs considered in this study is given below. Each GP identified is followed by its categorization (abbr.):

- **Reservoir Dimension (Ge)**
- **Reservoir Geometry (Ge)**
- **Preferred Orientation of Structures (St)**
- **Deformation (Ph)**
- **Elasticity (Ph)**
- **Rock Compressibility (Ph)**
- **Rock Rigidity (Ph)**
- **Stress Regime in-situ (St)**
- **Electromagnetism (Ph)**
- **Thermal Properties (Th)**
- **Geological Properties (Ge)**
- **Water Content (Hy)**
- **Gas and Oil Content (Hy)**
- **Fluid Properties (Hy)**

- **Fluid Flow (Hy)**
- **Faulting/Folding (St)**
- **Rock Cohesion (St)**
- **Fracturing (St)**
- **Radioactivity (Ph)**

According to the different fields of reservoir analysis, we associate to each GP one or more specific MQs. In some cases the same MQ can be associated to different GP, for instance MQ strains and stresses can be associated to GP stress regime in-situ and rock cohesion or fracturing. The meaning of some MQs will be explained in the next section, relating to the monitoring techniques.
The complete list of MQs associated to their relative GPs is shown in Table 1.

1.4 Overview of the Geophysical Monitoring Techniques

We have previously introduced the Geophysical Properties (GPs) and Monitored Quantities (MQs) in a hydrocarbon reservoir, showing examples of their associations. A monitoring technique can be applied in a reservoir to monitor several quantities, hence we distinguish *"multi-tasking"* from *"single-tasking"* techniques. The former monitor several quantities, while the latter only monitor a single technique at a time.
Each Geophysical Monitoring Technique (GMT) will be presented relating it to its associated MQs. Table 2 shows a comprehensive lookup on the GMTs, listed in alphabetical order, flagging the associated MQs with a 'V'. This table allows us to identify which GMT is multi- or single-tasking technique.
According to the methodologies currently used in monitoring, the GMTs can be divided mainly into eight classes (the word techniques in each item is omitted):

- **Magnetic (MA)**
- **Electrical (EL)**
- **Electromagnetic (ELM)**
- **Borehole Logging (LO)**
- **Nuclear (NU)**
- **Static (ST)**
- **Seismic (SE)**
- **Geodetic (GD)**

For sake of clarity, this classification is not a rigid order neither an attempt to rank the GMTs. The abbreviations indicated after each technique have the main purpose to help in cataloging and classifying the GMTs.
In our analysis we include the oldest GMTs, namely those in usage 40-50 years ago in applied geophysics, such as gravimeters, hydrometers, tiltmeters, strainmeters, etc. and the techniques applied in water contamination studies such as the spontaneous potential, nuclear logs, etc. (e.g., (2)).
Other techniques such as time-lapse techniques, are considered, since they provide an efficient way of imaging reservoir changes, based on comparison among snapshots of the reservoir taken at different time.
We discuss recent developments in geodetic techniques (remote sensing) such as the GPS satellite and the InSAR interferometry which have practical usage in the estimation of the subsurface deformation (see 4).
For its basic principle, InSAR measurements can be used to monitor the fluid flow in the subsurface, and the sealing properties of faults. InSAR has been used to monitor the deformation associated with the extraction of water or hydrocarbons, to monitor the heaving of the surface caused by cyclic steam injection in the recovery of heavy oil, and in fault re-activation studies (4).
Figure 2 shows the subsidence observed with InSAR and associated with hydrocarbon extraction between August 1997 and July 1998; differences in color scale indicate the phase-wrapped vertical displacement. It is noticeable that the two fault lines delimit the subsidence associated with the hydrocarbon extraction, implying that they may likely act as barriers for the fluid flow (4).
We revise the seismic techniques as well.
Noise cross-correlation techniques, by using the coda of cross-correlation functions, have the capability to detect small variations in the correlations. The basic idea is to associate these small variations to perturbations in structures and velocity. This feature holds considerable promise for monitoring a hydrocarbon reservoir. With these techniques it is possible to measure: surface wave group and phase velocities, changes in velocities of body wave arrival, conversion P-to-S and S-to-P. In addition the anisotropy can be inferred in structure changes, combined with shear-wave splitting (5), due for example to the preferred orientation or presence of faulting/folding and and fracturing.
In the context of a hydrocarbon reservoir monitoring, bulk changes of a reservoir can be mapped and tracked. During HF treatments a surface array should be capable to detect the induced microseismicity, inferring some important rock properties such as rock cohesion in presence of fracturing or faulting.
Examples from the literature show applications to reservoir monitoring by ambient noise techniques. (1) investigated the reliability of daily reservoir-scale near-surface continuous monitoring of the subsurface by ambient noise techniques, concluding that it may be useful for early detection of short-time-scale hazards (days to weeks) such as migrating gases and fluids. (3) by analyzing ambient seismic noise cross correlations, observed a significant loss of waveform coherence, horizontally and vertically constrained to the injection location of the fluid in a geothermal reservoir.

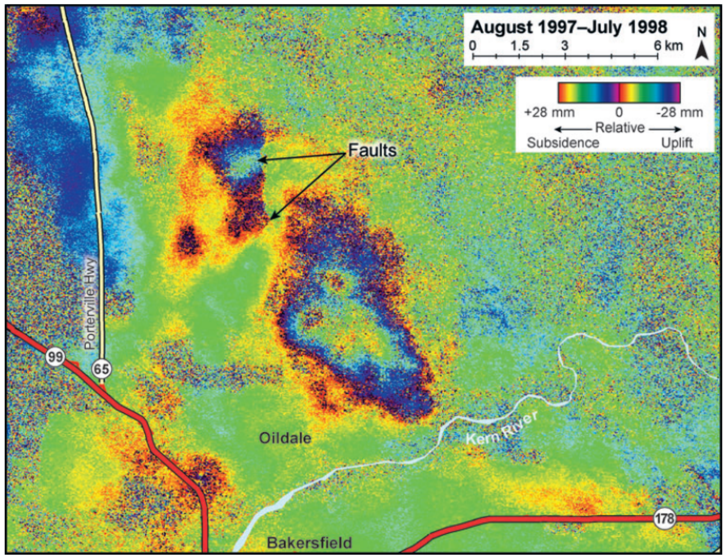

Figure 2: InSAR-observed subsidence north of Bakersfield, California, associated with hydrocarbon extraction between August 1997 and July 1998 (from 4).

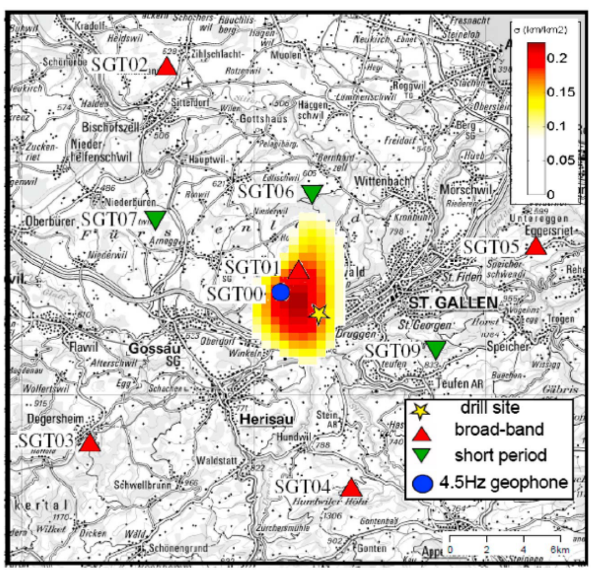

Figure 3: Observed changes around the injection well using ambient seismic noise techniques, indicating a causal relationship with the activities at the well (from 3).

The loss of waveform coherence has been interpreted as a local perturbation of the medium. Figure 3 (from 3) maps the loss of waveform coherence (σ) allowing for causal relationships with the well activities. They concluded that ambient seismic noise analysis can be used to assess the aseismic response of the subsurface to geomechanical well operations and may help recognize the reservoir dynamics at an earlier stage than the microseismic response allowed.

Table 1: Geophysical Properties (GPs) with the associated Monitored Quantities (MQs) in a hydrocarbon reservoir.

GPs	**MQs**
Reservoir Dimension	Size
Reservoir Geometry	Shape
	Volume
	Depth
Preferred Orientation of Structures	Seismic Anisotropy/Orientation/Imaging
Deformation	Rise/Fall/Subsidence/Dilation
Elasticity	Elastic Parameters
Rock Compressibility	Compressional Velocity
Rock Rigidity	Shear Velocity
Stress Regime in-situ	Strains and Stresses
	Pore Pressure
	Lithostatic Pressure
Electromagnetism	Resistivity/Conductivity
	Electromagnetic Anisotropy
	Magnetic Susceptibility
	Eletromagnetic Polarization
Thermal Properties	Temperature
Geological Properties	Lithology
	Rock Density
	Lithostatic Pressure
	Compaction/Cementation
	Sediment Thickness
Water Content	Porosity
	Water Saturation
	Saline Concentration
Gas and Oil Content	Porosity
	Gas Saturation in Water
	Flow (in production)
Fluid Properties	Fluid Density
	Hydrostatic Pressure
	Hydrocarbon Pressure
	Hydraulic Connectivity
Fluid Flow	Permeability
	Hydraulic Connectivity
Faulting/Folding	Microseismicity
	Seismic Anisotropy
Rock Cohesion	Microseismicity
	Strains and Stresses
Fracturing	Microseismicity
	Strains and Stresses
	Seismic Anisotropy
	Stimulated Volume (SRV)
Radioactivity	Radioactive Isotopes Concentration

List of Monitored Quantities (MQs)

- MQ1 Size
- MQ2 Shape
- MQ3 Volume
- MQ4 Depth
- MQ5 Seismic Anisot./Orientation/Imaging
- MQ6 Rise/Fall/Subsidence/Dilation
- MQ7 Elastic Parameters
- MQ8 Compressional Velocity
- MQ9 Shear Velocity
- MQ10 Strains and Stresses
- MQ11 Pore Pressure
- MQ12 Lithostatic Pressure
- MQ13 Resistivity/Conductivity
- MQ14 Electromagnetic Anisotropy
- MQ15 Magnetic Susceptibility
- MQ16 Electromagnetic Polarization
- MQ17 Temperature
- MQ18 Lithology
- MQ19 Rock Density
- MQ20 Compaction/Cementation
- MQ21 Sediment Thickness
- MQ22 Porosity
- MQ23 Water Saturation
- MQ24 Saline Concentration
- MQ25 Gas Saturation in Water
- MQ26 Flow (in production)
- MQ27 Fluid Density
- MQ28 Hydrostatic Pressure
- MQ29 Hydrocarbon Pressure
- MQ30 Hydraulic Connectivity
- MQ31 Permeability
- MQ32 Microseismicity
- MQ33 Stimulated Volume (SRV)
- MQ34 Radioactive Isotopes Concentration

List of Geophysical Monitoring Techniques (GMTs)

- GMT1 Acoustic Logs (LO)
- GMT2 Airborne Surveys (ELM)
- GMT3 Borehole Imaging Logs (LO]
- GMT4 Borehole Television (LO)
- GMT5 Caliper Logs (LO)
- GMT6 Chemical Tracers (NU)
- GMT7 Dynamometers (ST)
- GMT8 Electrical Surveys DC (EL)
- GMT9 Electromagnetic TEM/MT (ELM)
- GMT10 Extensometers (ST)
- GMT11 Flowmeters (LO)
- GMT12 Fluid Logs (LO)
- GMT13 Focal Mechanisms (SE)
- GMT14 Gamma-Gamma Logs (NU)
- GMT15 Gamma-ray Logs (NU)
- GMT16 Gamma Spectrometry Logs (NU)
- GMT17 GPS Satellite (GD)
- GMT18 Gravimeters (ST)
- GMT19 Ground-Penetrating-Radar (GPR) (ST)
- GMT20 Hydrofracs (ST)
- GMT21 Hydrometers (ST)
- GMT22 Hydrophones (SE)
- GMT23 Induction Logs (LO)
- GMT24 InSAR Interferometry (GD)
- GMT25 Magnetometers Fluxgate (MA)
- GMT26 Magnetometers Optic.-Pumping (MA)
- GMT27 Magnetometers Proton (MA)
- GMT28 MilliVoltmeters (EL)
- GMT29 Multiphase Meters (LO)
- GMT30 Neutron Logs (NU)
- GMT31 Nuclear Magnetic Resonance (NU)
- GMT32 Overcoring (ST)
- GMT33 Pressure Sensors and Gauges (LO)
- GMT34 Seismic 2D (SE)
- GMT35 Seismic 3D (SE)
- GMT36 Seismic 4D Time-Lapse (SE)
- GMT37 Seismic Ambient Noise (SE)
- GMT38 Seismic Anisotropy techniques (SE)
- GMT39 Seismic Cross-well (SE)
- GMT40 Seismic Down-hole (SE)
- GMT41 Seismic Earthqu./Micro-earthqu. (SE)
- GMT42 Seismic Interferometry (SE)
- GMT43 Seismic Reflection (SE)
- GMT44 Seismic Refraction (SE)
- GMT45 Seismic Surface Waves (SE)
- GMT46 Seismic Up-hole (SE)
- GMT47 Seismic While Drilling (SE)
- GMT48 Spontaneous Potential Log (LO)
- GMT49 Strainmeters (ST)
- GMT50 Temperature ATS (LO)
- GMT51 Temperature DTS (LO)
- GMT52 Temperature Gauges (LO)
- GMT53 Tensometers (ST)
- GMT54 Tiltmeters (ST)
- GMT55 Time-Lapse Electromagnetic (ELM)
- GMT56 Vertical Seismic Profiling (VSP) (SE)

GMT	MQ																																	
	MQ1	MQ2	MQ3	MQ4	MQ5	MQ6	MQ7	MQ8	MQ9	MQ10	MQ11	MQ12	MQ13	MQ14	MQ15	MQ16	MQ17	MQ18	MQ19	MQ20	MQ21	MQ22	MQ23	MQ24	MQ25	MQ26	MQ27	MQ28	MQ29	MQ30	MQ31	MQ32	MQ33	MQ34
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Table 2: Associations between Geophysical Monitoring Techniques (GMTs) and Monitored Quantities (MQs) in a hydrocarbon reservoir.

1.5 Discussion

We will not describe each technique in detail; we prefer referring the reader to a report on the existing geophysical monitoring techniques which will be released soon as part of the FracRisk project.
The work presented on existing geophysical monitoring techniques does not pretend to be a complete and exhaustive manual since there is extensive literature in the matter. Rather, one of the take-home message is a suggestion to go beyond the microseismicity techniques or hydrofracs, since we deem that it is appropriate to extend the context of monitoring in a hydrocarbon reservoir.

This work on existing monitoring techniques in hydrocarbon reservoirs is primarily intended for the discussion within the FracRisk community. It provides a general description of the currently applied techniques that are well-established. In a wide field such as reservoir monitoring, it is clear that the exposure of individual techniques can only be rather short in such a text.
Beyond FracRisk, this work may also be used as consultation material by both industry and academy in reservoir geophysical monitoring or characterization.
The work may also be of interest for regulator agencies, to see what is possible in principle currently in monitoring reservoirs during HF, for eventually defining a good operation practice of geophysical monitoring in shale-gas reservoirs, in order to minimize its footprint on the environment.

1.6 Conclusions

A continuous massive usage of hydraulic stimulation in unconventional reservoirs requires an increasing demand of technology development in monitoring systems. This suggests the importance of adapting and updating the existing monitoring techniques. Hydrocarbon reservoirs appear in their initial state (unaltered) mainly under the regime of natural variations. However significant deformations happen after hydraulic-fracturing treatments in reservoir; these can be associated to changes in the rock properties, temperature or fluid flow. Keeping track of such changes is useful on one hand for an enhanced hydrocarbon recovery, and on the other hand to verify the safe and proper mode of operation. We describe the basic elements of geophysical monitoring, identifying properties and monitored quantities in a hydrocarbon reservoir. The current available monitoring techniques are then reviewed according to the different field of analysis in reservoir.

This work has been carried out as part of the FracRisk project (Horizon2020 European Union), which encourages proficient collaboration between the Academy and Industry for minimizing the environmental footprint of shale-gas exploration and exploitation, which also involves the regulatory bodies and the concerns of the public opinion.

1.7 Acknowledgments

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