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Geologic control of natural marine hydrocarbon seep emissions, Coal Oil Point seep field, California

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Abstract High-resolution sonar surveys, and a detailed subsurface model constructed from 3D seismic and well data allowed investigation of the relationship between the subsurface geology and gas-phase (methane) seepage for the Coal Oil Point (COP) seep field, one of the world's largest and best-studied marine oil and gas seep fields, located over a producing hydrocarbon reservoir near Santa Barbara, California. In general, the relationship between terrestrial gas seepage, migration pathways, and hydrocarbon reservoirs has been difficult to assess, in part because the detection and mapping of gas seepage is problematic. For marine seepage, sonar surveys are an effective tool for mapping seep gas bubbles, and thus spatial distributions. Seepage in the COP seep field occurs in an east–west-trending zone about 3–4 km offshore, and in another zone about 1–2 km from shore. The farthest offshore seeps are mostly located near the crest of a major fold, and also along the trend of major faults. Significantly, because faults observed to cut the fold do not account for all the observed seepage, seepage must occur through fracture and joint systems that are difficult to detect, including intersecting faults and fault damage zones. Inshore seeps are concentrated within the hanging wall of a major reverse fault. The subsurface model lacks the resolution to identify specific structural sources in that area. Although to first order the spatial distribution of seeps generally is related to the major structures, other factors must also control their distribution. The region is known to be critically stressed, which would enhance hydraulic conductivity of favorably oriented faults, joints, and bedding planes. We propose that this process explains much of the remaining spatial distribution.

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Introduction

Methane seepage and atmospheric budgets

Hydrocarbon seepage is an important geological process whereby fossil geologic carbon (without ^{14}C), primarily consisting of the important greenhouse gas methane, CH_4, escapes from the lithosphere to the hydrosphere and atmosphere. Geologic CH_4 sources such as marine seeps contribute an estimated 20–30 Tg year^{-1} (1 Tg=10^{12} g), with terrestrial microseepage and mud volcanoes adding 30–55 Tg year^{-1} (Kvenvolden et al. 2001; Judd 2004; Etiope et al. 2009). The total global CH_4 budget is 580 Tg year^{-1}, of which ~18% (i.e., 104 Tg year^{-1}) is estimated to be fossil (IPCC 2001 2007; Denman et al. 2007). This suggests the natural fossil CH_4 budget arises almost entirely from seeps, with marine seeps contributing 20–30%.

Recent studies suggest that methane's radiative forcing over its entire chemical atmospheric lifetime in the troposphere and stratosphere could be ~30% of the radiative forcing of carbon dioxide, CO_2 (Shindell et al. 2005). Because methane's atmospheric residence time (decade) is far shorter (Lelieveld et al. 1998) than that of

CO_2 (century), CH_4 regulatory efforts can affect the atmospheric radiative balance more easily than for CO_2 (Shindell et al. 2005; Etiope 2009). As a result, future Kyoto-type treaties likely will seek to reduce and regulate anthropogenic CH_4 emissions, including those related to fossil fuel activities. Therefore, quantifying natural fossil CH_4 is key to monitoring and reducing anthropogenic CH_4 emissions.

Estimates of global CH_4 contribution from marine seeps have been based on extrapolation of data from the seep field offshore Coal Oil Point (COP), California—the site of the present study—and by assuming that the global seep-emission probability distribution is log normal (Hovland et al. 1993; Hornafius et al. 1999). Other approaches have considered theoretical aspects (Kvenvolden et al. 2001), or evaluated atmospheric fossil CH_4 budgets and sources (Etiope 2009). Hovland et al. (1993) fitted a log normal distribution to an inventory of global seepage sites, and derived an annual budget of 8 to 65 Tg $year^{-1}$. Kvenvolden et al. (2001) assumed a leakage rate for global gas and oil reservoirs, and derived an estimate for marine seeps of 20 Tg $year^{-1}$. Hornafius et al. (1999) calculated a global emission of 18–48 Tg $year^{-1}$, assuming the COP seep field flux is among the top 0.1–1% of a global log normal seep field emission distribution.

Geology and seeps

Vertical migration of CH_4 from the reservoir strata to the seafloor occurs along focused, permeable migration pathways (Judd 2003), often created by faults and fractures (Hunt 1995; Whelan et al. 2005). Marine seepage from these pathways manifests at the seafloor as mud volcanoes, pockmarks, and bubble plumes (Milkov 2000; Kopf 2002; Whelan et al. 2005). Important controlling factors are tectonic; for example, mud volcanism most commonly is associated with compression settings (Kopf 2002). Fold-and-thrust fault belts are a prominent setting for fluid migration from deeper layers through faults and fractures, allowing accumulation of hydrocarbons in anticlines and other traps (Bonini 2007). In some settings, geologic structures close to the seabed, such as authigenic carbonates (Boetius and Suess 2004) and low-permeability sediment (e.g., clay) layers (Naudts et al. 2006), can be important factors controlling flux rates.

In this study, we present a unique, very high spatial-resolution view of the COP seep field that shows a linkage between the subsurface geology and the gas seepage distribution at the seafloor.

The Coal Oil Point seep field

The COP seep field (Fig. 1) is among the largest and best-studied areas of active marine seepage in the world. These perennial and continuous oil and gas seeps have been active on the northern edge of the Santa Barbara Channel for at least 500,000 years (Boles et al. 2004). Surveys with sonar (Hornafius et al. 1999) and direct gas capture (Washburn et al. 2005) suggest that ~ 1.0–$1.5 \times 10^5 \, m^3 \, day^{-1}$ gas escapes from $\sim 3 \, km^2$ of seafloor to the atmosphere, with a roughly equal amount dissolving into the coastal ocean (Clark et al. 2000). Oil seepage, which occurs along with gas seepage, is estimated at over 100 barrels (1.6×10^4 barrels day^{-1}; Clester et al. 1996; Hornafius et al. 1999). Seepage at COP primarily is associated with the offshore South Ellwood oil field that has been in production from Platform Holly (Fig. 1) since 1966, and which taps reservoirs within the Miocene Monterey Formation, the primary source of petroleum hydrocarbons in the Santa Barbara Channel (Ogle et al. 1987). Total production has been $9.49 \times 10^6 \, m^3$ oil (5.97×10^7 barrels) and $1.48 \times 10^9 \, m^3$ gas ($5.22 \times 1 \, 0^{10} ft^3$) as of September 2008 (data from Venoco Inc., Carpinteria, CA 2008).

For the South Ellwood Field, the Miocene-age Monterey Formation is composed of siliceous shales, organic shale, porcellanite, chert, and dolostone, and is both an active hydrocarbon source and a fractured reservoir (Kamerling et al. 2003). Active hydrocarbon formation occurs at depths below ~ 3 to 4 km (Olsen 1982; Mero et al. 1992; Kamerling et al. 2003). Permeability of the rock matrix typically is low, ranging from 0.1 to 10 milli-Darcies, but open fractures and fault damage zones provide important migration pathways (Finkbeiner et al. 1997; Boles and Horner 2009). The Monterey Formation is overlain by the relatively impermeable, Pliocene-age Sisquoc Formation, which is the seal for hydrocarbon accumulation. Hydrocarbons migrate from subsurface accumulations to the seabed by pathways that have been presumed related to faults, fractures, joints, bedding planes, and outcrops (Fischer 1978; Boles and Horner 2009).

Methodology

Sonar surveys

Sonar is an effective tool for mapping seeps, because gas bubbles in water are strong acoustic scatterers (e.g., Hornafius et al. 1999; Quigley et al. 1999). A chirp sonar (model 424 Edgetech, 4 to 16 kHz) was towed along a series of parallel transect lines that cover the seep field. Seepage in water shallower than 16 m was not surveyed due to obstruction by kelp beds. The root mean square (rms) amplitude of the sonar backscatter from seep bubbles, σ, was calculated within a water-column depth window spanning from 5 m above the seabed to 10 m deep (always more than 1 m thick), which then was normalized by the mean rms
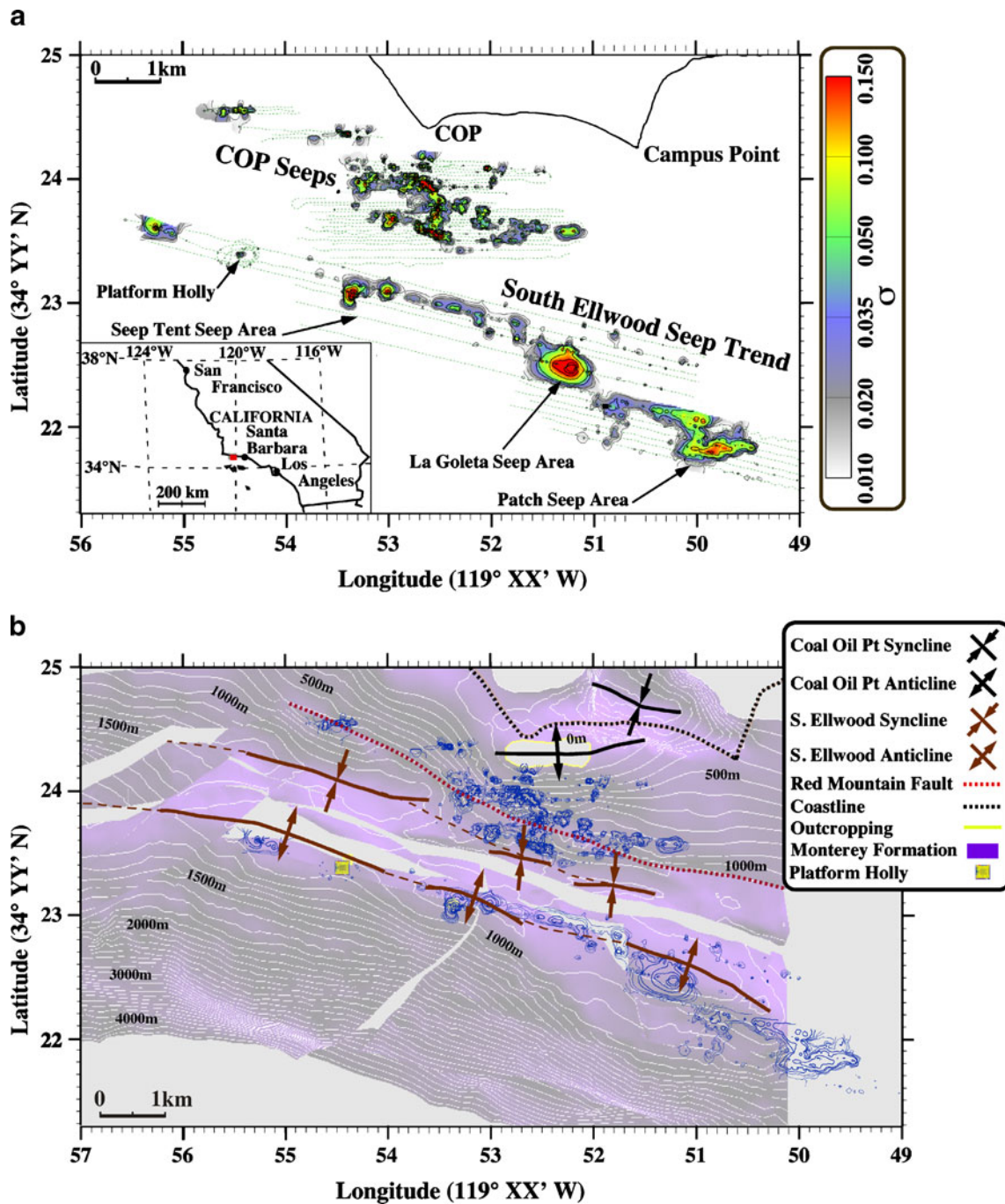
Fig. 1 **a** Water column-, bottom bounce-normalized rms sonar return (σ) amplitude map of the seep bubble plumes in the Coal Oil Point (*COP*) seep field, Santa Barbara Channel, California. The South Ellwood seep trend was surveyed in April 2005. The *inset* shows the southwest US, and the seep field location (*red box*). Seep names are informal. Contours and color map are logarithmically spaced. The *bar scale* (*right*) indicates normalized seepage strength. **b** Map of the top of the Monterey Formation (see Figs. 2 and 3), contour interval 100 m. Trends of anticlines (diverging arrows) and synclines (converging arrows) are shown as *dashed* (average trend) and *solid lines* (local highs and lows). The Red Mountain Fault line shows where it cuts the Monterey Formation (data from Venoco Inc., Carpinteria, CA)

bottom-bounce amplitude for each survey line. To account for non-linearity in the characteristic sonar response due to instrument settings and other factors, σ was normalized further to match the probability distribution of background noise between transect lines. That value was multi-pass gridded

(Smith and Wessel 1990) by first averaging all normalized σ within each grid cell at a coarse resolution grid of 80 m. Empty grid cells were filled by a harmonic interpolation algorithm. Then, the original data and interpolated values were combined and re-gridded for 20-m cells.

Mapping (Fig. 1) revealed several seepage trends. Furthest offshore lies the South Ellwood seep trend (at ~70 m water depth), which extends several kilometers in an approximately west northwest–east southeast (N70W) direction. Closer to shore are a number of shallower (15 to 45 m) seep trends that are aligned subparallel to the offshore seeps trend, but include a secondary trend that is N20E or north northeast–south southwest. A 1996 and 2006 survey showed an absence of seepage between these trend lines.

Subsurface mapping

The subsurface geologic model (Figs. 2 and 3) was constructed with data from a 3D seismic survey, 2D seismic reflection lines, surface geology, and 168 wells (see Fig. 3c for some well paths). The subsurface structure of the field was interpreted in the mid-1980s utilizing 1983 vintage 2D and 3D seismic data. Integrated geologic studies continued in the early 1990s based on the original structural interpretation. Venoco Inc. (Carpinteria, CA) acquired the South Ellwood Field in 1997, and initiated a modern reservoir characterization study of the field (Horner and Ershaghi 2002). The earlier 3D seismic data (Christensen et al. 2000; Kamerling et al. 2003) were reprocessed and reinterpreted by including reservoir production and pressure

data. This allowed construction of a new, 3D geologic model incorporating the new seismic interpretation, well logs, dipmeter, core, and outcrop information (Christensen et al. 2000; Kamerling et al. 2003).

Results

Seepage, and faults and folds

Fischer (1978) noted a relationship between the South Ellwood seep trend and the South Ellwood anticline (Fig. 1). Here we present a new and detailed model of geological structures underlying the COP seep field, and further explore this relationship. The anticline axes in Fig. 1 were drawn from maps of the depth to the top of the Monterey Formation. The major structures are two approximately WNW–ESE-trending anticlines separated by a syncline that is faulted on both flanks (Fig. 2). The co-location of the furthest offshore seepage distribution with the South Ellwood anticline crest suggests that folding of the Monterey and Sisquoc Formations plays a dominant role in controlling seepage here.

The top of the Monterey Formation rises very gradually from the mid-Santa Barbara Channel northward until ~4 km offshore where it is ~5 km deep, then rises steeply
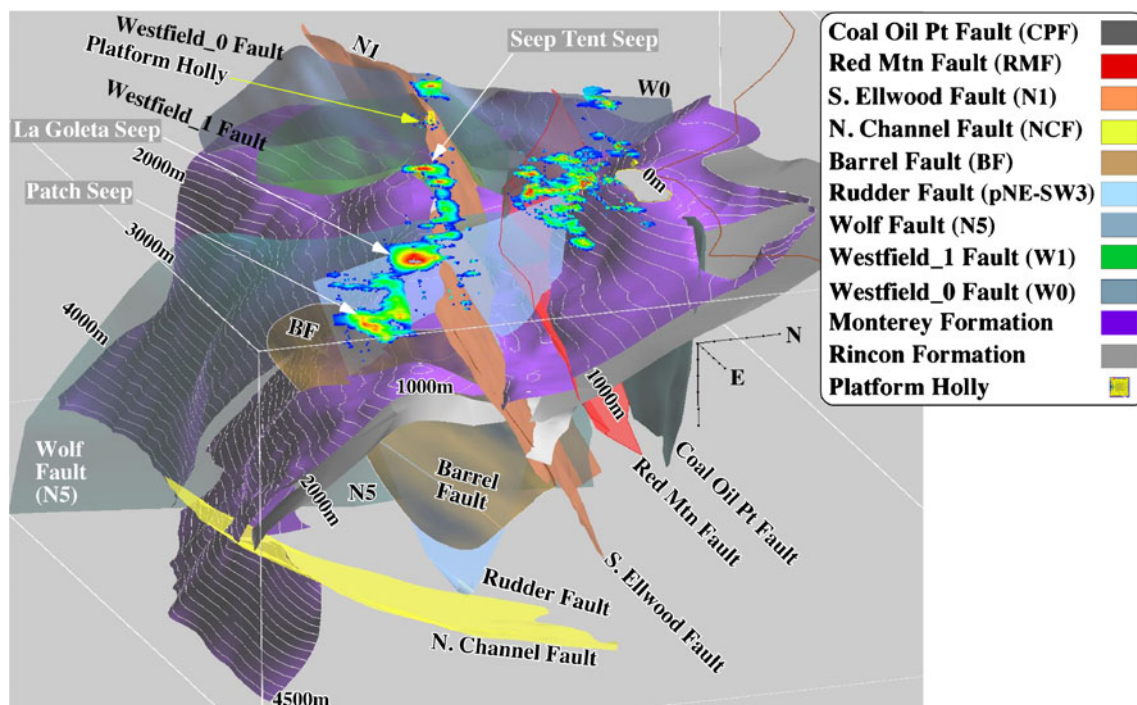

Fig. 2 Oblique view from above looking northwest at the Coal Oil Point seep field distribution, underlying geologic structure showing faults, Monterey Formation (MF), and Rincon Formation (i.e., base of the MF), and seep bubble spatial distribution (*red* strong, *blue* weak emission). Hydrocarbon formation occurs for depths below 3 km. Depth contours every 100 m. Projection is uniform. Orientation axis has size scale dots every 200 m on axes. Fault codes are from Venoco. Platform Holly is owned and operated by Venoco Inc., Carpinteria, CA
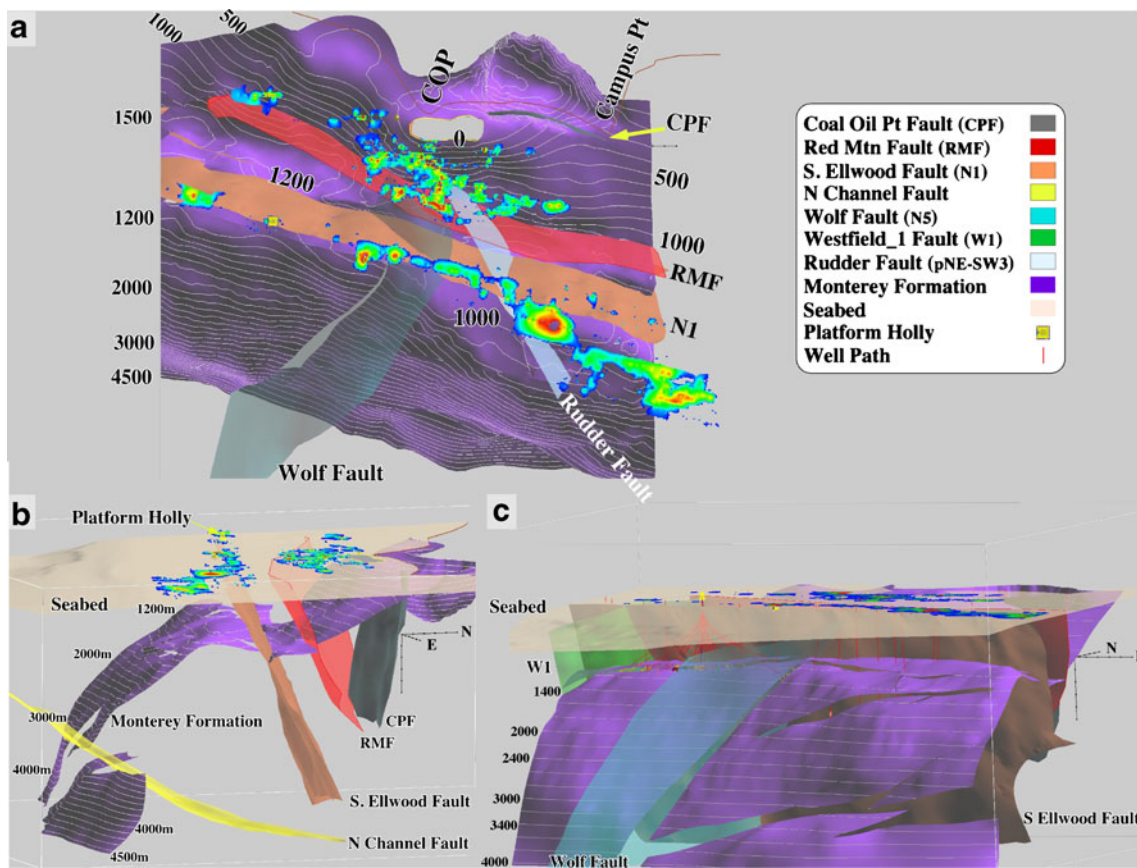
Fig. 3 Coal Oil Point seep field, underlying geologic structure showing the Monterey Formation (MF), and seep gas spatial distribution (*red* strong, *blue* weak emission). **a** Map view. **b** West–northwest view with partially transparent seabed and labeled faults. **c** Oblique northward view showing wells (*red lines*). Note that not all faults are shown on all figure parts. MF depth contours on **a** and **c** every 100 m. Projection is uniform. Orientation axis with size scale dots at 200-m intervals. Fault codes are from Venoco Inc., Carpinteria, CA

toward the shore. In the COP area, the top of the Monterey Formation is the shallowest for many tens of kilometers along the coast (Ogle et al. 1987). Nearshore, the Monterey Formation is cut by the north-dipping blind-thrust North Channel Fault (Fig. 2), which has been proposed to have caused the magnitude 5.1 Santa Barbara earthquake of 1978 (Hornafius et al. 1996). The Monterey Formation then rises to the north until it is about 1 km deep at the crest of the South Ellwood anticline. The anticline is cut on its north limb by the South Ellwood Fault System (SEFS), of which several parallel faults have been identified (Figs. 2 and 3). The SEFS is comprised of reverse faults that have been rotated into apparent normal throw (Christensen et al. 2001). Well data show a thick damage zone (<20 m) associated with the SEFS.

Inshore (north) of the SEFS, the top of the Monterey Formation lies about 1 km deeper in a down-dropped block. This block extends about 1 km further north, where the Monterey Formation is offset upward by several hundred meters across the Red Mountain Fault (RMF), a major, north-dipping left-oblique reverse fault. The Monterey Formation is thicker within the down-dropped block than

to the south of the SEFS and to the north of the RMF. The RMF plays a significant role in shaping the north side of the Santa Barbara Basin (Jackson and Yeats 1982). North of the RMF, the Monterey Formation rises and is exposed in a "peanut-shaped" seafloor outcrop at the crest of the E–W-trending COP anticline (0-m contour, on Fig. 3a). North of this anticline axis, the Monterey Formation dips north, with the steepest portions along the Coal Oil Point Fault.

Seepage trends, faults, and anticlines

The furthest offshore seepage trend (South Ellwood seep trend) closely follows the axis of the South Ellwood anticline (Fig. 1) east of the roughly northeast–southwest (N70W)-trending left-lateral Wolf Fault (Figs. 2 and 3), with the strongest seepage (La Goleta Seep) near but not at the shallowest portion of the anticline crest (Figs. 1 and 3a). The seepage decreases both toward the east (Patch Seep Area; Fig. 2) and west of the La Goleta Seep, where the anticline crest is deeper. West of the Rudder Fault, the South Ellwood seep trend follows the main SEFS (Figs. 2 and 3a), extending to the seep field's western edge. The La Goleta

Seep is constrained to the west by the approximately northwest–southeast (N15W)-trending right-lateral Rudder Fault (Fig. 2), while a short NE–SW (N30E) seepage trend at the southeast edge of the La Goleta Seep area follows the NE–SW (N45E)-trending left-lateral Barrel Fault (Fig. 2; for clarity, the Barrel Fault is not displayed in Fig. 3). The Rudder Fault cuts across the RMF (Fig. 3a), and intersects several inshore seep areas and possibly the Wolf Fault. The Westfield_0 and Westfield_1 Faults are left-lateral cross faults that trend approximately NE–SW (N50E, N40E), and cut the SEFS (Figs. 2 and 3c). They appear to delineate the seep field's western edge (the northern end of the West-field_1 Fault was not mapped due to an absence of seismic data). Although seepage is found south of the SEFS, it is almost entirely absent immediately north of this fault over the syncline in the down-dropped block between the SEFS and RMF. The South Ellwood anticline to the west of the approximate location of the Wolf Fault is under oil and gas production (Fig. 3c). In contrast, the South Ellwood Anticline is not reached by wells from Platform Holly (Horner and Ershaghi 2002), suggesting seepage here is minimally affected by production activities.

Overall, the relationship between seepage and structure appears to be straightforward in the South Ellwood seep trend. Hydrocarbons seep from above the shallowest part of the South Ellwood anticline through (unmapped) fractures and joints in the capping Sisquoc Formation to the seafloor. Flexure in the anticline places the rock at the crest under tension, tending to open fractures and joints. Here, the damage zone associated with the SEFS creates pathways to the seabed through which hydrocarbons migrate; however, migration is largely absent to the north of the SEFS over the down-dropped syncline block. The almost complete absence of seepage from the down-dropped block most likely is because of sealing by the overlying Sisquoc Formation; it is highly impermeable, is thicker here (2 km, compared to 1 km), and is under compression in a faulted syncline, causing fractures and joints to be closed. Instead, seepage preferentially occurs to the seafloor through the adjacent fault zones (the SEFS and RMF) bounding the block (Fig. 3b).

Inshore seepage patterns are more complex; seepage is restricted to the hanging wall (north side) of the RMF, which intersects the seabed at the southern boundary of the inshore area of seepage (Figs. 2 and 3). Inshore seepage is concentrated immediately to the south of the outcropping of the Monterey Formation in the COP anticline. The area immediately south of the anticline is where the Monterey Formation dips south most steeply (Fig. 3a). This appears to demonstrate a correlation between seepage and the deformed nature of the Sisquoc and Monterey Formations, with steeper dips related to the strongest areas of seepage. This is consistent with the proposed model of Bonini

(2007) that related seepage to fractures in regions of high curvature in folds (e.g., crests of anticlines).

Complicating the interpretation of the inshore seepage control is the apparent but unmapped nexus of cross faults (e.g., Westfield_0, Westfield_1, Wolf, Barrel, and Rudder Faults), suggesting that fractures are focused where these faults intersect. This would promote seepage by creating multiple migration pathways (Fig. 2).

The Santa Barbara Basin is a tectonic compression setting, and the seep trends inshore of the Red Mountain Fault possibly indicate a critically stressed (near failure) fault and fracture system. Therefore, fractures and faults that are favorably oriented for failure in the dominant horizontal, NE–SW-oriented stress system of the region (Finkbeiner et al. 1997) should contain numerous low-resistance migration pathways promoting hydraulic conductivity and thus seepage.

Migration and recharge

Detailed migration pathways to the seafloor at COP can be inferred from the high-resolution mapping of both the subsurface geology and the gas bubble (with oil) plumes within the ocean. Recharge of the hydrocarbon reservoir in the South Ellwood anticline occurs through updip migration along bedding planes primarily from the deeper Monterey Formation to the south (Ogle et al. 1987). Recharge also will occur from the east and west—the COP seep field is at an east–west crest of the Monterey Formation (Ogle et al. 1987). As a result, along-coast migration likely occurs along both syncline and anticline axes, allowing recharge also to occur through the dropped block between the SEFS and RMF where Venoco well data show the presence of hydrocarbons. Well data and production thermal geohistory calculations for the Point Arguello Field (~70 km west of the COP seep field in the offshore Santa Maria Basin) show hydrocarbon formation for the Monterey Formation deeper than 3 km, while data from the COP seep field for wells that penetrate the dropped block show a similar temperature gradient and the presence of hydrocarbons, demonstrating migration through this pathway. Imaged strata dip slightly south within this down-dropped block, allowing updip hydrocarbon migration into the overhanging RMF and the Monterey Formation in the hanging wall. These hydrocarbons, as well as hydrocarbons from offshore under the channel, likely contribute to inshore seepage.

Discussion and conclusions

A close relationship between tectonic compression structures and seepage long has been recognized (Hunt 1995). Our unique data suite, including high-resolution sonar surveys of marine gas seepage and 3D subsurface geology

determined from seismic and well data, offers a highly detailed view of the relationship between subsurface geology and hydrocarbon seepage for one of the world's largest and best-studied marine seep fields, the Coal Oil Point (COP) seep field. The COP seep field is located in an active fold-and-thrust belt (Namson and Davis 1990) that is the result of contraction (compression) tectonics that has persisted in this region of the Pacific–North American plate boundary since the Late Miocene sub-epoch (Atwater 1989).

In the COP seep field, significant seepage (i.e., leakage) occurs from near the crest of a faulted fold (offshore seeps), and within the hanging wall of a reverse fault where the reservoir and capping formations are deformed but without mapped faults obvious faulting (inshore seeps). Of the two major mapped seep areas, the area farther offshore shows a clearly defined first-order relationship between a faulted anticline and seepage locations. The inshore seep area, on the other hand, does not show an obvious relationship with structure, other than being located in the hanging wall of a major reverse fault. We suggest seepage here is controlled by critically stressed fractures (Finkbeiner et al. 1997) in the hanging wall of the east–west-trending Red Mountain and Coal Oil Point Faults. Subsurface studies in the South Ellwood field by Venoco show that the principal horizontal stress is oriented ~N20E. Thus, strike slip faults oriented ~N50E and ~N10W could be critically stressed. Candidates are the Wolf Fault (N55E), and less so the Rudder Fault (S30E) and Barrel Fault (N30E).

The North Channel Fault (Figs. 2 and 3b) is favorably oriented for thrust failure, but is not an obvious source of seepage. The Red Mountain Fault and South Ellwood Fault System are steeply dipping, and so are not favorably oriented for failure, based on assuming a simple Anderson model for faulting. These faults should have very high normal stresses. Permeability of the damage zone adjacent to the South Ellwood Fault System explains the high productivity of wells and enhanced seepage along this fault. Wells penetrating this fault system through the typically impermeable Sisquoc Formation have hydrocarbon shows that indicate hydrocarbon migration along the fault. Deformation in the hanging wall of the Red Mountain Fault in association with intersecting cross faults could explain the complex patterns of abundant seepage in this area (see Fig. 3a).

Using our high-quality surface and subsurface data, it is not entirely obvious from the mapped structures alone what is controlling the seep spatial distribution; some of the high-permeability pathways at Coal Oil Point are below the resolution of the geologic model. Thus, simple geologic models—for example, based on fold curvature (Bonini 2007)—may adequately describe the seepage distribution only in part. The farthest offshore seeps are well predicted in some places, but in the southeast, these seeps are focused

south away from the prominent South Ellwood Fault System and the underlying anticline crest. The inshore seeps are even less clearly related to structure, beyond being restricted to the hanging wall of the Red Mountain Fault. The implication is that fracturing without faulting (e.g., favorably oriented joints without offsets), fault intersections, and fault damage zones are significant preconditions for seepage. This seems obvious in concept, but difficult to either map or predict.

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