RELATIONSHIP BETWEEN OIL AND GAS PRODUCTION AND NATURAL SEEP INTENSITY
IN THE SOUTH ELLWOOD FIELD - SANTA BARBARA CHANNEL
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EXECUTIVE SUMMARY

Venoco is proposing to adjust the existing lease boundary for the South Ellwood oil field into an adjacent area for additional oil and gas recovery as part of the South Ellwood Lease Line Adjustment Project (the “Project”). As part of the environmental review of Venoco’s Project, the California State Lands Commission is seeking to define the degree to which oil and gas production leads to a reduction in the amount of natural seepage on the seafloor, and the beneficial effects of the reduction in seepage, in particular, in reducing the emissions of greenhouse gases (GHG) and reactive organic gases (ROCs). The goal of this report is to use existing data to address this question; both oil and gas seepage are discussed, although the focus is on gas seepage.

Ramboll Environ’s evaluation of the subsurface interactions between oil and gas production and natural seepage rates found the same geological conditions, including the presence of the currently highest intensity seeps at the crest of the folded, faulted, and fractured anticlinal trend, are observed to be continuous across the lease line into the Lease Line Adjustment Area. Therefore we conclude that, should the Lease Line Adjustment be granted, the proposed wells that cross into the Lease Line Adjustment Area will lead to substantial reduction or cessation of submarine seepage overlying the produced zone. Based on observed long-term reduction and cessation of seepage and seep tent production near Platform Holly, it is expected that the reduction in seepage in the Lease Line Adjustment Area would persist well beyond the life of the Project. Below is a summary of the estimated ranges of project-related air emissions reductions in the Lease Line Adjustment Area:

- The total Project-related methane reductions in the Lease Line Adjustment Area were estimated to be between 8.0 to 32 tonnes/day.
- The total Project-related GHG emissions reductions in the Lease Line Adjustment Area were estimated to be between 198 to 798 tonnes/day.
- The total Project-related ROC emissions reductions in the Lease Line Adjustment Area were estimated to be between 3.3 to 13 tonnes/day. The estimated reduction in ROCs, a precursor to ozone formation, is substantial when compared to the total ROC inventory in Santa Barbara County in 2008 (29.3 t/day) (SBCAPCD and SBCAG, 2015).
1. INTRODUCTION

Venoco is proposing to adjust the existing lease boundary for the South Ellwood oil field into an adjacent area for additional oil and gas recovery as part of the South Ellwood Lease Line Adjustment Project (the “Project”). As part of the environmental review of Venoco’s Project, the California State Lands Commission is seeking to define the degree to which oil and gas production leads to a reduction in the amount of natural seepage on the seafloor, and the beneficial effects of the reduction in seepage, in particular, in reducing the emissions of greenhouse gases (GHG) and reactive organic gases (ROCs). The goal of this report is to use existing data to address this question; both oil and gas seepage are discussed, although the focus is on gas seepage.

The South Ellwood oil field is located in California state waters approximately two miles offshore in the Santa Barbara Channel. Venoco produces oil and natural gas from Platform Holly in the South Ellwood Field, and processes the resources at an onshore facility (Figure 1). Venoco acquired the rights to Platform Holly from Mobil in 1997 and has operated continuously since that time. Platform Holly was built in 1966 and reached peak production in 1984.

The South Ellwood field is approximately seven miles long and is part of a regional east-west trend of similar geologic structures running along the northern flank of the Santa Barbara channel. This structural trend encompasses several oil and gas fields that, over their respective lifetimes, are each expected to produce over 100 million barrels of oil, according to the California Division of Oil, Gas, and Geothermal Resources. The Monterey Formation, particularly the naturally-fractured shale portions of the formation, is the primary oil reservoir for the fields. Current operations are performed under existing State Leases PRC 3120.1 and 3242.1, however a significant portion of the South Ellwood Field sits to the east of the existing PRC 3242.1 lease line (Figure 1). Venoco is seeking a lease-line adjustment to allow for more efficient and accelerated recovery of the known remaining oil and gas within that portion of the South Ellwood Field.
Introduction

1.1. Natural Seeps and Relevant Literature for the South Ellwood Field

The existence of an offshore oil and gas field was suspected prior to exploration as a result of the observation of persistent natural seepage of oil from the sea floor; the Coal Oil Point seep field is one of the largest and most spectacular such zones in the world (Hornafius et al. 1999).

Figure 2 is a schematic diagram of a conceptual natural seep that is sourced from an oil and gas bearing reservoir, migrates upwards through natural fractures, and enters the water column. Heavy oil tends to accumulate near the source of the seep, smaller droplets are transported with the current to either form a layer floating on water, or depositing as a fallout plume. Gases in part dissolve in water and in part are vented to the atmosphere.
Figure 2: Schematic depiction of a natural seafloor oil seep.

There are three primary references that address the potential for interaction between oil and gas production and natural seepage rates; these include numerous useful references to secondary data sources:

1. Hornafius, Quigley, and Luyendyk (1999, JGR vol 104, pp. 20,703-20,711). The world’s most spectacular marine hydrocarbon seeps (Coal Oil Point, Santa Barbara Channel, California): Quantification of emissions.

2. Quigley, Hornafius, Luyendyk, Francis, Clarke, and Washburn (1999, Geology vol 27, pp 1,047 to 1,050). Decrease in natural marine hydrocarbon seepage near Coal Oil Point, California, associated with offshore oil production.


Hornafius et al. (1999) focus on seep-related methane emission rates from the marine environment. However, in comparing mapped distribution of seeps from 1946, 1953, and 1973 they note that the locations are mostly unchanged, with the exception of the seepage field in the vicinity of Platform Holly. The authors note that there was a substantial reduction in seepage during this time within a 1-km radius from Platform Holly, and they attribute the
reduction to reduction in reservoir pressure as a result of oil and gas development. Specific to Platform Holly, Hornafius et al. compare the 1977 seep emission rate (Fisher 1977) with their data from 1995, and identify an 80% reduction in seepage rate within 1 km of Platform Holly. A more recent survey of seep tent data (Liefer et al. 2010) shows further reduction, as discussed further below. They state that the reduction is due to the reduction in reservoir pressure as a result of production from Platform Holly.

Quigley et al. (1999) primarily focus on the connection between oil and gas production at Platform Holly and reductions in seep intensity within a 1 km radius of Platform Holly. In addition to the data cited in Hornafius et al., Quigley et al. also include data from the seep tents near Platform Holly. They note that because there are only two measurements of seep extent (1977 and 1999) that correspond to the time of measurements from the seep tent, it is difficult to correlate seep extent and emission rates in the seep tents. They conclude that the seep rate is controlled by the reservoir pressure. Accordingly, the reduction in reservoir pressure tapped by Platform Holly would explain the observed decreases in gas emission and seep extent in the vicinity. Quigley et al. also conclude that a secondary effect is that, as the reservoir pressure has decreased, ocean water has been drawn into the reservoir. As discussed further in this report, this sets up a counterflow that would further inhibit the upward flow of seepage from the reservoir.

Boles (2015) focuses directly on the connection between oil and gas production and seep intensity. Boles concludes that oil and gas production from Platform Holly has reduced seep intensity in the vicinity. He attributes this reduction to the interaction of several factors, discussed further in this report:

1. Buoyancy of oil and gas compared to water, seawater, and surrounding rocks, a hydrostatic condition.
2. Reduction of reservoir pressure reducing a second driving force for seepage, a hydrodynamic condition.
3. Counterflow of seawater drawn in to the reservoir as a result of the drop in reservoir pressure, another hydrodynamic condition.

Boles also presents a discussion of the relationship between production from Platform Holly well 3242-15RD1 and the shallower well 3242-7RD2. These wells intersect the potential source fault for the gas captured in the seep tents, and the wells have high gas production rates. As described in text, the gas production from these wells correlated with the progressive reduction and termination of natural gas capture at the seep tents.

In addition to these data sources, we also reviewed data held by Venoco related to the structural characteristics of the South Ellwood Field, production history and plans, reservoir pressure, and related information.

1.2. Study Objectives

In order to achieve the goal of this report (use existing data to address the relationship between oil and gas production and natural seepage, including the environmental benefits, if any), the following study objectives have been established:

1. Examine and determine whether there is a causal link between hydrocarbon production and seepage rate.
   a. Identify the correlation, and whether it would be expected to occur within the Lease Line Adjustment Area.
   b. Describe causative mechanisms for the observed correlation.
Relationship Between Oil and Gas Production and Natural Seep Intensity In the South Ellwood Field - Santa Barbara Channel

c. Evaluate alternate causative mechanisms for the observed correlation.
d. Quantify changes to seepage rates.
e. Identify changes, if any, to seepage composition
f. Identify changes, if any, to the ultimate fate of the materials emitted from theseeps

2. Quantify the amount of GHG (i.e., methane and CO₂) and ROC that is captured by the oil and gas production that would otherwise be released to the atmosphere, if any.

The second objective seeks to quantify the potential air quality and greenhouse gas benefits of production east of the current State Lease PRC 3242.1 lease line.
2. **SUBSURFACE INTERACTIONS**

This section uses existing information to evaluate the subsurface interactions between oil and gas production and natural seepage rates and to provide an estimate of the change in gas flux rate from seeps that result from these interactions.

2.1. **Observed Correlations**

Several correlations are evident in the data, including (1) a correlation of seep location to underlying geological structure; (2) an inverse correlation of seepage intensity near Platform Holly with petroleum production; (3) an inverse correlation of seepage intensity at the seep tents with petroleum production, and (4) similarity in geological and seepage conditions in the proposed Lease Line Adjustment area. Each is discussed below.

2.1.1. **Correlation of seep areas with underlying geological structures**

The South Ellwood structure belongs to a regional east-west anticlinal trend that includes the northern flank of the Santa Barbara Channel and the onshore Ventura Basin. The South Ellwood field is a ∼9-mile long doubly-plunging and faulted anticline that trends northwest. The structure verges to the south, with reverse faults near-parallel to the anticlinal axis on the south flank and a fault-bounded syncline on the north. The syncline partially separates the main part of the field from the next anticline to the north (Coal Oil Point structure).

The Monterey Formation in the Santa Barbara Channel area is comprised of a thick sequence (800’ to ∼7000’ in the deeper basinal areas) of interbedded siliceous rocks (porcelanites & cherts), dolomites, limestones, organic-rich shales, and claystones originally deposited in a deep marine environment during the Miocene Epoch approximately 20 million years ago. Oil and gas developed in the Monterey shale over the last ∼1 million years, and the hydrocarbons have migrated up-structure to be trapped within the South Ellwood anticlinal structure. Fractures and faults are conduits for the hydrocarbon migration, with fractures forming both from diagenetic alteration of the rocks during burial, and through tectonic forces (structural deformation, faulting, and folding which created the anticlines). The overlying shales of the Sisquoc Formation form the seal above the highly fractured Monterey Formation, trapping the oil within the fractures and pore spaces of the Monterey.

Continuous production of the Monterey Formation at South Ellwood Field began in 1972. The Ellwood Onshore Facility processes the produced fluids to provide sales quality oil and gas. The Monterey Formation produced water that is processed out of the oil and gas stream is re-injected into the South Ellwood Field Monterey Formation. No other forms of enhanced oil recovery are planned at South Ellwood Field.

Figure 3 presents a detailed structural interpretation of the Coal Oil Point and offshore area using the latest maps and data analysis. Figure 3 shows that the offshore seep trend at Coal Oil Point is related to the main South Ellwood anticline, which partially corresponds to the South Ellwood fault trace in the west. In Figure 3, the crest of the anticline is shown as a light blue, dashed line. The seeps are aligned along the anticlinal crest; the intensity of seepage is shown as purple (high), green (medium) and tan (low). The South Ellwood Field seeps clearly correlate with the crest of the anticline. Currently, the largest and most intense area of seepage occurs along this trend to the east of State Lease PRC 3242. The alignment of the seep trend with the underlying anticline suggests that the seep pathways are related to the underlying geology and hydrocarbon accumulation rather than other hydrocarbon
sources. As described in this report, the intensity of the seeps has decreased substantially or disappeared in areas of active production, first near Platform Holly, then to the east near the seep tents.

Figure 3: Correlation of geological structure with seep locations.

Figure 4: Cross section along anticlinal trend showing seep trace (red lines on top of cross section), some existing wells from Platform Holly (solid dark lines) and some proposed wells in the proposed Lease Adjustment Area (dashed dark lines).
Figure 4 shows a cross section across the boundary between Venoco’s existing State Lease, and the proposed expansion to the east, and demonstrates a continuity in geological structure and stratigraphy across the lease line.

Figure 5 is a cross section perpendicular to Figure 4, at the lease line. This figure shows the anticlines clearly, as the “A”-shaped structures. The cross section also shows that the crests of the anticlines are faulted, and that the faults extend to the sea floor. The locations of mapped seeps across the line of section are shown on the cross-section figure as red lines at the surface. Note also that some seeps to the north do not correlate with the hinge of anticlinal axes. The focus of this report, however, is on those seeps that may be affected by the proposed lease line adjustment.

Figure 6 shows a cross section located 8,000 feet east of Venoco’s current lease boundary, within the Lease Line Adjustment area. The figure shows that the South Ellwood anticlinal crest is similarly faulted to that shown in Figure 5, and that the mapped seeps also correlate with the folded and fractured hinge of the anticlinal structure. The location of the test well has been projected in to the line of the cross section and are not actually in the plane of the drawing. The test well depicted in Figure 6 was drilled to the deeper Rincon formation, and tested all of the major zones overlying the Rincon. The proposed lateral wells, however, are in the shallower Monterey Formation and therefore are likely to affect seepage rates. Therefore, the locations of the seeps correlate to the underlying geological structure. Mapped seeps in the South Ellwood Oil Field align along the crest of the anticline in the area. The subsurface oil and gas reservoir also lines up with the anticlinal trace.
Figure 6: Cross section within the lease line extension area
2.1.2. Correlation of Reduction of Seepage Associated with Platform Holly Near the Platform

Between 1973 and 1995, most of the oil and gas production from Platform Holly was concentrated in the near vicinity of the platform. The results of studies in seep location and intensity are shown in the following two figures.

### Seep Reduction/Cessation

<table>
<thead>
<tr>
<th>Figure 7: Reduction in seep intensity in the near vicinity of Platform Holly preferentially decreases compared to elsewhere along the trend; the time correlates with production focused near the platform.</th>
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<td>Figure 8 shows the same general information in cross section through the ocean. By 1995, seep intensity had substantially diminished or disappeared near Platform Holly, but persisted at the future location of the seep tents. On the broadest areal scale, seepage around Platform Holly has been greatly reduced based on sonar scans of bubble intensity in the water column. All of the work clearly shows a large seepage trend along the axis that is known as the South Ellwood anticline in 1973 and that by 1995 seepage near Platform Holly had substantially reduced or ceased. Therefore, oil and gas production focused near Platform Holly correlates with the substantial reduction or near cessation of seepage near the Platform.</td>
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"Comparison of the seep distributions over time reveals more than 50% decrease in the areal extent of seepage, accompanied by declines in seep emission volume...Declines in reservoir pressure and depletion of seep hydrocarbon sources associated with oil production are the mechanism inferred to explain the declines..."

"Oil production from the Monterey Formation oil and gas reservoir caused subsequent declines in reservoir pressure, thus removing the primary driving mechanism of the seepage"

(Quigley et al. 1999)
2.1.3. Correlation of Seepage Associated with the Seep Tents

The South Ellwood Field is the only area of offshore seepage at which operators installed submarine structures, known as seep tents, to capture natural oil and gas seeps. Arco originally installed seep tents in 1982 and they are still in place today. They provide a unique opportunity to quantify the volume and composition of oil and gas seepage in those areas and to test the correlation with oil and gas production from the deeper geological reservoir.
Seep Containment Project

- The Seep Containment Project was developed in 1962 by ARCO to capture naturally seeping gas.
- Two 50-foot high steel pyramids (tents) were positioned on the ocean floor over this seep. They weigh 500,000 pounds each and measure 100 feet by 100 feet.
- At peak, the tents captured over 1,600 Mcf of seeping gas per day. To date the seep tents have captured 7.6 Bcf of gas and stopped producing in 2013 (no flow).
- The tents provided a unique opportunity to directly measure seep rates and can be used to extrapolate the effect of oil and gas production beyond the limited footprint of the tents.
- Data from the tents provide the most conclusive evidence of a relation between hydrocarbon production and seepage.

Figure 9: Seep containment (seep tent) project.

Figure 9 shows the seep containment project and production volume over time. The purpose of the project was to capture and produce seep gas escaping at the sea floor in order to obtain emission offset credits for future development projects. The tents initially produced some oil (a total of about 600 bbls) with the gas, but oil seepage into the tent stopped in 1989. At their peak, the tents were removing more than six tons of reactive hydrocarbons a day from the atmosphere, more than one fourth of Santa Barbara’s air emission from manmade sources. The seep tents are unique in the world as they are the only place that a long term (over 30 years) seep capture system has been in place on the sea floor over a relatively large area (>20,000 ft²). They provide the most conclusive evidence of a relation between hydrocarbon production and seepage and provide the opportunity to make direct estimates of gas seepage rates and understand the gas composition overtime.

In approximately the late 1980’s to early 1990’s, slant and horizontal wells were drilled and produced that extended the zone of production from Platform Holly down the geological trend of the anticline structure. The production extended beyond the immediate vicinity of Platform Holly, to include the zone underlying the seep tents.

Quigley and others (1999) were the first to relate seepage into the seep tents to hydrocarbon production. They noted an overall decline in seep rate at the seep tent between
1989 and 1995, which was the limit of their data. They attributed the decline to hydrocarbon production at Platform Holly:

“[d]eclines in reservoir pressure and depletion of seep hydrocarbon sources associated with oil production are the mechanisms inferred to explain the declines in seep area and emission volume”.

Taking the data up to 2015, an overlay of the gas production rate at Holly against the seep rate at the tent between 1982 and 2015 reveals that the drop in gas seepage rate at the tent correlates with a drop in gas production at Holly (Figure 10). The few periods of deviations from the correlation are annotated on the figure, and described below:

- 1982 to 1985 was a period of testing and attempts to withdraw oil from the tents. There were also days during this early period where the tent was shutdown. The spikes seen in these first few years are most likely due to commissioning of the tents, evaluation, testing and the resulting optimization.
- In 1986, the tents were modified with curtains to capture gas escaping near the perimeter of the tents. This resulted in a significant increase in capture rate.
- The sudden decrease in production in 1993-1994 time period is attributed to mechanical issues in the flow-lines, which is also discussed in Quigley et al. (1999).
- The 2007-2008 decrease was also due to a flow line issue that was subsequently repaired.

![Figure 10: Comparison of daily seep tent production to daily Monterey gas production at Platform Holly. From Boles (2015) Figure 12](image-url)
Boles (2015) focuses on the relationship between production at two Platform Holly wells that traverse the faults that feed the natural gas in the seep tents, and the cessation of natural gas entering the seep tents. First, is the correlation between production from Well 3242-7RD2 at Holly and gas seepage rate measured at the seep tents, about a mile east of Platform Holly. The well is positioned approximately 3,500 feet beneath the seep tents and relatively close to a fault believed to be feeding the surface seepage. Well 3242-7RD2, completed in June 2002, produced especially large amounts of gas (up to 2500 Mcf/day) and can be shown to affect seepage rate into the tents (Figure 11, taken from Boles 2015). The fact that the production from this well can be correlated to production at the seep tent demonstrates a direct hydrodynamic connection between the seepage at the sea bed and the South Ellwood reservoir. Figure 11 shows gas production at the seep tent related to production from Well 3242-7RD2. The figure shows that when 3242-7RD2 is brought on line, seep tent production goes down; and that when production is halted, seep tent production goes up, showing a direct connection.

The second individual well correlation is for well 3242-15RD1, shown in Figure 12 (taken from Boles (2015)). Well 3242-15RD1 was drilled in mid-2013 and completed approximately 2,500 feet beneath the tent in a previously undeveloped portion of the reservoir. The well is approximately 1,000 feet above Well 3242-7RD2 and is positioned high within the crest of the anticlinal structure. Well 3242-15RD1 came on production in July of 2013 and also produced relatively large amount of gas (up to 1500 Mcf/day). Within a period of two months after Well 3242-15RD1 came on line, gas flux into the seep tent went from about 250 Mcf/day, a background level which the tent had been producing since at least 2008, to zero (Figure 12).
Production from this single well resulted in the ultimate cessation of measurable seepage into the tent. Seepage into the tent has not returned since, despite a 10 day shutdown of Platform Holly in October 2013 and an extended 6 month shut-down of the Platform in May of 2015. Multiple efforts were made by the company to revive production from the tent including “pigging” the line between the tent and the Ellwood processing plant (a process to rule out problems within the pipeline, e.g. leaks and blockage) and submarine remotely operated vehicle inspection of the tent (to rule out leaks). No defects were identified and no measurable gas seepage has occurred since August 2013.

Figure 12. Cessation of measurable production from the seep tents, coinciding with the onset of well 3242-15RD1. From Boles 2015.

2.1.4. Correlation with Tidal Variation
Boles (2015) presents data indicating a correlation of the amplitude of tidal variation with the variation of pressure in the oil and gas reservoir produced by Platform Holly (Figure 13, taken from Boles 2015). This observation implies a connection between the ocean and the producing reservoir. As noted later in the review, this correlation cannot be explained if the seeps tap a different petroleum-bearing zone than the producing zone. This demonstration of a tidal signal in the reservoir pressure establishes the likelihood that reductions in reservoir pressure can affect surface pressures, specifically gas seepage rates. The actual gas seepage rate depends on additional factors besides tidal variation.
Figure 13. Tidal signal observed in Well 3242-13. The actual amplitude of the tidal signal in the well is < 50% of the expected amplitude. From Boles 2015.

2.1.5. Similar Conditions East of the Existing Lease Line

As described in the previous sections, there are strong correlations between the location of seeps along the South Ellwood anticlinal trace and the location of the oil and gas reservoir relative to the subsurface geology; between production from Platform Holly and reduction of near-field seeps; between later production by slant and horizontal wells and cessation of production from the seep tents; and between reservoir pressure and tidal stage.

Figures 4, 5, and 6 in Section 2.1.1 show that the geologic structure is consistent into the Lease Line Adjustment Area. The same fractured, folded anticlinal structure hosts both the oil and gas reservoir and the surface seeps. First, there is the same connection to the underlying geological structure; the faulted hinge of the same anticline is found in a comparable location to the seeps. Second, the proposed wells will traverse the same faulted anticline that led to the observed associated with production from nearby wells and the cessation of seeps in the vicinity of Platform Holly, and the cessation of seeps at the seep tents. Third, based on the structural mapping of the area proposed for drilling, the wells should tap the same fault systems that feed the seeps, establishing the same relationship that was seen from the seep tent data for Well 3242-15RD1 and Well 3242-7RD2.
Therefore, it is predicted that the same conditions that are observed in connection with the
correlation between oil and gas production and decreases or cessation in seafloor seepage
would also be observed to the east of the existing State PRC 3242.1 lease line, where the
re-drilling is proposed.

2.2. Physical Explanations and Causative Mechanisms For the Correlation

The correlations between increased production at Platform Holly, decreased reservoir pressure,
and decreased gas seepage presented in Section 2.1 and clear and intuitive. This section
evaluates the physical mechanisms that explain the observed correlations. Taken together, the
observed correlations and the physical mechanisms establish causation. The causation, in turn,
can be used to predict effects of new production as a result of the lease line adjustment Project.

Boles (2015) cites three physical mechanisms for the correlation between oil and gas production
and natural seepage rates: buoyancy, reservoir pressure, and seawater counterflow. Each
mechanism helps support the interpretation that the observed correlations are due to a direct
relationship between oil and gas production and gas seepage intensity. Buoyancy is relatively
constant for this setting and supports rise of gas from the reservoir; seawater counterflow is
difficult to quantify but may impede gas rise. Variation in reservoir pressure acts in the same
sense as buoyancy (supporting gas rise), and the variation in reservoir pressure explains the
major trends of gas seepage rate. Each physical explanation is briefly summarized below; Boles
(2015) contains a fuller discussion.

**Buoyancy.** The presentation of buoyancy follows the “manometer model” for subsurface
fluid buoyancy relationships. This model compares the density of the surrounding crust, with
the density of the column of fluid within fractures that feed the seeps. The size of the resulting
buoyancy force is sufficient to establish a physical connection between oil and gas in the
subsurface reservoir and the seeps. The degree to which the fractured pathway from the
reservoir to the surface is not continuous or has higher capillary resistive forces from smaller
fractures, reduces the buoyancy force. Boles refers to buoyancy as a hydrostatic driving
force.

**Reservoir Pressure.** Reservoir pressure acts similarly to buoyancy. Declines in pressure are
degrees in the driving force leading to seeps being observed at the surface. Assuming a
physical connection between the reservoir and the seeps (which is demonstrated by the tidal
variation evident in reservoir pressure, among other observations), the reservoir pressure is
certainly a causative mechanism. Changes in reservoir pressure and seepage intensity cited
above are consistent with this causative mechanism. Buoyancy and reservoir pressure both
support vertical rise of the gas to the surface, but the variations in reservoir pressure appear
to be the principal factor affecting gas seepage rate.

**Seawater Counterflow.** Oxygen isotopic measurements (Boles, 2015) demonstrate that
seawater is present in the oil and gas producing reservoir tapped by Platform Holly.
Downward flow of seawater towards the reservoir could impede upward migration of gas to
the seeps. Although the process is demonstrated by the oxygen isotopic measurements, the
strength of this countering factor is difficult to quantify.

In addition to these mechanisms, Boles points out that the fact that large quantities of
hydrocarbons have been produced from a reservoir also means there are fewer hydrocarbons
to leak. In other words, even if low fluid pressures exist at depth, hydrocarbons have to be
present in order to observe leakage at the surface. Thus, low fluid pressures by themselves
are not the only cause for lowering seepage rates.

All of these factors (sub-hydrostatic fluid pressure due to both reduced buoyancy and reduced
reservoir pressure; removal of large quantities of hydrocarbons; and counter flow of fluid from
the sea bed) are present at South Ellwood Field and are important in explaining the observed correlation between hydrocarbon production at Platform Holly and reduced seepage rates. Determining the strength of these forces relative to one another, or the presence of other forces, would require further study. However, these mechanisms are shown convincingly to be sufficient causative mechanisms to explain the observed correlations between oil and gas production and submarine gas seepage.

2.3. Alternate Causative Mechanisms for the Correlations

Could the same correlations be due to oil and gas from a different, shallower reservoir feeding the seeps? The methane gas from the seeps at the seep tent has an isotopic composition identical to the reservoir gas at Platform Holly, and is different from that for bacterial methane (Boles 2015). This fact demonstrates that the gas is not being generated by bacterial processes in the shallow sediment. The seep oils are also very similar in composition to reservoir oils, suggesting the oils have a common origin (Farwell et al., 2009). The rapid degradation of the oils at the surface can make them difficult to match exactly to reservoir oils (see Lorenson et al., 2011). The alignment of the South Elwood seep trend with the underlying anticline demonstrates that the seep pathways are related to the underlying geology and hydrocarbon accumulation rather than other hydrocarbon sources.

Would fluid injection increase pressures sufficiently to counteract reservoir depletion, thereby maintaining the seep intensity? Reservoir pressures have declined significantly since production began. Initial reservoir pressure at South Ellwood (about 3881 feet subsea level) was approximately 1800 psi. In 1985, the reservoir pressure had dropped to a range from 1450 to 1300 psi, which is 80% to 72% of the initial pressure. Reservoir pressure was relatively constant from about 1985 until about 2012. In July of 2013, the completion of Well 3242-15RD1 resulted in a large amount of gas being produced, and reservoir pressure dropped even further to about 1000 psi in a number of wells in the vicinity of 3242-15RD1. Current reservoir pressures are sub-hydrostatic at the reservoir level and only 56% of the initial reservoir pressure. As a result of reservoir pressure being less than hydrostatic, there is some local influx of sea water (seawater counterflow) into the reservoir (Boles 2015). Therefore, the reservoir pressure continues to decrease despite re-injection of produced water; there is not an overpressuring of the reservoir that could counteract the causative mechanisms for decreased seepage as described above. Furthermore, with extraction of oil and gas there is a net decrease in fluids that could only be made up by injecting more water than is being produced from the wells.

2.4. Quantification of Seepage Rates

Boles (2015) quantifies changes in gas seepage rates in this geographic area. We have reviewed the method used and have determined that it represents the most reliable methodology currently available. However, Boles' (2015) use of historical sonar data to estimate reductions in gas seepage does not account for potential changes in flux or area of the gas seeps, which may result in an overestimate of the gas seepage rate. In addition, Boles (2015) does not quantify the uncertainty associated with his estimate of the Project-related reduction in gas seepage in the Lease Line Adjustment Area, or indicate the time period over which reductions in gas seepage rate will occur. A review of the findings of Boles (2015) is summarized in this section.

The total gas seepage along the South Elwood anticline is estimated to be between 1.5 and 4.2 MMCF/day. The gas seepage along the Coal Oil Point area is estimated to be between 0.2 and 0.7 MMCF/day. The total gas seepage of the two areas is summed to be between 1.7 and
4.9 MMCF/day. Gas seepage in the most intense areas of the South Ellwood anticline trend is estimated by Hornafius et al. (1999) to be >0.1 m³/m²·day, which would result in about 5.0 MMCF/day along the South Ellwood trend. The 2003 flux buoy survey of Washburn and others (2005) estimated a gas flux of 0.03 to 0.6 m³/m²·day from a relatively small area of the La Goleta Seep. These numbers are consistent with estimates from Hornafius et al. (1999).

The total gas seepage in the proposed development area east of existing State Lease PRC 3242 has been estimated by measuring (digitizing) the areas of the different gas seepage rates shown by Hornafius et al. (1999) and summing the values. The total area of gas seepage in the proposed development area covers about 2 km² within the South Ellwood anticline trend and an additional 0.4 km² within the Coal Oil Point trend. The gas seepage at South Ellwood is the strongest and most extensive of the two trends.

Boles’ (2015) methodology relied on gas fluxes and gas seep areas estimated from sonar data collected in 1994-1995, which may not be representative of current gas fluxes and gas seep areas. Boles (2015) showed distinct differences between the gas seep outlines based on sonar surveys in 1994-1995 (Hornafius et al., 1999) and 2005 (Leifer et al., 2010), as indicated in Figure 14. The sonar data collected in 2005 have not been calibrated to provide gas flux readings. However, assuming the gas fluxes in any given area were similar for the two surveys, the observed decrease in the areas of the gas seeps from 1994-1995 to 2005, approximately 50%, would have resulted in an overall decrease in the gas seepage rate in the Lease Line Adjustment Area from 1994-1995 to 2005. Thus, Boles’ (2015) estimate of the gas seepage rate in the Lease Line Adjustment Area may be overestimated by about a factor of two. Additional reductions in the areas or magnitude of gas fluxes of the seeps from 2005 up to the current time (i.e., 2015) would further contribute to overestimation of the gas seepage rate in the Lease Line Adjustment Area.

Based on his estimate of the methane reduction associated with the lease line adjustment Project, discussed further in Section 3.2.1, Boles (2015) appears to have assumed that the Project results in at least a 70% reduction of the gas seepage rate in the Lease Line Adjustment Area, calculated based on the maximum gas seepage rate (i.e., 4.9 MMCF/day). Based on observed gas seepage area reductions in the vicinity of Platform Holly and the seep tents, this appears to be a reasonable estimate. As indicated in Figure 7, Quigley et al. (1999) estimated the reduction in gas seepage area within 13 square kilometers of Platform Holly was approximately 50% from 1973 to 1995. A comparison of the gas seep areas in the same area in 1995 and 2005 indicates a further reduction of up to 20% (see Figure 14). Additional reductions in gas seepage area in vicinity of Platform Holly could have occurred between the start of operation in 1966 and the sonar survey in 1973, and subsequent to 2005. Thus, the actual percentage of reduction in the vicinity of Platform Holly could in fact have been greater than 70%. Based on the reductions observed in the vicinity of Platform Holly, and assuming similar reductions in the Lease Line Adjustment Area as a result of the Project, it is reasonable to estimate a range of 50 to 70% reduction in gas seepage rate in the Lease Line Adjustment Area as a result of the Project.

Boles also does not indicate the time period over which he anticipates the gas seepage reductions to occur. Oil and gas production began at Platform Holly in 1966 and sonar readings in 1973 showed substantial seep activity in the area around Platform Holly almost seven years later (Quigley et al., 1999). As indicated above, sonar readings in 1995 indicate only a 50% decrease in the area of seep activity within 13 square kilometers of Platform Holly compared to the 1973 sonar data (Quigley et al., 1999). Thus, it is likely that oil and gas production associated with the Project will result in gas seepage reductions in the Lease Line Adjustment Area of 50 to 70%. The magnitude and rate of reductions in seepage and associated air
emissions following inception of the Project will depend on the production start date for the redrilled wells, the levels of oil and gas production at the redrilled wells and the associated impact on the subsurface interactions with the underlying oil and gas reservoir.

The amount of oil associated with the gas seepage estimate is unknown, but based on inshore seep studies and the early production of oil at the seep tent, there could be a considerable amount of oil being released to the shallow sediment and ocean. Hornafius et al. (1999) estimate about 6 MMCF/day gas and 100 bbls oil/day leaking from the Coal Oil Point area which includes the inner and outer seep areas plus the seep tent. However, Boles does not quantify changes in oil seepage rates as a result of the Project.

Figure 14: Offshore Seep Surveys through Time (from Boles, 2015)

2.5. Summary of Findings for Subsurface Interactions

The data clearly indicate a strong correlation between the trend of the folded, faulted, and fractured hinge of the anticlinal structure beneath the South Ellwood Field and the location of abundant subsurface oil and gas deposits, and some of the largest submarine seeps observed in the world. The South Ellwood anticline has produced an economic oil and gas field, and the same geological factors have also led to the presence of the seeps, some of which have been of sufficient intensity to themselves be produced for sale (seep tents).
The data also clearly indicate that, when production was focused on that part of the reservoir in the near vicinity of Platform Holly, the intensity of gas seepage decreased substantially, and in part ceased. The sonar data shows this finding most clearly.

The data indicate that as 1 wells were drilled in proximity to the seep trend, the intensity of gas seepage as measured by the seep tents decreased substantially and is now ceased. As production moves down along the anticlinal trend with time, seepage intensity also decreases and ceases along the same trend.

The same geological conditions along the South Ellwood anticlinal trace, including the presence of the currently highest intensity seeps at the crest of the folded, faulted, and fractured anticlinal trend, are observed to be continuous across the lease line to the Lease Line Adjustment area.

Therefore we conclude that, should the Lease Line Adjustment be granted, that the proposed wells that cross into the Lease Line Adjustment area will lead to substantial reduction or cessation of submarine gas seepage overlying the produced zone. Production of oil and gas from the reservoir that feeds the seeps reduces the driving force for seepage. Seepage slows or stops as a consequence. Extension of production into the Lease Line Adjustment area is highly likely, therefore, to reduce seepage significantly.
3. MARINE FATE AND ATMOSPHERIC EMISSIONS OF GHGS AND ROCs

3.1. Description of Composition of and Air Emissions Associated with Seepage in the COP Seep Field

3.1.1. Introduction

Natural oil and gas seepage in the Coal Oil Point seep field releases hydrocarbons and carbon dioxide to the marine environment from seep vents on the seafloor. Although measurements near the release point indicate substantial quantities of CO2 in the seep gas, studies of seep gas composition indicate that CO2 concentration in gas bubbles near the sea surface is below or near the detection limit, signifying that nearly all CO2 dissolves in the water column as gas bubbles transit to the surface (Clark et al., 2003, 2010). According to NOAA (2015), CO2 dissolved in seawater at the sea surface may take up to a year to equilibrate with the ambient atmosphere, during which time it may be dispersed over wide areas by ocean currents and diffusion. Therefore, the fate of CO2 dissolved in the water column from gas bubbles is not further evaluated in this section. Ramboll Environ’s review of the literature indicated three potential fates for hydrocarbons emitted as gas (Clark et al., 2000, 2003, 2010; Hornafius et al., 1999; Leifer et al., 2010):

1. Transit of gas bubbles to the sea surface and emission of hydrocarbons to the atmosphere.
2. Dissolution of hydrocarbons from gas bubbles into the water column followed by microbial oxidation; and
3. Dissolution of hydrocarbons from gas bubbles into the water column followed by diffusion to the surface and emission to the atmosphere via sea-air gas exchange.

In the following sections, Ramboll Environ provides a summary of information and data related to the marine fate and air emissions of natural oil and gas seepage in the COP seep field and evaluates potential Project-related impacts on marine fate of seepage and air emissions of GHGs and ROCs associated with seepage in the Lease Line Adjustment Area. As part of this assessment, Ramboll Environ also evaluates Boles’ discussion of the fate of emitted gaseous hydrocarbons and oil from seepage at the COP seep field and whether available data and information support Boles’ estimate that oil and gas production associated with the Project would reduce air emissions associated with natural oil and gas seepage in the Lease Line Adjustment Area by over 50 tons per day.

3.1.2. Marine Fate and Atmospheric Emissions Associated with Gas Seepage

At the seafloor, gas bubbles are primarily composed of methane, with smaller quantities of carbon dioxide, ethane, propane, nitrogen, oxygen, hydrogen sulfide and higher hydrocarbons (Clark, et al., 2000). As seep gas bubbles rise through the water column from the seafloor to the sea surface, hydrocarbons and carbon dioxide from the gas bubbles are dissolved in seawater, and nitrogen and oxygen in the seawater are transferred into the gas bubbles (Clark et al., 2003, 2010; Leifer, 2010). This exchange of gases between the seep gas bubbles and seawater results in lower concentrations of hydrocarbons (i.e., methane, ethane, propane and higher hydrocarbons) and CO2 in seep gas bubbles at the sea surface relative to the seafloor, and higher concentrations of nitrogen and oxygen in seep gas.
bubbles near the surface relative to the seafloor, as demonstrated in several studies (Clark et al., 2000, 2003, 2010; Leifer et al., 2000, 2006; Mau et al., 2010).

The physical properties of seep gas bubbles, release parameters associated with the seeps, and ambient marine conditions determine the extent to which hydrocarbons from gas bubbles dissolve in sea water as they rise to the surface (Clark et al., 2010; Leifer, 2010), the resulting concentrations of hydrocarbons in the water column and in seep gas bubbles at the sea surface, and the corresponding air emissions associated with gas bubbles and dissolved hydrocarbons. These physical properties, release parameters and ambient marine conditions include composition of gas bubbles at the seafloor, thickness and composition of the oil on bubble surfaces, bubble size distribution, gas flux, release depth, presence and velocity of upwelling flow in the water column, strength of currents, and existing concentrations of hydrocarbons in the water column (Clark, 2000).

Hornafius et al. (1999) estimated the gas emission rate to the atmosphere from the entire COP seep field, including the seep tents, as 1.67 ±0.3 x 10^5 cubic meters per day (m³/day) based on sonar data collected in 1994-1995. Assuming 470 tonnes of methane and 155 tonnes of non-methane hydrocarbons per million cubic meters of seep gas, Hornafius et al. (1999) estimated a methane emission rate of 80 ± 12 metric tons per day (t/day) and a non-methane hydrocarbon (NMHC or ROC²) emission rate of 26 ± 4 t/day. Clark et al. (2000) estimated that approximately half of the methane emitted from seep vents on the seafloor in the COP seep field is dissolved into the water column during transit of gas bubbles to the surface (i.e., 2.1 x 10¹⁰ grams per year (g/yr), or 58 t/day of methane dissolved in the water column) and that a similar mass of methane is emitted to the atmosphere (i.e., 2 to 5 x 10¹⁰ g/yr or 55 to 137 t/day).

Hydrocarbons dissolved in the water column may be oxidized by microorganisms or diffuse vertically to the sea surface where they are emitted to the atmosphere via sea-air gas transfer (Mau et al., 2012). Microbial oxidation of hydrocarbons dissolved in the water column may occur as a result of microorganisms in seafloor sediments or on microbial mats (i.e., communities of microbes organized by layers) that grow around seep vents or by bacteria present anywhere in the water column (Hornafius et al., 1999; Mau et al., 2007; Ding and Valentine, 2008). Sea-air gas transfer resulting in emission of hydrocarbons to the atmosphere occurs when hydrocarbons diffuse to the sea surface.

The rates of microbial oxidation and vertical diffusion to the sea surface are relatively slow, therefore hydrocarbons dissolved in the water column may be carried great distances (i.e., on the order of tens to hundreds of kilometers) from their source seeps and dispersed by currents and horizontal turbulent diffusion (Clark et al., 2000; County of Santa Barbara, 2002; Mau et al., 2007) before they are oxidized or emitted to the atmosphere. Mau et al. (2007) estimated that 1.4%, up to a maximum of 10%, of dissolved methane in seawater is emitted to the atmosphere via sea-air gas transfer within 30 kilometers of the source seeps, with the remainder either oxidized by microbes or emitted to the atmosphere farther from the source. In a subsequent study, Mau et al. (2012) confirmed that approximately 1% of

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¹ Sonar data were collected at a depth of 18-28 meters below the sea surface. At this depth, it is likely that gas exchange is still occurring between the gas bubbles and water column (Clark et al., 2000, Figure 10). Thus, volumetric flow rate of gas at the sea surface is likely lower than predicted by the sonar survey.

² Note that NMHC includes ethane, whereas ROC does not. Therefore, these two groups of chemicals are not identical.
dissolved methane is emitted to the atmosphere via sea-air gas transfer within 50 kilometers of the COP seep field, 1% of dissolved methane was oxidized by microbes within 50 kilometers of the COP seep field, and the remainder was transported out of the study area as a result of currents and dispersed via horizontal turbulent diffusion. Based on computer modeling, Mau et al. (2012) estimated that ultimately, approximately 60% of dissolved methane in the COP seep field is microbially oxidized and 40% of dissolved methane is emitted to the atmosphere via sea-air gas transfer. Boles (2015) references only the 2007 study by Mau et al., indicating that a maximum of 10% of dissolved methane is emitted to the atmosphere within 30 kilometers of the plume source.

Seep gas bubbles that reach the sea surface release hydrocarbons (mostly methane, with smaller amounts of ethane, propane and heavier hydrocarbons), nitrogen, oxygen and hydrogen sulfide to the atmosphere. The volume of methane and ROC emissions to the atmosphere due to transport of gas bubbles to the surface depends on the gas flux at the surface, the area of the sea surface over which the gas flux occurs, and concentrations of methane and ROCs in the gas bubbles at the sea surface. These three parameters have been shown to vary by location and over time (Leifer et al., 2004, 2006). Measured gas fluxes have shown the greatest degree of variability, with considerable temporal and spatial fluctuations (Leifer et al., 2004). This large temporal variability in surface gas flux suggests that earlier estimates of seep flux over the entire COP seep field, which were based on a “snapshot” of sonar data, may have a higher degree of uncertainty associated with them than reported.

The variability in surface gas flux noted by Leifer et al. (2004) includes large, transient seepage events (i.e., “blowouts”). Individual seeps or group(s) of seeps may experience periodic blowouts that release relatively large amount of seep gas over a relatively short time period. Blowout events typically generate strong upwelling of water and gas bubbles with larger diameters that have greater buoyancy. These factors contribute to shorter transit times for bubbles to reach the sea surface, resulting in decreased dissolution of hydrocarbons in the water column and higher atmospheric emissions of methane and ROCs (Clark et al., 2003; Leifer et al., 2004, 2006). Leifer et al. (2004) provided evidence that blowout events occur frequently in the COP seep field, however, further study is required to determine what fraction of total gas flow is represented by blowout events, or whether the gas flow represented by blowout events is properly captured in the measurements. Given the potential magnitude of the blowout events, it is not even clear that they are fully captured by the seep tents. Boles (2015) did not consider the impact of blowout events in his discussion of the fate of emitted gaseous hydrocarbons, as discussed in further detail in Section 3.2.1.

### 3.1.3. Marine Fate and Atmospheric Emissions Associated with Oil Seepage

Oil may be emitted from seep vents on the seafloor in the COP seep field in the form of oil globules or as a coating of oil on the surfaces of gas bubbles (Hornafius et al., 1999). Similar to gas bubbles, oil globules rise to the sea surface as a result of buoyancy or upwelling flow due to releases of gas bubbles. Once released from seep vents at the seafloor, volatile hydrocarbons in oil globules or in oil on the surface of gas bubbles may be partially or fully dissolved in the water column as they rise to the sea surface (Leifer et al., 2000).

Hornafius et al. (1999) estimated oil seepage of approximately 100 barrels (bbl) per day for the Coal Oil Point seep field. According to Hornafius et al. (1999), this estimate only included oil on the surface of gas bubbles and did not include oil seepage in the form of pure oil globules, which was released closer to shore near Coal Oil Point and was estimated at 50 – 70 bbl per day.
Dissolved hydrocarbons from oil may be oxidized by microorganisms at the seafloor or as they rise through the water column. Lorenson et al. (2014) has asserted that anaerobic biodegradation of oil in the COP seep field contributes additional methane and/or CO₂ to the water column that has not been previously accounted for or studied. According to Lorenson et al. (2014), methane is generated from anaerobic biodegradation of oil emitted from seeps, and has resulted in the formation of asphaltic mounds that have been observed at many locations in the Santa Barbara Channel, including near Coal Oil Point and Goleta Point, both within the COP seep field. Assuming the current mass of the asphaltic mounds represents 40% of the original mass of the oil, that 60% of the original mass was transformed into methane and/or CO₂ and the age of the mounds are no older than the early Holocene (i.e., approximately 10,000 years old), Lorensen et al. (2011) estimated that approximately 1.4 x 10⁸ kilograms per year (kg/yr) (384 t/day) of CO₂ would be generated, if none of the CO₂ is converted to methane, and 5.0 x 10⁷ kg/yr (137 t/day) methane, if all of the CO₂ is converted to methane. Lorenson et al. (2014) proposed a mechanism for conversion of CO₂ to methane, however, it is unclear how much of the CO₂ would be converted to methane.

Dissolved hydrocarbons in the water column may also diffuse to the surface or be carried to the surface by upwelling flow. Similar to hydrocarbon gases dissolved in the water column, the rates of microbial oxidation and vertical diffusion to the sea surface are relatively slow, therefore hydrocarbons dissolved in the water column may be carried great distances (10s to 100s of kilometers) from their source seeps and dispersed by currents and horizontal turbulent diffusion before the hydrocarbons are oxidized or emitted to the atmosphere.

Volatile hydrocarbons in oil that reaches the sea surface, either in globule form or as a thin film on gas bubbles, may be oxidized or volatilized, and heavier hydrocarbon fractions are dispersed into the water column, washed onto shore, or sink back down to the seafloor.

### 3.2. **Evaluation of Project-related Impacts on Air Emissions of GHGs and ROCs Associated with Seepage**

Based on his correlation of oil and gas production data at Platform Holly with data indicating reductions in seepage in the vicinity of Platform Holly, physical explanations to support the correlation and extrapolation of the correlation to seeps in the Lease Line Adjustment Area, Boles (2015) concluded that “it is reasonable to expect significant decreases in seepage in the adjacent proposed development area” that “would be long lasting.” Using sonar data from Hornafius et al. (1999), Boles (2015) quantified the Project-related impacts on air emissions associated with gas bubble seepage in the Lease Line Adjustment Area, predicting the Project “could result in a major reduction in seepage on the scale of several million cubic feet per day or over 50 tons of methane per day (this is equivalent to over a thousand tons of carbon dioxide equivalent (CO₂e) per day).”
The Project-related impacts on air emissions of GHGs and ROCs associated with gas and oil seepage were evaluated for each of the fates identified in Section 3.1.1 and further discussed in Sections 3.1.2 and 3.1.3. These impacts were grouped by the form of the gas or oil seepage in the water column, as indicated below, and presented in the following sections:

1. Gas bubble seepage
2. Gas seepage dissolved in the water column
3. Oil seepage on the surface of gas bubbles and as oil globules
4. Oil seepage dissolved in the water column

3.2.1. Project-related Impacts on Air Emissions Associated with Gas Bubble Seepage that Reaches the Sea Surface

Boles (2015) evaluation of Project-related impacts on air emissions associated with seepage in the Lease Line Adjustment Area only considered gas bubble seepage that reaches the sea surface. Boles (2015) estimated reductions in atmospheric emissions associated with gas bubble seepage that reaches the sea surface on the scale of several million cubic feet per day, and specified the reduction in methane emissions as over 50 tons of methane per day (i.e., over 45 t/day methane).

As indicated in Section 2.4, Ramboll Environ has determined that Boles’ (2015) methodology for estimating the Project-related methane emissions reductions to the atmosphere associated with gas bubble seepage that reaches the sea surface in the Lease Line Adjustment Area represents the most reliable methodology currently available. However, Boles did not account for the reduction in the gas seepage area in the Lease Line Adjustment Area associated with the historical sonar measurements he utilized to estimate gas seepage rates, nor did he account for the uncertainty associated with his estimate of the Project-related reduction in gas seepage in the Lease Line Adjustment Area, as described in Section 2.4. Ramboll Environ estimated the Project-related reductions in methane, GHGs and ROCs associated with gas bubble seepage reaching the sea surface in the Lease Line Adjustment Area using Boles’ range of gas seepage rates (i.e., 1.7 to 4.9 MMCF/day) with an adjustment to account for observed reductions in the area of the seeps from 1994/1995 to 2005 (i.e., factor of two reduction in the gas seepage rate), Ramboll Environ’s estimated range of Project-related gas seepage rate reductions (i.e., 50 to 70%), and the concentrations of methane and ROCs in seep gas reported by Hornafius et al. (1999). Ramboll Environ estimated the Project would result in reductions in methane, GHGs and ROCs associated with gas bubble seepage that reaches the surface in the Lease Line Adjustment Area ranging from 5.7 to 23 t/day, 140 to 570 t/day and 1.9 to 7.5 t/day, respectively.

Boles’ (2015) methodology also did not evaluate or account for the impact of the Project on several factors that may affect air emissions associated with gas bubble seepage, including composition of gas bubbles, bubble size distributions and frequency and magnitude of blowouts (Clark et al., 2010; Leifer, 2010; Leifer et al., 2000, 2004, 2006, 2010). An evaluation of Project-related impacts on each of these factors and the associated impacts on air emissions of GHGs and ROCs are discussed below.
(a) Composition of seep gas. Ramboll Environ reviewed seep gas composition data collected at the seep tents from October 1982 to April 1983, June to October, 1986 and May to June, 2012 to determine if production at Platform Holly had any impact on seep gas composition. As shown in Figure 15, the composition data appear to show an increase in methane concentration of about two percent from the 1982/1983 period to the 2012 time period. Conversely, the ethane and propane concentrations appear to decrease approximately 10 to 20 percent from the 1982/1983 period to the 2012 period. Based on these data, it appears that oil and gas production at Platform Holly has had an impact on seep gas composition. Assuming that oil and gas production associated with the Project would have a similar impact on seep gas composition, reductions in methane emissions associated with the Project could be ~2% smaller and reductions in ROC emissions associated with the Project could be 10 to 20 percent larger.

(b) Bubble size distribution. Several studies provide information indicating that bubble size distributions can vary widely in the COP seep field (Clark et al., 2010; Leifer, 2010; Leifer and Culling, 2010). Leifer and Culling (2010) found wider bubble distributions, including larger bubbles, above seeps with larger gas fluxes, whereas bubble size distributions were more uniform and bubbles were generally smaller above seeps with
lower gas fluxes. As indicated by Boles (2015), seep gas flux in the Lease Line Adjustment Area is likely to decrease as a result of the Project, resulting in more uniform bubble size distributions and a decrease in bubble sizes. A decrease in bubble sizes would result in increases in bubble transit times to the surface and greater dissolution of hydrocarbons in the water column. An increase in dissolution of hydrocarbons in the water column would result in lower concentrations of hydrocarbons in bubbles reaching the sea surface and decreased GHG and ROC emissions to the atmosphere, assuming the water column is not already saturated with hydrocarbons. This effect could result in larger reductions in methane, GHG and ROC emissions due to the Project.

(c) Frequency and magnitude of blowouts. Leifer et al. (2004, 2006) discuss natural marine seepage blowouts in the COP seep field, focusing on Shane Seep, located in the current lease areas at a depth of 20 meters. However, Ramboll Environ is not aware of any information or data related to frequency or magnitude of blowouts in the Lease Line Adjustment Area. Neither study by Leifer et al. (2004, 2006) provide data or information that could be extrapolated to estimate the frequency or magnitude of blowouts in the Lease Line Adjustment Area. Ramboll Environ is not aware of specific information or data or that would indicate the Project would have any impact on the frequency or magnitude of blowouts. However, if the Project results in decreased gas fluxes, it is likely that the frequency and/or magnitude of blowouts would also decrease, resulting in increases in bubble transit times to the surface and dissolution of hydrocarbons in the water column. These increases would contribute to lower concentrations of hydrocarbons in bubbles reaching the surface and would further reduce methane, GHG and ROC emissions to the atmosphere.

3.2.2. Project-related Impacts on Air Emissions Associated with Gas Seepage Dissolved in the Water Column

As seep gas bubbles rise to the surface, hydrocarbons in the bubbles dissolve in the water column. Dissolved hydrocarbons in the water column may be oxidized by microorganisms or diffuse vertically to the sea surface, where they are emitted to the atmosphere via sea-air gas transfer (Mau et al., 2012). Clark et al. (2000) estimated that approximately half of the methane emitted from seep vents on the seafloor in the COP seep field is dissolved into the water column during transit of gas bubbles to the surface (i.e., $2.1 \times 10^{10}$ grams per year, or 58 t/day of methane dissolved in the water column across the entire COP seep field. Clark et al. (2000) also estimated that a similar amount of methane, approximately $2$ to $5 \times 10^{10}$ g/yr, is emitted to the atmosphere from bubbles that reach the sea surface.

Boles (2015) estimated the Project would result in a reduction in methane emissions to the atmosphere associated with gas bubbles that reach the sea surface of at least 50 tons/day (i.e., 45 t/day). Accounting for the reduction in gas seepage area associated with Boles’ use of historical sonar measurements and the uncertainty associated with Boles’ use of Project-related reductions in gas seepage rates in the Lease Line Adjustment Area, Ramboll Environ estimated the Project would result in a reduction in methane emissions associated with gas bubble seepage that reaches the surface of 5.7 to 23 t/day. This corresponds to a roughly equivalent reduction in the amount of methane dissolved in the water column (i.e., 5.7 to 23 t/day methane).
Assuming that the fraction of NMHCs (ROCs) in gas bubbles that dissolve in the water column is similar to the fraction of methane in gas bubbles that dissolves in the water column, and utilizing the ratio of ROCs to methane in seep gas reported by Hornafius et al. (1999), the Project would result in a 1.9 to 7.5 t/day reduction in ROCs dissolved in the water column. According to Mau et al. (2010), ultimately 40% of dissolved methane is emitted to the atmosphere via sea-air gas transfer, with the rest oxidized by microorganisms. This corresponds to a reduction in sea-air gas transfer to the atmosphere of up to 2.3 to 9.1 t/day of methane and 0.75 to 3.0 t/day of ROCs as a result of the Project. Only about 1% of the emissions of methane and ROCs would be emitted within 30 - 50 kilometers of the source seeps (Mau et al., 2007, 2012). Microbial oxidation of dissolved hydrocarbons away from the immediate seep area would likely not be impacted by the Project.

As indicated in Section 3.2.1, Project-related impacts on composition of seep gas, bubble size distributions, and frequency and magnitude of blowouts can all impact the amount of seep gas dissolved in the water column and corresponding air emissions. However, the magnitude of the impacts of these factors on air emissions of GHGs and ROCs due to sea-air gas transfer would be lower than the level of impacts of these factors on air emissions resulting from gas bubbles reaching the sea surface because only 40% of dissolved hydrocarbons are eventually emitted to the atmosphere, with only 1% emitted within approximately 30 kilometers of the plume source. As distinct from GHGs, which are a global issue, emissions of ROCs is a local issue and emissions of ROCs outside of the Santa Barbara County Air Pollution Control District (SBCAPCD) would not substantially impact ozone formation in the SBCAPCD jurisdiction. ROC reductions that occur within the SBCAPCD should be considered when modeling ozone.

3.2.3. Project-related Impacts on Air Emissions Associated with Oil Seepage on Bubble Surfaces and as Oil Globules

Air emissions related to oil seepage can result from oil on the surfaces of gas bubbles that rise to the sea surface or oil globules rising to the surface as a result of buoyancy or upwelling flow. Hornafius et al. (1999) estimated oil seepage of approximately 100 barrels (bbl) per day for the Coal Point seep field. However, this estimate only included oil on the surface of gas bubbles and did not include oil seepage in the form of pure oil globules, which was released closer to shore near Coal Oil Point and was estimated at 50 – 70 bbl per day (Hornafius et al. (1999).

The reduction in oil seepage that reaches the sea surface in the Lease Line Adjustment Area was estimated utilizing the oil-gas ratio reported by Hornafius et al. (1999) (i.e., 94 cubic centimeters per liter) and the Project-related reduction in gas bubble seepage in the Lease Line Adjustment Area corresponding to the range of methane reductions estimated in Section 3.2.1. Based on these assumptions, the reduction of oil seepage that reaches the sea surface was estimated as 7.1 to 29 bbl per day in the Lease Line Adjustment Area. The reduction in ROC emissions to the atmosphere due to volatilization of oil from the sea surface in the Lease Line Adjustment Area may be estimated utilizing the same assumptions as Hornafius et al. (1999) (i.e., oil density of 1 gram per cubic centimeter and 57% volatilization of oil constituents), resulting in a reduction of 0.64 to 2.6 t/day of ROCs.

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3 According to Mau et al. (2010), approximately 5 – 43% of methane in seep gas bubbles dissolves in the water column and 7 – 42% of propane in seep gas bubbles dissolves in the water column.
The calculation above assumes that that the oil-gas ratio reported by Hornafius et al. (1999) (*i.e.*, 94 cubic centimeters per liter, established at the seep tents in November 1995) is also applicable to seeps in the Lease Line Adjustment Area. Fluorescence experiments conducted by Leifer et al. (2000) to study dissolved oil in seawater found that gas bubbles at the Seep Tents Seep (*i.e.*, where the oil-gas ratio was determined) were the least oily of the seeps studies. These experiments also found that seeps in the La Goleta Seep (LGS) area, one of the most active seeps areas in the Lease Line Adjustment Area (Leifer, 2010), “may supply a significant amount of dissolved oil to the surface of the ocean.” Thus, the use of the oil-gas ratio developed at the seep tents for other areas of the COP seep field, including the Lease Line Adjustment Area, may under-predict reductions in oil seepage and associated ROC emissions associated with the Project.

### 3.2.4. Project-related Impacts on Air Emissions Associated with Oil Seepage Dissolved in the Water Column

As oil seepage on the surfaces of gas bubbles or as globules rises through the water column, volatile hydrocarbons (ROCs) from the oil may dissolve in the water column. Once dissolved in the water column, these ROCs may be transported to the surface via vertical diffusion or upwelling flow and emitted to the atmosphere via sea-air gas transfer. Dissolved ROCs may also undergo microbial oxidation that may generate methane. This methane could undergo further oxidation in the water column, or it may be transported to the sea surface via diffusion and emitted to the atmosphere via sea-air gas transfer. Ramboll Environ is not aware of any information or data indicating the quantity of ROCs in oil that dissolves in the water column or the relative amounts of dissolved ROCs that are oxidized or emitted to atmosphere. As indicated in Section 3.2.3, Ramboll Environ assumed that all oil seepage associated with oil globules and gas bubbles reached the sea surface and that volatile components were emitted to the atmosphere. If a fraction of oil seepage is assumed to have dissolved in the water column, the reduction in air emissions of ROCs associated with the Project would have been lower as only a fraction of dissolved ROCs diffuse to the sea surface and are emitted via sea-air gas transfer. However, to the extent that Project may reduce considerable quantities of oil seepage that would be dissolved in the water column and undergo microbial oxidation to produce methane, reductions in the amount of methane emitted to the atmosphere via sea-air gas exchange may be underestimated.

### 3.2.5. Summary of Project-related Impacts on the Marine Fate of Seepage and Air Emissions Associated with Seepage

Ramboll Environ analyzed the Project-related impacts on the marine fate of gas and oil seepage and the air emissions associated with gas and oil seepage. Ramboll Environ revised Boles’ estimates of Project-related methane reductions associated with gas bubble seepage that reaches the sea surface in the Lease Line Adjustment Area to account for the reduction in gas seepage area associated with Boles’ use of historical sonar measurements and the uncertainty associated with Boles’ use of Project-related reductions in gas seepage rates in the Lease Line Adjustment Area. Ramboll Environ also evaluated, and estimated where possible, potential Project-related air emissions reductions associated with gas seepage dissolved in the water column, oil seepage at the sea surface or oil seepage dissolved in the water column. The total Project-related methane, GHG and ROC air emissions reductions in the Lease Line Adjustment Area were estimated as 8.0 to 32 t/day, 198 to 798 t/day and 3.3 to 13 t/day, respectively. Although data are not sufficient to quantify the impacts on air emissions associated with Project-related impacts on seep gas composition, gas bubble size distributions and frequency and magnitude of blowouts, taken together, these factors would
likely have an overall effect of increasing Project-related reductions of methane, GHGs and ROCs in the Lease Line Adjustment Area. The estimated reduction in ROCs, a precursor to ozone formation, is substantial when compared to the total ROC inventory in Santa Barbara County in 2008 (29.3 t/day) (SBCAPCD and SBCAG, 2015). The gas and oil fluxes that form the basis for the estimates of methane, GHG and ROC emissions reductions are highly variable both spatially and temporally, and Project-related air emissions reductions were estimated as a range to account for this variability. The magnitude and rate of increase in reductions in seepage and associated air emissions following inception of the Project will depend on the production start date for the redrilled wells, the levels of oil and gas production at the redrilled wells and the associated impacts on the subsurface interactions with the underlying oil and gas reservoir. Based on observed long term reduction and cessation of seepage and seep tent production near Platform Holly, it is expected that the reduction in seepage would persist well beyond the life of the Project.
4. CONCLUSIONS

Venoco’s proposed South Ellwood Lease Line Adjustment Area Project would adjust the existing lease boundary for the South Ellwood oil field to an adjacent area for more efficient oil and gas recovery. As part of the environmental review of Venoco’s Project, the California State Lands Commission is seeking to define the degree to which oil and gas production leads to a reduction in the amount of natural seepage on the seafloor, and the beneficial effects of the reduction in seepage, in particular, in reducing the emissions of greenhouse gases (GHG) and reactive organic gases (ROCs). In order to address this question, Ramboll Environ conducted an evaluation of available information and data and relevant literature.

The specific objectives of Ramboll Environ’s evaluation included:

1. Examination and determination of whether there is a causal link between hydrocarbon production and seepage rate.
2. Quantification of the amount by which emissions of GHG (i.e., methane and CO₂) and ROC would be reduced as a consequence of oil and gas production.

Ramboll Environ’s evaluation of the subsurface interactions between oil and gas production and natural seepage rates found the same geological conditions, including the presence of the currently highest intensity seeps at the crest of the folded, faulted, and fractured anticlinal trend, are observed to be continuous across the lease line into the Lease Line Adjustment Area. Therefore we conclude that, should the Lease Line Adjustment be granted, the proposed wells that cross into the Lease Line Adjustment Area will lead to substantial reduction or cessation of submarine seepage overlying the produced zone. Based on observed long-term reduction and cessation of seepage and seep tent production near Platform Holly, it is expected that the reduction in seepage in the Lease Line Adjustment Area would persist well beyond the life of the Project.

Ramboll Environ also evaluated the fates of gas and oil seepage from seafloor vents in the vicinity of the South Ellwood field and quantified the reductions in air emissions associated with Project-related reductions in gas and oil seepage in the Lease Line Adjustment Area. Methane, GHG and ROC emission reductions were estimated based on Boles’ (2015) range of gas seepage rates associated with gas bubble seepage that reaches the sea surface in the Lease Line Adjustment Area (i.e., 1.7 to 4.9 MMCF/day). Ramboll Environ has determined that Boles’ (2015) methodology for estimating seepage rates is the most reliable methodology currently available. However after critical review we have made two adjustments: 1) Reduced the areal extent (50%) of the seep field within the Lease Line Adjustment Area to better represent the area as mapped in the most recent sonar survey (Leifer et al 2010); and 2) limited the range of Project-related gas seepage rate reductions to 50-70% of total seepage within the proposed Lease Line Adjustment Area. In addition to Project-related air emissions reductions associated with gas bubble seepage that reaches the sea surface, Ramboll Environ also evaluated, and estimated where possible, methane, GHG and ROC emissions associated with gas seepage dissolved in the water column, oil seepage
at the sea surface or oil seepage dissolved in the water column. As indicated in Table 1, the total Project-related methane, GHG and ROC air emissions reductions in the Lease Line Adjustment Area were estimated as 8.0 to 32 t/day, 198 to 798 t/day and 3.3 to 13 t/day, respectively. Although data are not sufficient to quantify the impacts on air emissions associated with Project-related impacts on seep gas composition, gas bubble size distributions and frequency and magnitude of blowouts, taken together, these factors would likely have an overall effect of increasing Project-related reductions of methane, GHGs and ROCs in the Lease Line Adjustment Area. The estimated reduction in ROCs, a precursor to ozone formation, is substantial when compared to the total ROC inventory in Santa Barbara County in 2008 (29.3 t/day) (SBCAPCD and SBCAG, 2015).

The magnitude and rate of increase in reductions in seepage and associated air emissions following inception of the Project will depend on the production start date for the redrilled wells, the levels of oil and gas production at the redrilled wells and the associated impacts on the subsurface interactions with the underlying oil and gas reservoir.

<table>
<thead>
<tr>
<th>Type of Air Emissions</th>
<th>Estimated Range of Project-Related Air Emissions Reductions in the Lease Line Adjustment Area (tonnes/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Methane</td>
</tr>
<tr>
<td>Gas bubble seepage at the sea surface</td>
<td>5.7 to 23</td>
</tr>
<tr>
<td>Sea-air gas transfer of gas seepage dissolved in the water column</td>
<td>2.3 to 9.1</td>
</tr>
<tr>
<td>Volatilization of oil seepage at the sea surface</td>
<td>Not estimated⁴</td>
</tr>
<tr>
<td>Total</td>
<td>8.0 to 32</td>
</tr>
</tbody>
</table>

Table 1: Summary of Estimated Ranges of Project-Related Air Emissions Reductions in the Lease Line Adjustment Area

⁴ Composition data for oil seepage was not available. Methane and GHG emissions associated with oil seepage assumed to be negligible.
5. REFERENCES


County of Santa Barbara, Energy Division. 2002. Natural Oil Seeps and Oil Spills.


Additional references to consult/cite:


