Cold seepages: An economic tool for hydrocarbon appraisal

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Spontaneous cold fluid seepages are a renowned phenomenon occurring in a wide range of geologic and geodynamic settings, including deep sea fans, rapidly subsiding basins, and compressive tectonic settings (e.g., Dimitrov, 2002; Morley et al., 2011; Oppo et al., 2013, 2014). Cold seepages are marked by various structures, both on land and offshore, such as mud volcanoes (MVs), methane-derived authigenic carbonates (MDACs), and chemosymbiotic communities. Their formation mechanism requires the increase of pore-fluid pressure above the lithostatic gradient with the subsequent upward fluid migration through hydrofracturing or along carrier beds and tectonic discontinuities.

Cold seepages have long been investigated, especially for the information that they may provide for the exploration of hydrocarbons present in different types of reservoirs associated with this phenomenon (e.g., Link, 1952; Heggland, 1998; Abrams, 2005). Although the relation between cold seepages and hydrocarbon reservoirs has not been completely enlightened in numerous settings, as in fold and thrust belts, it is established that the occurrence of gas, frequently associated with oil, is a common characteristic that most of the seepage areas show. In particular, the spontaneous leakage of oil and gas represents a prime indication of hydrocarbons occurrence in the subsurface and valuable source of information on the petroleum system. The associated fluids also provide evidence of the geochemistry of deep-seated hydrocarbons. A useful example of this association is represented by the oil and gas field exploited near MVs along the coast and offshore in the Caspian Sea (e.g., Planke et al., 2003; Davies and Stewart, 2005; Oppo et al., 2014; Oppo and Capozzi, 2016).

COLD-SEEPAGE FEATURES IN OUTCROP

The spontaneous cold seepages of the northern Apennines illustrated here and in Capozzi et al. (2017) represent a long-lasting phenomenon, mainly characterized by present-day MVs activity. According to a renowned definition, MVs are structures linked to

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sedimentary processes involving the periodic emission on the surface of a mixture composed of hydrocarbons, connate water, and sediments (usually pelites and clasts), which originate in parent layers at depth (Higgins and Saunders, 1974).

The first descriptions of MVs in this area are presented in *Naturalis Historia* by Pliny the Elder during the first century AD (Pliny the Elder, 1945). In more recent times, exhaustive inventories and descriptions of the fluid-seepage features in the northern Apennines have been compiled (Spallanzani, 1795; Stoppani, 1871; Scicli, 1972; Ferrari and Vianello, 1985), although it is only in the last decades that scientific works focused on their nature, pointing to the geological setting (Bonini, 2007; Capozzi and Picotti, 2010), geomicrobiology (Heller et al., 2011), and to the geochemistry of the emitted fluids (Minissale et al., 2000; Oppo et al., 2013).

In the northern Apennines, the cold seeps are roughly aligned along two belts striking northwest–southeast, respectively located close to the main water divide and along the foothills (Figure 1). The present-day active MVs are scattered alongside the foothills, whose main example is the "Salse di Nirano" MV field, covering a surface of approximately 75,000 m^2 (~18.5 ac) and representing one of the largest MV complexes occurring in Italy and Europe (Figure 2A–C). In the northern Apennines, the MV fields are often located in close proximity to a normal fault or are bounded by fracture systems, which favor the upward migration of the fluids (Oppo et al., 2013).

The mud volcanism in this region forms mud cones up to 2–3 m (6–10 ft) high (Figure 2C), with a main central vent where muds containing small amounts of clasts and bioclasts are emitted on the surface. This mud breccia contains elements representing the different sedimentary intervals of the parent layers involved when fluids rise from depth. Alongside the sediments, the MVs discharge relevant amounts of connate saline water and hydrocarbons. The volume of emitted fluids can significantly vary among the different outcrops, even within a single MV field, because of the natural periodic fluctuations of the MV activity.

The hydrocarbon leakage is a common characteristic of all the MVs; most of the hydrocarbon volumes consist of methane gas, which is associated with minor amounts of biodegraded condensates and oils (Figure 2D, F). The geochemical correlation among these hydrocarbons and those sampled from deep wells piercing the Miocene reservoirs in nearby areas shows that the MVs of the northern Apennines represent a direct link between the surface and the hydrocarbon reservoirs at depth (Oppo et al., 2013).

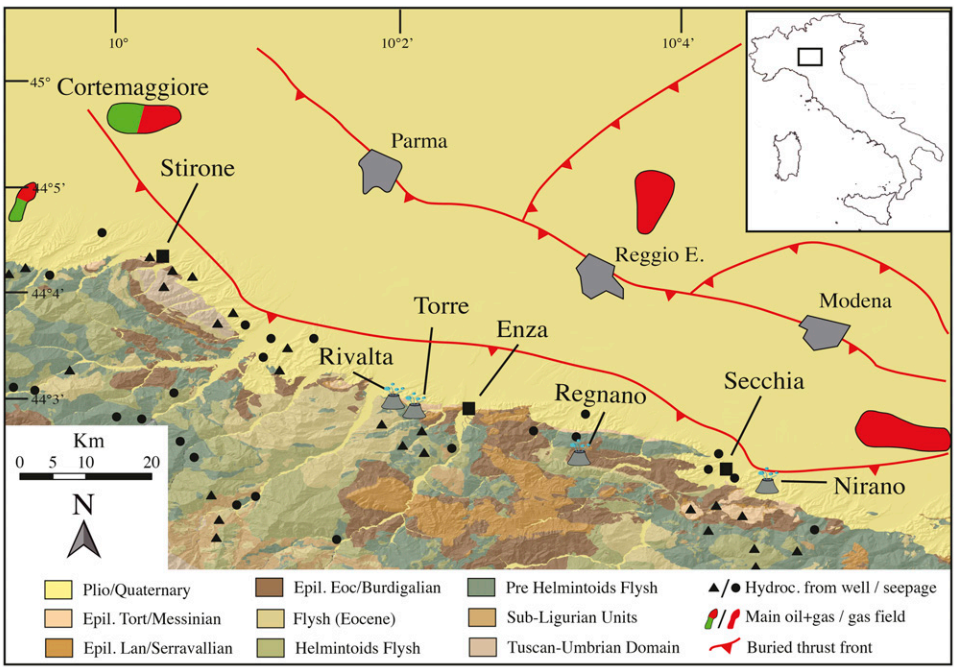

Figure 1. Geological map of the central sector of northern Apennines. Main outcrops of mud volcanoes (Rivalta, Torre, Regnano, and Nirano) and methane-derived authigenic carbonate (MDAC; Stirone, Enza, and Secchia rivers) are shown. Fossil MDAC cold seeps are indicated by solid rectangles. Modified after Oppo et al. (2013). Eoc = Eocene; Epil = Epiligurian; Hydroc = Hydrocarbon; Lan = Langhian; Plio = Pliocene; Reggio E. = Reggio Emilia; Tort = Tornonian.

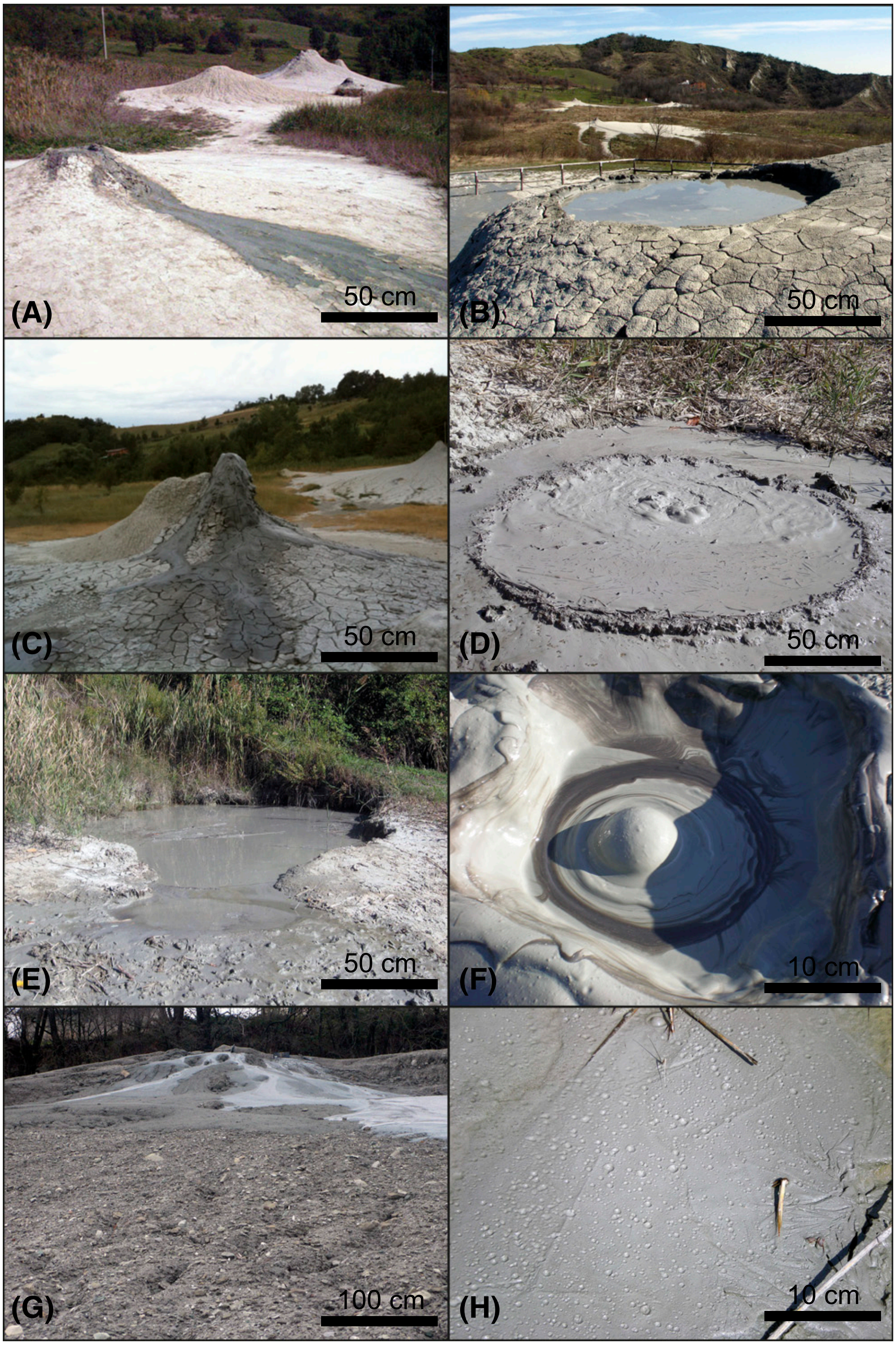

Figure 2. Examples of the various features observed in the mud volcano fields along the northern Apennines. (A) Small mud cone (gryphon) occurring in the Nirano mud volcano field (NMVF), with a small mud flow developing on its flank. A cluster of mud cones can be observed in the foreground. (B) The NMVF is located at the bottom of a calderalike depression (its edge can be seen in foreground) likely formed in consequence of the persistent mud emission over time. Four clusters of emission vents, formed by 3- to 4-m-high (10 to 13 ft) mud cones, occur. (C) Mud cone where the emission of dense mud, which is responsible for the steep slopes of the cones in this mud volcano field, is visible. (D) Emission at Torre mud volcano field, where the low content of sediments allows building a 5-cm-tall (2 in.) mud cone. Note the intense methane degassing. (E) Mud pool at Torre, where the sediment emission is lacking. Only methane gas and low quantities of water are emitted. (F) Small mud cone in the Rivalta mud volcano field, formed by very dense mud. The occurrence of oils and condensates is particularly evident in the Rivalta mud cones. (G) Mud breccia emitted by the volcanoes at the Regnano mud volcano site. The volcano edifice is mainly formed by mud breccia containing decimeter-scale clasts scraped off the underlying sedimentary intervals during particularly intense emission periods. On top of the cone, the active emission of fluids is forming a new mud flow. (H) Close up of a mud flow at Torre mud volcano field evidencing the elevate content of methane, which is released into the atmosphere.

Surrounding the main cones, various elements related to the emission activity, such as mud flows, gryphons, and mud pools, can be commonly observed. The mud flows generated by the MVs in the northern Apennines have variable density and thickness according to the content of connate water and dispersed gas bubbles, which are progressively released in the atmosphere (Figure 2H). Sporadically, paroxysmal events occur and are responsible for both the extrusion of larger quantities of mud breccia rich in decimeter-scale clasts (Figure 2G) and the increase of water and gas fluxes from the vents. Surrounding the main mud cones, the gryphons represent smaller conical vents (Figure 2A), which contribute to the fairly continuous degassing and usually show minor emission intensity, involving mud with a higher content of water and hydrocarbons. Often, when the suspended sediment is scant, the emission is not able to build a cone, and a mud pool forms (Figure 2E). These negative features can be commonly observed in the MV fields and range in diameter from less than one to a few meters.

Mud volcanism in the northern Apennines represents the modern on-land expression of a long-lasting cold seepage that started in marine conditions during the progressive fold and thrust belt formation. The fossil remnants of this seepage activity can be mainly observed along some of the main river valley incisions at the foothills, in the form of methane-derived authigenic carbonates and chemoherms (Taviani, 2001; Oppo et al., 2015).

The carbonate concretions, mainly composed of dolomite with minor calcite occur in defined intervals of marine pelitic successions, which comprise Pliocene (Stirone and Secchia rivers) and Pleistocene (Enza River) age deposits (Figure 1; Cau et al., 2015; Viola et al., 2015). Commonly, MDACs have two main prevailing morphologies: slab and pipelike (Figure 3). The slabs intervene within strata showing coarser grain size, usually fine sand, which favored the fluid diffusion. Indeed, the migration of methane in water-saturated sandy sediments is governed by capillary invasion, causing the progressive pore-water displacement and methane infiltration in the pore spaces (Choi et al., 2011). This mechanism allows a pervasive fluid diffusion and, possibly, increased gas fluxes. For this reason, the thickness of slabs interlayered in the pelitic successions ranges from a few centimeters to tens of centimeters (Figure 3C, H), depending on the more intense and/or prolonged gas leakage and on the thickness of fine sand beds (Oppo et al., 2015). Commonly, the slabs are massive and have relatively smooth external surfaces because of the confining pelitic strata, which prevented further fluid diffusion. Some bioturbation occurs only on the surfaces of the carbonate slabs.

When the fluid pressure rises above the hydrofracturing gradient, the gas infiltrates into the hosting pelites by conduit opening and fracturing, laterally displacing the sediment particles along zones with lower grain packing density (Choi et al., 2011). This forced intrusion of fluids appears to be the most suitable process to explain the formation of pipelike concretions, also named chimneys (Figure 3D–F), even if possible preexisting discontinuities, such as fractures and burrows in the shallow subsurface, could act as preferential migration pathways (Paull et al., 2008). Because of the gas migration mechanisms within the mainly pelitic successions, the chimneys can be frequently observed crosscutting or originating from slabs (Figure 3C, G). As a result of their generation mechanism, the chimneys do not have a preferred orientation with respect to the hosting strata, though in the northern Apennines outcrops they are usually subvertical or develop perpendicularly to the bed dip (Figure 3A–C). The chimneys are easily identifiable in the field, because they have a distinct pipelike morphology, which can show either an open central vent or a massive structure without visible vents (Figure 3D, E). Where the sandy-clayey sediments are interlayered within mainly pelitic successions, slab–chimney hybrids could form, generating irregularly shaped concretions showing multiple venting areas (Figure 3G).

COLD SEEPAGES AND PETROLEUM EXPLORATION

The spontaneous hydrocarbon leakage has been exploited since the times of ancient Greeks and Romans, when oil and tar collected from seepages were used as lighting fuels and at war. With the development of modern geology, the occurrence of cold seepages in sedimentary basins has often been employed to characterize petroleum presence at depth, supporting more successful hydrocarbon exploration.

Despite its apparent simplicity, the study of spontaneous seepages for exploration purposes can be difficult and lead to misinterpretations about the real nature and origin of hydrocarbons. The key to overcoming this problem is the use of an improved, low-cost, multidisciplinary methodology and data interpretation practice, which is able to characterize the present-day petroleum systems in various geologic settings through the study of seepage-related

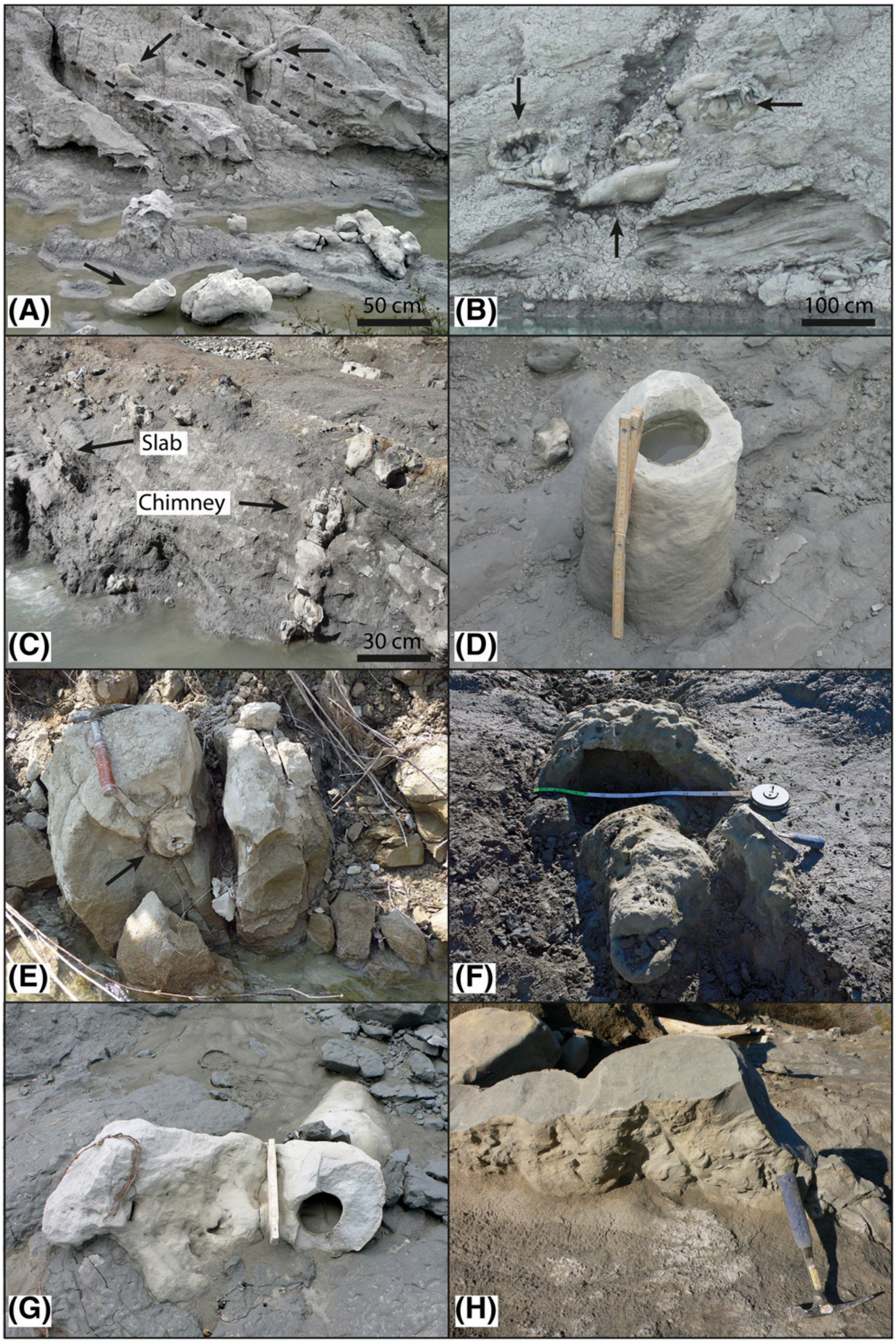

Figure 3. Examples of the various methane-derived authigenic carbonate (MDAC) features occurring in the northern Apennines. (A) Chimneys and irregular carbonate concretions outcropping along the Enza riverbanks. Arrows indicate chimneys perpendicular to the stratification of the hosting sediments (strata indicated by dashed lines). Note the chimney emerging from the water in the foreground. (B) Bulbous, slablike MDACs in the Secchia riverbanks. Arrows point to the main concretions. The MDACs are roughly aligned to the sediment stratification, which is exposed in the lower-right corner of the image. (C) Thin and discontinuous slab (~5 cm [~2 in.] thick) occurring in the Enza MDAC field. The slabs develop according to the strata bedding, also visible in the image, whereas the chimneys mainly show a perpendicular orientation. (D) Well-developed chimney showing an open central vent. Ruler is 40 cm (16 in.) long. (E) Stirone chimney approximately 1 m (3 ft) wide with the conduit filled by cemented sediments (arrow). (F) "Double chimney" concretion along the Enza riverbanks. A completely cemented chimney formed inside a wider one, probably resulting from different episodes of gas migration (measuring tape is 70 cm [27 in.] long). (G) Irregularly shaped slab–chimney association in the Enza MDAC field. The chimney (open vent and concretion behind) develops perpendicularly to the slab, which is still in place, evidence of the common relation that can be observed between these two concretion typologies. (H) Slab interlayered in the sedimentary succession along the Enza riverbanks. Thicker slabs present channellike track on the surfaces, probably representing bioturbation imprints.

features. To accurately forecast the characteristics of hydrocarbons at depth, the interpretation of seepage-related data sets needs to identify potential influences and bias caused by, for example, different sources of organic matter, bacterial petroleum degradation, mixing of fluids of various origins, contamination, and fractionation operated by the pelitic cover when fluids rise. Therefore, evaluating the data sets' reliability, making opportune adjustments, is essential to determine the use of seepage-related information during prospect evaluations.

The main challenge of this approach is appropriately merging different disciplines, including geochemistry, stratigraphy, and tectonics, to obtain a complete reconstruction of the fluid generation, expulsion, and migration stages that originated the various seepage-related features observed in outcrop. Indeed, fluid migration and accumulation are mainly related to the stratigraphic and structural evolution of the basin, and features such as the MVs could strongly deform the pierced sedimentary succession, generating structural traps and favoring the hydrocarbon accumulation into shallower intervals. Furthermore, during the study of MDACs, the correlation between carbonate concretions and the fluids possibly responsible for their formation using only a geochemical approach could be misleading, and the reconstruction of the geological evolution is a fundamental tool to better constrain the significance of the examined geochemical parameters.

The northern Apennines provide an excellent example of an exploration scenario in a fold and thrust belt, where the petroleum system components started forming in marine conditions and were progressively included in the chain deformation. The widespread and diversified fossil and active cold seepages in this area, which are related to the occurrence of deep-seated petroleum reservoirs, have been extremely useful for reconstructing the hydrocarbon source rocks and the fluid migration pathways, significantly improving our understanding of the regional petroleum system. This result has been achieved through the use of this multidisciplinary methodology, which also involved the geochemical characterization of saline water and hydrocarbons seeping from the major MVs along the foothills and their comparison with fluids sampled from dismissed exploration wells piercing the reservoir intervals.

Moreover, the present-day activity of cold seeps, where fluids are emitted from reservoirs of different ages, has been used for the first time to accurately define the relations between the feeding fluids and the characteristics of associated MDACs formed in marine conditions (Oppo et al., 2015; Viola et al., 2015). Furthermore, the occurrence of MDACs in relation to sediment deposition and coeval tectonic deformation has also been investigated, adding information on the fluid migration mechanisms in this region. The study of active cold seepages associated with the reconstruction of the MDACs' formation mechanisms has been proven to be a key aspect, which shed light on various aspects of the petroleum system history, to identify a new source rock and to highlight that the Tertiary foredeep still has an interesting residual potential (Oppo et al., 2013, 2015).

CONCLUDING REMARKS

Natural seeps have long been considered indicators of the possible occurrence of hydrocarbon deposits. The appropriate study of outcropping present-day and fossil seepages can be employed as a cost-effective tool to characterize the local petroleum system during the initial phases of exploration. The decreased oil price could push oil companies to increase the use of cold seepages as an economic tool to assess the hydrocarbon potential before employing more traditional and expensive exploration techniques.

The accurate analysis of the geological setting and the characterization of the petroleum system components through the seepage-related features are fundamental to better unravel the fluid generation and migration history in a sedimentary basin and in deformed settings, such as fold and thrust belts. The northern Apennines example shows that the reasoned and integrated interpretation of a multidisciplinary data set related to cold seepages, including sedimentological, structural, geochemical, and biostratigraphic data, could lead to the identification of new source rocks, even in supposedly well-understood petroleum provinces.

This study methodology has thus been proven successful in creating further knowhow useful for possible new explorations and enhanced appraisal of petroleum provinces occurring in different geologic settings.

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