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Application and analysis of geodetic protocols for monitoring subsidence phenomena along on-shore hydrocarbon reservoirs

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A B S T R A C T

In this study, we tested the "land-subsidence monitoring guidelines" proposed by the Italian Ministry of Economic Development (MISE), to study ground deformations along on-shore hydrocarbon reservoirs. We propose protocols that include the joint use of Global Positioning System (GPS) and multi-temporal Differential Interferometric Synthetic Aperture Radar (DInSAR) techniques, for a twofold purpose: a) monitoring land subsidence phenomena along selected areas after defining the background of ground deformations; b) analyzing possible relationships between hydrocarbon exploitation and anomalous deformation patterns. Experimental results, gathered along the Ravenna coastline (northern Italy) and in the southeastern Sicily (southern Italy), show wide areas of subsidence mainly related to natural and anthropogenic processes. Moreover, ground deformations retrieved through multi-temporal DInSAR time series exhibit low sensitivity as well as poor spatial and temporal correlation with hydrocarbon exploitation activities. Results allow evaluating the advantages and limitations of proposed protocols, to improve the techniques and security standards established by MISE guidelines for monitoring on-shore hydrocarbon reservoirs.

1. Introduction

Land subsidence represents a relevant issue that affects highly developed urban and industrialized areas worldwide, especially those located along the coasts (Antonioli et al., 2017). Possible causes of subsidence processes can be listed as follows: a) natural factors, e.g., tectonic activity, self-weight consolidation of recent sedimentary deposits, oxidation and shrinkage of organic soils (Dokka, 2006; Galloway et al., 1999; Heywood and Pope, 2009); b) anthropogenic processes, e.g., groundwater pumping (Amelung et al., 1999; Bell et al., 2008; Bonì et al., 2015; Galloway and Hoffmann, 2007; Raspini et al., 2013; Taniguchi et al., 2009), urban development (Polcari et al., 2014; Stramondo et al., 2008) and hydrocarbon exploitation (Carbognin et al., 1984; Gambolati et al., 1991; Teatini et al., 2006).

Either natural or anthropogenic ground subsidence may severely affect the environment and the population with dangerous consequences, such as the malfunctioning or collapse of buildings, sinkholes, changes of watercourses, flooding, retreat of coastlines and relative-sea level rise (e.g., Antonioli et al., 2017; Modoni et al., 2013), induced seismicity (Keranen et al., 2014). Natural phenomena, such as thermal and tectonic processes, contribute to induce subsidence with rates of a few millimeters per year. Anthropogenic activities, such as the exploitation of aquifers, are responsible for the largest subsidence contribution with maximum rates of several centimeters per year (e.g., Albano et al., 2016; Bonì et al., 2015; Chaussard et al., 2014; Stramondo et al., 2007; Serpelloni et al., 2013). In addition, the hydrocarbon extraction from crustal reservoirs may accelerate the subsidence process, with rates up to some tens of millimeters per year (Allison et al., 2014; Kolker et al., 2011). Consequently, a proper understanding of the subsidence mechanism is essential to calibrate protocols and best practices for monitoring natural and anthropogenic phenomena, with the aim to reduce the risk for infrastructures, economies, natural environments and human life.

Focusing on subsidence processes associated with hydrocarbon exploitation, the Italian Ministry of Economic Development (hereinafter MISE) has defined general guidelines to monitor production activities in areas with high seismic and hydrogeological risk (Ministero dello Sviluppo Economico, DGS-UNMIG, 2014). Such guidelines describe best practices and protocols for the management and monitoring of anthropogenic activities, particularly focused on induced seismicity,

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ground deformation and pore pressure changes related to hydrocarbon exploitation. One of the main goals of these general guidelines was to establish procedures to analyze the spatial and temporal evolution of environmental parameters, as well as their possible correlations with underground anthropogenic activities. This analysis would allow defining risk mitigation plans for the safety of people, environment and industrial facilities.

In this study, we test these guidelines on some pilot areas to verify how far they can be generalized and consolidated in a larger variety of cases. Along with this rationale, we applied and discussed a land-subsidence monitoring methodology to on-shore hydrocarbon reservoirs. In detail, we jointly use Global Positioning System (GPS) and Differential Interferometric Synthetic Aperture Radar (DInSAR) techniques, which are both well suited for monitoring anthropogenic and/or natural subsidence phenomena (Bamler and Hartl, 1998; Guglielmino et al., 2011; Svigkas et al., 2016; Vollrath et al., 2017; Zhou et al., 2009). Indeed, GPS data provide punctual precise measurements of 3-dimensional (3D) ground deformation fields, with millimeter-level accuracy for the linear long-term rates. The high frequency sampling (usually every 30 s) guarantees a time-continuous monitoring, capable to identify short- and long-term ground displacements. In addition, multi-temporal DInSAR techniques provide time-series of 1D-displacement measurements along the sensor line of sight (LOS), with sparse temporal sampling (revisit time from few days to few weeks), dense spatial sampling, large coverage and high spatial resolution. Hence, they are able to capture signals related with both local and larger-scale phenomena. The combination and integration of the two techniques allow providing a complete description of the ground deformation for the temporal and spatial scales of our problem.

Here, we present results achieved for two selected pilot areas: the Ravenna coastal area (northern Italy) and the southeastern Sicily (southern Italy). These areas exhibit subsidence signals of about several mm/yr (e.g., Devoti et al., 2011; Serpelloni et al., 2013).

The final objectives of this study are:

- The application and testing of geodetic protocols to describe, characterize and monitor local subsidence along on-shore hydrocarbon reservoirs, identifying the most critical areas requiring additional monitoring activities;
- The definition of reference background settings for the multi-temporal and multi-spatial evolution of ground deformations along selected test areas;
- The analysis of possible temporal and spatial relationships between hydrocarbon exploitation activities and surface deformation measurements;
- The evaluation of advantages and limitations of the proposed approach, hence providing feedbacks to improve guidelines established by MISE.

2. Pilot areas

In this section, we describe the pilot areas in terms of geological and tectonic settings as well as natural and anthropogenic activities. Regional information about seismic, tectonic and geological settings have been provided through different sources, such as the Italian parametric and instrumental seismic database (ISIDe), the Italian Seismic Bulletin, the Catalogue of Italian Seismicity, the Database of seismogenic sources, the Italian Accelerometric Archive (ITACA).

2.1. Ravenna coastal area

The Ravenna coastal area (Fig. 1a) is a Quaternary sedimentary basin bounded to the SW and North by the northern Apennines and the southern Alps, respectively (Doglioni, 1993).

Buried under the thick cover of sediments of the Po Plain, the Apennines accretionary wedge is defined by seismic and well data (e.g., Pieri and Groppi, 1981). The wedge consists of three arcuate thrust systems, whose easternmost arc is the active Ferrara-Romagna one (Fig. 1a). These systems are delimited externally by thrust faults, which separate them from the Pedealpine monocline. The structure of the Ferrara-Romagna arc can be subdivided into three second-order features, i.e., Ferrara, Romagna and, more to the East, Adriatic folds (Fig. 1a). Moving SE-ward, the prolongation of the Apennine thrust front in the central Adriatic Sea is less evident (Scrocca et al., 2007).

Since Lower Miocene, the Apennines chain has been characterized by an eastward migration of contemporaneous, co-axial, coupled processes, i.e., compression in the foreland, and extension in the hinterland (e.g., Faccenna et al., 2003; Malinverno and Ryan, 1986). This migration produced a zone of active sedimentation above the deforming accretionary wedge in the western part of the Apennines, and a thinned crust in the eastern side. These processes are still ongoing, as demonstrated by crustal stress (Montone and Mariucci, 2016) and geodetic strain (e.g., Anderlini et al., 2016; Bennett et al., 2012; Serpelloni et al., 2005) measurements. They generate active compression in the present-day foreland (i.e., Adriatic coast and off-shore), and active extension along the axial culmination of the Apennines. This activity is clearly highlighted by the seismicity distribution with many strong (M > 6) damaging earthquakes occurred in the last 40 years, e.g., Norcia 1979, Colfiorito 1997, L'Aquila 2009, Emilia 2012 and Central Italy seismic sequence 2016 (DISS Working Group, 2015; Pondrelli et al., 2006, see Fig. 1a).

Within this complex seismotectonic framework, intensive groundwater pumping and hydrocarbon exploitation activities characterized the Ravenna coastal area in the last 40 years (Chahoud and Zavatti, 1999; Regione Emilia-Romagna and ENI-AGIP, 1998; Teatini et al., 2006). A monitoring network of wells, deployed along the region since the middle of 1970s, demonstrated the close relationship between land settlement and groundwater withdrawal. Maximum piezometric decline (up to 40 m) and largest settlement rates (up to 110 mm/yr) were recorded between 1972 and 1973 (Carbognin et al., 1978). Starting from the '80s, the piezometric measurements revealed a significant decrease of subsidence rate (Gambolati et al., 1999). Nevertheless, a residual land settlement was measured all over the region, due to the delayed aquitard consolidation (Teatini et al., 2006).

The study area is also characterized by many hydrocarbon reservoirs (see Fig. 2a). They were generated along the North African continental margin during the Mesozoic and the lower Paleogene, where the continental sedimentation was mainly made by carbonates (Casero and Bigi, 2013). The flexural history of Adriatic lithosphere was the main factor responsible for the generation and accumulation of biogenic/thermogenic hydrocarbons (Casero, 2004). Most of the Italian gas production comes from the Northern Adriatic Sea. The older source is thermogenic gas-prone, the younger source is biogenic gas one. The latter is mostly located in the outer Plio-Pleistocene foredeep domain, which characterizes the eastern Po Plain and Northern Adriatic Sea (Bertello et al., 2010). Nowadays, the study region hosts the most important Italian gas fields, explored since 1950 (Fig. 2a).

2.2. South-eastern Sicily

The geological-structural setting of SE Sicily is part of the complex tectonic features of the Mediterranean basin, dominated by the Neogene-Quaternary convergence between Nubia and Eurasia plates (Faccenna et al., 2001). The Hyblean Foreland (Fig. 1b) mostly represents the investigated area. It consists of an isolated and elevated fore-bulge structure, formed since the early Miocene by bending of the foreland lithosphere beneath the load of the advancing Maghrebian Chain (Billi et al., 2006). The autochthonous sedimentary wedge (about 7 km thick) consists of Triassic to Pleistocene carbonate succession, with intercalated submarine hydro-volcanoclastic units and minor lava flows (Grasso et al., 2004). A major N-S oriented, 70 km long, shear zone, known as Scicli line or Scicli-Ragusa Fault System (SRFS in