Hydrocarbon Production from the South Ellwood Oil Field (Platform Holly) and the Effects on Naturally Occurring Oil and Gas Seeps

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INTRODUCTION

There is clear scientific evidence that hydrocarbon production from Platform Holly has reduced naturally occurring oil and gas seepage in the surrounding areas. This observation should not be a surprise, as removal of hydrocarbon reduces the amount of oil and gas available for seepage. Early works including Fischer and Stevenson, (1973), Quigley and others, (1999) and Hornafius and others (1999) have come to the same conclusion. The removal of a large amount of hydrocarbon also results in a reduction in buoyancy force, which is the driving force for hydrocarbon escape. Furthermore, the rate of hydrocarbon extraction from producing wells far exceeds the rate of natural hydrocarbon generation, migration, and accumulation. As a result, reservoir fluid pressure is reduced and the rate of seepage decreases due to the pressure reduction. All of this is occurring in the vicinity of Platform Holly where production from wells is influencing hydrocarbon escape to the surface. One of the most surprising aspects of the effect of hydrocarbon production on seepage is how quickly the effect takes place, for example when wells are drilled within the crest of the anticline where gas accumulation is greatest or near faults that provide high permeable pathways for hydrocarbon flow.

BACKGROUND

Geologic Evidence of Prehistoric Seepage

Hydrocarbons have been observed as inclusions within calcite crystals in fault zones. This is indicative of ancient oil seepage along these faults. The oldest hydrocarbon seepage documented in the Santa Barbara area is from calcite in the Refugio-Carneros fault zone along the southern slope of the Santa Ynez Mountains, due north of the offshore South Ellwood oil field. Uranium series dating indicates that the calcite formed from between 125,000 to 500,000 years ago, which means that the breaking of the overpressure seal and resulting hydrocarbon seepage occurred during the Pleistocene (Boles and others, 2004). The calcite found within these faults has hydrocarbon inclusions and extremely light carbon isotopic composition ($\delta^{13}C = -40$), indicating that carbon was derived from oxidation of thermogenic methane. Crystallization temperatures of 100°C (from fluid inclusions) indicate that fluids were from relatively deep crustal levels. The estimated depth of origin, based on the current temperature gradient for the basin of 3.65°C/100m (2°F/100’), is about 2740 m or 9000 ft. Calculations show that overpressure (0.8 of lithostatic pressure) within the Santa Barbara hydrocarbon basin would have been required to rapidly transport hot fluids up to shallow levels.

Tar mounds are well known from the Santa Barbara Channel, particularly from the Point Conception area (Vernon and Slater, 1963; Fischer and Stevenson, 1973). Draut and others (2009) estimate the volume of tar emitted in that area to be the equivalent of 170 Million barrels of oil. Recently, several large tar mounds (estimated to contain up to 3 Million barrels of oil) have been found in the Santa Barbara Channel west of Platform Gail (Valentine and others, 2010; see map p. 39 in Boles and others, 2012). Radiocarbon dating of calcite cements enclosed within these tar mounds had dates of 31,000 to 44,000 years. There are a number of tar accumulations in the channel that will yield similar Pleistocene ages as found in onshore calcite inclusions (approximately 11,000 to 2,000,000 years old). It is interesting that these hydrocarbon expulsions are roughly Pleistocene age, suggesting that this was a time of early overpressure in the hydrocarbon generating basins of the Santa Barbara Channel. Also of note is that *none* of the offshore fields were highly overpressured at the time of development in the 1960s, indicating that pressure had been bled off by that time. This may have been due to breaking of seals and release of oil and gas through seepage during the Pleistocene.

Historic Evidence of Seepage

The oldest historic records of hydrocarbon seeps in the area are objects made by the coastal Chumash tribe. Tar was used for sealing baskets and caulking canoes at least 7000 years ago (Wilkinson, 1971). There are numerous written records from early explorers describing tar seeps, oil slicks and the smell of hydrocarbons in the area from at least the 1500s when Juan Rodriguez Cabrillo noted the Chumash use of tar for canoe caulking. In 1772, Pedro Fages, commandant of the Monterey Presidio, described oil and tar seeps during his exploration of the southern California coastal area. In 1792, English explorer George Vancouver noted oil slicks and the scent of burning tar in the Santa Barbara channel. In the 1850's asphalt mining began in the More Mesa area as well as Carpinteria (see Galloway, 1998) and this was one of the earliest commercial applications of hydrocarbons in the area. A telling description of the amount of leaking hydrocarbon in the area comes from Henry G. Hanks (1886), State Mineralogist, while passing through the Channel: "*At 2 o'clock passed Goleta, and saw petroleum spreading over the sea rising from submarine springs. As the ship throws aside the water in her passage, a strong smell of coal oil is observed. I had often heard of this locality and the oil springs, but I did not realize the extent of surface covered or the signification from an economic standpoint. The smell is not of asphaltum, but of light coal oil, which to the experienced sense is distinctly different*".

Description of Seepage in the Coal Oil Point Area

The Coal Oil Point (COP) area consists of two major seep trends (Fig. 1). The most recent structural analysis indicates the inner trend is in shallow water and is on the hanging wall (north side) of the Red Mountain thrust fault (Leifer et al., 2010). The outer trend follows the South Ellwood fault and the crest of the South Ellwood anticline. The outer trend appears to deviate away from the Ellwood fault in the easterly area and continues to follow the South Ellwood anticline structure (Fig. 1). Platform Holly and the seep tents occur along this outer seep trend. Currently, the largest and most intense area of seepage occurs along this outer trend to the east of State lease PRC 3242.

Causes of Hydrocarbon Seepage

Hydrocarbon seepage to the surface in a *hydrostatic system* occurs when the buoyancy force of the hydrocarbons is greater than the resistive capillary forces within small pores and fractures. We can assume that the resistive capillary forces are largely constant over time for given fluids and that any change in seepage is mainly due to changes in the buoyancy force. Where pore spaces are large or open fractures are present, flow rate can be expressed by the *hydrodynamic* related Darcy expression, in which flow is proportional to the pressure differential in the vertical direction and related to it by the permeability constant. In either approach for analyzing vertical flow (i.e. where flow is considered either hydrostatic or hydrodynamic), the rate of fluid movement is related to a pressure differential. In a hydrostatic system where there are no lateral hydrodynamic forces, the buoyancy force is dependent on the density of the hydrocarbons and the height of the hydrocarbon column relative to the ambient formation water pressure gradient (Schowalter, 1976). As hydrocarbons are removed from the reservoir, the buoyancy force decreases at the top of the hydrocarbon column, which results in a decrease in the driving force for seepage. This decrease could be offset to some extent by a gas cap forming due to degassing of the oil with a drop in reservoir pressure. The extent to which this occurs depends on the gas content of the oil and the pressure drop.

Typical buoyancy gradients for oil-water systems might be 0.1 psi/ft, which is the difference between a water gradient of 0.433 psi/ft and an oil gradient of 0.333 psi/ft. Sea water of salinity 35,000 ppm total dissolved solids (TDS) has a gradient of 0.444 psi/ft. Buoyancy forces for a gas column are much greater than for an oil column, due to the lower density of gas relative to oil. Natural gas pressure gradient in the subsurface typically ranges from 0.001 to 0.22 psi/ft. Thus, the buoyancy gradient from gas-water systems can range from 0.2 psi/ft to 0.5 psi/ft (the high value representing a very saline water gradient). The lithostatic gradient due to the rock load is generally considered to be 1.0 psi/ft.

The fluid pressure in a reservoir can be sub hydrostatic if fluid is removed at a greater rate than can be replaced by hydrodynamic flow into the reservoir. A sub hydrostatic pressure gradient means that if a tube extended from the reservoir to the surface, the fluid column would not reach the surface. In the case where the pressure gradient in the reservoir is lower than the ambient hydrostatic gradient (assumed in the above to be 0.433 psi/ft), the buoyancy force will be even less than shown above (lower difference of water versus oil gradients), and thus seepage will be further decreased. The South Ellwood field has been sub hydrostatically pressured since 1985. 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. When a pathway to the surface exists such as a fault zone, a *hydrodynamic* condition may exist where there is a counter flow of fluid from the sea bed into the reservoir. Such a counter flow would present an additional resistance to the buoyancy force (i.e. or tendency of seepage to occur). As shown later in this paper, all of these factors (sub hydrostatic fluid 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 understanding how hydrocarbon production at Platform Holly has affected seepage rates.

Fate of Emitted Gaseous Hydrocarbons

Clark and others (2000) made an important observation that only about 50% of the emitted seep gas on the sea bed escapes to the atmosphere. The remainder goes into solution in the water column. At COP, they used a tracer gas (SF_6) to determine the current direction (which flowed both west and east in their experiment) and by tracing the current and analyzing samples they were able to show significant dissolution of methane. Mau and others (2007) showed the dissolved methane plume is concentrated along the coast at COP in the water column. They report that at most, 10% of the dissolved methane escapes to the atmosphere within 30 km of the plume source, and most is oxidized by bacteria. The methane enriched waters appear to be swept to the west by currents (Mau and others, 2007). The importance of these studies is showing that the volume of gas that escapes to the atmosphere is significantly less than is emitted at the sea floor and that the ultimate fate of methane in the water column is oxidation to CO_2.

Fate of Emitted Oil

Oil emitted from natural seeps is known to form surface slicks and this has been used to estimate volumes of leaked oil in the Coal Oil Point area (e.g. Allen et al., 1970). Recent studies have shown that, at least for the oils in COP area, the oils are subjected to rapid alteration in the marine environment (Wardlaw et al., 2008; Farwell et al., 2009). Two-dimensional gas chromatography-time-of-flight mass spectrometry was used and clearly showed how the oil was being molecularly modified in the plume moving away from the source. They conclude that alteration includes evaporation of volatiles, dissolution, and biodegradation, but only a minor contribution from photo oxidation. As a result of the alteration process, the oil becomes relatively dense and settles to the bottom to be incorporated as tar balls in the sediment. To date, there have been no sediment tar studies in the seep trend along the South Ellwood anticline trend. Due to its proximity to shore, seepage from COP and the South Ellwood area result in an abundance of tar balls reaching the shoreline before they sink. The occurrence of tar balls is very common along the entire southern California coastline (Del Sontro et al., 2007; Lorensen et al., 2009).

Distribution of Seepage Patterns Relative to Geology

Early studies (Fischer and Stevenson, 1973b) noted that the seeps in the COP area are related to the sediment thickness, whereas abundant seepage is associated with thin sediment cover. They also noted the seeps were positioned over the elongate anticlinal structures in the area. Eichhubl and others (2000) confirmed this for much of the Santa Barbara basin using side scan sonar and an ROV from the Monterey Bay Aquarium Research Institute (MBARI). They also noted slump scarps to be important areas for seepage in the Santa Barbara Channel.

Leifer and others (2010) presented a detailed structural analysis of the COP area using the latest maps and interpretations (Fig. 1). Their work shows that the offshore seep trend at COP is related to the main South Ellwood anticline, which partially corresponds to the South Ellwood fault trace in the west. Further to the east, the seep trend follows the main anticlinal crest rather than the fault. This suggests that in the area to the east of existing State lease 3242, the seepage may be more related to tension fractures along the crest of the anticline, whereas in the westerly area seepage is related to both the main fault zone and its splays. The inboard seep trend at COP is on the hanging wall (north side) of the Red Mountain fault rather than on the fault trace itself. The authors also suggest that the numerous cross faults in that area may contribute to the abundant seepage.

Estimate of Seep Rate from Sonar Bubble Traces

Sonar returns have been a useful method to estimate gas volumes escaping through the water column (Sweet, 1973: Tinkle and others, 1973). This is by far the most common method used to estimate gas seepage rate over large areas in the COP area. At a minimum, it is a useful visual tool to see where seepage is occurring over large areas, and if properly calibrated to known seepage rates, it can provide quantitative estimates of seepage. The strength of the sonar return is proportional to the bubble size and bubble frequency. Bubble plumes show as dark columns on sonar traces, and the darkness is related to the intensity of the bubble stream. A single beam sonar source has a characteristic resonance frequency depending on the frequency of the source, so bubble populations that fall within that size must be avoided (see discussions in Hornafius and others, 1999; Lorenson et al, 2011). The sonar frequency most commonly used has been 3.5 kHz, but 30 and 50 kHz have also been employed. Lorenson and others (2011) report that single beam sonar is very insensitive to flux in flow rate. They concluded that multibeam sonar would be the best sonar method for future studies, however they point out the main difficulty of processing the very large volume of data. To date, there are no published results using this method.

Estimate of Oil Seepage for Coal Oil Point

The earliest quantitative estimates of oil seepage at COP came from Allen and others, (1970) using both direct and indirect methods. They estimated oil seepage by direct collection of oil from a few vigorous seeps using inverted jugs. They also measured oil globule transfer via time lapse photography and quantified a flux, and finally they measured oil slick surface areas and quantified oil amounts within the slick by measuring oil absorbed onto mats. They estimate a total of 50 to 70 bbls oil/day being released in the area of study, which was in less than 30m of water.

An oil collection experiment at the sea surface over the seep tents allowed an estimate of oil/gas ratio to be about 94cc of oil/liter of gas (Clester and others, 1996). Hornafius and others

(1999) used this ratio and their sonar estimates of gas seepage over the COP area to estimate about 100 bbls oil per day are leaking from the seeps. They suggest this amount is a minimum because Allen and others (1970) report 50-70 bbls/day of oil globules close to shore at Coal Oil Point alone. A barrel of oil weighs about 300 lbs.; thus, 100 bbls/day is about 15 tons oil/day. If the near shore area is included, the total for COP is about 160 bbls/day, or 25 tons/day.

Estimate of Hydrocarbon Seepage Rate from Tar Balls in Sediment

Farwell and others (2009) have looked at the fate of oil release from natural seeps at Coal Oil Point by determining the amount of tar in sediment. They showed first from biomarkers that the inboard seep oil was very similar to Monterey reservoir oil. Their work also showed that oil transferred to the ocean surface is quickly altered due to evaporation of volatiles, dissolution, and biodegradation. Farwell and others report that 10% of the total petroleum hydrocarbon evaporates within minutes from oil arriving at the sea surface. Much of this altered, denser oil settles back to the sea bottom where it is incorporated as tar balls in the sediment. Fifteen sediment cores were taken in the upper 5 cm of sediment in a series of traverses across a calculated plume path, which extends to the west from Coal Oil Point. The resultant tar content was extrapolated to depths between 50 cm and 500cm (assuming sediment cover in the area) over the area of the plume. The calculations indicate that the amount of oil as tar in the sediment far exceeds (up to 80 times) the amount of oil spilled in the *Exxon Valdez* disaster. Farwell and others (2009) state that 20-25 tons of oil is being emitted daily from the near shore COP seeps, however they do not provide any support for this estimate. The importance of Farwell and others (2009) is that it demonstrates a match between the offshore oil composition and the oil at the inboard seeps. It also shows that as oil is altered and becomes increasingly dense, a substantial amount of it sinks and becomes incorporated into the sediment column on the ocean floor. Their study did not look at the outer seep trend which forms the majority of the seepage in the area.

Estimate of Gas Seepage for Coal Oil Point Area

Figure 2 is a summary of the sonar seep surveys in the Coal Oil Point area. The earliest published sonar survey of the COP area was done using 3.5 kHz sonar in the early 1970s and reported by Fischer and Stevenson (1973b). The original sonar traces of Fischer were obtained by UCSB graduate student Derek Quigley and remapped using the same sonar intensity criteria that UCSB was using for their 1994 and 1995 sonar surveys. The result was that Quigley (1997) could compare the early work of Fischer to his own. This work was published by Quigley and others (1999) and extended by Hornafius and others (1999). The results of the comparison of Quigley and others (1999) to the work of Fischer are highlighted later in this paper.

Hornafius and others (1999) conducted sonar surveys in 1994 and 1995 in the Coal Oil Point and outer South Ellwood trends. They estimate that 1.7 x 10^5 m^3d^{-1} natural gas and 100 barrels oil d^{-1} was seeping from the Coal Oil Point area, including gas captured at the seep tent, which at the time was about 1.9 x 10^4 m^3d^{-1}. The gas volume estimates were made with a 50 kHz sonar signal that was calibrated to gas emissions from scuba tanks. The darkening of the bubble plume on the paper trace was calibrated and related to the emission rate. In addition, the method was quantified using the seep tent. Prior to their November 1994 survey, there was a mechanical malfunction at the seep tent which caused release of a known flux rate of gas. This malfunction was fixed before the 1995 survey, and this allowed a comparison to calibrate the sonar traces. Sources of error (discussed by the authors) include bubble size, rate of bubble ascent, and saturation of the 50 kHz signal at high gas emission rates. They report that 90% of signal recorded was where the emission/signal record was linear.

Washburn and others (2005) used the flux buoy in a 2002-2003 survey of Shane Seep in 20 m of water, Horseshoe Seep in 40 m of water, and importantly, the outboard seepage at La Goleta seep in 65m of water. They estimate a total of 7400 m^3/day or 260 MCF/day for the three seeps they studied. Visual observations made during shipboard sampling showed that La Goleta Seep was the weakest of the three seeps. The seep areas covered by the buoy are very small compared to the much larger scale sonar surveys. The small rectangle in the intense outboard seep (Fig. 2) is the La Goleta Seep area surveyed in 2003.

Horseshoe Seep was the strongest seep recorded by Washburn and others (2005). They show the La Goleta Seep as having an area of concentrated seepage of about 1400 m^2. Their estimate of the La Goleta seep rate (after subtracting background noise) was 800 m^3/day. The location they show for the maximum seepage area (Figure 2, Washburn and others, 2005) is almost exactly where Hornafius and others (1999) and Leifer and others (2005) show the maximum seepage. As will be shown in the calculations below for the outer seep area, the flux buoy estimate of emission rate is as much as 3 times greater than the minimum sonar estimates shown by Hornafius and others (1999). The Washburn and others gas emission rate at the La Goleta seeps may be even greater than indicated above if only the small area of intense seepage is considered (see Fig 6 in Washburn and others, 2005).

The most recent sonar seep survey is that of Leifer and others (2010), which was conducted in 2005. Their mapping work (Fig. 2) highlighted the intensity of the sonar returns but does not have quantitative estimates of gas flux. The La Goleta Seep shows up especially strong on their map.

DISCUSSION

Why Natural Seepage Rates Should Decrease with Hydrocarbon Production

As described above buoyancy is the main driving force for hydrocarbons to escape from the sea bed. Buoyancy is related to the type and height of the hydrocarbon column in the reservoir and its relation to the ambient fluid pressure gradient in the area. At South Ellwood, there are three interrelated conditions which contribute to a decline in seep rate at the overlying sea bed (1) removal of large volumes of hydrocarbons from the reservoir, (2) declining reservoir pressure, and (3) some counter flow of sea water into the reservoir along the seepage pathway, which opposes seepage. All of these factors are addressed below.

The following conditions would have to be present for hydrocarbon production to have no effect on overlying surface seeps: (1) no connection to the subsurface reservoirs (2) the hydrocarbons, regardless of source area, are being replenished at a rate equal to or faster than the leakage rate and (3) the movement of hydrocarbon is so slow that any effects from production would be too slow to be observed within our lifetimes. None of these conditions are true based on available data.

In the case of the offshore Santa Barbara channel seep trends, for the production to have no effect on overlying seepage would require that hydrocarbons be generated above the reservoir depth, or the migration path of the surface seeps would have to circumvent the underlying reservoir rock. All of these assumptions are unrealistic. The methane gas from the seeps at the seep tent has an isotopic composition identical to the reservoir gas at Platform Holly rather than bacterial methane (Boles and others, 2004). This 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, demonstrating the oils have a common origin (Farwell et al, 2009), although the rapid degradation of the oils at the surface can make them difficult to match exactly to reservoir oils (see Leverson et al., 2011).

The alignment of the 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. The argument that the seeps cannot be affected on short time scales by production is shown to be incorrect by looking at the sonar results on bubble seep intensity (1973 versus 1995; see Quigley, 1999) and the production history of the seep tent relative to Platform Holly. One of the most surprising aspects of the seepage is how quickly it has responded to the underlying production. This was something that was not known when offshore oil development began in the area some 40 years ago.

Industry Mapping of Seeps

Fischer and Stevenson (1973b) compared industry maps from 1946-1947 (Signal Hill Oil company) and 1953-54 (Continental, Union, Shell, Standard Oil Companies) for the offshore COP area. The maps show a marked decrease in frequency of seep and tar localities over the seven year time period (Figs. 3a and 3b). This is interesting as many of the seep localities are far from shore where most of the oil development has yet to occur. Off shore development in this area was more than 10 years away. Fisher and Stevenson (1973b) were the first to note the decrease in seepage in this area from the industry data as well as a comparison to their own sonar survey conducted in 1972.

Sonar Estimates of Seep Localities

Evidence for the relationship between natural seepage rate and hydrocarbon production comes from several methods and on different time scales. On the broadest areal scale, seepage around Platform Holly has been greatly reduced based on sonar scans of bubble intensity in the water column. Figure 2 shows the published offshore seep surveys and the year they were measured. The early 1973 sonar surveys of Fischer were published by Fischer (1977) and shown by Quigley and others (1999) for comparison to their later survey of August 1996. All of these surveys used 3.5 kHz records, except Hornafius and others (1999) used a 50 kHz signal.

All of the work clearly shows a large seepage trend along the axis that is known as the South Ellwood anticline and a parallel trend to the Red Mountain fault (see (Fig 1). The northern trend is parallel to, but south of, the trend of the Coal Oil Point anticlines (see Fig. 3 in Quigley et al., 1999). Unfortunately, the 1973 survey did not extend further east than the eastern boundary of State lease PRC 3242, so we have no comparison of the 1970s to the 1990s in that area. Comparison of the 1973 survey with a later and more extensive 3.5 kHz sonar surveys from July 26-27, 1995 and August 15-17, 1996, clearly shows the decrease in water column bubble trains from natural gas seepage in the vicinity of Platform Holly (Fig. 4). Furthermore, the more recent survey shows extensive seepage along the anticlines between Coal Oil Point and Goleta Point (Campus Point) (see Fig. 5). Much of this area lies to the east of State lease PRC 3242. Although quantifying the amount of seepage reduction that has occurred is difficult, Quigley and others (1999) conclude that there has been a 50% reduction in areal extent of seep emission accompanied by a reduction in seep emission volume. The general conclusion that seepage has been reduced around the Platform is unquestionable. The only *quantitative* estimate of seepage to the east of existing State lease PRC 3242 is the work of Hornafius and others (1999) who described surveys in 1994 and 1995 (Fig. 5). These data will be used in the latter part of this paper to calculate seepage in this area.

Production at Platform Holly

Hydrocarbon production at Platform Holly began in 1967 and continues today. As of January 2015, total cumulative production is 77.9 MM bbls oil, 114.5 MM bbls water, and 73.6 BCF gas. The cumulative amount of Monterey gas production is 57 BCf. Oil and gas production has gradually declined through the life of the field, whereas water production has increased markedly. However, the fluid production rate must be exceeding the water influx rate as the reservoir pressure has been less than hydrostatic for a number of years. Both of these factors had a significant influence on natural seep rates in the area. Figures 6 and 7 show the daily production rate and cumulative production at Platform Holly since the late 1960s. Note the increase in daily water production over time, as well as the large amount of cumulative water that has been produced in recent years. Also note that there has been a recent increase in hydrocarbon production, mainly due to well completions in the more easterly part of the field, near the existing easterly boundary of State lease PRC 3242.

The decrease in volume of the oil column has resulted in a decrease in the buoyancy pressure of the column. This means that fewer hydrocarbons have sufficient buoyancy to overcome the capillary pressure necessary to escape the reservoir. In addition, withdrawal of hydrocarbons from the reservoir at a faster rate than they are naturally replenished has resulted in a significant drop in fluid pressure. Thus, the buoyancy pressure of the hydrocarbon required to displace the water is much less, because of the decrease in fluid pressure at depth.

Reservoir Pressure

Reservoir pressures have declined significantly since production began. Initial reservoir pressure at South Ellwood (about 3881' subsea level) was approximately 1800 psi (Fig. 8). Thus, the initial fluid pressure gradient was about 0.464 psi/foot. The pressure gradient for sea water is 0.444 psi/ft, therefore the South Ellwood reservoir would initially have been slightly over pressured. In 1985, the reservoir pressure had dropped to about 1450 to 1300 psi (Fig. 8), which is 80% to 72% of the initial hydrostatic gradient (i.e. sub hydrostatic). 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 (Table 1). Current reservoir pressures are sub hydrostatic and only 56% of the initial reservoir pressure. Reservoir pressure at this value indicates that water in an open tube to the surface would only fill the tube approximately 50% of the length to the surface. As a result of reservoir pressure being less than hydrostatic, there is some local influx of sea water into the reservoir. Evidence for this comes from two sources (1) tidal signals within the reservoir (Fig. 9, Boles and others, 2010; Boles and others, 2012) and (2) geochemistry of the reservoir water in the wells close to permeable faults (Fig. 10, Boles and others, 2012). The importance of this downward flux of sea water is that the flow presents a dynamic counter force opposing to the upward seepage of hydrocarbons. This ultimately results in reduction of seepage at the surface.

Seep Tents

ARCO deployed two large steel pyramids (referred to as tents) on to the sea floor in September of 1982 (Fig. 11). The purpose of this project was to capture and produce seep gas escaping at the sea floor in order to obtain emission offset credits for future development projects (Rintoul, 1982). As mentioned above, the tents initially produced some oil (a total of about 600 bbls) with the gas, but oil seepage into the tent stopped in about 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 pollution (Galloway, 1998). 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 ft^2). 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.

Quigley and others (1999) were the first to relate seepage into the seep tents to hydrocarbon production. They noted the 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 (Fig. 12). They made no effort however to compare individual Holly well records to the seep tent records. They concluded that the *"Declines 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"* (p. 1047). An overlay of the gas production rate at Holly against the seep rate at the tent between 1982 and 2015 reveals a fairly good correlation that indicates the drop in gas seepage rate at the tent correlates with a drop in gas production at Holly (Fig. 12).

Correlation of Seep Tent Flux to Individual Well Production at Holly

Another direct line of evidence for hydrocarbon production influencing seepage rate is a direct 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 3500 feet beneath the seep tents and relatively close to a fault believed to be feeding the surface seepage (Fig. 13). 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 (Fig. 14). The fact that the production from this well can be correlated to production at the seep tent, demonstrates a hydrodynamic connection between the seepage at the sea bed and the South Ellwood reservoir. Even though seepage goes up when Well 3242-7RD2 is shut off (possibly because of a rise in pressure during shut-down), the overall effect of production at Platform Holly has been a decrease in seepage parallel to, but lagging behind the production rate in the field. Note that the drop in seep tent production at about 2008 (Fig.12) is parallel to a drop in gas production at around 2008. The higher seepage rate into the seep tent when the well is shut-in is interpreted as additional gas being available that is not being captured when Well 3242-7RD2 is on production. This is clearly some of the most compelling evidence of a link between production at Platform Holly and nearby seepage rates.

Cessation of Seepage into the Seep Tents

Perhaps the single most conclusive piece of evidence supporting the connection between offshore production and a decrease in naturally occurring oil and gas seepage is the response of the seep tent to recent drilling activity and production in mid-2013. Well 3242-15RD1 was completed approximately 2500 feet beneath the tent in a previously undeveloped portion of the reservoir. The well is approximate 1000 feet above Well 3242-7RD2 and is positioned high within the crest of the anticlinal structure (Fig. 15). This well came on production in July of 2013 and 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 (Fig. 16). Production from this single well resulted in the ultimate cessation of measureable seepage into the tent. Seepage into the tent has not returned since, despite the annual 10 day shutdown of Platform Holly in October 2013 when all wells in the field including Well 3242-15RD1, were shut in. 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 ROV inspection of the tent (to rule out leaks). No defects were identified and no measurable gas seepage has occurred since August 2013.

Effect of Future Oil and Gas Production on Natural Hydrocarbon Seepage

The South Ellwood anticline and corresponding South Ellwood oil field extend to the east far beyond the existing eastern boundary of State lease PRC 3242 (Fig. 17). Known oil and gas reserves exist in this area and they are located directly below some of the most active seeps. The oil and gas reserves located in this area are very large and it has been proposed by previous operators (ARCO and Mobil), and more recently by Venoco Inc., to develop these reserves. The only quantitative estimates of amounts of seepage in the *entire* proposed development area are calibrated sonar images of bubble plumes by Hornafius and others (1999) (Fig. 9). From this data, the potential effects of production on seepage and resultant environmental benefits can be inferred. Recalling that the sonar estimates are based on bubbles in the water column, the presumed dissolved methane (nearly 50 % of the flux) has been ignored in the estimates given below, as these bubble plumes represent methane being transferred to the surface. Hornafius and others (Fig. 3., 1999) used 50 kHz sonar data to quantify seepage rate in the proposed development area and it is this data that will be used to quantify possible effects of production on seepage rates in this area. None of the other sonar surveys provide more than a qualitative estimate of seepage intensity (Fig. 6). The exception is the flux buoy survey of Washburn and others (2005), which has an estimate of gas flux at a small area in the La Goleta Seep.

The total seepage in the proposed development area east of existing State Lease PRC 3242 has been estimated by measuring (digitizing) the areas of the different seep rates shown by Hornafius and others (1999, Fig. 17) and summing the values (Table 2). The total area of seepage in the proposed development area covers about 2 km^2 within the South Ellwood anticline trend and an additional 0.4 km^2 within the Coal Oil Point trend. The seepage at South Ellwood is the strongest and most extensive of the two trends. The total seepage along the South Ellwood anticline is estimated to be between 1.5 and 4.2 MMCF/day. The seepage along the Coal Oil Point anticline trend is estimated to be between 0.2 and 0.7 MMCF/day. The total seepage of the two areas is summed to be between **1.7 and 4.9 MMCF/day** (Table 2). Seepage in the most intense areas of the outer seep trend is estimated by Hornafius and others (1999) to be >0.1 $m^3/m^2 \cdot day$, 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 flux of 0.03 to 0.6 $m^3/m^2 \cdot day$ from a relatively small area of the La Goleta Seep. These numbers are in-line with estimates from Hornafius and others (1999). 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 and others (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.

Based on these estimates, it is obvious that a large amount of hydrocarbon is being released from the undrained proposed development area. The seep tent installed in 1982 has captured on average 672 MCF/day until all seepage stopped in 2013. In terms of the seep tent gas capture, the amount of gas seeping in the undeveloped area is estimated to be 2.5 to 6.0 times greater. It is difficult to determine with accuracy, what fraction of this seepage would be removed by producing the underlying hydrocarbons in this area. It is reasonable however to assume that the affect will be significant based on the data and trends observed in State lease PRC 3242. The seep tents provide a unique opportunity to estimate seep rates and can be used as a guide to extrapolate the effect of future oil and gas production on seepage in the proposed undeveloped area. Based on data outlined in this paper, there is strong evidence supporting the potential to remove most of this seepage. Presumably, many of the wells would be completed along the crest of the anticlinal structure where much of the seepage is concentrated. Furthermore, the seep tent data clearly showed that wells that were strategically placed close to the migration pathways can have a major impact on the shallow seepage.

CONCLUSIONS

There is clear scientific evidence that hydrocarbon production from Platform Holly has reduced naturally occurring oil and gas seepage in the surrounding areas. This observation should not be a surprise, as removal of hydrocarbon reduces the amount of oil and gas available for seepage. Early works including Fischer and Stevenson, (1973), Quigley and others, (1999) and Hornafius and others (1999) have come to the same conclusion. The removal of a large amount of hydrocarbon also results in a reduction in buoyancy force, which is the driving force for hydrocarbon escape. Furthermore, the rate of hydrocarbon extraction from producing wells far exceeds the rate of natural hydrocarbon generation, migration, and accumulation. As a result, reservoir fluid pressure is reduced and the rate of seepage decreases due to the pressure reduction. All of this is occurring in the vicinity of Platform Holly where production from wells is reducing hydrocarbon escape to the surface. One of the most surprising aspects of the effect of hydrocarbon production on seepage is how quickly the effect takes place, for example when wells are drilled within the crest of the anticline where gas accumulation is greatest or near faults that provide highly permeable pathways for hydrocarbon flow.

The area to the east of existing State lease PRC 3242 contains the most prolific and active natural oil and gas seeps in the Santa Barbara Channel. Future oil and gas production from that area would result in removal of a large amount of hydrocarbons and a reduction in reservoir pressure. Consistent with observations made within the existing State lease PRC 3242 it is reasonable to expect significant decrease in seepage in the adjacent proposed development area. Development could result in a major reduction of 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 (CO_2e) per day). It is also reasonable to assume that the reduction of seepage would be long-lasting. The rate at which hydrocarbons are removed from the reservoir due to production of oil and gas is considerably faster than the geologic processes that replenish the reservoir.

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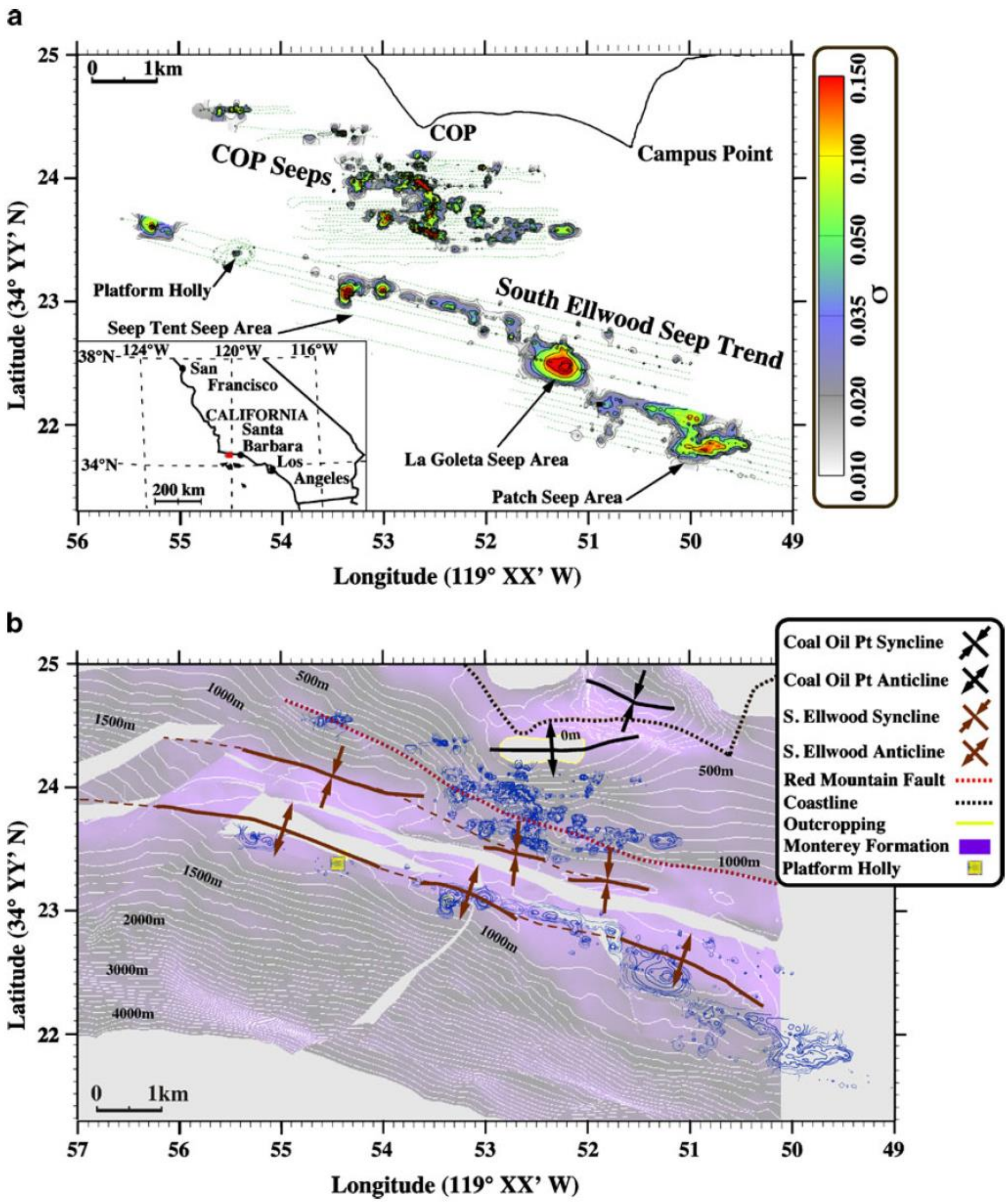


Fig. 1. Relation of seeps to structures, from Leifer and others 2010.

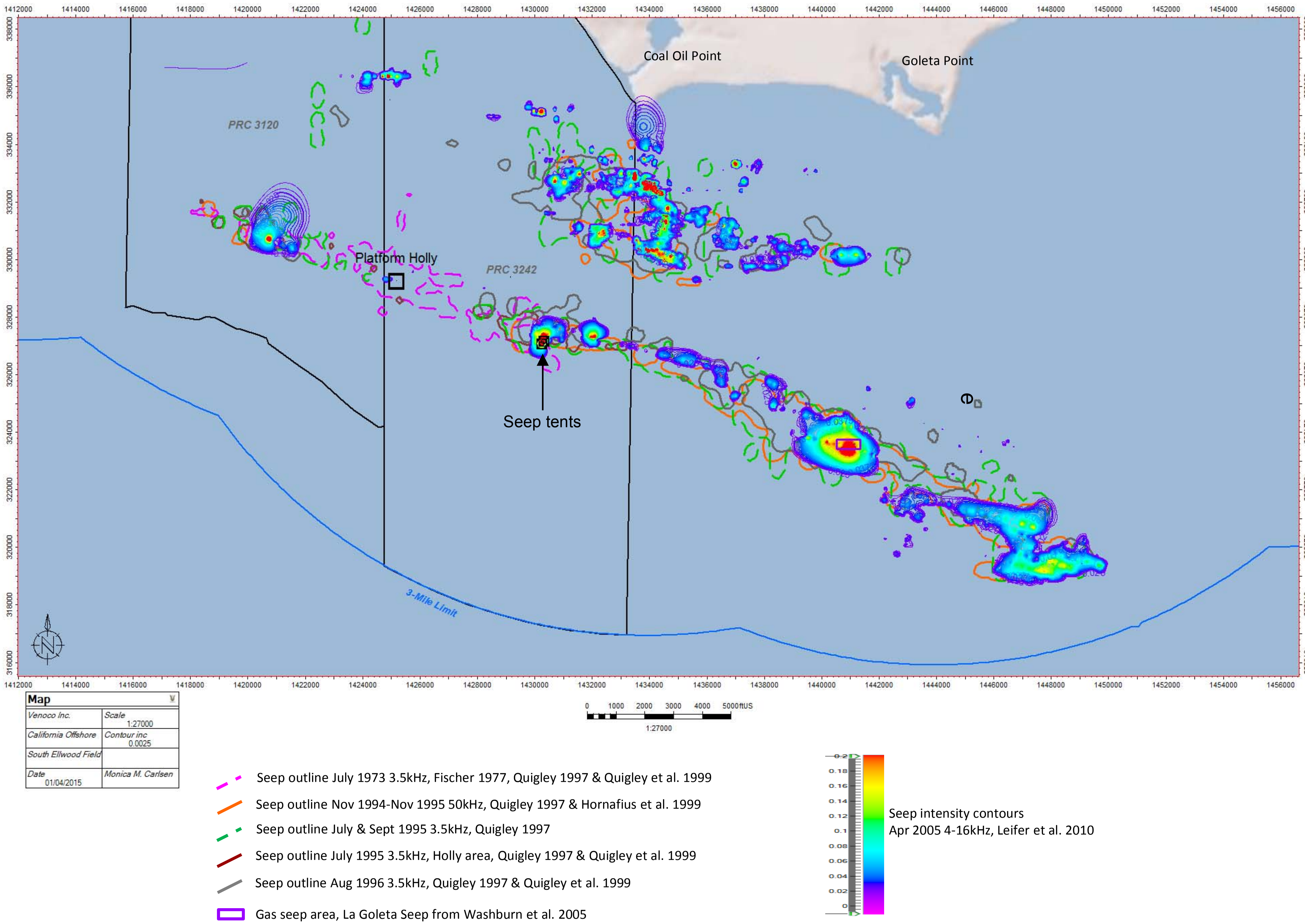


Figure 2. Offshore seep surveys through time

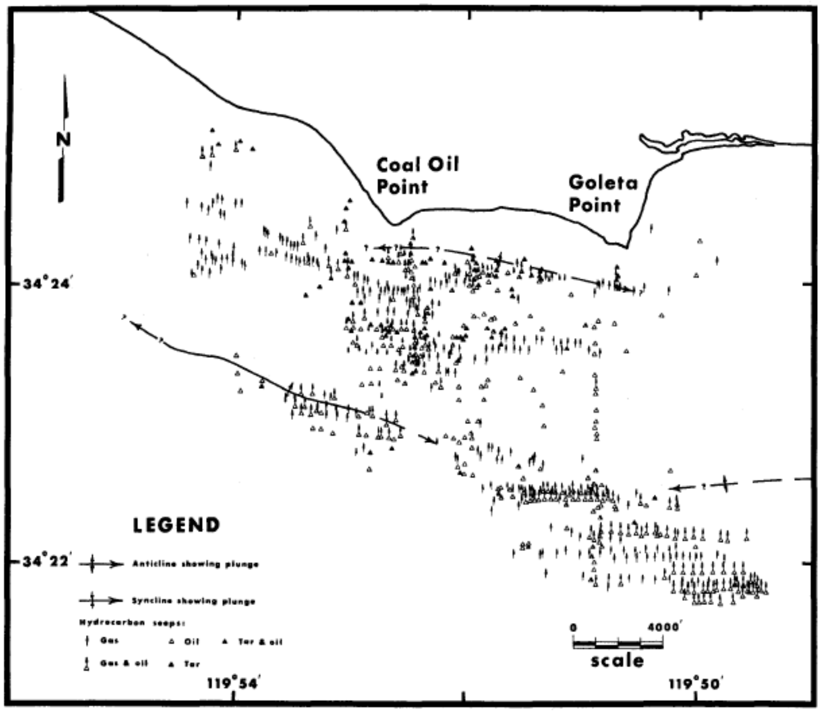


FIGURE 5 — Coal Oil Point area, natural hydrocarbon seeps: 1946-1947 (from industry data).

1946-47

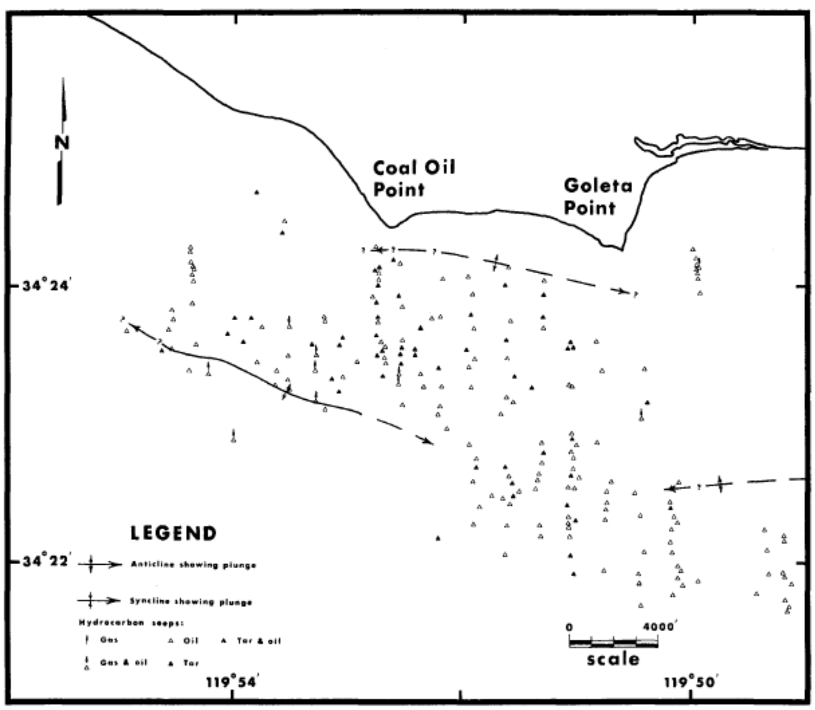


FIGURE 6 — Coal Oil Point area, natural hydrocarbon seeps: 1953-1954 (from industry data).

1953-54

Fig 3a. Seep occurrences. After Fischer and Stevenson (1973b)

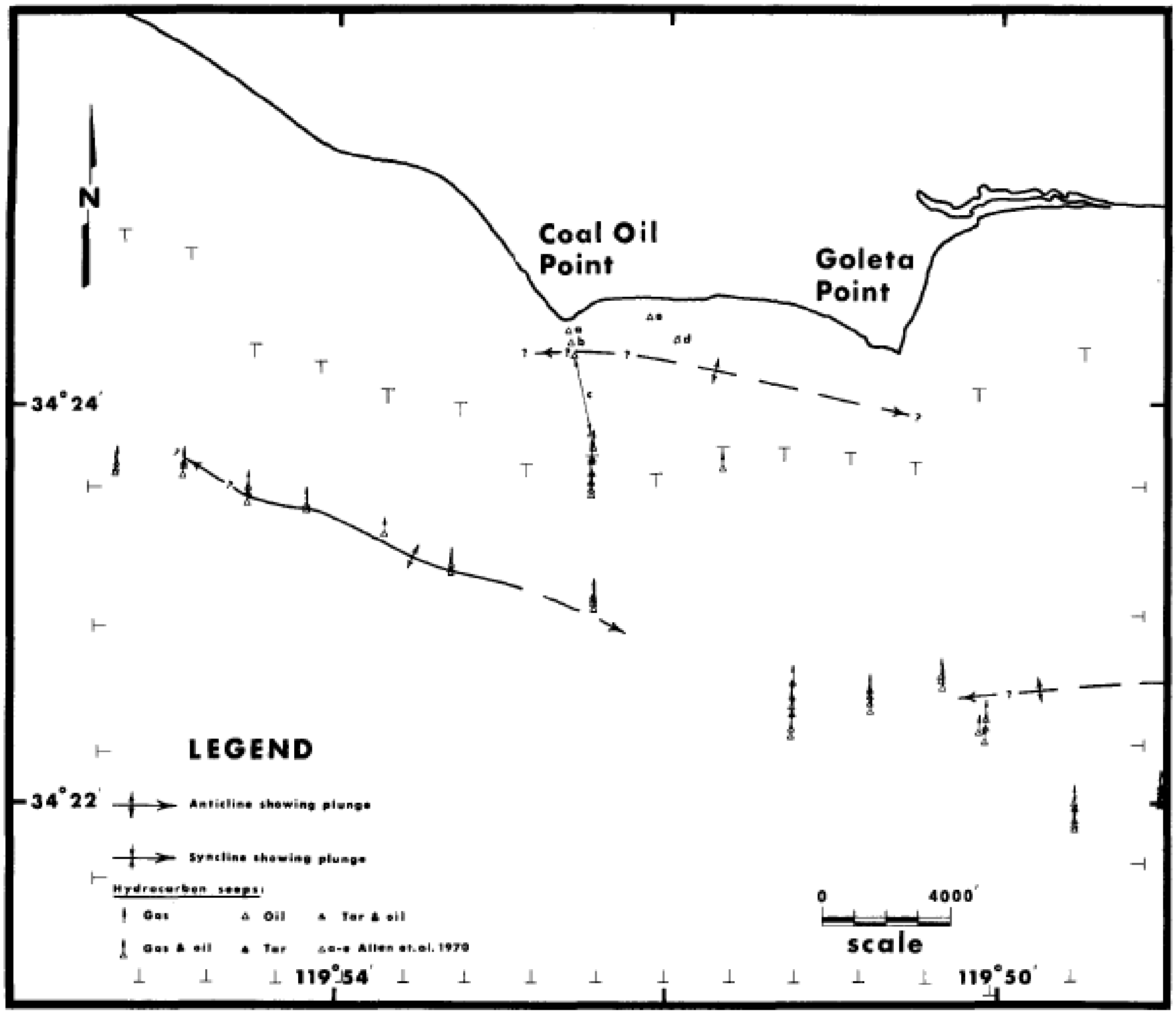


FIGURE 7 — Coal Oil Point area, natural hydrocarbon seeps: 1972 (from high resolution profiles).

24

Fig 3b. 1972 sonar survey after Fischer and Stevenson (1973b)

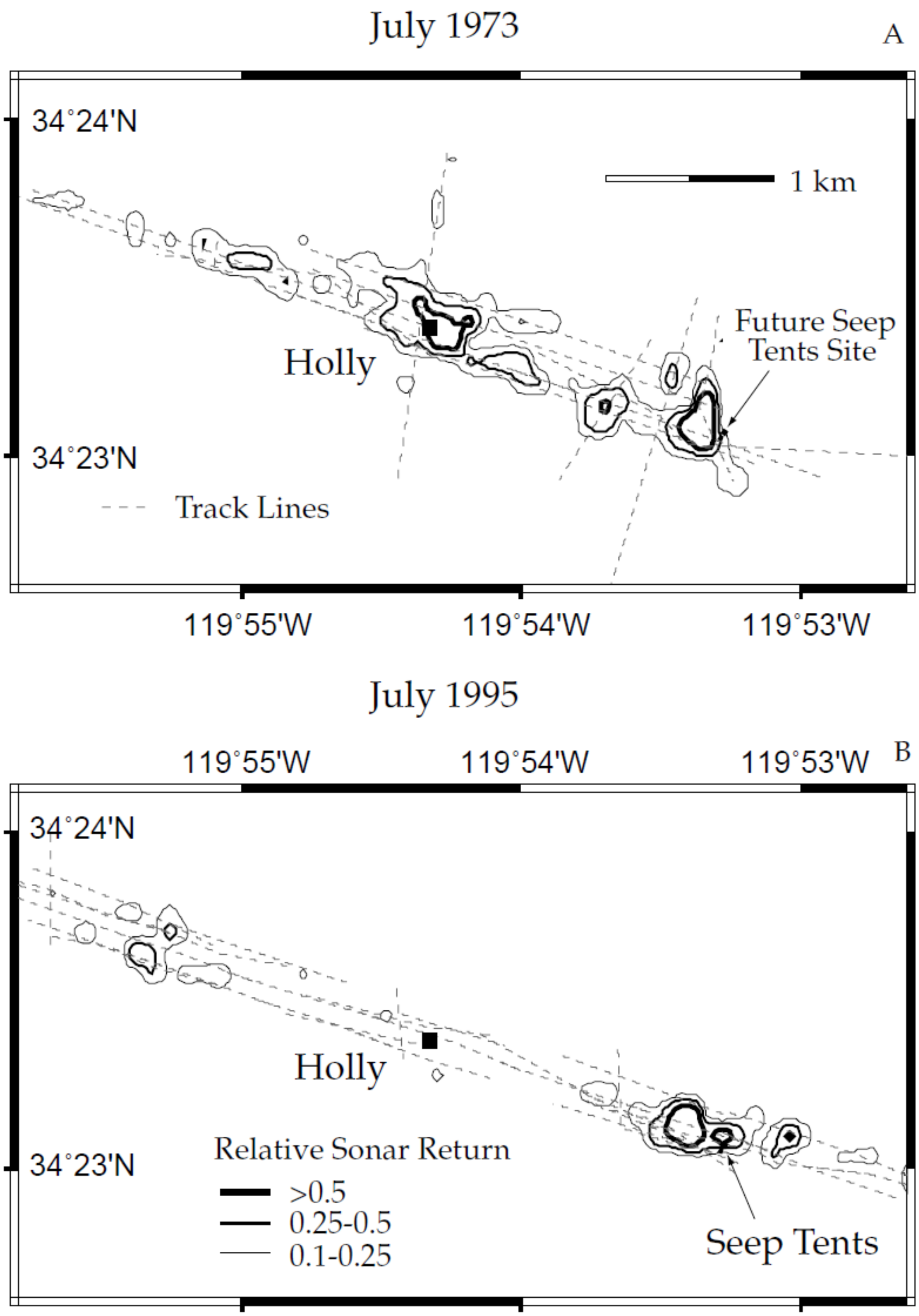


Fig. 4. Comparison of gas emission (sonar estimates) for 1973 and 1995. From Quigley and others , 1999

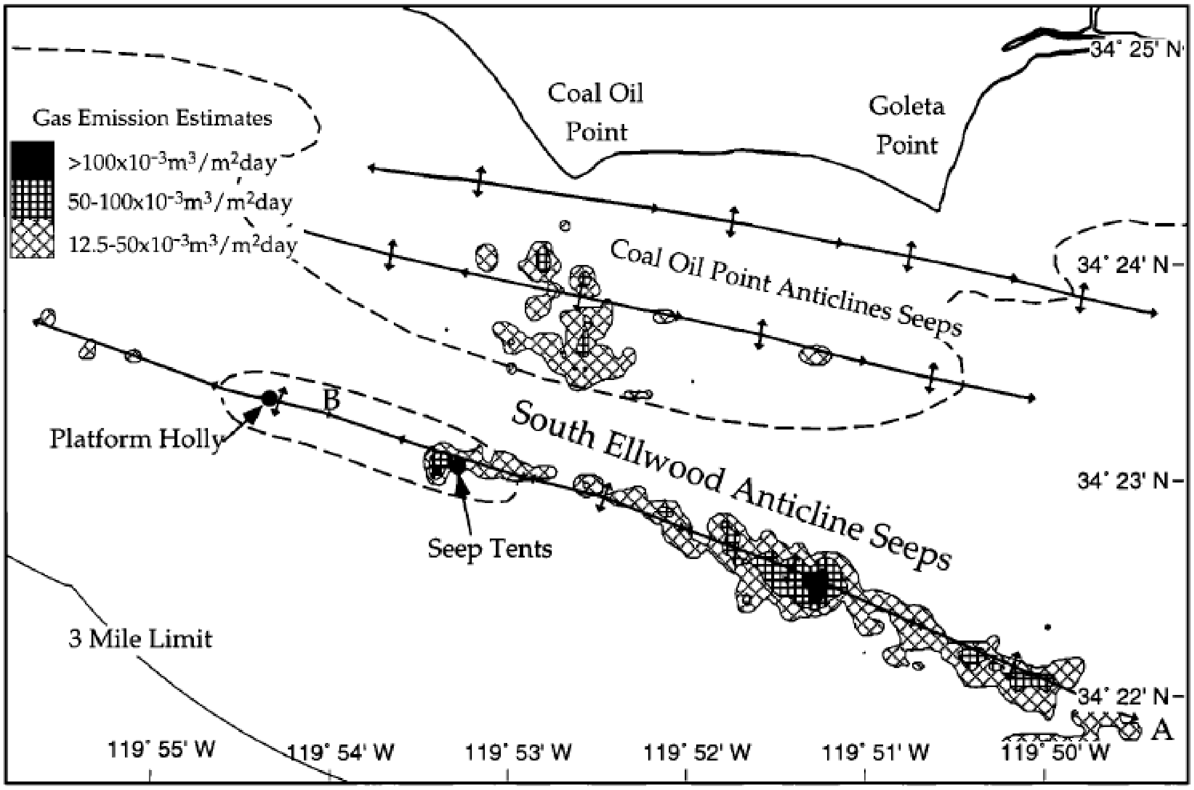


Fig. 5. Gas emission at Coal Oil Point estimated from calibrated sonar data. From Hornafius et al, 1999

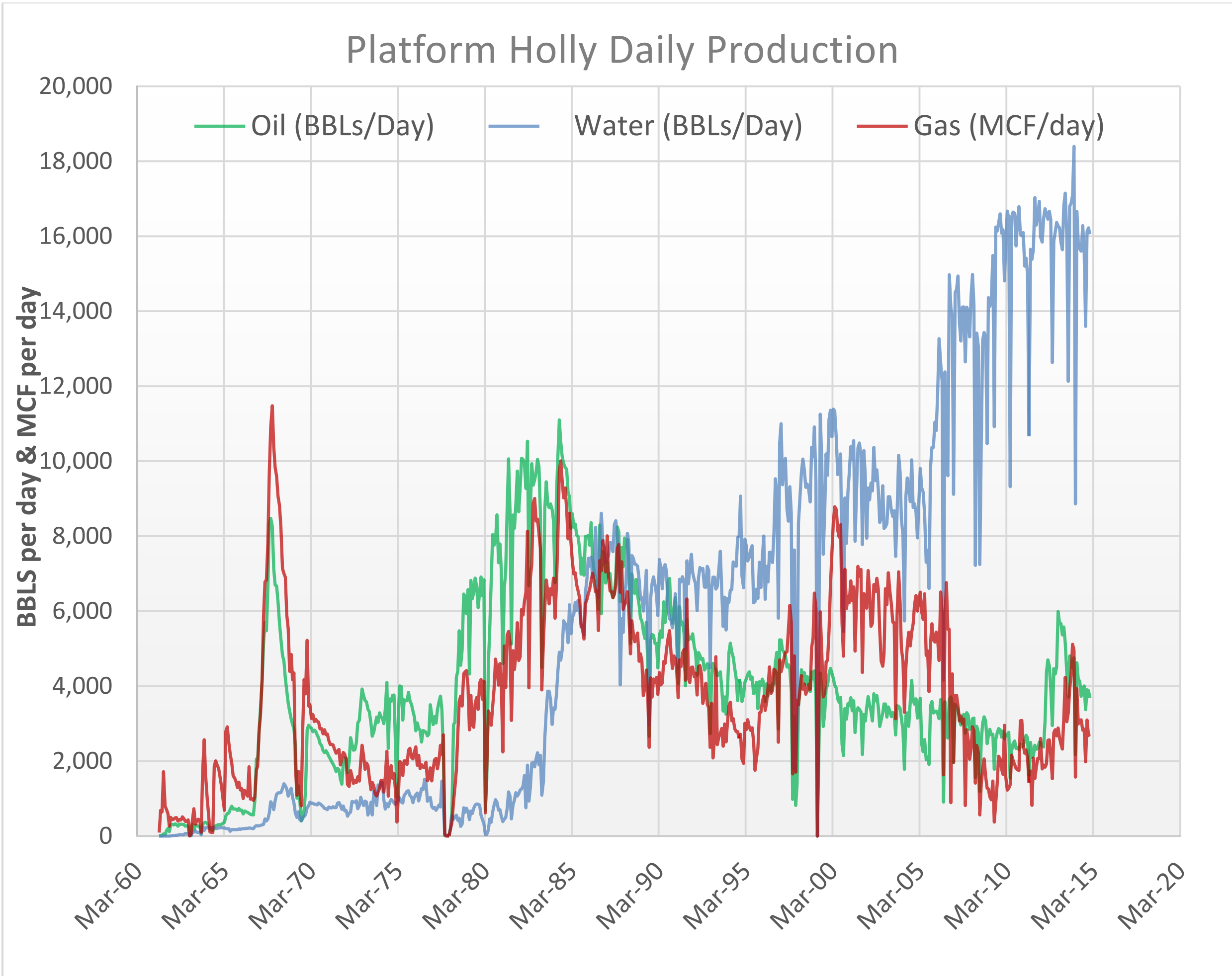


Figure 6. Platform Holly Daily Production.

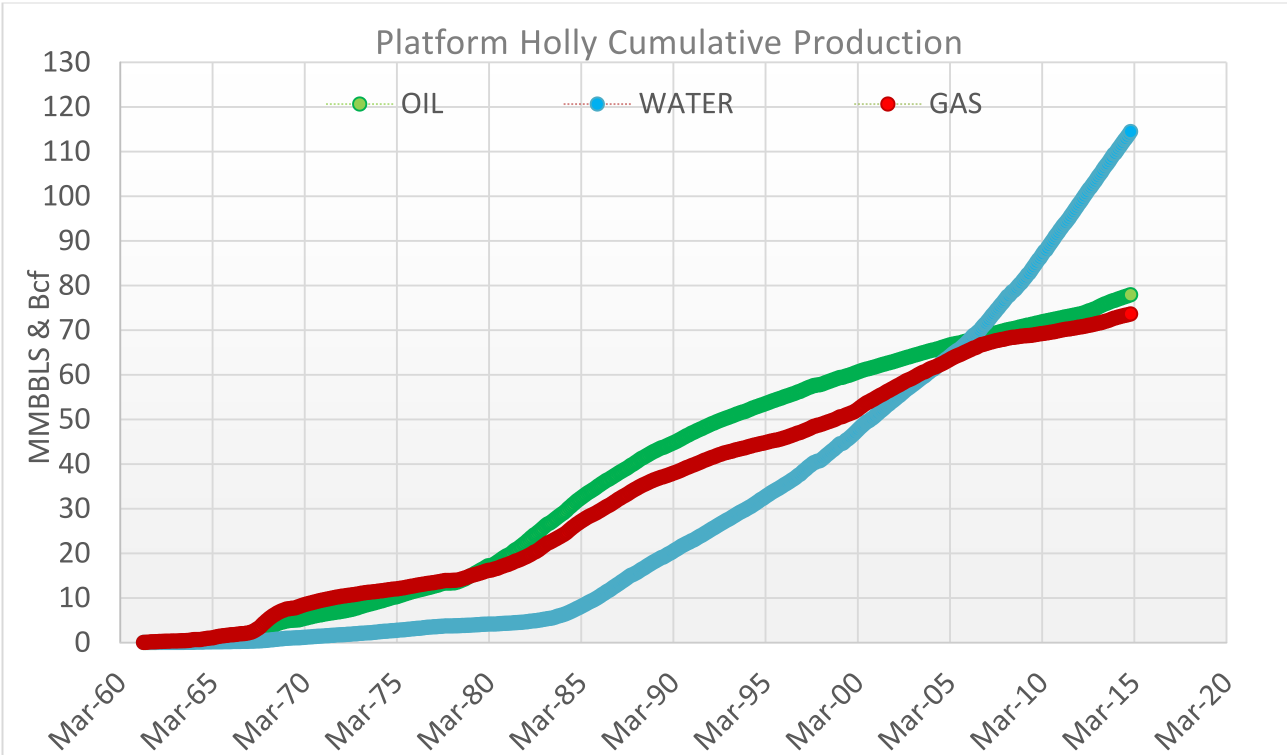
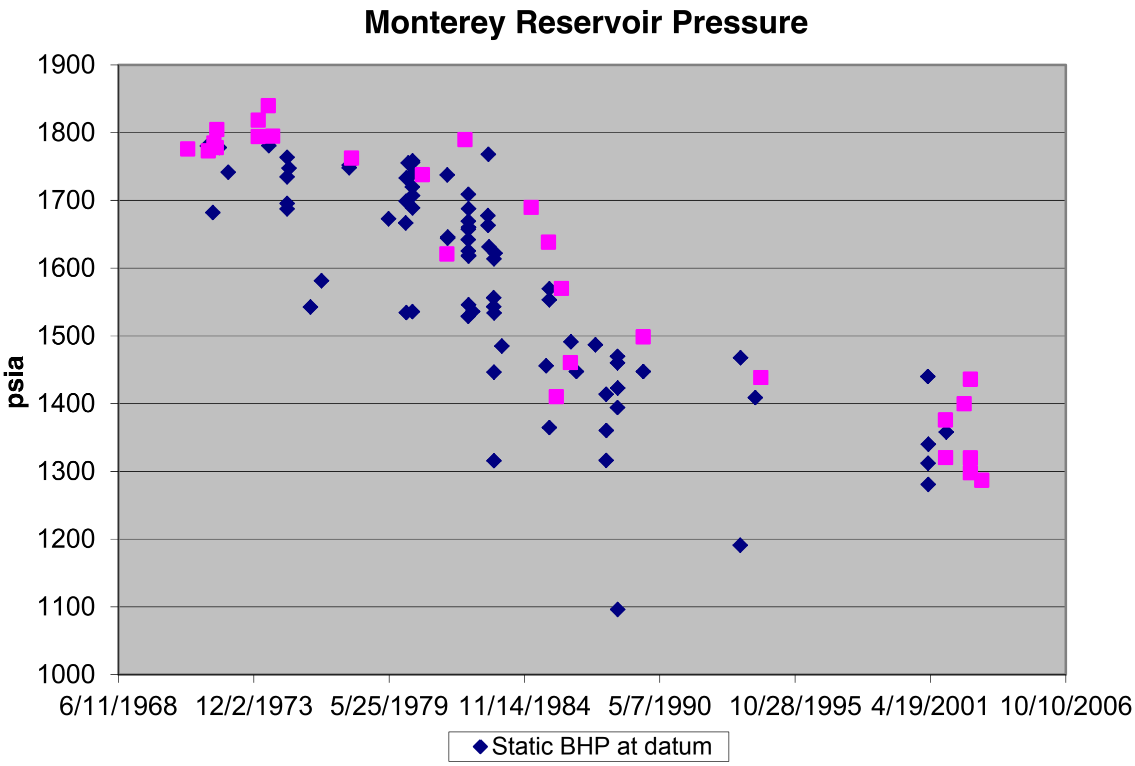


Figure 7. Platform Holly Cumulative Production



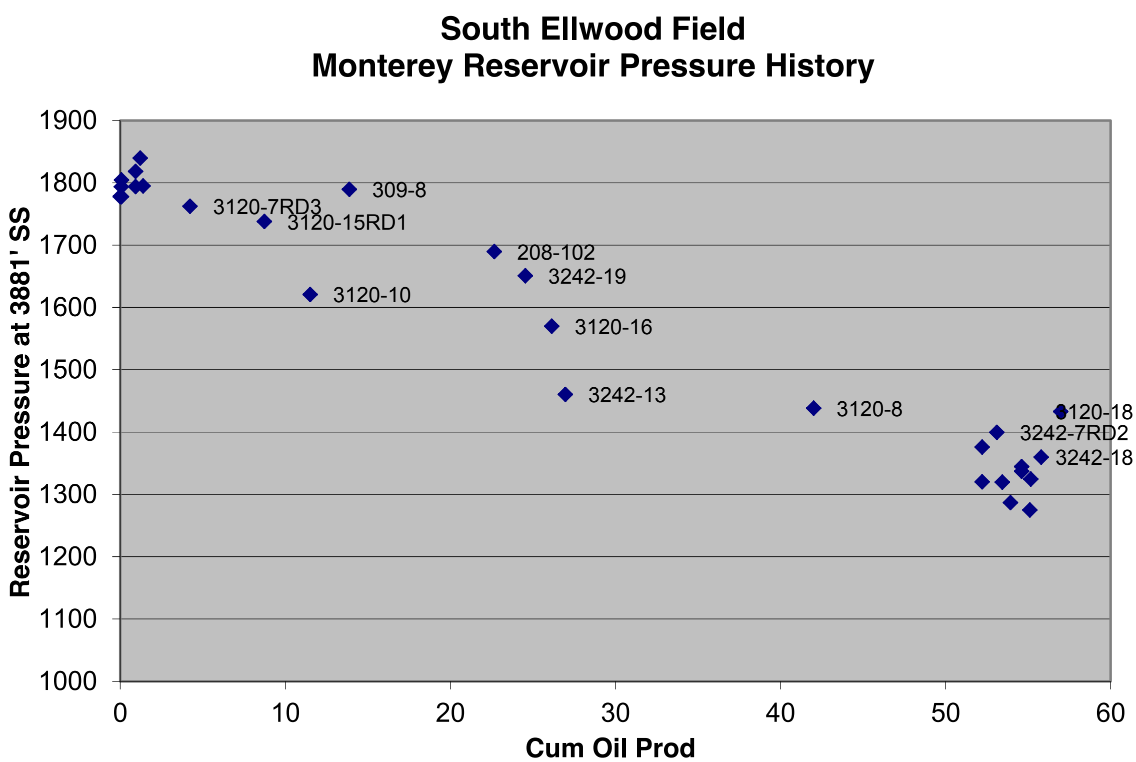


Figure 8. Holly reservoir pressure with time and cumulative production.

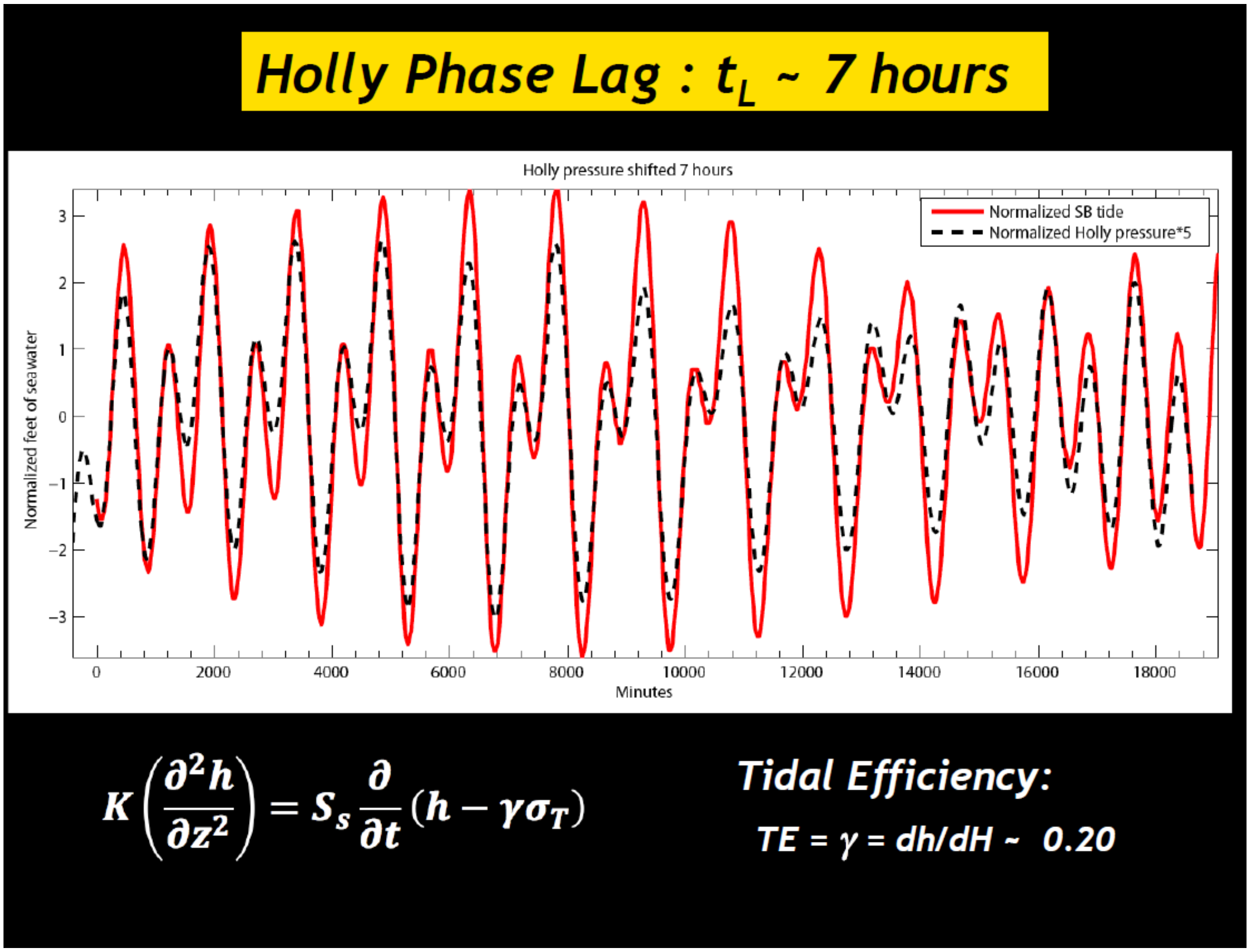
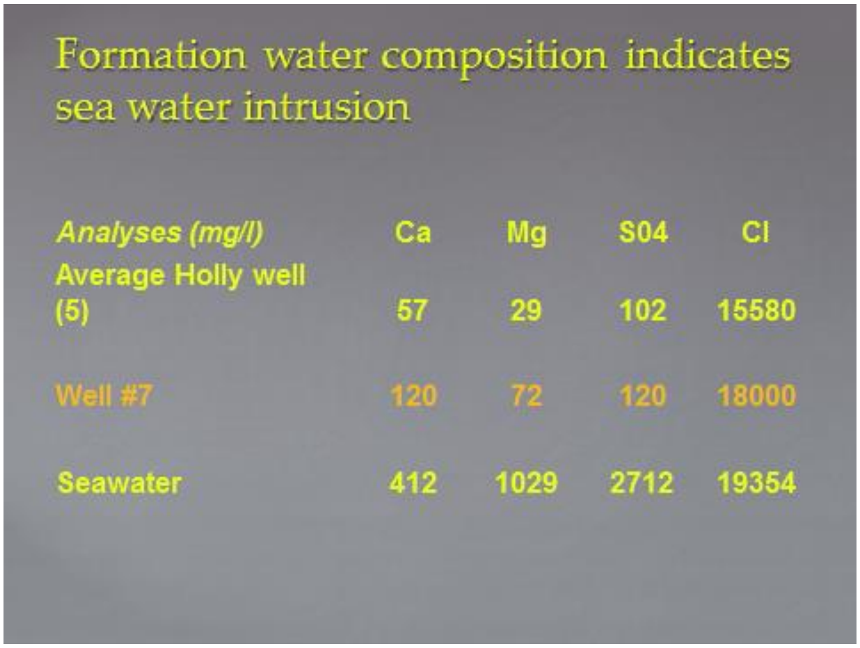


Fig. 9. Tidal signal observed in Well 3242-13. The actual amplitude of the tidal signal in the well is < 50% of the expected amplitude. From Garven, Stone, and Boles 2013 (AGU talk)



Formation water composition indicates sea water intrusion

Analyses (mg/l)	Ca	Mg	S04	Cl
Average Holly well (5)	57	29	102	15580
Well #7	120	72	120	18000
Seawater	412	1029	2712	19354

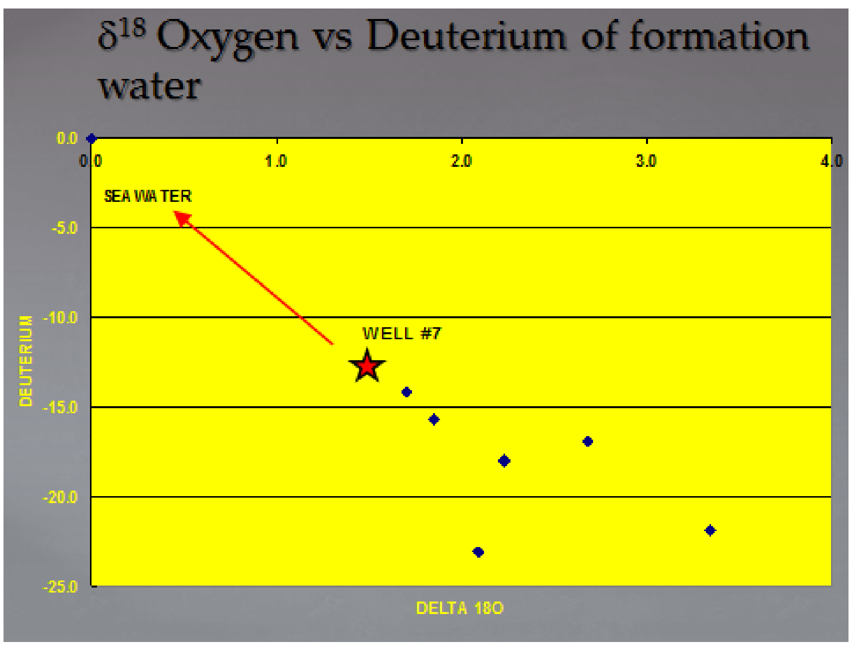


Fig. 10. Evidence for sea water incursion in the vicinity of Well 3242-7RD2. See Boles and others, 2013.

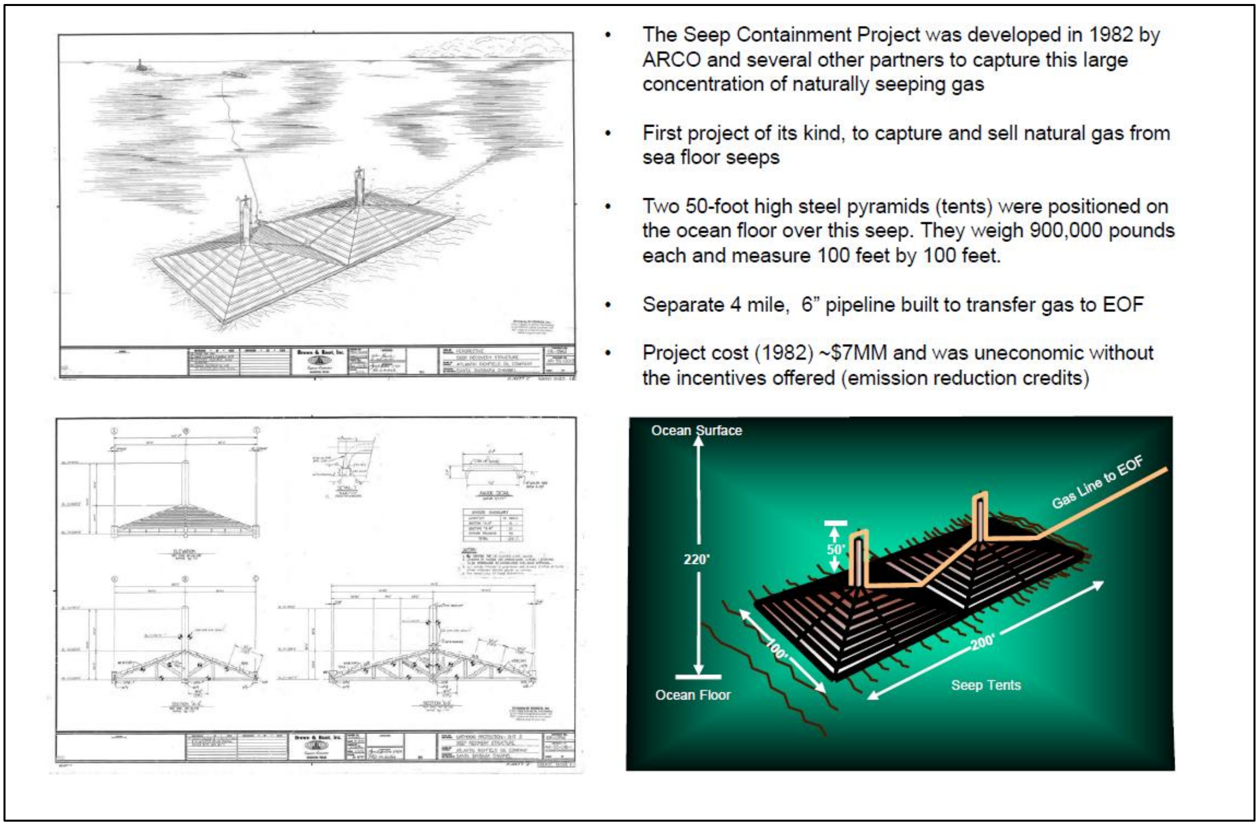


Fig. 11. The seep tents.

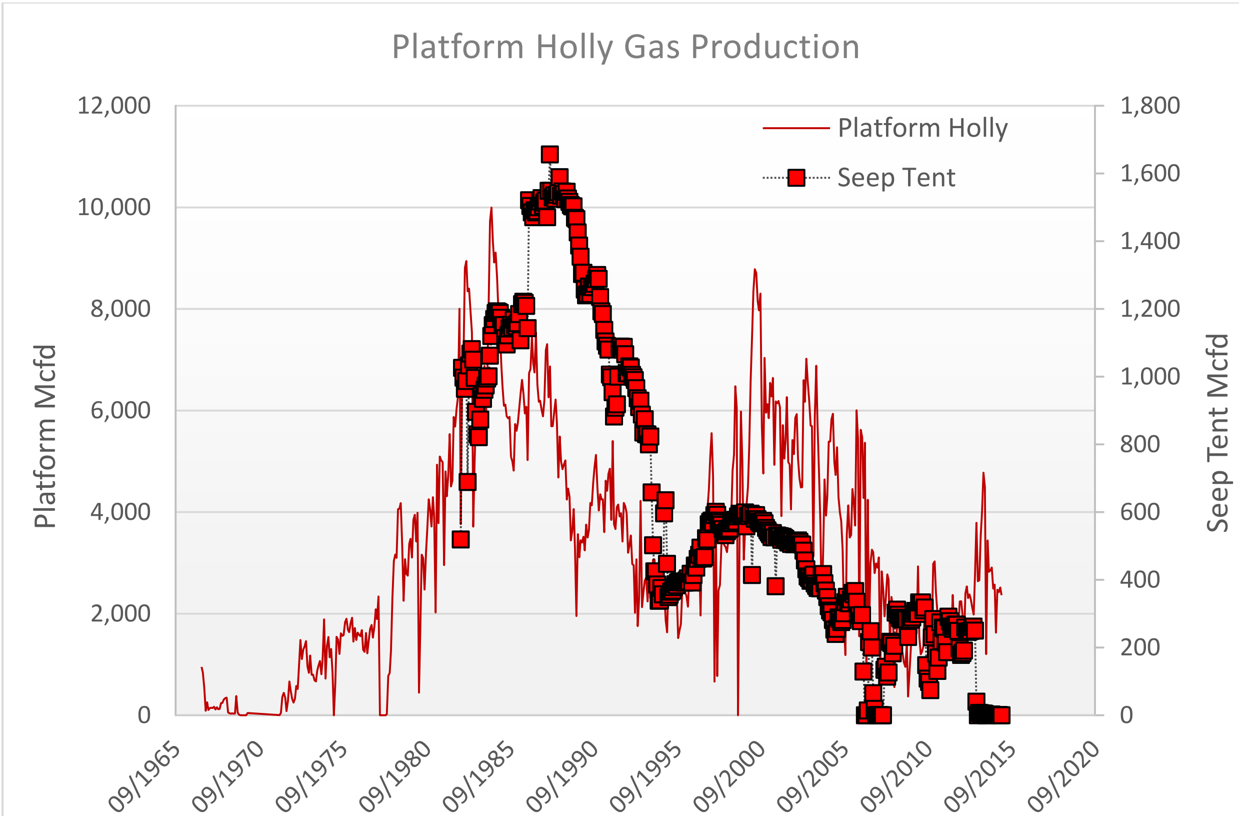


Fig 12. Comparison of daily seep tent production to daily Monterey gas production at Platform Holly.

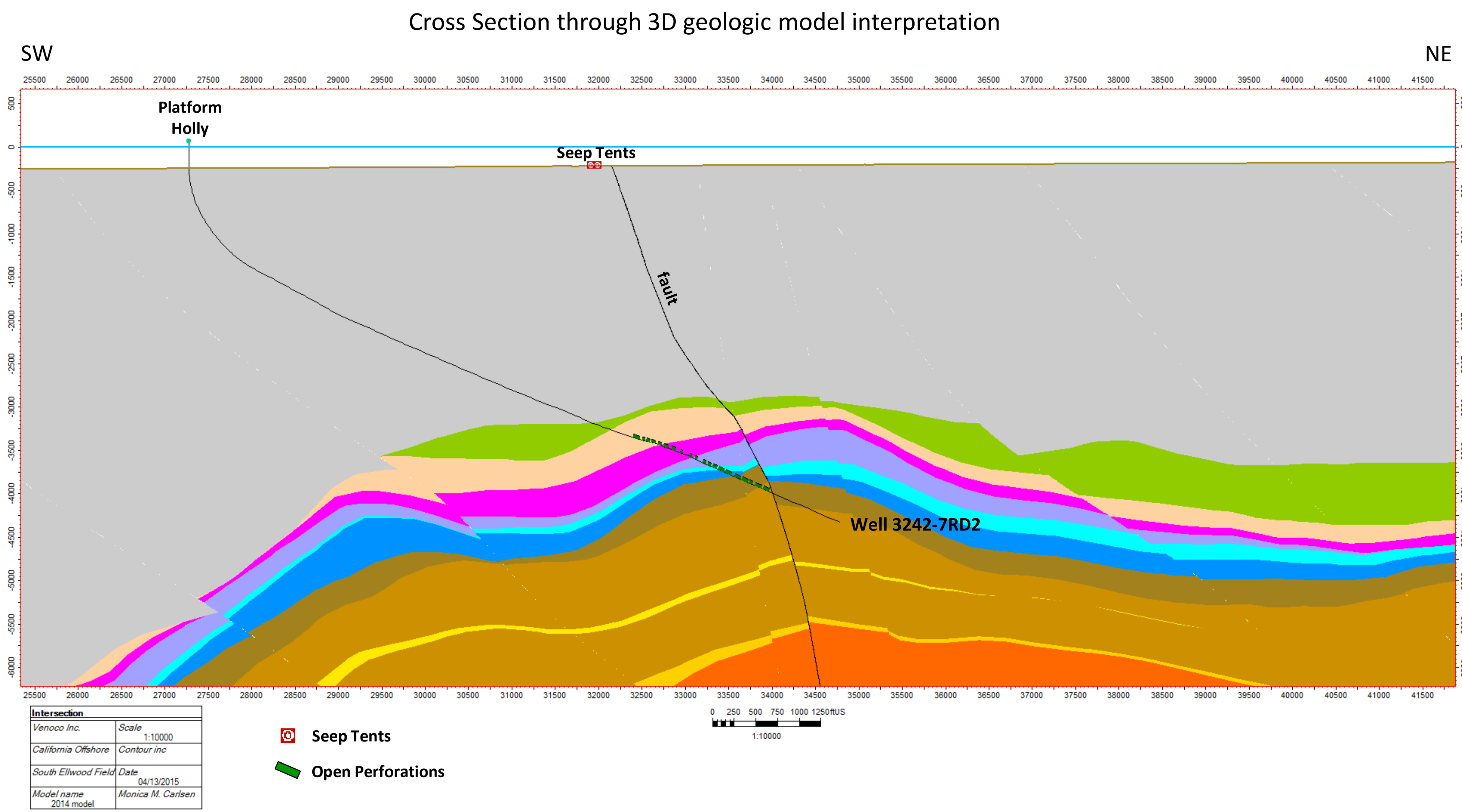


Figure 13. Cross section through 3D geologic model along a traverse between the seep tents and Well 3242-7RD2. An interpreted fault encountered in the well likely extends upwards to the vicinity of the seep tents.

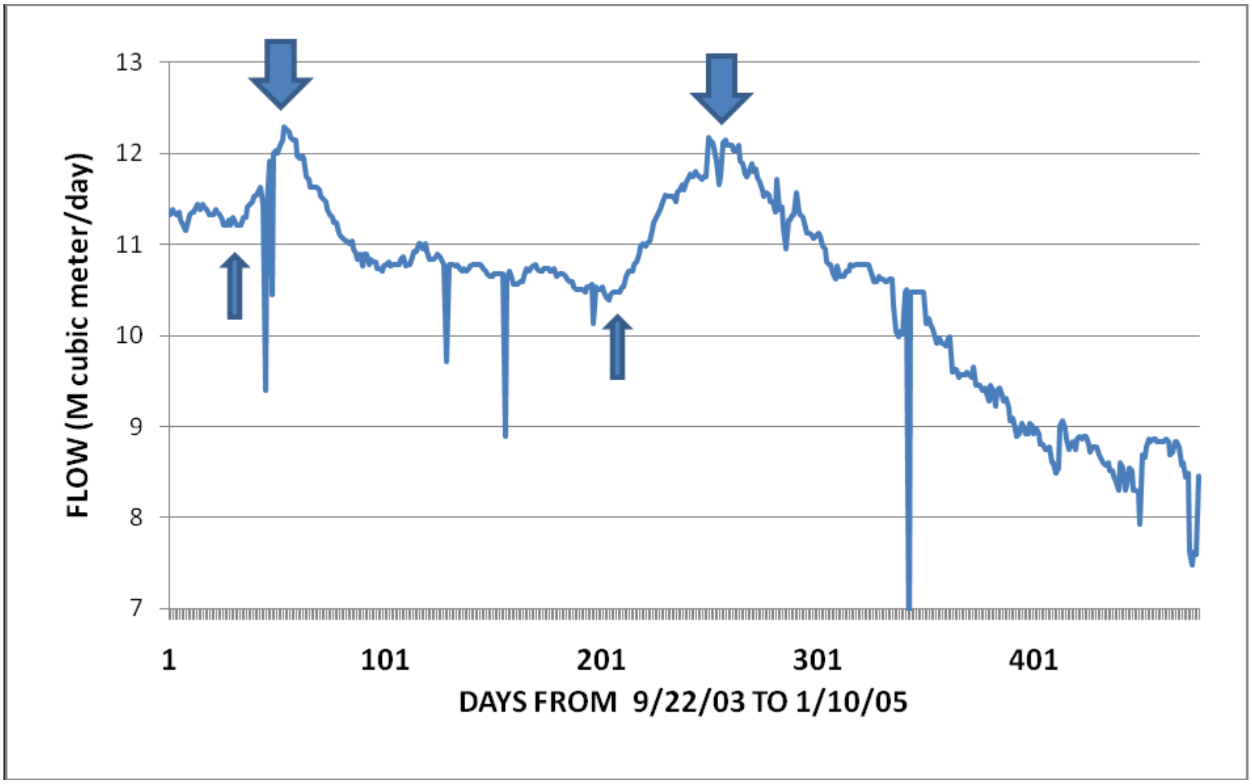


Figure 14. Seep tent response to Well 3242-7RD2. Bottom arrows indicate the point at which Well 3242-7RD2 was shut-in, top arrows indicate when Well 3242-7RD2 was returned to production. From Boles et al. 2010.

Cross Section through 3D geologic model interpretation

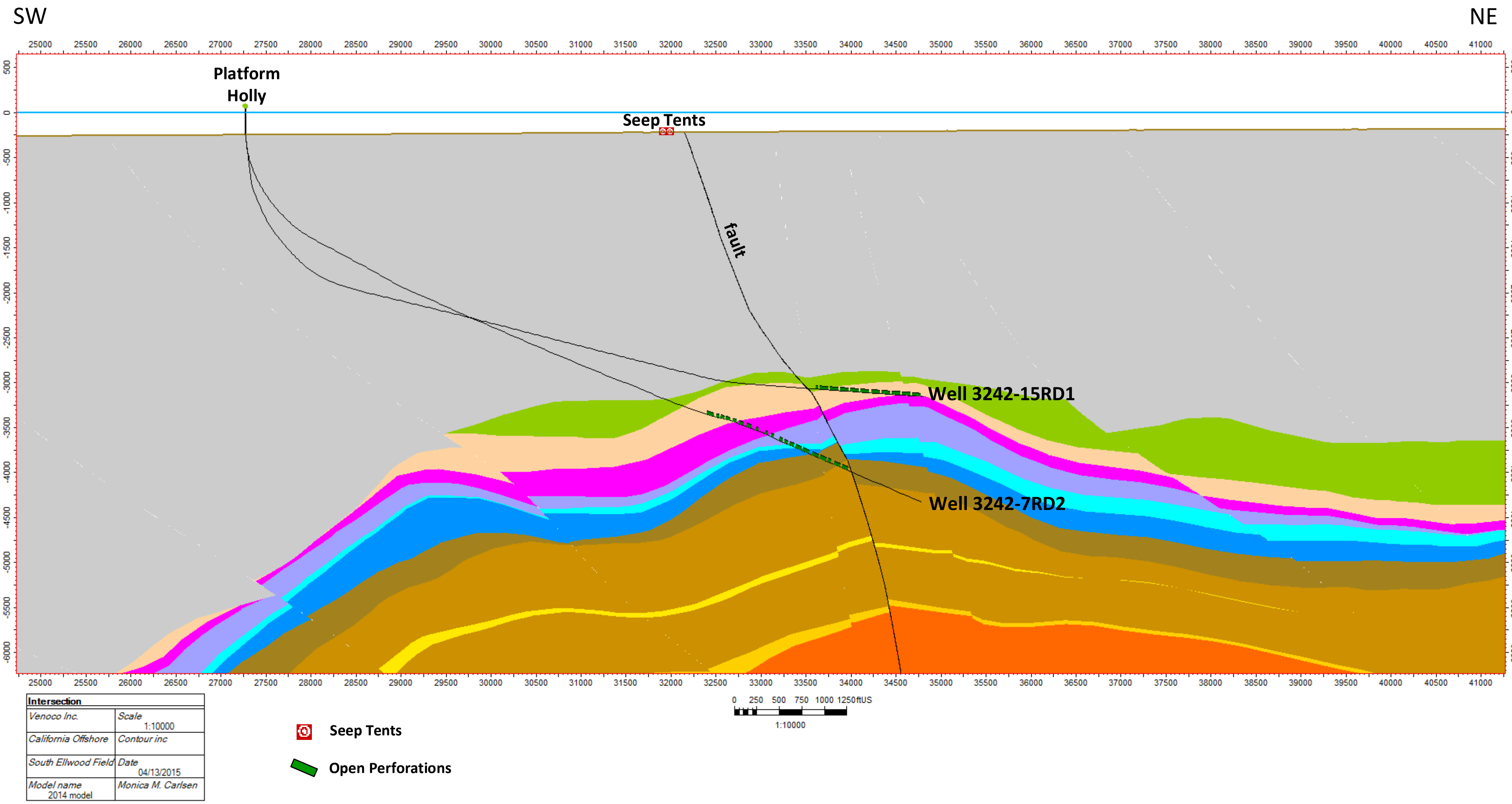


Figure 15. Cross section through 3D geologic model along a traverse between the seep tents and wells 3242-7RD2 and 3242-15RD1. An interpreted fault likely extends upwards to the vicinity of the seep tents.

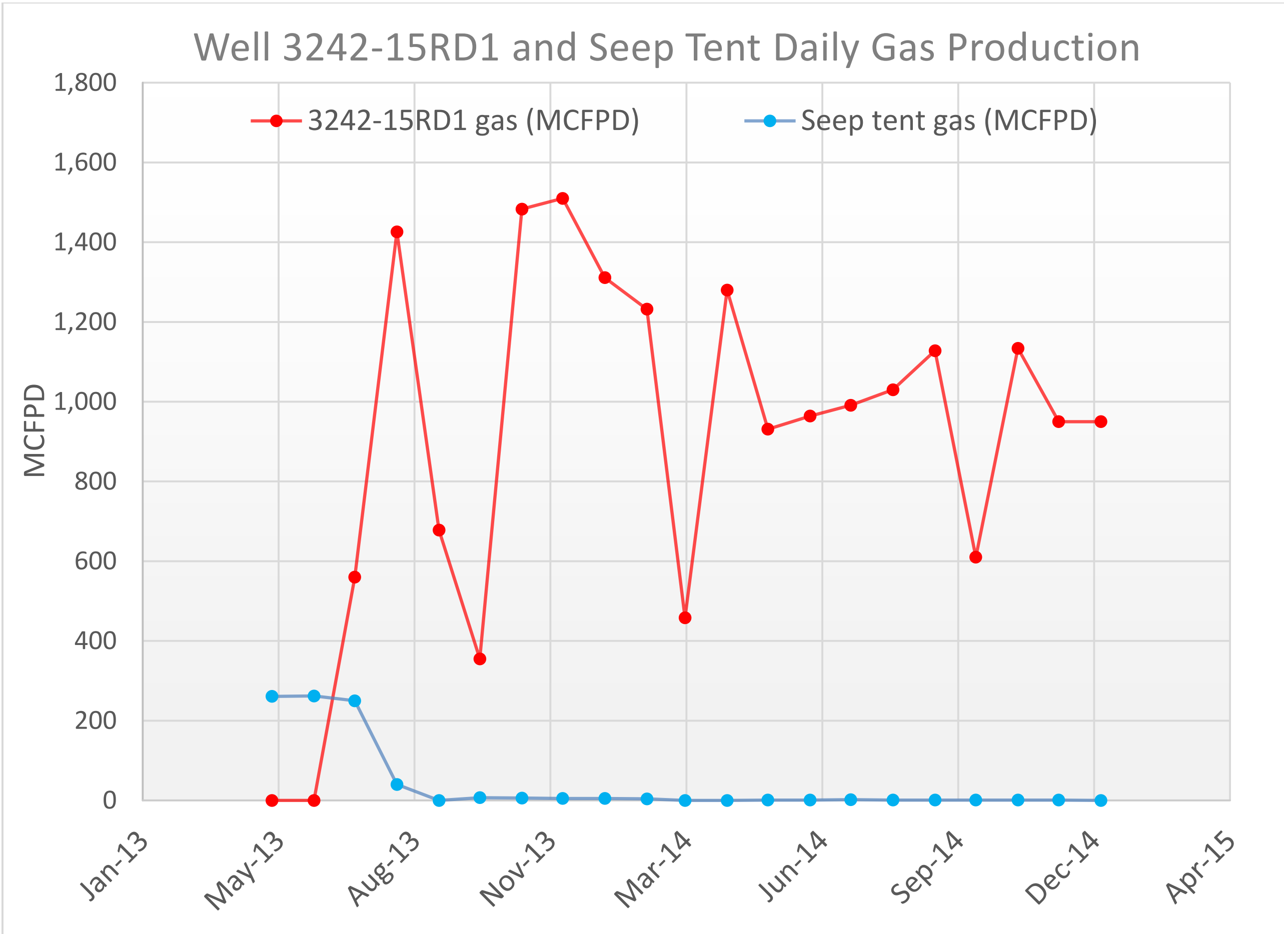


Fig 16. Cessation of measurable production from the seep tents, coinciding with the onset of well 3242-15RD1.

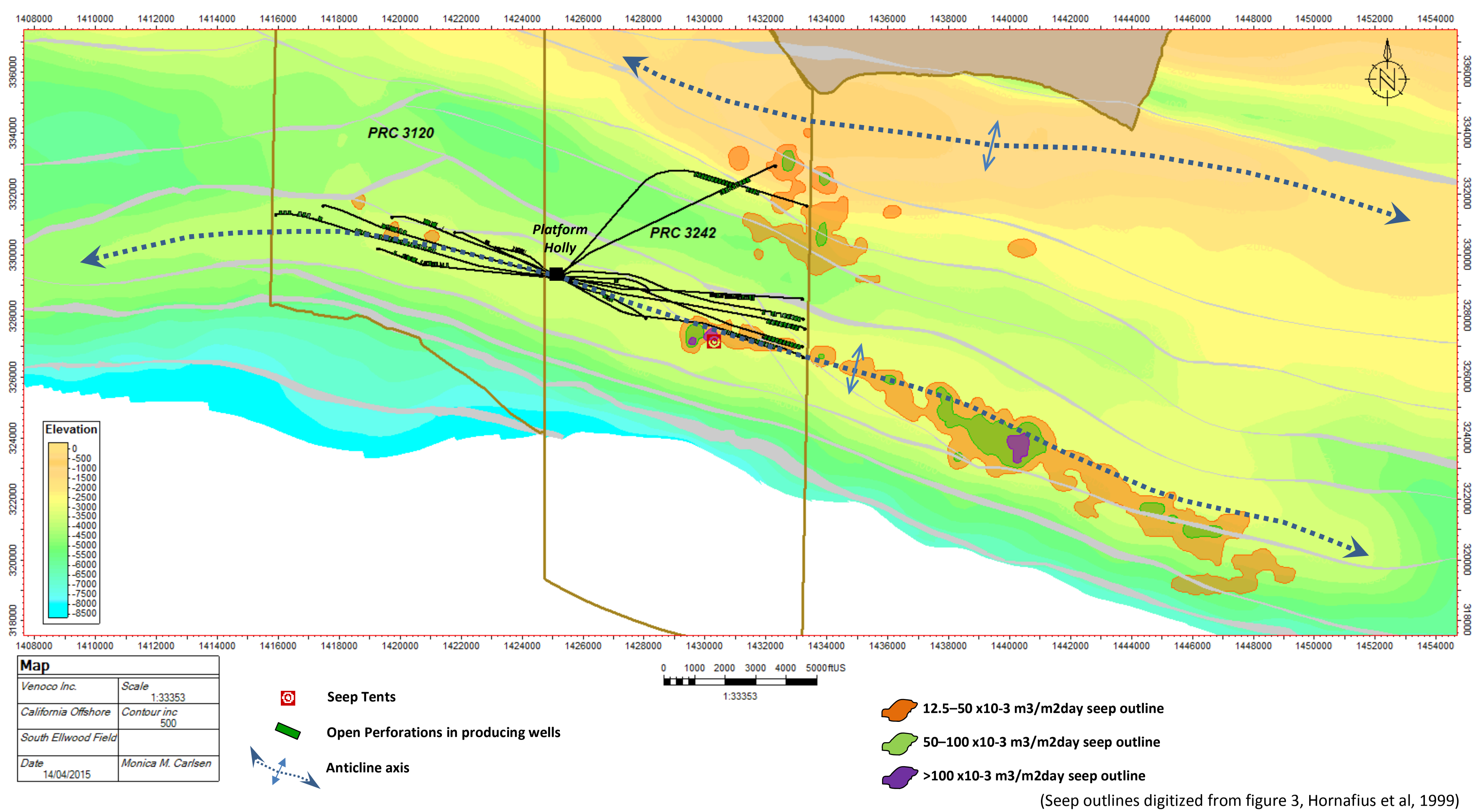


Figure 17. South Ellwood Field and Coal Oil Point Area anticlines and seeps extend far beyond existing lease boundaries. Digitized seep rate outlines from Hornafius et al, 1999 are overlain on top Monterey structure contours, with seep tents and Platform Holly producing wells.

Table 1.

Platform Holly Reservoir Pressure Data

from 10/2013 pressure buildup survey

Well	BU Date	Pi@3500 ft TVD
3120-11	Oct-13	1,647
3120-14RD1	Oct-13	932
3242-4RD3	Oct-13	1,019
3242-7RD2	Oct-13	1,237
3242 12RD1	Oct-13	920
3242 15RD1	Oct-13	996
3242 18	Oct-13	1,141

Table 2. Calculated methane flux for proposed lease extension area.

Gas flux and seep area taken from Hornafius and other (Figure 3, 1999). Areas digitized and converted to square feet.
The data was collected during 1994 and 1995 sonar surveys of seep bubble intensity (50 kHz)

1 square foot =.0929 sq meters

South Ellwood anticline

	sq ft	sq meters	flux meter^{3}x10^{-3}/meter^2-day	flux meter^{3}x10^{-3}/meter^2-day	Minimum meter3/day	Maximum meter3/day	
	467521	43433	12.5	50	543	2172	
	13057346	1213027	12.5	50	15163	60651	
	2661570	247260	12.5	50	3091	12363	
	23696.5	2201	50	100	110	220	
	98476.7	9148	50	100	457	915	
	2985887	277389	50	100	13869	27739	
	300786	27943	50	100	1397	2794	
	71858.2	6676	50	100	334	668	
	498291	46291	50	100	2315	4629	
	64235.5	5967	50	100	298	597	
	473023	43944	100	100	4394	4394	
SUM	20702691	1923280		SUM (cu meters)	41972	117142	cubic meters
	1 cubic meter = 35.31 cu ft						
				SUM (cu feet)	1482218	4136835	cubic feet/day

Min 1.488 MMCF/day
Max 4.136 MMCF/day

Coal Oil Point anticline

	sq ft	sq meters	flux	flux	Minimum meter3/day	Minimum meter3/day	
	243683	22638	12.5	50	283	1132	
	83319	7740	12.5	50	97	387	
	158276	14704	12.5	50	184	735	
	2789050	259103	12.5	50	3239	12955	
	482370	44812	12.5	50	560	2241	
	114747	10660	50	100	533	1066	
	195770	18187	50	100	909	1819	
SUM	795795	377844		SUM (cu meters)	5805	20335	cubic meters
				SUM (cu feet)	204995	718109	cubic feet/day

Min .205MMCF/day
Max .718MMCF/day

Proposed Lease Extension (Coal Oil +South Ellwood areas)

Total Minimum	1.693	MMCF/day
Total maximum	4.854	MMCF/day