NOTE

Oil seeps from the Patagonian shelf: their thermosteric fate

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ABSTRACT. Radar images are commonly applied to recognize and monitor oil seeps on surface waters over continental shelves. In San Jorge Gulf, Patagonia, between 46° S and 48° S, oil slicks have been surveyed performing ellipse patterns in response to mesotidal dynamics. These effects were assigned to recent episodic increments of summer bottom temperatures at depths between 100 and 120 m, which are 2 °C warmer than those recorded during the 20th century. Slicks are assumed to have their origin from faults already known by the oil industry onshore. The effects here described should be envisaged in a climate-change scenario leading to temperature increases of the oceans' shallow waters, together with other effects such as the human-induced global sea level rise. Under such warmer conditions seeps from continental shelf floors will become more frequent, and their contribution to the atmospheric C budget should be globally assessed.

Key words: SAR images, continental shelf, Argentina.

Filtraciones de petróleo desde la plataforma patagónica: su destino termoestérico

RESUMEN. Las imágenes de radar se aplican comúnmente para reconocer y monitorear las filtraciones de petróleo en las aguas superficiales sobre las plataformas continentales. En el Golfo San Jorge, Patagonia, entre los 46° S y 48° S, se han relevado manchas de petróleo que presentan patrones de elipse en respuesta a la dinámica mesotidal. Estos efectos fueron asignados a incrementos episódicos recientes de las temperaturas del fondo del verano a profundidades entre 100 y 120 m, que son 2 °C más cálidas que las registradas durante el siglo XX. Se supone que las manchas tienen su origen en fallas ya conocidas por la industria petrolera en tierra. Los efectos aquí descritos deben contemplarse en un escenario de cambio climático que provoque un aumento de la temperatura de las aguas poco profundas de los océanos, junto con otros efectos como el aumento global del nivel del mar inducido por el hombre. Bajo tales condiciones más cálidas, las filtraciones de los suelos de la plataforma continental serán más frecuentes y su contribución al balance de C atmosférico debe evaluarse globalmente.

Palabras clave: Imágenes SAR, plataforma continental, Argentina.

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Natural oil seeps have been surveyed at different locations worldwide. The most accurate figure was about 6×10^5 t y^{-1}, although it could vary from 2×10^5 to 2×10^6 t y^{-1} (Kvenvolden and Cooper 2003), while estimates of CH_4 contributions to the atmosphere from geological sources indicated 45 Tg y^{-1} (Kvenvolden and Rogers 2005). Synthetic Aperture Radar (SAR) images are progressively applied to detect and monitor oil spills. Wavelengths of C-band are preferentially applied to L and X-bands for detecting oil slicks (Marghany 2014; Nunziata and Miglioaccio 2015; Asl et al. 2017; Jafarzadeh et al. 2021).

San Jorge Gulf has been reported as the most polluted area of the Argentine coast. Highest hydrocarbon concentrations are associated with sandy sediments and gravel. This was primarily attributed to the extraction and transportation of oil through two loading buoys in Caleta Córdova and Caleta Olivia (Commendatore et al. 2000) (Figure 1). During the summer months of the Southern Hemisphere (January), three oil spills were detected close to San Jorge Gulf (Argentina) between 2017 and 2023. They were not related to known anthropogenic-triggered activities (spills); instead, they were related to oil seeping from the bottom of this productive basin. This paper described and analysed the occurrence and possible causes of these oil slicks.

San Jorge Gulf is located in the eastern Patagonia between 44° S and 47° S. Provinces of Chubut and Santa Cruz share the gulf. Tidal ranges increase from 3.5 m at the outer edge to more than 5 m at the interior (Isla et al. 2002). The sedimentary basin below the gulf has been producing oil and gas since 1910, covering an area of 170,000 km^2. San Jorge basin is known for its normal faults, which are common for the Salamanca Formation (Foix et al. 2008). Oil extraction is related to normal faults deepening 60°-65° prevailing E-W and ESE-WNW alignments (Sylwan 2001; Foix et al. 2008). The gulf was originated during the Holocene sea-level transgression (Desiage et al. 2023). Today, the sediment is supplied by cliffs subjected to coastal erosion, and occasionally by the wind (including ashfalls) and southerly coastal currents (Desiage et al. 2018). The gulf circulation is dominated by westerly winds and tidal currents (Isla et al. 2002). Temporal variability of the atmospheric heat flux increases from spring to summer (Palma et al. 2020).

In order to map these slicks, Sentinel 1-A radar images (C-band, 5.6 cm wavelength) were processed from different areas of the outer shelf of San Jorge Gulf during summer months. The VV polarization procedure gave better results for

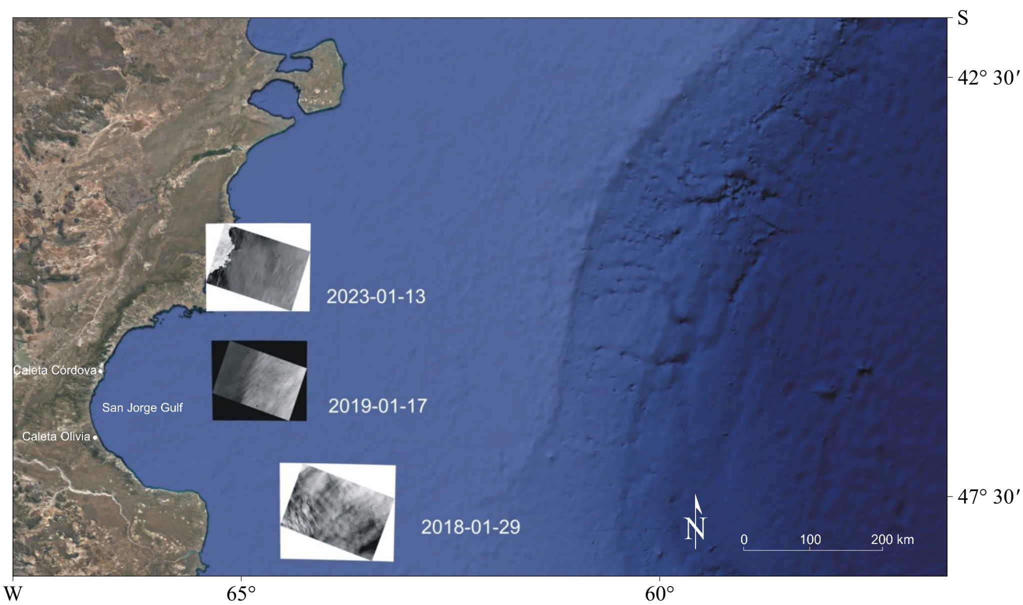

Figure 1. Location of seeps and dates recorded by Sentinel radar images.

those purposes than the HH polarization. The WV-GRD acquisition mode was preferred for scenes of 20 × 20 km, spatial resolution of 5 × 20 m, and vertical angle between 23° and 36.5°. The Copernicus Open Access Hub (European Space Agency, ESA) and the Alaska Satellite Facility of the National Aeronautics and Space Administration (NASA) were accessed for this research. Images from the interval 2015-2023 were analysed for different meteorological conditions. Radiometric, geometric and speckle noise (Lee Sigma and Frost) were performed with conversion to decibels and geolocalization through a Shuttle Radar Topography Mission (SRTM) masking the land territories. The SNAP 8.0 (SeNtinel Applications Platform; ESA) program was applied to get areas, perimeters and axis lengths of darks stains (Marzialetti 2012). False positives were assigned to surfactants liquids or biological detritus. In order to analyse the occurrence of these seeps during recent summers, the BARDO statistical database (Baldoni et al. 2008) of the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP, Argentina) was consulted (https://www.inidep.edu.ar/datos-oceanograficos).

Oil seeps were registered out of San Jorge Gulf during summer months of the southern hemisphere (January 2018, January 2019 and January 2023). Seeps of 2018 were reported by CGG Geoconsulting (2019). As the area is subjected to tidal ranges between 2 and 4 m, seeps configure ellipses with longer axis between 3 and 5 km (Figure 2). A careful examination denoted that some of these ellipses were oriented into lines.

Episodic temperatures three degrees warmer were recorded since the year 2000 at 120 m depth (Figure 3).

As slicks were distributed along lines or in clusters, they were assigned to faults that are evident at cliffs (Figure 4) and that have been detected by reflective seismic (Fígari et al. 1999). Comparing beach samplings performed between 1989 and 1995, highest values were recognised at Caleta Córdova and Comodoro Rivadavia, although no spills were related to these anomalous values (Commendatore et al. 2000). However, episodic natural spills at the outer gulf could explain these higher values.

Although oil seeps have been surveyed at the Argentine Exclusive Economic Zone (EEZ) (CGG Geoconsulting 2019), no prospection was carried out offshore San Jorge Gulf. Biological impacts of oil pollution in San Jorge Gulf were already analysed considering them of anthropogenic origin (Klotz et al. 2018).

Significant changes in the deep water temperature of oceans have been reported worldwide (Abraham et al. 2013). It was also postulated that

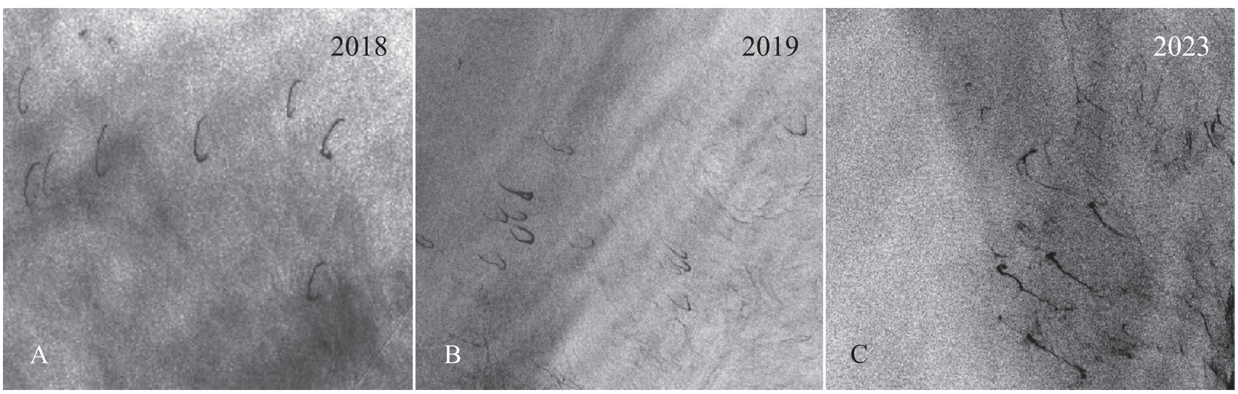

Figure 2. Partial ellipses from the outer area of San Jorge Gulf captured by radar Sentinel 1A, band C, image taken at 9.10 AM local time. A) January 29, 2018 (major axis 3.4 km). B) January 11, 2019 (major axis 5 km). C) January 13, 2023.

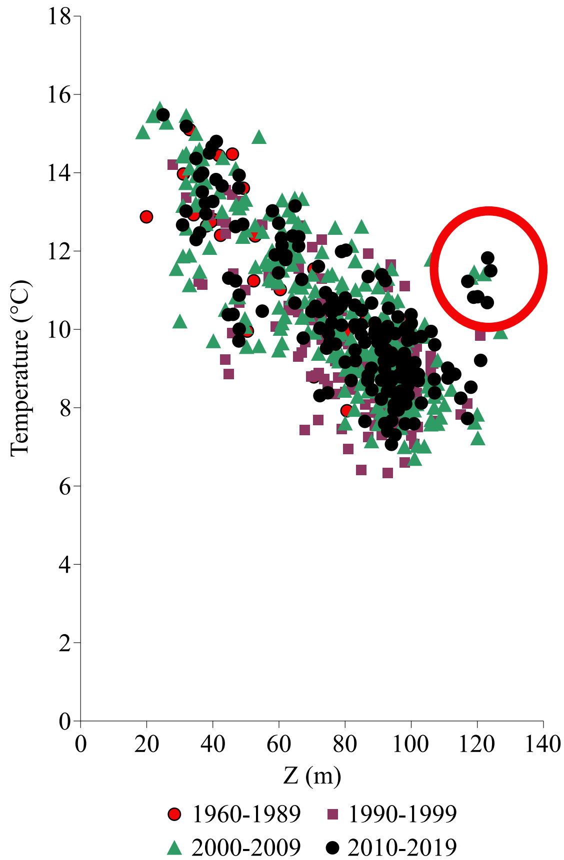

Figure 3. Water temperature records at different depths in San Jorge Gulf. The circle highlights the anomalous measurements (courtesy of INIDEP).

increments of intermediate water temperatures could release hydrocarbon gas along the Gulf Stream current to the uppermost planet cycle (Phrampus and Horbach 2012). The Argentine shelf is assumed to be warming in the last years with a possible migration of the convergence of Brazil and Malvinas currents due to a southwards displacement of Brazil current (Risaro et al. 2022; Chidichimo et al. 2022).

Increase in the tidal ranges could lead to an increase in the buoyancy of shallow-shelf oil accumulations (Idier et al. 2017; Pickering et al. 2017). Some models have been proposed to explain the behaviour of seeps in the Gulf of Mexico (Asl et al. 2017).

The upward velocity of droplets produced at the bottom depends on temperature, salinity (both as function of depths) and the diameter size of droplets (Najoui et al. 2018). Considering the sea-level rise trends expected for the next century (Oppenheimer et al. 2019), it is concluded that the buoyancy will increase and seeps will therefore be more frequent.

In the case of San Jorge Gulf, faults are conduits for hydrocarbons to reach the bottom (Figure 5). In Punta Peligro, sediment-filled fissures filled with friable, fine-grained sandstone strata, suitable for liquefaction/fluidization processes (Rio Chico Formation) (Foix et al. 2008) gave idea of the seepage probability of recurrence. According to the hook-shaped of the spills in January 29, 2018 and January 11, 2019, it would take at least 3 h the reversal of tides to produce those shapes. Faults were also reported to cause natural oil seeps monitored from Lower Congo Basin (Jatiault et al. 2017). According to a collection of SAR images, these spills lasted 3.25 h in relation to the wind speed. Considering wind statistics along the year it was estimated that this site was supplying 4,380 m^3 y^{-1} to the ocean surface and therefore considered the third biggest supply province from natural leakage (Jatiault et al. 2017). Applying ENVISAT-ASAR images from the South China Sea, it is rather difficult to know whether spills have been generated by gas hydrates or petroleum seeps (Wang et al. 2013). Although anthropogenic oil spills have been drastically diminishing worldwide in the last years (ITOPF 2022), oil tankers activities (Kluser 2006) along the trip from Buenos Aires to Tierra del Fuego are suspected of illegally cleaning of their deposits.

CONCLUSIONS

1) Natural oil seeps were repeatedly detected close to San Jorge Gulf during the summer months.

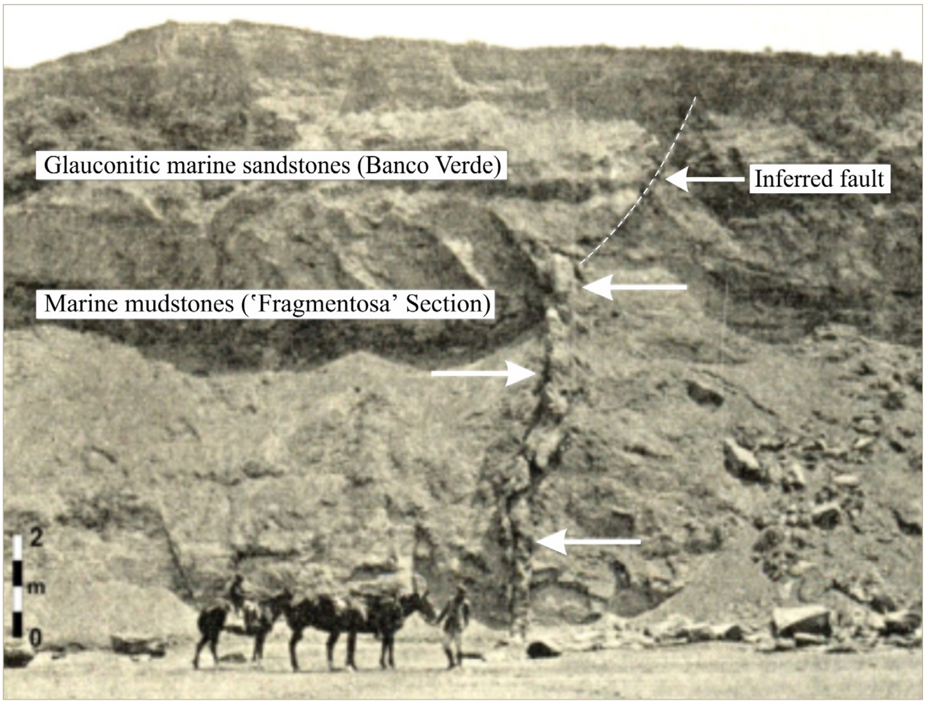

Figure 4. Fault at the coast of San Jorge Gulf (modified after Foix et al. 2008).

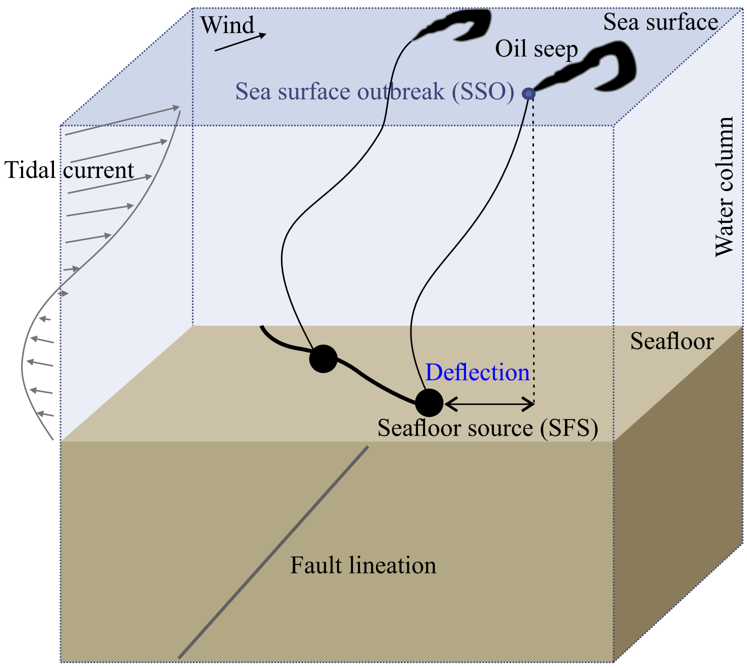

Figure 5. Seepage explanation of San Jorge Gulf seepage processes (modified from Najoui et al. 2018).

2) Anomalous bottom temperature increments in the gulf have been detected since 2000.
3) C-band and VV polarization radar images were the most useful to discriminate hydrocarbon stains related to seeps.
4) The SNAP software permitted to approximate the direction of these slicks and the wind velocity at the moment of the image captures.
5) L-band images (Alos Palsar) were compared to the C images showing less details due to the longer wavelengths.

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Author contributions

Federico I. Isla: conceptualization, investigation, supervision, validation, writing-original draft, writing-review and editing. Luis C. Cortizo: image processing, formal analysis, investigation, methodology.

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