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SIGNATORIES

PREPARED BY: ______________________ DATE: 28 June 2014

Jeffrey Unruh — Lettis Consultants International, Inc. (LCI)
Printed Name — Organization

VERIFIED BY: Robert Yeats DATE: 30 June 2014

Dr. Robert Yeats — Earth Consultants International, Inc. (ECI)
Printed Name — Organization

APPROVED BY: Richard Klimczak DATE: Sept. 10, 2014

Richard Klimczak — Geosciences
Printed Name — Organization

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Attachment 1 Report Verification Summary

ABBREVIATIONS AND ACRONYMS

2D	two-dimensional
3D	three-dimensional
AB 1632	Assembly Bill 1632
AWD	accelerated weight drop
CDP	common depth point
CEC	California Energy Commission
DCPP	Diablo Canyon Power Plant
ECI	Earth Consultants International, Inc.
FCL	Fugro Consultants, Inc.
ft	feet
GIS	geographic information system
GMP	AB 1632 Geologic Mapping Project
ITR	Independent Technical Reviewer
km	kilometer(s)
LCI	Lettis Consultants International, Inc.
m	meter(s)
Ma	million years ago
MBES	multibeam echosounder
mm/yr	millimeter per year
ONSIP	Onshore Seismic Interpretation Project
PG&E	Pacific Gas and Electric Company
PI	Project Instruction
PPD	Project Planning Document
QA	quality assurance
SSHAC	Senior Seismic Hazard Analysis Committee
USGS	U.S. Geological Survey

1.0 PURPOSE

This report presents an interpretation of seismic-reflection data collected in the Irish Hills and Los Osos Valley along the Central California coast during 2011 (Figure 1-1). The data were acquired as a part of a program to satisfy the requirements of California State Assembly Bill (AB) 1632, which directed the California Energy Commission (CEC) to assess the potential vulnerability of the state's largest baseload power plants to earthquakes and other events (including aging) that could cause a major disruption of service. In response to AB 1632, the CEC (2008a, 2008b) recommended that Pacific Gas and Electric Company (PG&E) acquire new state-of-the-art geophysical data to characterize the three-dimensional (3D) subsurface geology in the vicinity of the Diablo Canyon nuclear power plant (DCPP) and resolve remaining uncertainties in the characterization of key fault structures included in the DCPP seismic hazard model.

PG&E consequently undertook a multidisciplinary program in 2011 and 2012 that included acquisition of new two-dimensional (2D) and 3D seismic-reflection data in the Irish Hills directly adjacent to the DCPP and in the offshore areas to the west. This report focuses exclusively on interpretation of the 2011 onshore seismic-reflection data. Other reports document data acquisition and processing (FCL, 2014a), as well as interpretation of the onshore data collected in 2012, which were acquired in the southern Irish Hills near the DCPP (FCL, 2014b).

The primary objective for interpretation of the 2011 Onshore Seismic Interpretation Project (referred to herein as "ONSIP") is to reduce uncertainty in the subsurface geology beneath the Irish Hills. This study focuses specifically on using the subsurface imaging capability of reflection data to

- Constrain the downdip geometry of faults that are included in the present seismic hazard model for the DCPP.
- Identify any other potentially significant structures that have not been previously observed and/or characterized.

The scope of this study is limited to evaluating fault geometry and subsurface structure of the Irish Hills through the analysis of the seismic-reflection data. PG&E is conducting separate studies to evaluate activity of faults in the Irish Hills and to integrate this information in a seismic hazard model for the DCPP.

2.0 DATA

The ONSIP study area lies within the Irish Hills, a west-northwest-trending range bounded by San Luis Obispo Bay to the southeast, the Pacific Ocean to the south and west, Estero Bay and Morro Bay to the west and northwest, and Los Osos Valley to the north (Figure 1-1). The DCPP is located in the southern Irish Hills along the coast. The Irish Hills are approximately 19 kilometers (km) long and 13 km wide. Hilltop and crest elevations in the central Irish Hills range from approximately 1,200 to 1,500 feet (ft; 365–460 meters [m]). San Luis Obispo Creek flows across the southeast end of the Irish Hills (adjacent to California Highway 1; Figure 1-1) and effectively separates them from the narrower and lower Edna Hills, which continues along the same northwest-southeast structural and physiographic trend approximately 20 km southeast to the Arroyo Grande area.

The following sections describe the seismic-reflection data used in the study, and summarize stratigraphic and structural data that are relevant for interpreting the seismic data.

2.1 Seismic-Reflection Data

The network of 2D seismic lines acquired for the ONSIP in 2011 is shown at a small scale on Figure 1-1, and at a larger scale on Plate 1. The 2011 2D reflection data were acquired using two different approaches (see FCL, 2014a, for a detailed discussion of the acquisition and processing of the 2011 data):

- A series of seismic lines was acquired using an accelerated weight drop (AWD) acoustic source. We refer to these data herein as “AWD lines.” The AWD source consists of a heavyweight hammer that is mounted on a truck or trailer. A high-pressure gas is used to accelerate the hammer against a base plate that is coupled to the ground. The collision of the hammer with the plate generates an acoustic pulse that propagates through the earth as a seismic wave. The source-receiver spacing and geometry for the AWD lines were configured to optimize imaging and resolution in the upper 3,000–5,000 ft of the crust (~900–1,500 m depth).
- Several lines also were acquired using a vibroseis source. We refer to these data herein as “vibroseis lines.” A vibroseis source is a mechanical vibrator mounted on a truck. The vibrator is coupled to the ground via a base plate, and when activated generates a continuous acoustic wave train that can sweep through a range of frequencies. The source-receiver spacing and geometry for the vibroseis lines were configured to image reflective structure to a depth of approximately 12,000 ft (~3,660 m). The greater depth of imaging of the vibroseis data comes at the cost of lower resolution in the upper 3,000–5,000 ft relative to the AWD data. In general, the vibroseis lines are longer than the AWD lines, and fewer total vibroseis lines were acquired than AWD lines.

In addition to the 2D AWD and vibroseis lines, an irregular 3D volume was acquired in the northern Irish Hills as part of the 2011 effort (Figure 1-1). Part of the 3D volume includes swaths of finite width adjacent to some of the crooked 2D acquisition lines in the northern Irish Hills. These swath lines allowed straighter arbitrary lines to be extracted from the 3D volume locally surrounding the 2D lines, which minimize geometric distortions of the reflective structure and facilitate interpretation.

The seismic-reflection data were processed by Agile Seismic LLC in Houston, Texas, under the direction of Fugro Consultants, Inc. (FCL). The processed, depth-migrated reflection data were evaluated for quality by FCL and transmitted to the ONSIP team for analysis and interpretation under FCL's QA program procedures. The FCL data processing report presents a complete discussion of the acquisition and processing of the 2011 2D and 3D reflection data (FCL, 2014a).

2.2 Geologic Data

The following sections describe the tectonic setting and major geologic map units in the 2011 ONSIP study area.

2.2.1 Tectonic Setting

The Irish Hills are located in the Los Osos tectonic domain, a triangular region along the central-western California margin that is bounded on the south by the western Transverse Ranges, on the west by the dextral Hosgri-San Simeon fault zone, and on the east by the Oceanic–West Huasna fault zone (Hanson et al., 2004; Lettis et al., 2004; Figure 2-1). The interior of the Los Osos domain is divided into a series of west-northwest-trending structural blocks bounded by reverse faults (Lettis et al., 2004; Figure 2-1), listed as follows, from northeast to southwest:

- Cambria
- Los Osos
- San Luis/Pismo (includes the Irish Hills)
- Santa Maria Valley
- Casmalia
- Solomon Hills
- Purisima Hills
- Vandenberg/Lompoc

Many of these structures (e.g., the San Luis/Pismo block) are coincident with west-northwest-trending Cenozoic folds that deform Miocene and Pliocene strata (Lettis et al., 2004).

The Neogene tectonic history of the Los Osos domain is dominated by distributed deformation associated with rigid clockwise rotation of the western Transverse Ranges to the south (Lettis et al., 1994, 2004, and references therein; Figure 2-1). Beginning approximately 24 million years ago (Ma), a segment of the subducting Farallon Plate (the Monterey microplate) stalled beneath what is now the western Transverse Ranges and was subsequently captured or attached to the Pacific Plate. Reorganization of dextral plate motion along the western California margin following this event triggered clockwise rotation of the Monterey microplate and the overlying Transverse Ranges lithosphere as a large discrete block. This rotation was accompanied by opening of the

Santa Maria tectonic basin in the offshore region to the north (Nicholson et al., 1994). Paleomagnetic studies have documented approximately 90 degrees of clockwise rotation of the early Miocene rocks in the western Transverse Ranges around an axis near the modern trace of the San Gabriel fault (Luyendyk et al., 1985), as well as 40–50 degrees of clockwise rotations of Tertiary rocks in the Los Osos domain to the north near the latitude of San Luis Obispo (Greenhaus and Cox, 1979; Khan et al., 2001).

Given the magnitude of the paleomagnetic rotations, the crust that underlies the east-west-trending Transverse Ranges was originally oriented north-south prior to late Cenozoic rotation. With the onset of rotation, the triangular Los Osos domain to the north would have experienced a net increase in area as the Transverse Ranges swung away from the rest of California and rotated at higher angles to the azimuth of plate motion. The kinematics of this deformation are illustrated in detailed tectonic animations by Atwater (2011). Dilation of the Los Osos domain during early Neogene rotation of the Transverse Ranges can account for the well-documented coeval extension in the onshore Santa Maria and Pismo Basins (Luyendyk, 1991). Continued rotation eventually brought the Transverse Ranges approximately normal to the azimuth of plate motion; further rotation beyond this point progressively *decreased* the area of the Los Osos domain, which Luyendyk (1991) noted could account for the observed transition from regional transtension to transpression in the Santa Maria and Pismo Basins in late Neogene to Quaternary time.

Workers have proposed two general classes of models that relate Neogene extension in the Los Osos domain to rotation of the western Transverse Ranges. In one class of models, the west-northwest-trending structural blocks in the Los Osos domain are assumed to have translated to the northwest ahead of the rotating Transverse Ranges, primarily by dextral strike-slip faulting and moving parallel to their long axes with a minimum amount of rotation (e.g., Luyendyk, 1991). In these models, Neogene basins formed to minimize strain compatibility problems at the margins of the translating blocks. Another class of models assumes that the structural blocks of the Los Osos domain both translated and rotated clockwise to accommodate the motion of the western Transverse Ranges (e.g., Wilson et al., 2005). In these models, relative motions between the Los Osos domain structural blocks initially included net left-lateral slip as the Transverse Ranges rotated through the first 45 degrees of motion, then later relative right-lateral motion as the rotation carried the ranges closer to parallelism with the azimuth of plate motion. These models predict a more complex history of Neogene deformation in the Los Osos domain, including early sinistral transtension between blocks and later dextral transpression (Wilson et al., 2005).

Quaternary deformation in the Los Osos domain is characterized by net transpression, accommodated by dextral strike-slip faulting along the eastern and western margins of the domain, and uplift of the fault-bounded ranges within the interior of the domain (Lettis et al., 2004). For example, the Irish Hills are interpreted to have been uplifted approximately as a rigid block during the Quaternary by reverse slip on the Los Osos fault to the north, and reverse slip on faults comprising the Southwestern Boundary zone to the south (see Section 2.4 for further discussion of these structures). Based on mapping and correlation of marine terraces, the Irish Hills appear to be rising at a rate of approximately 0.1 millimeter per year (mm/yr) to the southeast and approximately 0.2 mm/yr to the west and northwest, with very little to no internal deformation (see PG&E, 2011, for further discussion). Regionally, transpression within the Los Osos domain and the greater Central Coast region may be driven by a combination of the following mechanisms (PG&E, 2011):

- Northward left-transfer of dextral slip from the San Andreas and related faults to the Hosgri–San Simeon fault system.
- Ongoing clockwise rotation of the western Transverse Ranges.
- Possible plate-normal convergence across the region.

2.2.2 Geologic Map Units

The seismic-reflection interpretation incorporates geologic map information (Figure 2-2 and Plate 1) and borehole data (Appendix E of PG&E, 2014) to extend map-scale stratigraphic and structural relationships at and near the surface into the subsurface. Stratigraphic units used in the seismic interpretation correspond with those documented in the Irish Hills and surrounding areas by the AB 1632 Geologic Mapping Project (GMP; PG&E, 2014). These stratigraphic units fall into three groups (Figure 2-3), as follows:

1. Mesozoic accretionary prism and forearc basin rocks of the ancestral western California convergent margin that now comprise the basement of the study area.
2. Late Oligocene and Neogene strata that accumulated in structural marine basins north of the Transverse Ranges.
3. Undifferentiated Plio-Quaternary continental deposits.

The following sections briefly describe the specific stratigraphic units employed in the interpretation. Detailed descriptions and additional geologic context are provided in the Shoreline Fault Zone Report (PG&E, 2011) and the GMP Report (PG&E, 2014).

2.2.2.1 Franciscan Complex

The structurally lowest map unit in the study area is the Mesozoic Franciscan Complex (Figure 2-3), which accumulated in an accretionary prism along the ancestral western California convergent margin. The Franciscan Complex is an assemblage of metavolcanic rocks, mudrock, sandstone, conglomerate, serpentinite, chert, and mélange. Contacts within the unit are almost exclusively faults (PG&E, 2014). A large, contiguous remnant of ophiolitic pillow lava is present within the Franciscan exposures in the east-facing sea cliffs north of Point San Luis (unit KJfo on Figure 2-2 and Plate 1). Although the Franciscan Complex generally lacks coherent internal stratigraphy, the geologic map shows contiguous and mappable bodies of serpentinite alternating with graywacke and metavolcanic rocks in the northern Irish Hills (Figure 2-2 and Plate 1).

2.2.2.2 Cretaceous Sandstone

Structurally overlying the Franciscan Complex are deformed Cretaceous marine sandstones that are interpreted to have originally accumulated in the Mesozoic western California forearc basin (Figure 2-3). The sandstone is a brown, moderately to well indurated, thickly bedded lithic wacke (PG&E, 2011). The Cretaceous sandstone is exposed in the southeastern Irish Hills between Point San Luis and Olson Hill (unit Ks on Figure 2-2 and Plate 1). The Mesozoic sandstone is not recognized or mapped in the northern Irish Hills, and its extent in the subsurface of the Irish Hills is not known.

2.2.2.3 Oligocene Strata (Vaqueros Formation)

The oldest Tertiary unit recognized in the study area is the Vaqueros Formation (Figures 2-2 and 2-3 and Plate 1), which consists of approximately 100 ft (30 m) or less of tan to gray arkosic wacke to lithic arenite, and conglomerate. Hall and Corbató (1967) interpret deposition of the Vaqueros Formation to mark the beginning of a late Oligocene–early Miocene inundation of an ancestral low-lying coastal region in Central California. The Vaqueros Formation is most extensively exposed in the northern Irish Hills, where it rests disconformably on Franciscan Complex and is conformably overlain by the early Miocene Rincon Formation (Figures 2-2 and 2-3). The Vaqueros sandstone is highly indurated and commonly underlies ridgetops. The Vaqueros Formation also is mapped at the base of the Tertiary section in the southeastern Irish Hills southeast of the DCPP by Hall (1973a). However, PG&E (2014) notes that outcrops in the southern Irish Hills are very limited and that Hall's mapping of the Vaqueros Formation here may represent an interpretation that the unit is present near the base of the Tertiary section rather than direct observations of these rocks in the field.

The Vaqueros Formation is inferred to postdate the Morro Rock–Islay Hill intrusive complex and Cambria Felsite, and has been dated at approximately 24–26 Ma (late Oligocene) using strontium isotope ratios on bivalves in near-basal strata (Keller et al., 1996). The Vaqueros Formation includes Saucesian and Zemorrian fauna and probably spans the Oligocene-Miocene boundary (Figures 2-3 and 2-4; Keller et al., 1996; Prothero, 2001).

2.2.2.4 Neogene Stratigraphic Units

The following sections describe Neogene (i.e., Miocene and Pliocene) stratigraphic units in the ONSIP study area: the Rincon, Obispo, Monterey, Pismo, and Careaga Formations.

Rincon Formation

The Miocene Rincon Formation overlies the Vaqueros Formation and Mesozoic basement rocks (Figure 2-3 and Plate 1). Exposures of the Rincon Formation in the Irish Hills generally consist of thinly bedded dark brown siltstone and silty claystone with interbeds of dolomitic sandstone (unit Tmr on Figure 2-2). Exposures of the Rincon Formation in the northern and southern Irish Hills suggest the unit is relatively thin (i.e., combined thickness of the Vaqueros and Rincon Formations is ~180 m; PG&E, 2011). A great thickness of Rincon Formation was reported in the Honolulu-Tidewater 1 well in the central Irish Hills; however, the thick section of “Rincon Formation” described in the Tidewater well log includes volcanic rocks, which are typically considered diagnostic of the younger Obispo Formation (Figure 2-3; see discussion in Appendix E of PG&E, 2014). It is possible that Obispo Formation was misidentified as Rincon Formation in the Tidewater well, and that the Rincon Formation is not anomalously thick in the subsurface of the Irish Hills. It is also possible that the section in the well has been repeated by thrust faulting (this issue is discussed in detail in Sections 5.1.5 and 5.5). Natural exposures in the study area are rare, and the Rincon Formation commonly is recognized and mapped by its association with landslides (PG&E, 2014). The Rincon Formation includes Saucesian and Zemorrian fauna (Figure 2-4) and is considered early Miocene in age (Figure 2-3; Tennyson et al., 1991; Prothero, 2001).

Obispo Formation

The Miocene Obispo Formation consists of marine volcanic and volcaniclastic rocks and locally is conformable on the Rincon Formation (Hall, 1973a, 1973b; Figure 2-3). Exposures of the Obispo Formation in the southern Irish Hills (Figure 2-2 and Plate 1) range from approximately 305 to 610 m (~1,000–2,000 ft ; PG&E, 2011) thick, and Hall and Corbató (1967) report that the maximum exposed thickness of the Obispo Formation along the reach of the Central Coast between San Luis Obispo and Nipomo is approximately 3,200 ft (975 m). Three subunits of the Obispo Formation are recognized in the southern Irish Hills near the coastline:

1. A crudely bedded to unstratified orange-brown to gray fine-grained zeolitized tuff (map unit Tmor; PG&E, 2014) that is a highly indurated and resistant ridge-forming unit.
2. A well-bedded, fine-grained light brown to gray sandstone and mudrock (map unit Tmof; PG&E, 2014) that fines upward and includes intervals of dolomitic, diatomaceous, and tuffaceous sandstones.
3. Brown aphanitic to phaneritic dikes and sills of intrusive diabase (map unit Tmod; PG&E, 2014). The diabase locally defines the base of the Obispo Formation and is observed to intrude the resistant tuff and fine-grained units (PG&E, 2014). Field relations suggest that emplacement of the diabase may have been coeval with deposition of the resistant tuff, and/or postdated deposition of the fine-grained unit (PG&E, 2011). The diabase is not observed to intrude the overlying Monterey Formation (PG&E, 2014).

Radiometric dates obtained from tuffs in the lower part of the Obispo Formation range from approximately 15 to 18 Ma (Cole and Stanley, 1998), and sparse marine fauna indicate a Saucesian to Relizian age (Figure 2-4; Hall and Corbató, 1967).

Monterey Formation

The Monterey Formation overlies the Obispo Formation and consists of white, gray, and brown bedded dolomitic siltstone, diatomite, and cherty shale (Figure 2-3). Exposed thickness in the Irish Hills is approximately 2,000 ft (600 m). The Monterey Formation is well lithified and exhibits a characteristic conchoidal fracture habit. The basal facies above the contact with the Obispo Formation near Point Buchon (Figure 2-2 and Plate 1) is an interbedded, fine-grained diatomaceous and tuffaceous sandstone that grades upward to siliceous shale and porcelaneous chert (PG&E, 2011). The upper part of the Monterey Formation becomes increasingly coarse and clastic with proximity to the base of the overlying Pismo Formation. The depositional environment for the Monterey Formation is deep marine, probably lower slope to distal basin (Schwalbach and Bohacs, 1996). Age dating analyses indicate an age of 11.4 to 10.5 Ma for the section at Point Buchon (Schwalbach and Bohacs, 1996). The Monterey Formation includes Relizian, Luisian, Mohnian, and Delmontian fauna and is considered middle to late Miocene in age (Figures 2-3 and 2-4; Finger et al., 1990; Keller and Barron, 1993; Prothero, 2001).

Pismo Formation

The Pismo Formation overlies the Monterey Formation (Figure 2-3) and primarily consists of interbedded gray to brown sandstone and mudrocks. The basal contact with the Monterey Formation at Point Buchon appears to be gradual and conformable; map relations show the Pismo Formation unconformably overlying the Rincon and Obispo Formations in the northern Irish Hills (Figure 2-2 and Plate 1). The thickness of the Pismo Formation measured from exposures in the northern Irish Hills is approximately 2,000 ft (600 m; PG&E, 2011).

Regionally, the Pismo Formation is subdivided into five members (Figure 2-3). Lithological and textural changes among these units record progressive constriction and shoaling of the ancestral basin in late Neogene time (PG&E, 2011). Nearly all of the Pismo Formation strata exposed in the ONSIP study area are represented by the two lower members, the Miguelito and Edna Members:

- **Miguelito Member:** Thinly bedded brown siltstone and claystone, with rare to common intervals of siliceous and dolomitic siltstone, opaline and porcelaneous shale, and bituminous sandy siltstone. The basal contact of the Miguelito Member with the Monterey Formation near Point Buchon is generally conformable, but is unconformable on the Obispo and Rincon Formations in the northern Irish Hills (PG&E, 2011, and references therein).
- **Edna Member:** Thinly bedded to unstratified gray to brown fine- to coarse-grained sandstone. The Edna Member is moderately well lithified with common bituminous, chert pebble conglomerate, and tuffaceous sandstone horizons. The Edna Member grades laterally into the Miguelito Member to the west and south (PG&E, 2011).

In ascending stratigraphic order, the upper three units of the Pismo Formation are the Gragg, Bellevue, and Squire Members (Figure 2-3). All three of these units are mapped extensively in the San Luis Range to the southeast of the Irish Hills (Hall, 1973b; Figure 1-1). The Squire Member is the most significant of these three units in the ONSIP study area, and exposures are characterized by very thin deposits of marine sandstone in the southeastern Irish Hills north of Point San Luis and west of San Luis Obispo Bay (Figure 2-2). For the purposes of seismic interpretation, we treat the Pismo Formation as a single stratigraphic unit and do not attempt to delineate the Miguelito, Edna, and Squire Members in the subsurface.

Keller and Barron (1993) studied the Miguelito Member of the Pismo Formation in Montaña de Oro State Park and conclude that

> "…on the basis of diatom and silicoflagellate assemblages, the coastal Miguelito section is thought to be equivalent in age to the upper part of the Monterey of the nearby Santa Maria and Santa Barbara-Ventura basins."

Keller and Barron (1993) provide an age range of late Miocene 10.4–10.6 Ma for the Miguelito Member exposed along the coast of Montaña de Oro State Park, which is equivalent to Upper Mohnian and Delmontian (Figure 2-4; Keller and Barron, 1993; Schwalbach and Bohacs, 1996).

Careaga Formation

The Careaga Formation is a late Pliocene shallow marine sandstone and siltstone that is equivalent in age to the upper part of the Pismo Formation, including the Gragg, Belleview, and Squire Members (Hall, 1973b). The Careaga Formation is mapped in the San Luis Range southeast of the Irish Hills (Hall, 1973b) and is known primarily from study of stratigraphy in the Santa Maria Basin. The Careaga Formation is not mapped in the Irish Hills, but subsurface investigations (e.g., Cleath & Associates, 2003, 2005) have interpreted the Careaga Formation to be present above Franciscan Complex bedrock in boreholes in the western Los Osos Valley.

2.2.2.5 Surficial Deposits

Surficial deposits in and around the Irish Hills consist of relatively thin (10–82 ft, or 3–25 m) accumulations of Quaternary-age fluvial, landslide, nearshore, and aeolian deposits (PG&E, 2011; Figure 2-3). The thickest surficial deposits in the ONSIP study area are present in the western Los Osos Valley, and consist primarily of alluvial fan and fluvial deposits derived from the Irish Hills to the south and the Islay Hills to the north. Aeolian deposits associated with relatively old, stabilized sand dunes are present in the northwestern Los Osos Valley adjacent to Morro Bay (Figure 2-2 and Plate 1). Nearshore marine deposits that are presently exposed near the coast in the western and southern Irish Hills include those related to marine terraces and modern beaches.

2.3 Map-Scale Structures

This section describes the major map-scale structures of the Irish Hills that are relevant to the interpretation of seismic-reflection data. Detailed descriptions of outcrop-scale faults and folds can be found in the Shoreline Fault Zone Report (PG&E, 2011).

2.3.1 Pismo Syncline

The core of the central and southern Irish Hills is a west-northwest trending, fault-bounded syncline generally referred to as the Pismo syncline (Surdam and Stanley, 1981; PG&E, 2011; Figure 2-2). The Pismo syncline is at least 8–10 km wide and can be traced southeast of the Irish Hills to the Arroyo Grande area for a total distance of approximately 35 km (Hall, 1973a, 1973b). Although the structure is more properly described as a synclinorium because there are numerous secondary folds on the primary north and southern limbs, we retain the term "Pismo syncline" for this report because of its ubiquity in the literature.

The Pismo syncline is a deformed remnant of the Neogene basin in which the Obispo, Monterey, and Pismo Formations accumulated (Surdam and Stanley, 1981). The Pismo Formation occupies the axis and most of the northern limb of the syncline (Figure 2-2) and is the youngest unit in the Irish Hills that is clearly involved in the folding. The southern limb of the syncline is a north-northeast-dipping panel that exposes the Monterey and Obispo Formations stratigraphically below the Pismo Formation (Figure 2-2). The average dip of the southern limb is approximately 40 degrees, although both shallower and steeper dips are found in secondary folds. The northern limb of the syncline is much narrower than the southern limb, and the Neogene section there is attenuated. Exposures of the Monterey Formation are thicker on the southern limb than the northern limb, which suggests that the unit thins northward or is bounded by unconformities. To date, Neogene microfaunal zones have not been mapped in detail in the Irish Hills to distinguish which of these possibilities is correct. The Edna Member of the Pismo Formation on the northern limb of the syncline variously overlies the Monterey, Obispo, and Rincon Formations and is locally faulted against the Obispo Formation and Franciscan Complex (Figure 2-2). Bedding dips on the northern limb generally are 40 degrees or less.

The asymmetry of the syncline indicated by the difference in the width of the northern and southern limbs suggests that the ancestral Neogene basin also may have been asymmetric. The combined thickness of exposed Obispo, Monterey, and Pismo Formations on the southern limb of the fold is approximately 1,600 m (5,250 ft; PG&E, 2011). In contrast, the Honolulu-Tidewater 1 well near or just north of the axis of the syncline (Figure 2-2) was drilled through over 10,000 ft (3,000 m) of Neogene strata and did not hit Mesozoic basement (Appendix E of PG&E, 2014). Although it is possible that the apparent section thickness in the Honolulu-Tidewater 1 well includes structural repetition by thrust faulting at depth, the fact that the basement was not encountered and repeated indicates it is unlikely that basement-involved faulting has fully doubled the section in the well. These relations suggest that the Neogene section thickens stratigraphically northward in the subsurface beneath the axis of the Pismo syncline. The thick section in the subsurface must be truncated and offset from the much thinner section exposed in the northern limb of the Pismo syncline; interpretation of the subsurface structure of the Pismo syncline is discussed in detail in Sections 5.1.5 and 5.5.

Numerous secondary folds are superimposed on the limbs of the Pismo syncline (Figure 2-2 and Plate 1). These structures trend west-northwest, subparallel to the trend of the Pismo syncline, and are most extensively developed in the Pismo Formation (Figure 2-2). The folds are well exposed in the uplifted marine wave-cut platforms along the coast north of Point Buchon. Individual secondary fold axes are approximately 2–4 km long, and some can be traced for 10 km or more along trend (Figure 2-2).

2.3.2 Edna Fault Zone

The Edna fault zone strikes west-northwest and is located in the northern Irish Hills along the northern margin of the Pismo syncline (Figure 2-2 and Plate 1). Stratigraphic and structural relationships, discussed in greater detail in the following sections, indicate that the Edna fault zone was likely the northern structural margin of the Neogene Pismo sedimentary basin (Stanley and Surdam, 1984). The Edna fault zone extends southeast of the ONSIP study area and appears to merge with the Los Osos fault south of the Irish Hills. The total mapped length of the Edna fault zone is approximately 13 km west of the point where it branches from the Los Osos fault zone (Figure 2-1).

A southern strand of the Edna fault zone, herein referred to as "Edna A," strikes into the ONSIP study area from the southeast and variously juxtaposes the Vaqueros, Rincon, Obispo, and Pismo Formations to the south with Franciscan Complex basement to the north (Figure 2-2 and Plate 1). The outcrop pattern of "V's" formed by the surface trace of the Edna A strand as it crosses drainages indicates that the fault dips south, so the south-side-down stratigraphic separation implies normal slip during deposition of the Neogene stratigraphic section. In the central part of the ONSIP study area, thin deposits of Rincon and Obispo Formations are present on the northern footwall block of the Edna A strand, and Pismo Formation is on the southern hanging wall (Figure 2-2).

The surface trace of the Edna A strand dies out along strike to the northwest in the central Irish Hills. Displacement appears to be transferred, at least in part, to a second, more northerly strand or strands of the fault herein referred to as "Edna B" (Figure 2-2). South-side-down separation along the Edna B strand and related structures is indicated by the juxtaposition of Vaqueros and Rincon Formations to the south with Franciscan Complex rocks to the north. The map trace of the Edna B strand and related splays turns abruptly to the north in the northwestern corner of the Irish Hills and juxtaposes Pismo Formation on the west with Franciscan Complex on the east. The increasing stratigraphic separation from southeast to northwest along the Edna B fault (or northwest-increasing preservation of Tertiary stratigraphic thickness) is consistent with the hypothesis that slip was transferred from the Edna A fault in an en echelon or relay fashion during deposition of the Neogene basin section. The Edna B trace is mapped as being buried by unfaulted Quaternary deposits in the northwestern Irish Hills (Figure 2-2).

In addition to south-side-down normal stratigraphic separation across the Edna A and Edna B strands of the fault zone, map relations suggest that a younger episode of contractional deformation and minor reverse slip has been accommodated by these structures. Numerous short-wavelength anticlines and synclines are mapped in the hanging wall of the Edna B fault trace (Figure 2-2). For example, Vaqueros, Rincon, and Obispo strata are folded about the axis of a small Franciscan-cored anticline near the south end of the Edna B fault. A similar Franciscan-cored anticline is present in the hanging wall of the Edna B fault at the northwest end of the Irish Hills, where it plunges gently west-northwest toward the Maino-Gonzales 1 well (Figure 2-2). This fold also involves the Pismo Formation, indicating the shortening is late Neogene in age or younger.

2.3.3 San Miguelito Fault Zone

As shown on Figure 2-2, the San Miguelito fault zone can be traced from the Avila Beach region westward into the southeastern part of the ONSIP study region. The San Miguelito fault zone consists of several distinct reaches that alternate between striking west-northwest/east-southeast and east-northeast/west-southwest. Strands of the fault in the 4 km long west-northwest-striking reach in the southern Irish Hills north of Point San Luis juxtapose the Obispo Formation (and possibly Vaqueros and Rincon Formations) to the north with the Franciscan Complex and Cretaceous sandstone to the south (Figure 2-2). Several splays of the fault are confined to the Neogene section and locally juxtapose Monterey Formation to the north with Obispo Formation to the south. These stratigraphic separations indicate relative north-side-down motion.

Approximately midway between Point San Luis and the DCPP, the San Miguelito fault zone appears to split into two discrete branches (Figure 2-2). The southerly branch of the fault zone turns to a southwest strike. It follows the northern and western exposures of Mesozoic bedrock units and continues westward as a single fault trace offshore, where it apparently terminates against the Shoreline fault (Figure 2-2). Although significant portions of this southerly reach are covered by landslide and marine terrace deposits, map relations indicate that the diabase unit of the Obispo Formation on the west is juxtaposed with Cretaceous sandstone to the east, suggesting west-side-down stratigraphic separation if the contact is indeed a fault. The more northerly west-northwest-striking branch of the fault zone includes multiple traces that are confined to the Obispo Formation and younger Tertiary units. The more northerly branch appears to die out westward into the Obispo and Monterey Formations (Figure 2-2).

2.3.4 Los Osos Fault Zone

The Los Osos fault zone strikes northwest-southeast to east-west, and forms the structural boundary between the northern Irish Hills and Los Osos Valley (PG&E, 2011; Figure 2-2). The fault zone is characterized by a series of discontinuous, subparallel and en echelon traces, and locally is up to 2 km wide. The fault zone has been mapped southeast of the ONSIP study area along the northern margin of the San Luis Range to an intersection with the north-northwest-striking West Huasna fault southeast of San Luis Obispo (Figure 2-1). The total length of the Los Osos fault zone is approximately 50 km (PG&E, 2011).

The Los Osos fault zone is interpreted to be a south-dipping, reverse structure that separates the uplifting Irish Hills to the south from the subsiding or southwest-tilting Los Osos block to the northeast (PG&E, 1988; Lettis and Hall, 1994; Lettis et al., 2004; Figure 2-1). At its west end, the Los Osos fault zone has been mapped as a buried or blind structure that deforms Quaternary marine terraces and accommodates a vertical separation rate of approximately 0.2 mm/yr (PG&E, 2011). To the east, the fault zone has modest tectonic-geomorphic expression: the fault is shown with a blind or buried trace in the north-central Irish Hills, and geomorphic features suggestive of surface faulting are limited to the east-central and eastern sections of the Irish Hills. As noted by PG&E

(2014), many lineaments associated with the Los Osos fault zone can be explained by either fluvial or tectonic processes.

2.3.5 San Luis Bay Fault Zone

The west-northwest-striking San Luis Bay fault zone extends from San Luis Obispo Bay westward into the southeastern part of the ONSIP study area (Figure 2-2). This structure is part of the longer Southwestern Boundary fault zone that forms the southern tectonic margin of the uplifted San Luis/Pismo structural block (Figure 2-1; see PG&E, 2011, and references cited therein, for a detailed discussion).

As described in the Shoreline Fault Zone Report (PG&E, 2011), the San Luis Bay fault zone is exposed near the mouth of San Luis Obispo Creek at Avila Beach (Figures 1-1 and 2-2). The San Luis Bay fault is a south-vergent-thrust or reverse fault that places Franciscan Complex over the Pliocene Squire Formation and Quaternary alluvium. Field relationships in the vicinity of Avila Beach indicate that the San Luis Bay fault zone dips moderately north and has accommodated reverse dip-slip motion (PG&E, 2011).

The fault zone is poorly exposed in the Irish Hills, and thus is less well characterized there. As mapped, a blind trace of the fault underlies the low saddle on San Luis Hill north of Point San Luis (Figure 2-2). West of this saddle, the fault branches into two splays that extend obliquely across and deform Quaternary marine terraces along the coast. The southern splay is referred to as the Rattlesnake fault and is located entirely within Cretaceous sandstone. According to the GMP Report (PG&E, 2014), the Rattlesnake splay of the San Luis Bay fault “separates similar facies of Cretaceous sandstone with little to no recognizable dip discordance.” The northern and westernmost splay is referred to as the Olson fault or Olson Hill deformation zone (PG&E, 2011). To date, this structure has not been observed in outcrop. It may be partially or completely blind, or it may be an active fold axial surface that has been locally ruptured through by faulting (PG&E, 2011).

2.3.6 Shoreline Fault

The west-northwest-striking right-lateral strike-slip Shoreline fault zone extends from San Luis Obispo Bay westward past Point Buchon in the offshore region along the southwestern boundary of the ONSIP study area (Figure 2-2). This structure is located between the San Luis Bay fault zone to the north and east, and the Hosgri fault zone to the south and west (Figure 2-1; see PG&E, 2011).

The Shoreline fault zone was originally identified as a seismicity lineament in 2008 (Hardebeck, 2010). Figure 2-5 illustrates the seismicity lineament using an updated and relocated seismicity catalog through the end of 2013 (J. Hardebeck, pers. comm., 2014). PG&E initiated an extensive program to acquire and interpret new geological, geophysical, and bathymetric data in 2009 and 2010 to study the seismicity lineament. Based on these studies, a coast-parallel, nearshore bedrock fault zone (named the Shoreline fault) was identified along the seismicity lineament (PG&E, 2011). As described in the Shoreline Fault Zone Report (PG&E, 2011), the Shoreline fault zone is divided into three segments based on differences in the geologic and geomorphic expression of surface and near-surface faulting, intersections with other mapped structures, features observed in magnetic field data (Langenheim et al., 2009; Figure 2-6), and variations in the continuity, trend, and depth of seismicity along the lineament. Mapping based on high-resolution multibeam echosounder (MBES) bathymetric data clearly shows a sharp, well-defined lineament that lies offshore and west of the DCPP and appears to juxtapose Tertiary sedimentary rocks and Mesozoic basement (Figure 2-2). Earthquake focal mechanisms indicate primarily right-lateral strike-slip motion on the Shoreline fault (Hardebeck, 2010).

PG&E (2011) concluded that the Shoreline fault zone appears to locally represent the reactivation of a preexisting Tertiary fault. This prior episode of faulting dates to either a mid-Miocene (~14 Ma) to early Pliocene (~4 Ma) period of transtensional deformation, or to a middle to late Pliocene (~3 Ma) episode of transpressional deformation (PG&E, 2011).

3.0 METHODOLOGY

The following sections describe the team approach to seismic interpretation, software used, and unit conversions.

3.1 Team Approach

ONSIP was conducted as a team effort involving earth science professionals from Lettis Consultants International, Inc. (LCI), and Fugro Consultants, Inc. (FCL), who are familiar with the general geology of the project area and are experienced at interpreting seismic-reflection data (see Figure 3-1 for project organization and personnel). Dr. Stuart Nishenko, of PG&E Geosciences, provided technical oversight and coordination. Dr. Robert Yeats, of Earth Consultants International, Inc. (ECI), served as Independent Technical Reviewer (ITR) for the project. Ms. Marcia McLaren, Quality Assurance (QA) Manager for PG&E Geosciences, provided surveillance and oversight of compliance with QA requirements. The team held a kickoff meeting on 7 February 2013, during which the Project Planning Document (PPD) was discussed and the team received QA training from Ms. McLaren. Formal Project Instructions (PIs) provided guidelines for the seismic interpretation workflow and the development of geologic cross sections.

The team members conducted their analysis by developing individual interpretations of the ONSIP data set. Multiple meetings were held during the interpretation phase of the project to present and discuss their interpretations, with the goal of identifying points of consensus where they exist and exploring viable alternative interpretations of the data.

Two workshops were held with the ITR, Dr. Yeats, at key milestones in the project. The first ITR meeting was held on 28 and 29 August 2013 to present work performed to date, with emphasis on the internal structure of the Pismo syncline and central Irish Hills. The ONSIP team solicited feedback from Dr. Yeats regarding the technical approach and use of supplementary data, such as well logs, geologic mapping, and potential field data to support the seismic interpretations.

Subsequent to the first ITR meeting, the ONSIP team completed their analysis of data from the Pismo syncline, arriving at a consensus about their preferred structural model (i.e., the Pismo syncline is a deformed Miocene extensional basin; see discussion in Section 5.1.5). The team developed primary and alternative interpretations of key seismic lines across the Pismo syncline to illustrate this model. In addition, the ONSIP team analyzed seismic lines crossing the Los Osos and San Luis Bay fault zones to evaluate the downdip geometry of these structures with the depth limits of resolution provided by the reflection data.

The second ITR meeting was held on 7 and 8 April 2014 to present mature seismic interpretations along with preliminary structure contour maps and geologic cross sections derived from analysis of the seismic data. This report presents and discusses the preferred seismic interpretations of the ONSIP team, as well as alternative interpretations that the team believes are viable and that highlight some of the uncertainty in the reflection data. The preferred interpretations are further developed with structure contour maps of elevations of key reflection horizons, and geologic cross sections that present interpretations of the structure below the imaging and resolution depth of the data.

3.2 Software

The team used IHS Kingdom Suite 3D/2D Pak Version 8.6 software as the primary platform for analysis and interpretation of the seismic-reflection data. This software was validated for use under FCL's nuclear QA program, and installation on FCL and LCI work stations was controlled by appropriate work instruction. Interpretation was performed at various scales depending on the size of the features being mapped. All available and appropriate spatial data (geologic, geographic information systems [GIS], and seismic-reflection data) were imported into the Kingdom Suite software and archived as a project database.

3.3 Unit Conventions

The presentation and discussion of the seismic data in this report observe the following conventions:

- English units are most commonly used in the oil and gas industry for measures of depth and distance. For example, Agile Seismic LLC delivered the depth-migrated seismic-reflection data to the ONSIP project with horizontal distances and depths in units of feet. We uploaded the data as received into the Kingdom Suite software and performed the interpretation using English units. Interpreted seismic images exported from Kingdom Suite for display in this report retain English units for depth and horizontal distance. In discussing the interpretation in this report, we discuss the absolute vertical position of features in the seismic data in terms of their elevation relative to sea level in units of feet, followed by the equivalent elevation in meters in parentheses. The vertical distance below the ground surface is described herein as "depth" and is relative to the local surface elevation only.
- For the report, the horizontal location of a feature in the seismic data is described by its horizontal distance in feet *along the seismic line*, measured from zero distance at one end of the line (usually the south end). The rationale for adopting this convention is that Kingdom Suite displays the reflection data with horizontal distance in units of feet as measured along the common depth point (CDP) version of the original acquisition line. The CDP lines for the ONSIP project are often crooked, so the horizontal distance of a point *along the seismic line* typically differs from the straight-line distance between the point and the beginning of the line. In maps showing the locations of the seismic lines, we plot increments of horizontal distance along individual seismic lines so that interested readers can readily locate features shown in the interpretations and discussed in the text.

4.0 ASSUMPTIONS

Interpretation of the 2011 ONSIP data set involved identifying and tracing reflectors imaged on individual seismic-reflection profiles. We assume that variations in the acoustic properties of the rocks that give rise to the seismic reflectors directly or indirectly represent real geologic structure. For example, vertical variations in the density (and thus acoustic velocity) of bedded sedimentary sequences commonly are imaged as sequences of layered reflectors in seismic-reflection data. Furthermore, we assume that bedded sedimentary sequences originally were subhorizontal, and thus reflective structure arising from undeformed sedimentary sequences generally should be subhorizontal and subparallel. Consequently, variations in the lateral continuity and amplitude of the reflectors, as well as departures from parallelism and horizontality, were the primary bases for interpreting faults, folds, unconformities and other geologic features. The general interpretation approach we adopted to relate reflective structure to geologic structure is similar that described and illustrated by Bally (1983).

Mapping the location and geometry of faults in the upper crust was a key focus of this study. We assume that movement on faults may truncate or offset acoustic variations in the rocks, resulting in truncation or discontinuity in reflectors arising from the 2D and 3D acoustic structure of the upper crust. Given this assumption, faults were identified based on criteria that include but are not limited to the following:

- Abrupt lateral truncation of reflectors.
- Displaced, offset, or broken reflectors.
- Correlations of offset reflectors across a fault plane.
- Direct fault-plane reflections.
- Acoustical anomalies (e.g., presence of diffractions, especially at a reflector termination or fault tip, or presence of laterally short and bright reflectors adjacent to a plane that appear as “flags” or contrasting acoustic signals separated by a plane).
- Visible drag and rollover of reflectors.
- Loss or substantial decrease in acoustic coherence beneath a fault plane, or distorted dips observed through a fault plane.

5.0 INTERPRETATIONS AND ANALYSIS

Discussion of the 2011 seismic-reflection data is organized into the following topics:

- Section 5.1: Internal structure of the Pismo syncline, including the Edna and San Miguelito fault zones.
- Section 5.2: Structure of western Los Osos Valley.
- Section 5.3: Los Osos fault zone.
- Section 5.4: San Luis Bay fault zone.

5.1 Structure of the Pismo Syncline

This section focuses on the analysis of AWD and vibroseis lines that image the subsurface structure of the Pismo syncline in the central and southern Irish Hills. The following key lines are discussed in this section and are shown on Figure 5-1:

- Line 103-104 (Section 5.1) crosses the axis of the Pismo syncline in the western Irish Hills.
- Line 204, both AWD and vibroseis versions (Section 5.2), provides oblique imaging of the northern limb of the Pismo syncline in the western Irish Hills.
- Line 112-140 (Section 5.3) provides oblique imaging of the southern limb of the Pismo syncline in the southeastern Irish Hills. Constraints on subsurface stratigraphy at the north end of Line 112-140 are provided by the nearby Honolulu-Tidewater 1 well, which was drilled to a depth of 10,788 ft (3,289 m; Appendix E of PG&E, 2014).
- Line 141-142 vibroseis North and South (Section 5.4) crosses the entire Pismo syncline at a relatively high angle in two north-trending sections with a lateral east-west offset across the northern limb of the Pismo syncline.

5.1.1 Seismic Line 103-104

Seismic Line 103-104 is approximately 12 km long and trends north-south to north-northeast/south-southwest across the western Irish Hills (Figure 5-1). At its south end, Line 103-104 begins approximately 1 km southeast of Lion Rock. From there it extends northwest, subparallel to the coast, past Point Buchon along the major public road through Montaña de Oro State Park, terminating to the north in the western Los Osos Valley approximately 0.75 km south of Morro Bay. From south to north, major geologic structures crossed by Line 103-104 include the axis of the Pismo syncline and an interpreted trace of the Los Osos fault that is blind or buried (Figure 5-1).

Several oil exploration wells, including the 1,749 ft (533 m) deep Spooner 1 well and the 6,146 ft (1,873 m) deep Montadoro 1 well, lie close enough to Line 103-104 to provide subsurface stratigraphic control for interpretation of the seismic data (Figure 5-1). When combined with the geologic map data (Figure 2-2), these wells suggest that basement is generally sloping toward the northwest (see Sections 5.1.5.1 and 5.2.1 for further discussion). It is important to note that projection of these wells onto Line 103-104 does not account for the uncertainty of the position of the northwest-sloping basement surface. As a result, we have used the well information as a guide for interpretation of the seismic data, but in some cases, our interpretations do not intersect precisely at the formation top identified in the well. For example, we interpreted basement as slightly deeper than top of Franciscan Complex identified in the Spooner 1 well to account for the uncertainty in the well projection.

Reflection data were collected along Line 103-104 using both AWD and vibroseis sources (FCL, 2014a). Our interpretation effort focused on the AWD version of Line 103-104. The vibroseis version of the line has a large data gap in a structurally critical section in Montaña de Oro State Park, and the vibroseis acquisition parameters did not favor detailed imaging of the layered Tertiary stratigraphy in the upper several thousand feet. In contrast, the AWD data were collected continuously along the entire length of the line, and the processed AWD data provide imaging of layered reflective structure in the upper 3,000–5,000 ft (~900–1,500 m) depth range.

At the north end of the seismic line, the nearby Spooner 1 and Maino-Gonzales 1 wells both encountered Franciscan serpentinite below Tertiary strata at approximately –1,250 to –1,300 ft (–381 to –396 m). When the data from these wells is projected onto the seismic line, the depth to serpentinite generally coincides with a subhorizontal reflector that lies at the base of a package of laterally continuous and closely spaced layered strata (Figure 5-2). We interpret this reflector to be the top of the Franciscan Complex basement. The Franciscan rocks below the basement reflector also are significantly reflective and characterized by a generally subhorizontal fabric punctuated with discontinuous high-amplitude reflectors (Figure 5-2).

Franciscan basement was encountered at –604 ft (–184 m) in the CCW Pecho well at the far north end of Line 103-104 (Figure 5-1; Appendix E of PG&E, 2014). We interpret the basement reflector to step down to the south across two south-dipping normal faults (Faults F1 and F2; Figure 5-2) between the CCW Pecho and Spooner 1 wells, where serpentinite was encountered at –1,283 ft (–391 m; Appendix E of PG&E, 2014). The basement reflector steps down again to the south across Fault F3 between the Spooner 1 and Maino-Gonzales 1 wells and is folded into a broad, low-relief antiform in the hanging wall of Fault F3. We note that the basement reflector is less distinct between Faults F2 and F3, and thus relatively uncertain north of Fault F3.

Moving southward across the northern limb of the Pismo syncline, we interpret the basement surface to step down across three additional blind, south-dipping normal faults (Faults F4, F5, and F6, respectively; Figure 5-2). Fault F4 truncates the shallow basement reflector in the footwall at horizontal distance of approximately 28,250 ft and is interpreted to offset layered reflectors above the basement. The interpreted basement reflector generally separates rocks with a laterally continuous layered character above from relatively more transparent rocks below. The resolvable detail in the seismic imagery decreases with depth, making it difficult to discern a contrast in reflective character or confidently identify the boundary between the Tertiary strata and Franciscan basement south of Fault F4. The top of basement in the hanging wall of Fault F4 is interpreted to coincide with the lower limit of the reflective character we associate with the sedimentary rocks in the footwall, and is highly uncertain. We interpret that the top-of-basement reflector is faulted below the maximum depth of imaging (i.e., below approx. –5,500 ft, or –1,676 m) across Faults F5 and F6, approximately beneath the axis of the Pismo syncline. Faults F5 and F6 are associated with truncations of layered reflectors in the upper 2,000 ft (610 m) depth; however, the downdip continuation of the faults is poorly imaged and uncertain.

Reflectors in the upper 1,000 ft (305 m) of the southern part of Line 103-104 are likely associated with the Obispo Formation, which has a minimum thickness of 1,000–2,000 ft (~305–610 m) in the Irish Hills (see Section 2.2.4.2). High-amplitude reflectors in the upper 2,000 ft (610 m) depth between horizontal distance 0 and horizontal distance 11,000 ft of Line 103-104 are laterally discontinuous and cuspate, and may be associated with diabase intrusions mapped in surface exposures of the Obispo Formation in the southern Irish Hills (Section 2.2.2.4.2). The seismic line turns subparallel to the bedding strike near the surface contact between the Obispo and Monterey Formations (approximately at horizontal distance 6,000 ft; Figures 5-1 and 5-2), and the reflectors here are probably imaged with a minimum of geometric distortion.

We questionably interpret the base of these relatively bright reflectors observed at a depth of approximately –2,750 ft (–838 m) to be the top of relatively more transparent basement. If this is correct, then the basement contact must rise southward beneath the southern limb of the Pismo syncline from –5,500 ft (–1,676 m) beneath the axis of the fold. We interpret that the basement steps up to shallower depths across several blind, north-dipping normal faults that underlie the southern limb of the Pismo syncline (Faults F7 through F10; Figure 5-2). Fault F10 is interpreted based on the northern termination of the cuspate reflectors we associate with the Obispo Formation. Fault F9 is interpreted along a series of subtle reflector truncations below approximately 2,000 ft (610 m) depth, and is very uncertain. Faults F8 and F7 are primarily interpreted from truncation of layered reflectors in the upper 2,000 ft (610 m) depth, and their extension to greater depths is uncertain. Our interpretation is that the top-of-basement contact passes below the Montadoro 1 well in the hanging wall of Fault F9, which bottomed at –5,771 ft (–1,759 m) in Obispo Formation or Rincon shale (Appendix E of PG&E, 2014). We acknowledge that the top-of-basement contact is poorly imaged and highly uncertain beneath the southern limb of the Pismo syncline; thus, our interpretation represents a minimum limiting depth for the top-of-basement consistent with the stratigraphic data for the Montadoro 1 well.

The contact between the Obispo and Monterey Formations (i.e., "top Obispo") is traced from map exposures in the southern part of Line 103-104 into the subsurface as the top of a reflective package of rocks that is approximately 3,000 ft (~900 m) thick. We interpret the contact to pass through the Montadoro 1 well; however, the top Obispo contact likely falls within the interval of the well at –3,612 to –3,875 ft (–1,101 to –1,181 m) that was not logged, and thus the elevation is not known precisely from existing well documentation (Appendix E of PG&E, 2014). North of approximately horizontal distance 10,000 ft, the seismic line becomes more parallel to the bedding dip, and the contact thus appears to abruptly plunge north at approximately 45 degrees as part of the southern limb of the Pismo syncline. We interpret that the top Obispo contact is faulted down to the north across Faults F10 and F8, and possibly slightly offset across Fault F9. Fault F8 is interpreted to pass through the Montadoro 1 well and cut out part of the Monterey Formation (Figure 5-2).

The contact between the Monterey and Pismo Formations (i.e., “top Monterey”) is projected from outcrop to depth northward along the base of a package of north-dipping layered reflectors (Figure 5-2). The lateral continuity and coherence of the overlying Pismo Formation reflectors are better expressed than those of the Monterey Formation, and we used this contrast in reflector character between the Pismo and Monterey Formations as a guide to trace the top Monterey contact northward in the subsurface. The contact is interpreted to be faulted down to the north across Faults F8 and F7 and flatten northward through the axis of the Pismo syncline (Figure 5-2). The contact likely passes through the Pecho 1 well, but the exact elevation of the contact in the well is not known: no log exists for the upper 2,287 ft (697 m) of the well, and the entire logged lower section of the well is assigned to the Monterey Formation (Appendix E of PG&E, 2014). Thus the maximum elevation of the top Monterey contact in the well is –2,110 ft (–643 m). We interpret the top Monterey contact to continue north in the subsurface with up-to-the-north offsets across Faults F6 and F5, and to terminate against Fault F4. The contact with Fault F4 is a buttress unconformity, making the fault the effective north end of the structural basin during Monterey Formation time.

North of Fault F4, we interpret that the Monterey Formation was never deposited or has been erosionally removed from the section beneath the northern limb of the Pismo syncline (Figure 5-2). This interpretation is consistent with stratigraphic relations exposed by uplift and erosion of a basement-involved anticline that plunges west-northwest toward the Maino-Gonzales 1 well (Figures 5-1 and 5-2). The anticline trends west-northwest and projects across Line 103-104 approximately at horizontal distance 23,000 ft (Figure 5-1). On the southern limb of the anticline between horizontal distance 30,000 and 33,000 ft, the basal Edna Member of the Pismo Formation unconformably overlies the Obispo Formation with no intervening Monterey Formation. The basal Pismo contact cuts downsection across the plunging nose of the anticline, and the Pismo Formation directly overlies the Rincon Formation on the northern limb of the fold (Figure 5-1).

Interpreted changes in the thickness of the Obispo, Monterey, and Pismo Formations across the faults in Line 103-104 imply time- and space-varying patterns of Neogene subsidence within the ancestral Pismo Basin (Figure 5-2). Whereas the Obispo Formation is interpreted to thicken progressively southward across Faults F4, F5, and F6, the Obispo thickness is relatively uniform in the southern part of Line 103-104 (~2,500 ft, or 761 m) south of Fault F9, indicating that the southern structural margin of the Obispo-age basin lay somewhere south of the modern Irish Hills. The depth to basement and thickness of the Obispo Formation increase dramatically between Faults F5 and F9, implying that the region approximately underlying the present axis of the Pismo syncline was a localized structural low during Obispo time.

A similar pattern of structural thickening along Faults F4, F5, and F6 beneath the northern limb of the Pismo syncline is interpreted for the Monterey Formation. By upper Monterey–lower Pismo time, we infer that activity of Fault F4 ceased and basal Pismo Formation lapped northward onto the footwall block of F4, unconformably overlying the Obispo and Rincon Formations in the hanging wall of Fault F3. It is possible that the northward progradation of the basal Pismo Formation was triggered by normal slip on Faults F1 and F2, and possibly other structures, all north of Fault F3.

Low-amplitude folds in the hanging walls of some of the Neogene normal faults interpreted on Line 103-104 provide evidence for post-Pismo reverse reactivation. For example, a short-wavelength anticline is present in the hanging wall of the northern splay of Fault F7 (Figure 5-2). The fold is documented at the surface by bedding-dip measurements in the Pismo Formation (Figure 5-1 and Plate 1) and is relatively well expressed by an antiformal closure in the top Monterey contact between Faults F7 and F6. The blind Fault F7a projects updip to the synformal hinge at the base of the forelimb of the anticline, indicating that the anticline is in the hanging wall of F7a and has formed as a fault-propagation fold by reverse slip on F7a. This structure is interpreted to have normal, north-side-down separation of the top Monterey contact (Figure 5-2), so the anticlinal folding represents post-Pismo reverse reactivation of Faults F7 and F7a.

The hanging-wall block of Fault F3 similarly shows evidence for post–Pismo Formation folding. As discussed previously, a fold we interpret in the seismic data at about horizontal distance 33,000 ft (Figure 5-2) is associated with a west-northwest-plunging anticline in the Pismo Formation (Figure 5-1 and Plate 1). This anticline can be traced southeast to an erosional exposure of the Pismo Formation and Rincon Formation folded about the axis of a basement-cored anticline in the hanging wall of the Edna B fault trace. At this location, the Obispo Formation is present on the southern limb of the anticline below the Pismo Formation but is cut out erosionally on the northern limb of the fold. We infer that similar stratigraphic relationships are present at depth in the hanging wall of Fault F3 on Line 103-104 (Figure 5-2). Given the similar stratigraphic and structural relationships along the trend of the anticline, we correlate Fault F3 on Line 103-104 with the Edna B fault trace mapped at the surface to the southeast. The surface and subsurface relationships are consistent with the Edna B fault originally having accommodated down-to-the-south normal separation during Rincon time (and possibly Obispo time), and subsequently being reactivated in a reverse sense after deposition of the Pismo Formation to generate the anticline in the hanging wall.

To explore uncertainty in the seismic interpretation, an alternative interpretation of Line 103-104 developed by the ONSIP team is presented on Figure 5-3. This alternative interpretation has many similarities and several key differences with the interpretation shown on Figure 5-2. Most importantly, the alternative interpretation of Line 103-104 shows a deformed extensional basin with a series of north- and south-dipping normal faults pointing to the center of the basin and the Pismo syncline (Figure 5-3), which is very similar to the first-order interpretation of Line 103-104 discussed above (Figure 5-2) and represents a consensus among the ONSIP team that the Pismo syncline is a deformed Neogene extensional basin. The alternative interpretation illustrated on Figure 5-3 also exhibits the following key similarities:

- The top Monterey contact is interpreted at a very similar depth throughout much of the line generally at the base of a package of high-amplitude subhorizontal reflectors.
- Folds are interpreted as forming in the hanging walls of buried normal faults due to reverse reactivation.
- The antiform on the northern limb of the Pismo syncline (from horizontal distance 28,000–34,000 ft) is interpreted as forming in the hanging wall of the south-dipping Edna B fault and is bounded on the south by a steeply south-dipping normal fault.
- The northern edge of the Tertiary basin is bounded by a steeply dipping, south-side-down normal fault at horizontal distance 38,000 ft.
- The top of the Mesozoic basement is interpreted at approximately –3,000 ft (–914 m) depth at the south end of the line.
- Both the Monterey and Obispo Formations are interpreted to thicken beneath the axis of the Pismo syncline.

The two interpretations exhibit the following key differences:

- The top of the Mesozoic basement on the northern limb of the Pismo syncline (from horizontal distance 28,000 to 34,000 ft) is interpreted as dipping more steeply south of the Maino-Gonzales 1 well in the alternative interpretation.
- Several additional geologic units (including the top of the Vaqueros, Rincon, and Pismo Formations) are interpreted on the north end of Line 103-104 in the alternative interpretation.
- The Monterey Formation is shown as pinching out stratigraphically between the Obispo and Pismo Formations on the alternative interpretations (horizontal distance of 32,000 ft; Figure 5-3) rather than pinching out against a normal fault (Figure 5-2).
- Several of the buried normal faults within the center of the basin are interpreted in slightly different locations, and, in some cases, these faults have steeper dips (although the dip directions are the same).
- The top Obispo contact from horizontal distance 10,000 to 16,000 ft is interpreted as slightly higher (above –1,000 ft, or –305 m) and folded on the alternative interpretation.

Finally, it is interesting to observe that a profile of the Bouguer gravity anomaly along Line 103-104 (Plate 2) shows steadily decreasing values from south to north across the western Irish Hills to the Los Osos Valley. The gradient steepens across the southern limb of the Pismo syncline, consistent with our interpretation of structural thickening of the Neogene section by growth faulting beneath the axis of the Pismo syncline. The gradient continues north of the Pismo syncline axis, however, and the anomaly values decrease even as the basement surface is rising northward. Well data shown on Plate 1 confirm that the basement surface rises a minimum of approximately 4,400 ft (~1,340 m) from north to south between the Montadoro 1 and Maino-Gonzales 1 wells, while the Bouguer anomaly decreases approximately 10 milligals over the same distance. The basement is rising northward, and the thickness of the overlying Tertiary section is decreasing as the gravity values decrease. These observations strongly suggest that the long-wavelength gravity gradient is probably related to density contrasts in the basement, rather than variations in depth to basement.

5.1.2 Seismic Line 204

Seismic Line 204 trends east-northeast/west-southwest in the northwestern Irish Hills (Figure 5-1). Reflection data were acquired along Line 204 using both AWD and vibroseis sources (FCL, 2014a). The AWD-sourced line is approximately 7 km long and terminates in Franciscan Complex rocks just north of the B trace of the Edna fault zone. The vibroseis version of Line 204 extends farther north than the AWD line and crosses the map trace of the Los Osos fault at the northern physiographic front of the Irish Hills (Figure 5-1), for a total length of approximately 10 km (see Section 5.3 for a discussion of the northern extension of Line 204 across the Los Osos fault). The discussion in this section addresses AWD Line 204 and the equivalent 7 km long west-southwest-trending reach of the vibroseis Line 204 that crosses the northern limb of the Pismo syncline. The northern part of vibroseis Line 204 that crosses the Los Osos fault is discussed in Section 5.3.3. The AWD and vibroseis lines image different aspects of the reflective character of the Neogene basin strata and basement rocks, and thus provide complementary information for interpretation.

The B strand of the Edna fault zone (Fault F1 on Figures 5-4 and 5-5) dips steeply south based on an interpreted alignment of truncations and disruptions of reflector fabric in the Franciscan bedrock below the surface trace. We interpret a high-amplitude southwest-dipping reflector imaged by the AWD line in the hanging wall of the Edna B fault (Figure 5-4) as the top of Franciscan basement. On the AWD line, this reflector separates relatively transparent sedimentary rocks above from more reflective Franciscan Complex rocks below. In contrast, the sedimentary rocks imaged above this same basement reflector on the vibroseis line are characterized by relatively high-amplitude layered reflectors that dip gently to moderately to the southwest (Figure 5-5). On both the AWD and vibroseis interpretations, the basement reflector is progressively offset down to the south across several blind, south-dipping normal faults beneath the northern limb of the Pismo syncline (i.e., Faults F2 through F6 on Figures 5-4 and 5-5). We interpret the basement surface to be faulted below the depth of imaging in the hanging wall of Fault F6 (i.e., below approx. –6,000 ft, or –1,830 m). Faults F4 and F5 are interpreted to be secondary north-dipping structures that are antithetic Fault F3. The downward projection of faults into the Franciscan Complex below the basement reflector is uncertain.

Line 204 is generally oblique to the dip of the northern limb of the Pismo syncline, and locally subparallel to the bedding dip and, presumably, the fault structure at depth (Figure 5-1 and Plate 3). This crooked and oblique geometry impacts the image quality and interpretability. For example, Fault F2 has an apparent listric geometry in the seismic lines because Line 204 locally is subparallel to bedding strike in the hanging wall of the fault (Figure 5-1). Thus, the fault plane is being imaged very obliquely west of the surface trace. Similarly, Line 204 turns subparallel to the strike of bedding and the trend of the Pismo syncline axis near the west end of the line (from horizontal distance 0 to 4,000 ft), making it impractical to interpret any west-northwest-striking faults and associated offsets of stratigraphy generally west of Fault F6.

South of the Edna B trace, Line 204 images several thousand feet of layered reflectors overlying the basement that dip toward the axis of the Pismo syncline. We interpret these reflectors to represent the Neogene sedimentary section (Figures 5-4 and 5-5). In both the AWD and vibroseis versions of Line 204, the Pismo Formation is characterized by a layered reflective fabric in the upper 500–2,000 ft (~150–610 m) depth. In contrast, individual reflectors within the Pismo Formation are difficult to trace laterally for any significant distance, and commonly are crosscut by processing artifacts.

We interpret the underlying package of laterally continuous and higher-amplitude reflectors to be Monterey Formation. The difference in reflective character between the Pismo and Monterey Formations is well expressed in the upper 3,000 ft (914 m) between Faults F3 and F6 on the AWD version of Line 204 (Figure 5-4). The underlying Obispo Formation is more transparent than the Monterey Formation on the AWD line, but it is characterized by coarsely spaced discontinuous high-amplitude reflectors on the vibroseis line (Figures 5-4 and 5-5). We interpret the top Obispo Formation contact to lie at the base of the layered high-amplitude reflectors associated with the Monterey Formation.

Seismic Line 204 crosses the map contact between the Obispo Formation and the underlying Rincon Formation between Faults F1 and F2 (Figure 5-1), and we interpret the contact to project to depth generally parallel to the basement surface. Although it is likely that the Rincon Formation is present beneath the Obispo Formation in the subsurface southwest of Fault F2, we do not attempt to interpret a top Rincon contact and instead show both Rincon and Obispo as undivided Obispo Formation above the Franciscan basement (Figures 5-4 and 5-5; also, Figure 2-3).

The faults that offset the basement reflector also disrupt the layered reflectors corresponding to the overlying Tertiary marine section. For example, well-defined reflector truncations, offsets, and growth relations consistent with northeast-side-down motion can be observed along antithetic Faults F4 and F5 in both the AWD and vibroseis versions of Line 204 (Figures 5-4 and 5-5). Faults F1 through F6 all show evidence (i.e., varying thickness of stratigraphic units in the hanging wall and footwall) for activity and growth during deposition of the Obispo Formation. Faults F2 through F6 also show evidence for activity and growth during Monterey Formation deposition. In contrast, we interpret only Faults F5 and F6 to show relatively clear evidence for growth during deposition of the Pismo Formation. Moreover, displacement of the top Monterey Formation contact along these structures during deposition of the Pismo Formation (~500 ft, or 152 m) is much less than the offset of the top Obispo contact during deposition of the Monterey Formation (~1,750 ft, or 530 m; Figures 5-4 and 5-5).

As discussed in the interpretation of Line 103-104 (Section 5.1), the hanging wall of the Edna B fault (Fault F1) has no preserved Monterey Formation (i.e., the basal Pismo Formation unconformably overlies the Obispo Formation), suggesting that no significant normal slip occurred on the fault during Monterey time to create accommodation space for deposition of Monterey strata. In our interpretation, the base of the Pismo Formation extends unfaulted to the northeast across Fault F2 onto the hanging wall of Fault F1, implying no post-Monterey normal separation on either of these structures.

To illustrate some of the uncertainty in the data interpretation, an alternative interpretation of AWD Line 204 was developed by the ONSIP team (Figure 5-6). These two interpretations exhibit the following key similarities (Figures 5-4 and 5-6):

- The Monterey and Obispo Formations dip toward the southwest and thicken across a series of steeply dipping, south-side-down normal faults.
- The top Monterey Formation contact is interpreted along the top of the same highly reflective, well-imaged reflector package in the central portion of Line 204 (horizontal distance 4,500–11,000 ft).
- The top Obispo Formation contact is interpreted at the base of a highly reflective unit within the central portion of the line (horizontal distance 5,000–9,000 ft).
- The Edna B fault is interpreted as a steeply south-dipping fault at the same location.
- A steeply south-dipping fault thickens the Monterey Formation in the vicinity of horizontal distance 12,000 ft.

The two interpretations exhibit the following key differences:

- Different reflectors are chosen for the top of the Mesozoic basement.
- The top of the Monterey Formation is cut out farther southwest (at horizontal distance 12,000 ft) on the alternative interpretation.
- The alternative interpretation (Figure 5-6) includes the Edna Member of the Pismo Formation, whereas this unit is not distinguished from the rest of the Pismo Formation on Figure 5-4.
- The alternative interpretation has fewer normal faults, and the faults are interpreted in slightly different locations in the central portion of Line 204. Also, no antithetic north-dipping faults are shown.
- The fault interpreted at horizontal distance 14,000 ft is shown entirely within Mesozoic basement, does not displace Tertiary stratigraphy, and has a steeper dip at depth in the alternative interpretation (Figure 5-6).
- The alternative interpretation does not show a fault at horizontal distance 4,500 ft, but rather maps a fault at the far south end of the line (horizontal distance 500 ft) that significantly thickens the section to the south.

In summary, the two interpretations of AWD Line 204 are very similar and contain many of the same major geologic features and structural elements. The differences between the interpretations result from the uncertainty of evaluating seismic-reflection data at depth where image resolution is low and a lack of well data result in greater uncertainty in the thickness of the Tertiary section.

5.1.3 Seismic Line 112-140

Seismic Line 112-140 is approximately 9 km long and trends north-northwest/south-southeast across the southeastern Irish Hills (Figure 5-1 and Plate 5; FCL, 2014a). From south to north, mapped geologic structures crossed by Line 112-140 include the San Luis Bay fault zone, the San Miguelito fault zone, and the southern limb of the Pismo syncline. The southern part of the seismic line crosses depositional and faulted contacts between Mesozoic basement rocks and the basal part of the overlying Tertiary section. The top of the basement, top of the Obispo Formation, and top of the Monterey Formation can be traced into the subsurface on Line 112-140 from outcrop exposures. The northern part of the line passes through the Honolulu-Tidewater 1 well (Figure 5-1). This well was drilled to a total depth of 10,788 ft (3,289 m) and provides subsurface control on the depth to the top of the Monterey and Obispo Formations, as well as the minimum thickness of Tertiary strata in the ancestral Pismo Basin (Appendix E of PG&E, 2014).

Reflection data were collected along Line 112-140 using both AWD and vibroseis sources (FCL, 2014a). The vibroseis version of the line extends north beyond the end of the AWD line, but has large data gaps in the vicinity of the Honolulu-Tidewater 1 well and across strands of the Edna fault zone that significantly compromise image quality and interpretability. The shorter AWD line has no data gaps and provides good imaging of layered reflective structure in the upper 5,000 ft (upper 1,524 m) along most of its extent (however, it does not extend north across the map traces of the Edna fault zone). Consequently, we focus exclusively on the AWD version of the line for interpreting structure beneath the axis and southern limb of the Pismo syncline, and we do not discuss the vibroseis version of Line 112-140 in this report.

The south end of Line 112-140 crosses the Cretaceous sandstone that underlies San Luis Hill (Figure 5-1 and Plate 5). Exposures in the sea cliffs bordering San Luis Obispo Bay to the east show that the sandstone is a relatively thin unit that structurally overlies pillow lavas and remnants of an ophiolite sequence (unit KJfo on Figure 5-1) within the Franciscan Complex. The map trace of this contact continues south and obliquely crosses from the east side of Point San Luis promontory to the west side with little deflection, suggesting that it dips steeply west. Bedding strikes and fold axes mapped in the sandstone are strongly oblique to the map trace of the contact, suggesting it is a fault that postdates at least some of the folding in the sandstone. We tentatively interpret this structural contact to coincide on Line 112-140 (Figure 5-7) with a distinct discordance in reflector dips in the elevation range of –1,000 to –1,800 ft (–305 to –549 m) between horizontal distances of 1,000 and 6,000 ft. The contact in the seismic line juxtaposes moderately south-dipping and folded reflectors above with north-dipping reflectors below. Although the discordance in reflector dip is the primary basis for interpreting the contact, we note that the dip of reflectors within the inferred sandstone does not correspond closely to bedding dips mapped at the surface, and thus we regard this interpretation as uncertain.

The interpreted Franciscan-Cretaceous sandstone contact in Line 112-140 appears to be truncated northward by steeply north-dipping faults that project upward to the map trace or traces of the San Luis Bay fault zone (Figure 5-7). Specifically, Fault F1, which is inferred to dip steeply north by tracing an apparent alignment of discontinuities and lateral truncations of reflectors within the Franciscan Complex, projects updip to the primary map trace of the San Luis Bay fault. This structure juxtaposes south-dipping reflectors in the footwall with subhorizontal reflectors in the hanging wall, consistent with bedding-dip orientations mapped north and south of the fault (Plate 5).

Interpreted Fault F2, also inferred from terminations and abrupt changes in reflector dip at depth, projects to the surface trace of a fault that is mapped as juxtaposing Franciscan Complex to the north with the Cretaceous sandstone to the south. Given that the Franciscan Complex originated as a structurally lower unit than the Cretaceous sandstone in the ancestral convergent margin, the present structural relationship across the fault is north-side-up. Subhorizontal reflectors of the Cretaceous sandstone in the upper 1,000 ft (305 m) depth in the hanging wall of Fault F1 are truncated northward against Fault F2 (Figure 5-7).

Fault F3, a third north-dipping fault with a splay in its footwall (Figure 5-7) is interpreted to be present south of Fault F1 based on truncations of the synformally and antiformally folded reflectors below –1,500 ft (–457 m). The updip continuation of this feature is uncertain due to processing artifacts at the south end of the line. We acknowledge that these interpreted faults are based on our preferred correlation of reflector discontinuities. Other correlations are possible, which could result in different structural interpretations at depth.

North of the San Luis Bay fault zone, Line 112-140 crosses several mapped traces of the San Miguelito fault zone. These faults (Faults F4 through F7; Figure 5-7) are interpreted to be subvertical to steeply south-dipping structures based on correlating trends of reflector truncations and discontinuities in the Franciscan Complex rocks below the mapped fault traces (Figure 5-7). As discussed above, the faults shown represent preferred interpretations, and we acknowledge that other interpretations are possible. Mapped strands of the fault zone cut across topography rather than follow it, suggesting a subvertical to steep dip. The pattern of V’s made by the southernmost strand of the San Miguelito fault zone as it crosses drainages also indicates a steep dip toward the south (Figure 5-1), consistent with our interpretation of the fault in the reflection data.

In contrast to the San Luis Bay fault zone, the strands of the San Miguelito fault zone consistently show north-side-down separation (Figure 5-1). Along the southern strand of the San Miguelito fault zone (Fault F4; Figure 5-7), Vaqueros Formation and basal Obispo Formation to the north are faulted down against Franciscan basement (Figure 5-1). Monterey Formation is faulted down to the north against Obispo Formation along the northernmost strand of the zone (Figure 5-1). These map relations suggest that the top of the Franciscan basement and its contact with overlying Obispo Formation should be relatively shallow at the south end of the San Miguelito fault zone and should dip northward beneath the southern limb of the Pismo syncline north of the fault zone. We interpret the top of basement to coincide with a reflector that separates consistently north-dipping layered rocks of the Obispo Formation above from rocks with chaotic reflector dips below (Figure 5-7 and Plate 5). This contact, and the abrupt discordance in reflector dip across it, is well resolved from horizontal distance 11,500–16,000 ft in the depth range of approximately –1,000 to –3,000 ft (–305 to –915 m). This finding implies an average dip of approximately 34 degrees, consistent with the dip of bedding in the overlying Obispo and Monterey Formations (Plate 5).

We interpret the top-of-basement contact to step down to the north across Fault F7, which is a blind structure beneath the southern limb of the Pismo syncline. The top of basement is further interpreted to step down consistently to the north across Faults F4, F5, and F6 of the San Miguelito fault zone (Figure 5-7). The Obispo Formation thickens northward across blind Fault F7. This finding suggests that this structure and perhaps the exposed strands of the fault zone were once part of the ancestral southern structural boundary of the Pismo Basin. If this is correct, then these structures would have been passively uplifted and tilted to their present steep dips during folding of the southern limb of the Pismo syncline.

North of Fault F7, the top-of-basement contact steps several hundred feet down to the north across blind Fault F8 and is displaced probably thousands of feet down to the north across a series of three moderately to steeply north-dipping faults (Faults F9, F10, and F11; Figure 5-7) that underlie the southern limb of the Pismo syncline. We interpret the basement to step down to the north below the depth of imaging (i.e., below approx. –6,500 ft, or –1,981 m) across Fault F9 and to not be recognizably imaged in the northern part of the seismic line. The Honolulu-Tidewater 1 well bottomed in the Obispo Formation at –9,162 ft (–2,793 m) near the north end of the seismic line (Appendix E of PG&E, 2014; Figure 5-7), implying that cumulative north-side-down displacement of the basement across Faults F9, F10, and F11 is approximately 5,000 ft (1,524 m) or more.

AWD Line 112-140 crosses the top Obispo contact with the Monterey Formation at about horizontal distance 12,000 ft (Figure 5-7). The contact dips north and is traced into the subsurface generally subparallel to the layered reflective fabric in rocks we interpret to be part of the Obispo Formation. The top Obispo contact is faulted down to the south across Fault F9 and is inferred to correspond to a change in reflector character in the hanging wall of F9 in the depth range of –3,000 to –3,500 ft (–914 to –1,067 m; Figure 5-7). The rocks above this depth, which we interpret to be Monterey Formation, have a more strongly expressed layered character than the underlying Obispo Formation, similar to the contrast in reflective qualities between the two units noted on AWD Line 204 (Section 5.2). Tracing this change in reflector character northward as the top Obispo contact, we interpret it to step down to the south across Faults F10 and F11. The top Obispo contact is poorly expressed in the seismic-reflection data as a distinct reflector or vertical change in reflector character north of Fault F10, however, and is inferred primarily from the depth call in the Honolulu-Tidewater 1 well farther north.

AWD Line 112-140 intersects the contact between the Monterey and Pismo Formations at about horizontal distance 19,200 ft (Figures 5-1 and 5-7). Surface bedding indicates the contact dips north, subparallel to layered reflective fabric in the upper 1,000 ft (305 m) depth of the seismic line. This reflective fabric is presumably associated with the Pismo Formation, based on map relations (Figure 5-1 and Plate 5). We note, however, that the shallow layered reflective fabric in AWD Line 112-140 dips less steeply than bedding in the Pismo Formation (~30°–60° north directly adjacent to the mapped Monterey–Pismo contact; Plate 5). We also note that reflectors within the Monterey Formation north of fault F10 appear to dip south and lose coherency in the –1,000 ft to –3,000 ft depth range between horizontal distance 21,000 ft and 26,000 ft (Figure 5-7). The pattern of reflector dip suggests there may be an angular unconformity between the Monterey and Pismo Formation, but we believe this relationship is very uncertain given the lack of correspondence between surface bedding dips mapped in the Pismo Formation and the shallow reflective fabric.

The top Monterey contact was called at a depth of 1,037 ft (316 m) in the Honolulu-Tidewater 1 well (Appendix E of PG&E, 2014), which is a shallower depth than anticipated if the top Monterey contact simply follows the dip of the reflective fabric in the seismic line. We interpret the contact to have been elevated in the hanging wall of Fault F12 by reverse slip as a way of reconciling the apparent discrepancy between the subsurface trajectory of the contact implied by the layered reflective fabric and the data from the Honolulu-Tidewater 1 well. It is possible that Fault F12 was originally a north-dipping normal fault that has been reactivated as a reverse fault. Alternatively, it may be a younger, post-Miocene reverse fault. We conclude that the data quality is such that AWD Line 112-140 provides no strong constraint on the location and geometry of the top Monterey contact in the subsurface. The interpretation of the contact on Figure 5-7 is very general and highly uncertain.

An alternative interpretation of AWD Line 112-140 developed by the ONSIP team is presented on Figure 5-8. The two interpretations exhibit the following key similarities:

- Both interpretations show the top of the Mesozoic basement at the south end of the line (between horizontal distance 12,000 and 16,000 ft) at approximately the same depth.
- The top of the Obispo Formation is interpreted between horizontal distance 16,000 and 23,000 ft as dipping north and offset by north-dipping normal faults between –2,000 and –3,500 ft (–609 to –1,066 m).
- The top of the Monterey Formation is shown following the same reflectors north of the Honolulu-Tidewater 1 well.
- At the south end of the line, the top of the Cretaceous sandstone is interpreted at the base of the same reflective package (although Figure 5-7 illustrates some uncertainty in the location of this horizon).
- The San Luis Bay fault is interpreted as a steeply north-dipping fault with two more shallowly north-dipping splays to the south.
- Strands of the San Miguelito fault zone are interpreted to be subvertical (although the dip direction varies).

The two interpretations exhibit the following key differences:

- The top of the Monterey Formation is shown following different reflectors south of the Honolulu-Tidewater 1 well and is generally shown as deeper with larger fault offsets in the alternative interpretation (Figure 5-8).
- Although the top of the Obispo Formation is interpreted at generally the same depth range from horizontal distance 16,000–23,000 ft, the two interpretations follow different reflectors, and the fault offset across the horizon is greater in the alternative interpretation (Figure 5-8).
- The alterative interpretation shows the north-dipping normal faults in the central and northern part of the line with steeper dips and in slightly different locations.
- The Obispo Formation is shown as offset by thrust faults in the Honolulu-Tidewater 1 well on the alternative interpretation (Figure 5-8), which accounts for the multiple (and potentially repeated) tuff horizons described in the well log (Appendix E of PG&E, 2014).

In summary, the two interpretations of Line 112-140 are similar and contain many of the same major geologic features and structural elements. The differences between the interpretations primarily result from the limited resolution of details in the central and northern portions of the line. For example, the top of the Monterey Formation is uncertain for two main reasons:

1. The subhorizontal reflectors in the vicinity of this contact do not correspond to the steep bedding dips mapped along this section of the seismic line.
2. No obvious change is present in the nature of the reflectors representing the formation top.

Likewise, the reflective fabric in the depth range of the top of the Obispo Formation is poorly resolved and allows for multiple non-unique interpretations. Thus, the tops of the Monterey and Obispo Formations are largely inferred based on constraints from the Honolulu-Tidewater 1 well and surface mapping. Other key differences result from the alternative ways to project faults to depth resulting from the generally indistinct imaging of the reflective packages at depth.

5.1.4 Seismic Line 141-142

Seismic Line 141-142 extends from near Green Peak on the south (east-northeast of the DCPP) to Los Osos Valley to the north, obliquely crossing the entire Irish Hills and Pismo syncline (Figure 5-1 and Plate 6). Although originally acquired as a single, albeit very crooked, 2D seismic line, the processed version of Line 141-142 is a hybrid of the 2D line and adjacent 3D data (Figure 1-1; Plate 1). The processed version of the line used herein has been divided into two straight, approximately north-south-striking segments (Figures 5-9 and 5-10). These segments trend at higher angles to bedding and fold axes in the central and southern Irish Hills than the original acquisition line shown on Figure 1-1, thus reducing geometric distortion in imaging of the subsurface structure.

Line 141-142 was acquired using a vibroseis source, and the acquisition parameters were configured to best image deep structure (FCL, 2014a). Consequently, resolution of shallow structure and stratigraphy is lower than in AWD Lines 103-104 and 112-140 (Sections 5.1.1 and 5.1.3, respectively). We thus concentrate primarily on interpreting the downdip geometry of faults within the Pismo syncline and the depth of key stratigraphic contacts in Line 141-142, with the caveat that details of these features are uncertain.

In the southern part of Line 141-142, closely spaced subhorizontal layered reflectors in the upper 1,500 ft (457 m; Figure 5-9) are associated with surface exposures of Obispo Formation (Figure 5-1 and Plate 6). The layered reflectors are underlain by rocks with a more chaotic reflective fabric, including very steeply dipping reflectors that terminate abruptly at the base of the layered package (Figure 5-9). We interpret the upper, layered reflectors to be Obispo Formation, the chaotic reflectors below to be Mesozoic basement (either Franciscan Complex or Cretaceous sandstone), and the boundary between them to be the top-of-basement contact, which ranges from approximately –900 to –2,200 ft (–274 to –671 m) between horizontal distance 0 and 5,000 ft (Figure 5-9). The imaging of the top-of-basement contact and contrast in character between the basement and overlying Obispo Formation in this line are very similar to those in Line 112-140 (see Section 5.1.3).

We interpret the top-of-basement contact to be progressively faulted down to the north across a series of four blind, north-dipping normal faults (Faults F1, F2, F3, and F4; Figure 5-9 and Plate 6) beneath the southern limb of the Pismo syncline. The key feature we used to identify the top of basement is a boundary between generally subhorizontal to north-dipping layered reflectors above and generally more chaotic and steeply dipping reflectors below. Whereas this feature is a distinct reflector between Faults F1 and F3, it is characterized as a less distinct vertical change in reflector character between Faults F3 and F4. We acknowledge that confident recognition of this boundary progressively decreases with depth and proximity to the axis of the Pismo syncline, and thus interpretation of the top-of-basement contact north of Fault F1 is very uncertain.

Data from the Honolulu-Tidewater 1 well, located approximately 2 km east-southeast of Line 141-142 (Figure 5-1 and Plate 6), further support the interpretation shown on Figure 5-9. The minimum elevation of basement in the vicinity of the Honolulu-Tidewater 1 well is –9,162 ft (–2,792 m). If the depth of the Tertiary basin is maintained to the west along the axis of the Pismo syncline, then we anticipate that basement is at a minimum elevation of approximately –9,000 ft (–2,743 m) at horizontal distance 14,000 ft on Line 141-142, near the Pismo syncline axis. Subhorizontal layered reflectors, which we associate with Tertiary basin fill rather than Mesozoic basement, can be observed to a minimum elevation of approximately –8,500 ft (–2,591 m) at horizontal distance 13,000 ft. This observation is consistent with our expectation that the deep structural basin continues west of the Honolulu-Tidewater 1 well, and with our interpretation that the basement is faulted down to a depth of approximately –9,000 ft (–2,743 m) across the north-dipping blind faults (Faults F1 through F4) beneath the southern limb of the Pismo syncline (Figure 5-9).

North of the Pismo syncline axis, the northern part of Line 141-142 (Figure 5-10) extends across the northern limb of the syncline and several strands of the Edna fault zone (Figure 5-1). The exposed B strand of the Edna fault zone is interpreted to dip steeply south through a series of distinct reflector truncations and reflector dip discordances in Franciscan Complex (Figure 5-10). We use similar criteria to infer a steeply south-dipping geometry for the A strand of the Edna fault zone (Figure 5-10). Line 141-142 crosses a short fault trace mapped between the A and B strands of the Edna fault zone at about horizontal distance 7,500 ft. We interpret this short fault to likely merge with the Edna A fault trace at approximately –7,000 to –8,000 ft (–2,133 to –2,438 m) at horizontal distance 3,500 ft (Figure 5-10). Stratigraphic separations indicate south-side-down normal separation across the Edna A fault as follows: Obispo Formation is faulted down to the south against Franciscan basement across the splay fault in the footwall of Edna A, and Pismo Formation is faulted down to the south against Obispo Formation along the main trace of Edna A. We interpret that the top-of-basement surface is located at approximately –2,250 to –3,000 ft (–686 to –914 m) in the hanging wall of Edna A based on the first appearance of bright, discordant reflectors that we associate with the Franciscan Complex (Figure 5-10). This interpretation appears to be generally consistent with data from the Townsend-Gunter 1 well approximately 4 km to the east (Figure 5-1), which encountered Franciscan Complex basement at –2,379 ft (–725 m) depth directly south of the Edna A fault (Appendix E of PG&E, 2014).

A blind normal fault (Fault F6; Figure 5-10) with a south dip similar to the Edna A and Edna B faults is present beneath the northern limb of the Pismo syncline. We interpret this structure to be a buried strand of the Edna fault zone, and we refer to it informally as "Edna C" (Figure 5-10). The Edna C fault consistently juxtaposes subhorizontal layered reflectors in the hanging wall with a chaotic reflective structure in the footwall. From the surface to approximately –3,500 ft (–1,067 m), the Edna C fault is interpreted to pass along the eastern margin of a synformal fold in the reflectors, which we interpret to be poorly imaged drag folding in the hanging wall of the fault or tilting of beds into the plane of the fault. Below approximately –4,000 ft (–1,219 m) we interpret the Edna C fault to continue generally downdip through reflector discontinuities and terminations, with the caveat that the trace is locally mapped through some apparently continuous reflectors (e.g., the reflector at approximately –8,250 ft (–2,514 m) at horizontal distance 1,500 ft; Figure 5-10). We interpret the basement to step down to approximately –9,500 ft (–2,895 m) depth across the Edna C fault, making it the most structurally significant strand of the Edna zone along Line 141-142 for accommodating subsidence in the Tertiary basin.

The Obispo and Monterey Formations are traced into the subsurface on Line 141-142 from exposures on the southern limb of the Pismo syncline (Figures 5-1 and 5-9). The Monterey Formation is characterized by generally north-dipping layered reflectivity. In contrast, layered reflectivity in the underlying Obispo Formation is subdued, and the reflectivity is characterized by a mottled pattern with local zones that are relatively transparent. Using this difference in reflective character as a guide, we traced the top Obispo contact beneath the southern limb of the Pismo syncline and interpret it to be displaced progressively down to the north across Faults F1 through F5, which are antithetic to the Edna C fault (Figure 5-9). The top Obispo contact is interpreted to be at approximately –3,000 ft (–914 m) depth beneath the axis of the Pismo syncline along

Line 141-142, similar to the depth at which the contact was encountered in the Honolulu-Tidewater 1 well to the east.

Similarly, we used apparent differences in reflector character between the Monterey and Pismo Formations to trace the top Monterey contact into the subsurface and through the axis of the Pismo syncline. North of horizontal distance 7,000 ft in the southern part of Line 141-142 (Figure 5-9), shallow reflectors associated with the Pismo Formation appear to be more closely spaced and distinctly layered than those associated with the underlying Monterey Formation (Figure 5-9). This relatively subtle distinction is difficult to discern in the upper 2,000–3,000 ft (609–914 m) depth in the hanging wall of the Edna C fault (Figure 5-10), and our interpretation of the top Monterey contact is very uncertain in the core of the Pismo syncline. Like the top Obispo contact, we interpret the top Monterey contact to be offset in a normal sense by both the north- and south-dipping normal faults underlying the Pismo syncline. We interpret normal separation of the top Monterey contact to be less than that of the top Obispo contact (Figure 5-9), implying structural growth during deposition of the Obispo, Monterey, and Pismo Formations.

5.1.5 Synthesis

Based on analysis of Lines 103-104, 204, 112-140, and 141-142 (Figure 5-1 and Plate 1), as well as geologic map relations and available well data, the Pismo syncline is interpreted to be a folded and deformed remnant of an extensional basin in which the Neogene stratigraphic section exposed in the Irish Hills was deposited. Data from the Honolulu-Tidewater 1 well document over 10,000 ft (more than 3,050 m) of Tertiary strata beneath the axis of the Pismo syncline and comparable down-to-the-south relief on the top of basement across a horizontal distance of approximately 6,500 ft (~2,000 m) normal to the Edna fault system. The apparent thickness of the Tertiary section from exposures in the southern limb of the Pismo syncline is approximately 6,000 ft (~1,830 m), indicating that the section must thicken by at least 4,000 ft (~1,200 m) northward through the syncline axis to account for the thickness of the Tertiary section in the Honolulu-Tidewater 1 well. We attribute the increase in stratigraphic thickness to extension and normal faulting in the Miocene basin.

In our preferred model, the northern structural margin of the basin was the south-dipping Edna fault system, including the exposed Edna A and Edna B fault strands and the blind Edna C strand beneath the northern limb of the Pismo syncline. Map relations document south-side-down stratigraphic and hence normal separation across these faults. As discussed in Section 5.1.4, the Edna C fault appears to have accommodated the greatest separation among the three major stands of the Edna system.

In this interpretation, subsidence in the ancestral Pismo Basin also was accommodated by north-side-down slip on a series of blind, north-dipping normal faults that underlie the southern limb of the Pismo syncline. The relationship between these structures and normal faults of the Edna system is illustrated on Figure 5-11, in which the northern and southern segments of Line 141-142 are joined approximately where they intersect the same fold axes along trend (Figure 5-1) to show a continuous depth section across the entire Pismo syncline. Because the north-dipping faults individually have accommodated less separation than the Edna C fault, we infer that they are second-order antithetic structures that probably terminate downdip against the Edna C fault at depth.

As an alternative hypothesis, the thickening of the Tertiary section beneath the Pismo syncline axis potentially can be explained by thrust repetition at depth. An example of this class of models was presented at the November 2012 DCPP SSHAC Workshop 2 by Dr. Russ Graymer of the U.S. Geological Survey. If it is assumed that the thickness of the Tertiary section on the southern limb of the Pismo syncline (i.e., approximately 6,000 ft, or 1,830 m) approximately represents its original depositional thickness, then this model requires a minimum of 4,000 ft (~1,220 m) of thrust repetition directly beneath the axis of the Pismo syncline to account for the thickness of the Tertiary section observed in the Honolulu-Tidewater 1 well. Additional observations from the Tidewater well supporting or suggesting thrust repetition include possible repetition of a tuff horizon in the upper part of the Obispo Formation, a Zemorrian-over-Saucesian (older-over-younger) biostratigraphic relationship at a depth of approximately 5,600 ft (1,708 m), and a fault contact that places an approximately 4,000 ft (~1,220 m) section of "Rincon Formation" over "Obispo Formation" near the bottom of the well. Finally, the dipmeter log for the well records moderate to steep dips throughout, with several abrupt dip reversals and intervals with slickensides that suggest the section is folded and faulted (Appendix E of PG&E, 2014).

The ONSIP team evaluated available data from the Honolulu-Tidewater 1 well and concluded that they do not provide definitive evidence for a minimum of 4,000 ft of thrust repetition of the lower part of the Tertiary section. Specifically, the strata called "Rincon Formation" in the lower part of the well log include beds of tuff and volcanic rocks throughout, which are generally considered diagnostic of the Obispo Formation in the modern definition of this unit (Section 2.2.2.4). Regarding the older-over-younger stratigraphic relationship, previous workers have observed that many middle Tertiary marine benthic foraminifers in California are time transgressive, including some that span the Zemorrian-Saucesian boundary (Poore, 1980; Miller, 1981; Prothero, 2001). According to the well data report (Appendix E of PG&E, 2014), fauna in the lower part of the well are indicative of "Obispo or Rincon Formation" (Saucesian or Zemorrian). It is possible that the reported Zemorrian-over-Saucesian relationship in the Tidewater well is due to overlap of these faunas near the Zemorrian-Saucesian boundary, not thrust repetition. We note that the alternative interpretation of Line 112-140 (Figure 5-8) shows a thrust repetition of a tuff in the upper part of the Obispo Formation, but it is possible that these are two separate tuff beds rather than a single bed that has been repeated, and this is the preferred interpretation of the ONSIP team (Figure 5-7).

In summary, the ONSIP team acknowledges that existing data can be used to support a model for thrust repetition as the primary mechanism for developing a Tertiary section 10,000 ft or greater (≥3,050 m) beneath the Pismo syncline (e.g., Graymer, 2012), and that the seismic-reflection data do not provide conclusive evidence for the presence of a deep, local Miocene extensional basin beneath the syncline axis. The ONSIP team prefers the extensional basin hypothesis, however, because the faults beneath the northern and southern limbs of the Pismo syncline are interpreted to consistently dip toward the syncline axis, and that to the extent resolvable in the seismic lines, the stratigraphic units appear to thicken in the hanging walls of the faults, consistent with extensional growth (Figure 5-11).

Given our preferred structural framework of a Miocene extensional basin deformed by folding, we developed tentative correlations of interpreted faults among the four primary seismic lines that image the Pismo syncline (i.e., Lines 103-104, 204, 112-140, and 141-142). The correlations are listed in Table 5-1. For convenience, the north-dipping blind faults beneath the southern limb of the Pismo syncline are numbered Faults 1, 2, 3, and 4, from north to south, and are all imaged in Lines 103-104, 141-142, and 112-140. In the eastern part of the ONSIP study area, an additional north-dipping fault, Fault 0, is interpreted to cut the Honolulu-Tidewater 1 well and probably intersects the Edna C fault at approximately –8,000 ft (–2,438 m; Figure 5-7). Correlations of these structures across the Irish Hills are discussed in greater detail in Section 5.1.5.1, below.

Table 5-1. Proposed Fault Correlations Among Seismic Lines

Fault Name	103-104	204	141-142	112-140
Edna B	F3	F1	F9	
Edna A	F4	F3	F7	
Edna C splay	F5	F6?		
Edna C	F6		F6	
Fault 0			F5	F12
Fault 1	F7		F4	F11
Fault 2	F8		F3	F10
Fault 3	F9		F2	F9
Fault 4	F10		F1	F8

To illustrate 3D relationships among interpretations of individual 2D seismic lines, we constructed a series of structure contour maps of several stratigraphic horizons within the Irish Hills. Individual maps were developed for the top of Mesozoic basement (Figure 5-12), the top of the Obispo Formation (Figure 5-13), and the top of the Monterey Formation (Figure 5-14). The elevations of horizons and faults were derived from the seismic interpretations (Plate 1; Figure 5-1). The elevation data for individual stratigraphic horizons were exported from the Kingdom Suite seismic interpretation software as both XYZ points and elevation contours, then imported into ArcGIS for the construction of the structure contour maps. The elevation data were contoured using standard-of-practice methods outlined in Tearpock and Bischke (2003). Given the relatively wide spacing of the 2D seismic lines, the contours were interpolated over distances of 1–6 km; thus the maps are uncertain and interpretive between seismic lines.

The structure contour maps were developed in tandem with a series of geologic cross sections across the Irish Hills (Section 5.5). Simultaneous development and iterative revision of the contour maps and cross sections helped to converge on consistent and geometrically reasonable interpretations of the subsurface structure. Details of individual structure contour maps are discussed in the following sections.

5.1.5.1 Top of Mesozoic Basement

The elevation of the top of basement drops from surface exposures north and south of the Pismo syncline to greater than –9,100 ft (–2,773 m) in the central Irish Hills (Figure 5-12). The Honolulu-Tidewater 1 well and interpretation of Line 141-142 (Figure 5-11) provide the primary basis for the indicated thickness of Tertiary basin fill and depth to basement beneath the central Irish Hills. Similar deep imaging and/or well control is not available for the western Irish Hills; the basement surface is not imaged at its presumably deepest point along AWD Line 103-104, nor was it reached in the Montadoro 1 well, which bottomed in Rincon Formation (?) at approximately –5,700 ft (–1,737 m; Figure 5-1; Appendix E of PG&E, 2014). Hence, it is unknown whether the basement in the western Irish Hills reaches the same depths indicated by the Honolulu-Tidewater 1 well.

The overall pattern of the structural contours shows that the top of the basement surface is broken into a series of elongate fault blocks bounded by west-northwest-striking normal faults (Figure 5-12). In general, the basement surface slopes toward the west-southwest in the hanging walls of the Edna C and Edna A faults. This slope is consistent with the interpretation that the faults may be connected by relay ramps to accommodate right en echelon transfer of normal slip among the structures during subsidence of the Neogene basin. Locally, the basement is folded into a west-plunging anticline in the hanging wall of the Edna B fault (Figure 5-12). The basement also is displaced down to the north along normal Faults 0 to 4 beneath the southern limb of the Pismo syncline, all of which are antithetic to the Edna system (Table 5-1; see discussion in Section 5.1.5). It is unclear to what degree that the north-dipping faults 1 and 2 are laterally continuous in the subsurface of the Irish Hills. A straight-line, one-to-one correlation of north-dipping faults between Lines 103-104 and 141-142 results in a fault strike that is counterclockwise to the trends of secondary folds within the Pismo syncline. Based on our interpretation that at least some of the secondary folds were created by reverse reactivation of blind normal faults, we believe that these structures indicate the presence and continuity of faults at depth, and thus we have favored fault correlations among the seismic lines that result in basement faults striking parallel to the trends of surface folds.

In the southern Irish Hills, a south-dipping normal fault is interpreted to offset basement in the vicinity of Green Peak south of Line 141-142. The rationale for including this structure in the basement map is discussed in detail in Section 5.5.

The basement map suggests that the ancestral Miocene basin was asymmetric, particularly in the vicinity of Lines 141-142 (Figures 5-9 and 5-10) and 112-140 (Figure 5-7). The majority of structural relief on the basement surface is accommodated by the Edna A and Edna C faults (Figure 5-12) beneath the northern limb of the Pismo syncline. Of these two structures, the Edna C fault strand likely accounts for nearly 5,000 ft (1,523 m) of south-side-down separation of the basement in the vicinity of the Honolulu-Tidewater 1 well, shifting the deepest part of the Obispo-age basin north toward the Edna fault system.

5.1.5.2 Top of Obispo Formation

The top of the Obispo Formation descends from elevations of approximately 1,000 ft (305 m) on the southern limb of the Pismo syncline to–5,500 ft or greater (–1,676 m or greater) beneath the central Irish Hills (Figure 5-13). The top Obispo contact is down-dropped along the same series of south- and north-dipping blind faults that displace the top of basement (Figure 5-12). The separation of the top Obispo contact varies from 500 ft (152 m) to more than 1,500 ft (457 m) on individual faults.

The top of the Obispo Formation contours generally trend west-northwest, parallel to the basin margins at the northern and southern edges of the basin. In the center of the basin, the strike of the contours locally is deflected about local lows and small closures (Figure 5-13). For example, some of the irregularity of the contours in the central part of the basin is driven by interpretation of the top Obispo Formation as subhorizontal or back-tilted toward the south in the hanging walls of the north-dipping blind faults on Line 141-142 (Figure 5-9). We emphasize, however, that the geometries of these contours are controlled by sparse data and uncertain interpretations of the top Obispo Formation in the seismic lines.

The top of the Obispo Formation contour map reveals the following key relationships:

- In the northwestern Irish Hills between Lines 103-104 and 204, the Obispo Formation pinches out or is eroded on the southern limb of the west-northwest-plunging anticline exposed in the hanging wall of the Edna B fault strand.
- In the western Irish Hills, the top of the Obispo Formation reaches depths of more than –5,500 ft (–1,524 m) in the hanging wall of the Edna C fault (Figure 5-13).
- In the eastern Irish Hills, the elevation of the top of the Obispo Formation is –3,500 ft (–1,066 m) in a synformal closure at the north end of Line 141-142 (Figure 5-13). The contours between the north-dipping Faults 2 and 3 are somewhat irregular because of the apparent southward tilt of the reflectors in Line 141-142 (Figure 5-11) relative to the northward tilt of the reflectors on Line 112-140 (Figure 5-7).
- In the central Irish Hills, projection of the elevation of the top Obispo Formation contact from Lines 141-142 and 112-140 westward to Line 103-104 suggests that several synformal closures may exist in the deeper contours (Figure 5-13). In contrast to the basement contour map (Figure 5-12), which shows the deepest part of the basin in the central Irish Hills near the Honolulu-Tidewater 1 well, the top of the Obispo Formation appears to be deepest in the western Irish Hills near the intersection of Lines 103-104 and 204 (Figure 5-13).

5.1.5.3 Top of Monterey Formation

As shown on Figure 5-14, the elevation of the top of the Monterey Formation varies between approximately +800 ft (+244 m) to –2,400 ft (–731 m) throughout the central Irish Hills. In the western Irish Hills, the Monterey Formation is interpreted to pinch out against the Edna A fault or a splay of Edna A between Lines 103-104 and 204, similar to the pinch-out of the Obispo Formation against this structure (Figure 5-13). Interpretations of Lines 103-104 and 204 indicate that the contours on the top of the Monterey Formation trend northwest on the north and south flanks of the basin. Near the center of the structural basin, between the south-dipping Edna C fault and north-dipping Fault 1, the Monterey Formation is folded into an anticline-syncline pair. The top of the Monterey Formation extends to about –2,400 ft (–731 m) in the synformal closure in the hanging wall of the Edna C fault (Figure 5-14), suggesting that the deepest part of the basin in Pismo Formation time was apparently located in this vicinity, near the intersection of Lines 103-104 and 204.

In the eastern Irish Hills, interpretations of Lines 141-142 and 112-140 indicate that the top of the Monterey Formation is shallower than in the western Irish Hills, reaching depths of only approximately –600 ft (–183 m). Similar to the top of the Obispo structure contour map, Line 112-140 is interpreted to be an antiformal closure in the top of the Monterey Formation near the Honolulu-Tidewater 1 well in the hanging wall of the Edna C fault (Figure 5-14). In general, faults in the eastern Irish Hills have less separation on the top of the Monterey Formation than those observed in the seismic-reflection lines to the west. Some of the faults interpreted in the reflection data appear to tip out in the Monterey Formation (Figure 5-7). Hence, the contours of the top of the Monterey Formation are more continuous and less commonly truncated against faults (Figure 5-14) than in the top of Obispo Formation (Figure 5-13) or top-of-basement (Figure 5-12) contour maps.

5.2 Structure of the Northwestern Irish Hills and Western Los Osos Valley

The western Los Osos Valley study area (Figure 5-15) is bounded by the Irish Hills to the south, Morro Bay to the west, and the Islay Hills to the north. The subsurface structure of this region has been the subject of multiple investigations (Lettis and Hall, 1994; Yates and Wiese, 1988; Morro Group et al., 1990; Cleath & Associates, 2003, 2005). This area encompasses the structural boundary between the Los Osos and the Cambrian blocks (Figure 2-1). Several seismic lines in this region cross a blind or buried map trace of the Los Osos fault along the northwestern Irish Hills range front (Figure 5-15). An integrated discussion of the Los Osos fault, including stratigraphic and structural relations interpreted from the seismic lines shown on Figure 5-15, is presented in Section 5.3 below.

The western Los Osos Valley study area includes AWD Lines 103-104, 117, 118, 121, and 207 and vibroseis Line 105 (FCL, 2014a). Many of the seismic lines are adjacent to water wells and boreholes that provide independent constraints on the depth to Franciscan Complex basement and the top of the Pliocene Careaga Formation (equivalent to the upper Pismo Formation; see Figure 2-3). PG&E (2014) compiled data for many of these wells, as follows:

- Spooner 1
- Maino-Gonzales 1
- S&T New
- CCW Pecho

- USGS-Palisades
- LOCSD-Palisades
- LOCSD-Ferrell #2
- LOCSD10th new
- LOCSD-SB Deep
- CCW-SB#1

Borehole data compiled for the present study come from Cleath & Associates (2003, 2005; see Figure 5-15 for locations).

This section first discusses Lines 207 (Section 5.2.1) and 103-104 (Section 5.2.2) in the southwestern Los Osos Valley, where the basement is well documented in outcrop and borehole data. We describe vibroseis Line 105 (Section 5.2.3) and Lines 117, 118, and 121 (Sections 5.2.4 through 5.2.6; see Figure 5-15 for locations), with a focus on tracking and mapping the basement eastward in the subsurface. The description and interpretation of the reflection data are followed by a synthesis of data and interpretations as captured in a structure contour map of the basement beneath the western Los Osos Valley (Section 5.2.7).

5.2.1 Seismic Line 207

Seismic Line 207 is approximately 2.1 km long (~1.3 miles), trends northwest-southeast to north-northwest/south-southeast, and was acquired within Hazard Canyon (Figure 5-15). This seismic line is oriented largely parallel to local northwest-southeast structural trends, and it crosses exposures of the Miguelito Member of the Pismo Formation. Line 207 does not cross any mapped surface faults or other structures. The seismic line is located directly adjacent to the 1,575 ft deep (480 m) Maino-Gonzales 1 well, which provides depth control on the top of Franciscan Complex basement with minimum projection error between the well and the seismic line.

Line 207 primarily images gently northwest-tilted Pismo Formation overlying the Franciscan Complex basement (Figure 5-16). For convenience, we refer to the top of the Franciscan Complex in the following discussion as simply “basement” or “top of basement.” At the west end of the seismic line, the nearby Maino-Gonzales 1 well encountered basement below Pismo Formation at –1,247 ft (–380 m). When the well data are projected onto the seismic line, the top of basement is located below a pair of subhorizontal to west-tilted high-amplitude reflectors. These reflectors lie at the base of a package of laterally continuous and closely spaced layered reflectors (Figure 5-16). We interpret these reflectors to mark the top of the basement. Along the eastern portion of the seismic line, the top of basement is marked by a change from tightly spaced, laterally continuous reflectors above, to a series of less continuous, higher-amplitude reflectors below. The Franciscan rocks below the top-of-basement contact are characterized by a generally subhorizontal reflective fabric punctuated with discontinuous high-amplitude reflectors (Figure 5-16). The top of basement is interpreted to be at approximately –250 ft elevation (–76 m) at the east end of the seismic line, and it slopes gently downward to approximately –1,500 ft elevation (–457 m) at the west end of the line. The top-of-basement contact does not appear to be faulted.

5.2.2 Seismic Line 103-104

Seismic Line 103-104 is discussed in detail in Section 5.1.1. Here we focus on the structural relief on the top of basement in the northern part of the line that is relevant for evaluating subsurface structure in the western Los Osos Valley.

The north end of Line 103-104 crosses the Quaternary aeolian deposits with outcrops of Pismo Formation exposed to the southeast (Figure 5-15). At the intersection with Line 207, we interpret the top-of-basement reflector in Line 103-104 at –1,250 ft (–381 m) using the interpretation from Line 207 and constraints on the minimum depth to basement from the Spooner 1 well (Appendix E of PG&E, 2014; Section 5.1.1). The Franciscan rocks below the basement reflector are significantly reflective and characterized by a generally subhorizontal fabric punctuated with discontinuous high-amplitude reflectors.

North of the intersection with Line 207, Franciscan basement was encountered at –604 ft (–184 m) in the CCW Pecho well at the far north end of Line 103-104 (Appendix E of PG&E, 2014). We interpret the basement reflector to step down to the south across two south-dipping normal faults (Faults F1 and F2; Figure 5-2) between the CCW Pecho well and the Spooner 1 well, where basement was encountered at –1,218 ft (–371 m; Appendix E of PG&E, 2014). The basement reflector steps down again to the south across Fault F3 between the Spooner 1 and Maino-Gonzales 1 wells and is folded into a broad, low-relief antiform. The log of the Maino-Gonzales 1 well records several hundred feet of Rincon Formation strata above the basement (Appendix E of PG&E, 2014).

A blind or buried trace of the Los Osos fault is mapped as crossing Line 103-104 in the vicinity of the Spooner 1 well. Although we interpret several south-dipping blind faults at the northern end of Line 103-104, we do not identify or correlate them with the Los Osos fault. As discussed in Section 5.1.1, the south-dipping faults mapped in Line 103-104 are interpreted to exhibit south-side-down separation of the basement surface and possible thickening of the lower Pismo Formation in the hanging walls, suggesting that these structures are related to the Neogene extensional basin. Post-Pismo Formation reactivation of the Edna B fault as a reverse fault to accommodate folding is documented in outcrop exposures east of Line 103-104. In the alternative interpretation of Line 103-104 (Figure 5-3), the basement surface is shown as dipping steeply north on Fault F2. It is possible that Fault F2 also has been reactivated to accommodate shortening, resulting in northward tilting of the basement surface and strata in the hanging wall, consistent with map relations showing northward-dipping Pismo Formation along Irish Hills range front north of Line 207 (Figure 5-15). The implications of this interpretation for assessment of the Los Osos fault are discussed in greater detail in Section 5.3.4.

5.2.3 Seismic Line 105

Seismic Line 105 is approximately 4.3 miles (6.9 km) long and was acquired with a vibroseis source. Line 105 trends east-west to east-southeast/west-northwest and extends from the north end of Line 103-104 to the east along Los Osos Valley Road (Figure 5-15). This line is oriented almost parallel to the northwest-striking structural grain in the valley; it primarily crosses Quaternary alluvium and aeolian deposits and a queried trace of the Los Osos fault. Line 105 intersects AWD Lines 103-104, 117, 118, 121, and 128 and provides an opportunity to tie the interpretations of these lines together across the western Los Osos Valley. From west to east, wells close to Line 105 include the CCW Pecho, 30S/11E-18M1, LOCSD-Palisades, LOCSD 10th new, CCW-SB#1, 30S/11E-20G02(GS-5), and 30S/11E-20J (Figure 5-15). These wells variously encounter basement, Tertiary rocks, and/or the Pliocene Careaga Formation.

In general, Line 105 images thin Pliocene and Quaternary sediments over unfaulted Franciscan Complex basement (Figure 5-17). Borehole data adjacent to the seismic line indicate that the "top of Franciscan" is very shallow (500–600 ft, or 152–183 m, depth) and has very little relief (Cleath & Associates, 2003, 2005). In projecting the borehole data onto the seismic line, we tentatively interpret the top of basement to coincide with a boundary that locally is characterized by closely spaced, layered reflectors above, and broader and higher-amplitude reflectors below. The Franciscan Complex is highly reflective in the western portion of the line (horizontal distance of 0–14,000 ft) above –6,000 ft (–1,829 m; Figure 5-17). To the east, basement reflectors appear to be largely discontinuous and steeply tilted to the west and to exhibit criss-crossing patterns. Given the lack of bedrock exposure along the line, it is difficult to determine whether these reflectors represent structure within the Franciscan Complex basement or whether they are processing artifacts.

The top of the Careaga Formation, as projected from borehole data, is very poorly imaged in Line 105 (Figures 5-15 and 5-17). This poor imaging probably arises because the vibroseis source and acquisition parameters are more appropriate for imaging deeper bedrock structure than very shallow, poorly consolidated deposits. The top of the Careaga Formation locally appears to coincide with a subtle change in reflective character (e.g., at approx. –600 ft, or –183 m, elevation at horizontal distance of 2,000 ft). However, the top of the Careaga Formation is commonly obscured by inclined near-surface reflectors that crosscut the inferred subhorizontal, layered depositional fabric (–600 ft , or –183 m, elevation at horizontal distance of 6,000 ft; Cleath & Associates, 2003, 2005).

5.2.4 Seismic Line 117

Seismic Line 117 is approximately 1.4 miles (2.2 km) long, trends northwest-southeast, and is located within the central portion of the western Los Osos Valley study area (Figure 5-15). Line 117 crosses the range front between Los Osos Valley and the northern Irish Hills, including a mapped blind or buried trace of the Los Osos fault. The line is close to the following wells with data on subsurface stratigraphy: USGS-Palisades, LOCSD-Ferrell #2, LOCSD-Palisades, LOCSD-10th new, 30S/11E-19H2, 30S/11E-20Ea, and 30S/11E-20M1 (Figure 5-15).

The top of the Careaga Formation was encountered in water wells between –420 and –500 ft (–128 to –152 m) at the northwest end of Line 117 and is interpreted to correspond to the lower limit of subhorizontal layered reflectivity (Figure 5-18). The top of basement was encountered in the LOCSD-Ferrell #2 well at approximately –510 ft (–155 m) elevation and probably corresponds to the boundary between a package of discontinuous high-amplitude and laterally continuous layered reflectors above and discontinuous lower-amplitude reflectors below. In places, this top-of-basement contact is marked by an angular discordance between the flat-lying reflectors above and apparently northwest-tilted or wavy reflectors below. At horizontal distance of approximately 4,000 ft, we interpret a subvertical fault (F1 on Figure 5-18) marked by reflector truncations. Fault F1 has up to 500 ft (152 m) of south-side-down separation of basement surface, preserving a thin sliver of overlying Pismo Formation (?). Fault F1 does not appear to offset or extend into the overlying Careaga Formation (Figure 5-18).

At the southeast end of Line 117 (horizontal distance 0–2,500 ft), the top of the Careaga Formation was encountered in the 30S/11E-20Ea and 30S/11E-19h2 (GS-6) water wells and appears to rise to the southeast (Figure 5-18). Beneath the Careaga Formation, we interpret a sliver of the Pismo Formation on top of Franciscan basement, based on nearby map relationships and shale encountered at the base of the 30S/11E-20Ea well (following Cleath & Associates, 2005). The top of the Pismo Formation is interpreted primarily on the well data and does not correspond to an identifiable reflector along this section of the seismic line (Figure 5-18). Top of basement identified in the 30S/11E-20M1 well is projected into the south end of the line. The north-dipping basement surface in this part of the line is obscured by south-dipping features that are possibly processing artifacts, thus rendering our interpretation uncertain. In addition, the poor image quality at the southern end of Line 117 does not permit assessment of the presence, absence, or geometry of a blind or buried trace of the Los Osos fault, which is mapped in this region (Figure 5-15).

To summarize, the first-order subsurface structure imaged on Line 117 is deformed Careaga Formation along the northern Irish Hills range front, and flat-lying Pliocene and Quaternary deposits in the Los Osos Valley to the north (Figure 5-18). At the southeast end of the line, the top of Careaga contact may be tilted or folded (as inferred from borehole data). If this is correct, then the shallow reflectors shown on Figure 5-18 do not accurately depict the subsurface structure and are likely artifacts. If folded, we assume a blind fault must be present at depth beneath the synclinal fold hinge. Alternatively, the shallow reflectors at the southeast end of the seismic line may be generally flat-lying and faulted up to the south. Figure 5-19 shows an alternative interpretation of Line 117 with steeply south-dipping reverse faults (F2 and F3 on Figure 5-19) accommodating up to 750 ft (228 m) of separation.

5.2.5 Seismic Line 118

Seismic Line 118 is approximately 4.2 miles (6.7 km) long, trends north-south, and crosses the central part of the western Los Osos Valley study area (Figure 5-15). Line 118 crosses Quaternary aeolian and alluvial deposits and encounters Franciscan basement at the north end of the line (horizontal distance 11,500 ft; Figure 5-15). The seismic line is located adjacent to the following wells that reach Franciscan basement and/or Pliocene Careaga Formation: CCW-SB#1, LOCSD-SB Deep, and 30S/11E-8M2 (Figure 5-15). To evaluate the structure in the western Los Osos Valley, we focus on the southern part of the line and limit discussion to horizontal distance 0 to 12,000 ft along the line.

Top of basement at the south end of Line 118 is constrained by the CCW-SB#1 well, which passed through 10 ft (3 m) of sandstone (presumably Franciscan Complex) at a depth of 740 ft (–590 ft, or –180 m, elevation). At this depth, the top of basement appears to coincide with the boundary between a series of subhorizontal to slightly north-tilted, tightly spaced reflectors above and more discontinuous lower-amplitude wavy reflectors below (Figure 5-20). Farther north, basement is constrained by the LOCSD-SB Deep well to be at 518 ft depth (–404 ft, or –123 m, elevation). The top of the Careaga Formation is interpreted at–429 ft (–131 m) in the CCW-SB#1 well and –360 ft (–110 m) in the LOCSD-SB Deep well. The top of the Careaga Formation in the wells does not appear to correspond to distinct reflectors in the seismic data. Our interpretation infers that the top of Careaga contact is subparallel to the layered reflective fabric in the seismic line, where visible.

We interpret Line 118 to show that Franciscan basement within the Los Osos Valley is generally flat-lying and offset by a south-side-down fault between the CCW-SB#1 and LOCSD-SB Deep wells (Figure 5-20). Based on reflector truncations, three steeply dipping normal faults (labeled F1, F2, and F3 on Figure 5-20) are interpreted on Line 118. Fault F1 dips 80–90 degrees and accommodates up to 500 ft (152 m) of south-side-down separation of the basement surface. Fault F2 is a steeply south-dipping fault based on reflector truncations within the Franciscan Complex and does not appear to offset the top of basement. However, Fault F2 is mapped along the northern boundary of a slightly elevated block of Franciscan Complex between Faults F1 and F2. It is unclear whether the base of the Careaga Formation is folded or offset by Fault F2. Fault F3 is a steeply north-dipping fault interpreted solely on reflector truncations.

5.2.6 Seismic Line 121

AWD Line 121 is 2.5 mi (4.1 km) long and located within the eastern part of the western Los Osos Valley study area (Figure 5-15). Line 121 crosses Quaternary aeolian and alluvial deposits and encounters Franciscan basement along the northern valley margin (at approx. horizontal distance 5,000 ft; Figure 5-15). Line 121 passes near water well 30S/11E-21D15, which encountered the top of the Careaga Formation and Franciscan Complex at approximately –51 ft (–16 m) and –91 ft (–28 m), respectively (Figure 5-21; Cleath & Associates, 2005).

In general, Line 121 images relatively flat-lying and shallow Franciscan basement beneath Los Osos Valley (Figure 5-21). The top of the Careaga Formation and Franciscan Complex horizons are not distinctly imaged in Line 121 because they lie within the upper 200 ft (61 m) of the seismic image, within a zone that was muted during data processing (D. O'Connell, pers. comm., 2014). As a result, the interpreted horizons shown on Figure 5-21 are based entirely on available borehole data, correlation with vibroseis Line 105, and extrapolation from nearby bedrock outcrops. Four faults (F1, F2, F3, and F4; Figure 5-21) are interpreted primarily based on lateral reflector truncations within bedrock. Fault F1 is a south-dipping structure mapped at up to –1,200 ft (–366 m) elevation beneath the Los Osos Valley. This fault does not correspond to a mapped fault at the surface. Faults F2 and F3 appear to juxtapose blocks of Franciscan Complex with distinctly different reflective characteristics (Figure 5-21).

5.2.7 Contour Map of the Western Los Osos Valley Structure

The seismic interpretations in Sections 5.2.1 through 5.2.6 are synthesized in a top-of-basement structure contour map for the western Los Osos Valley (Figure 5-22). The map illustrates the following key interpretations:

- The northern structural margin of the Neogene Pismo Basin extends beneath the southwestern Los Osos Valley.
- Pliocene and Quaternary deposits within the Los Osos Valley are thin (generally less than 1,000 ft, or 305 m, thick).
- Quaternary and Pliocene deposits are at maximum thickness in the central parts of the valley and abruptly thin to the east and north.
- The basement in the central part of the valley generally is between –500 and –600 ft (–152 and –183 m) in elevation.
- The top-of-basement contours define a broad west-northwest-plunging syncline subparallel to the northern Irish Hills range front.
- Faulting within the western Los Osos Valley appears to be limited.

These observations are discussed in more detail below.

A series of blind, south-side-down normal faults imaged in the northern part of Line 103-104 extends beyond the northern margin of the Irish Hills and are interpreted to represent a northern continuation of the Neogene Pismo structural basin (Figure 5-22). We assume that these faults strike northwest-southeast parallel to local trends in the Bouguer gravity field (Figure 2-5; Langenheim et al., 2014). We interpret these structures to merge with or be truncated eastward against the north-south strands of the Edna fault zone mapped in the northwestern Irish Hills (Figure 5-22; Plate 1). Interestingly, these faults have a more northwesterly strike than the local trend of the northern Irish Hills range front. It is unclear based on available data how these faults connect, intersect, or crosscut faults interpreted in the southern part of Line 117 (Figure 5-19). It is possible that the faults extend to the northwest and link with faults previously mapped in Estero Bay.

The structure contour map highlights two areas of post-Pliocene deformation in the western Los Osos Valley (Figure 5-22). One area is along the southern margin of the valley, where structure contours imply that the basement is uplifted and may be faulted or tilted downward to the north (Figures 5-20, 5-21, and 5-22). From south to north, the top of basement descends from approximately sea level to –750 ft (–229 m) over a horizontal distance of approximately 2,000 ft (625 m). Borehole data suggest a similar gradient on the top of the Pliocene Careaga Formation (Figure 5-19). As discussed above, this elevation gradient is coincident with the northern Irish Hills range front and can be explained by one of the following scenarios:

- Post-Pliocene fault-propagation folding above a blind, south-dipping reverse fault or faults (similar to Cleath & Associates, 2003, 2005).

- An east-west-striking blind reverse fault that would project to the top of basement near horizontal distance 2,500 ft on Line 117 (Figures 6-5 and 6-8), and displace the basement up on the south.

The uplift and tilting of the basement surface at the northern Irish Hills range front is generally coincident with a dotted trace of the Los Osos fault mapped in this region (Figure 5-15). As discussed in Section 5.2.2, however, an alternative explanation for the deformation of the basement surface is local reverse reactivation of Neogene normal faults, rather than activity of a relatively younger blind fault that presumably overprints the older Neogene extensional deformation. The implications of this interpretation for the Los Osos fault are discussed in Section 5.3.4.

In the center of the western Los Osos Valley study area, Faults F1 and F2 interpreted in Line 118 represent the northernmost post-Pliocene faulting imaged in the valley (Figures 6-6 and 6-8). In developing the structure contour map, these structures were projected to the northwest and southeast subparallel to (1) the northwest-trending step in the Franciscan structure contours and (2) a northwest-striking aeromagnetic lineament in Los Osos Valley (Figure 2-6; Langenheim et al., 2009). As discussed above, we tentatively interpret Faults F1 and F2 to bound a small northwest-trending horst block within the Franciscan Complex. Neither of these faults is interpreted to intersect Line 105, suggesting that the structures either lose slip or die out before reaching this seismic line. The available data indicate that Faults F1 and F2 accommodate very limited separation of the basement (<400 ft, or <122 m), suggesting that they are likely small faults with limited along-strike continuity.

It is important to note that the interpretation of Franciscan basement is poorly to moderately constrained from subsurface data largely because (1) stratigraphic descriptions compiled from existing data are generally limited and (2) alternative interpretations in assignment of formations are possible. Much of these data were collected during groundwater investigations (Cleath & Associates, 2003, 2005), of which the Franciscan Complex was not the subject. The Franciscan Complex is not generally permeable in the Los Osos Valley; thus the unit descriptions in the groundwater reports typically have few details, and the depth of penetration into bedrock is generally limited. For example, many of the basement units within the valley described as shale or sandstone are inferred to be Franciscan Complex. An alternative interpretation of sandstone and shale could be the Edna Member of the Pismo Formation. It is not unreasonable that some thin Pismo Formation could be preserved under the Pliocene and Quaternary valley fill. Despite these uncertainties, we did not change the assigned formation tops, and we gave deference to the judgment of the rig geologists (as reported by Cleath & Associates, 2003, 2005) in developing the contour map.

5.3 Los Osos Fault Zone

The map trace of the Los Osos fault zone in the north-central and northeastern Irish Hills is crossed by several AWD and vibroseis lines (Figure 5-23, Plate 1), as follows, from east to west:

- AWD Line 138-149

- AWD Line 150
- Vibroseis Line 204 (northern part)
- AWD Line 103-104

Interpretations of each of these lines are presented below, with emphasis on assessing the presence or absence of a subsurface fault or faults coincident with the map traces of the Los Osos fault zone.

5.3.1 Seismic Line 138-149

Seismic Line 138-149 is approximately 3 km long, trends approximately east-west, and was acquired with an AWD source. The majority of Line 138-149 is located in the northern Irish Hills west of the surface trace of the Los Osos fault (Figure 5-23); only the far east end of the seismic line crosses the fault.

The western part of Line 138-149 in the northern Irish Hills images distinct coherent reflective fabric in the Franciscan Complex to the maximum depth of imaging (~5,000 ft, or 1,524 m; Figure 5-24). For example, a package of synformally folded layered reflectors is clearly imaged in the –2,000 to –5,000 ft depth range (–600 to –1,500 m) in the western part of the seismic line, as well as the coherent layered reflectors beneath the east end of the line (Figure 5-24). In the absence of recognizable stratigraphic contacts within the Franciscan Complex, we rely on the continuity or discontinuity of these layered reflectors as a basis for identifying the presence or absence of faults.

Based on truncations of layered reflectors in the Franciscan Complex, we interpret the presence of south-dipping faults (labeled F1 and F2) or a fault zone beneath the southern margin of Los Osos Valley that projects updip to the surface trace of the Los Osos fault (Figure 5-24). The more northerly fault (F1) has a steeper dip (~70° in the plane of the seismic section) and can be traced as a planar feature downward through distinct truncations in Franciscan reflectors to approximately –4,500 ft (–1,3701 m). The more southerly fault (F2) has a less steep dip (60° in the plane of the section), and it may shallow downward slightly across a synformal kink or bend at a depth of approximately –4,000 ft (–1,200 m). The two faults appear to merge or intersect updip toward the surface. Assuming these faults are associated with the Los Osos fault, their true dips calculated from the apparent dip and the angle between the strike of the Los Osos fault and trend of the seismic line are 76 and 82 degrees for the northern and southern strands, respectively.

We interpret another distinct south-dipping discontinuity (labeled F3) in the reflector geometry in this line (Figure 5-24) to be a fault within the Franciscan Complex. There are no overlying Tertiary or Quaternary deposits to constrain the age of this fault or demonstrate that it is younger than Mesozoic.

5.3.2 Seismic Line 150

Seismic Line 150 is approximately 5.1 km long, trends approximately northeast-southwest, and was acquired with an AWD source (Figure 5-23). Line 150 begins in the northern Irish Hills to the southwest, extends across the range front and map trace of the

Los Osos fault, and continues northeast across Los Osos Valley and up onto the western flank of Bishop Peak. The west end of the line in the Irish Hills trends west-southwest/east-northeast and curves more to the north as it crosses the northern range front.

Line 150 images strongly reflective fabric in the Franciscan Complex (Figure 5-25), similar to Line 138-149 (see discussion in Section 5.3.1). Based on reflector truncations and dip discordances in the Franciscan reflective fabric, we interpret a south- and/or west-dipping fault (labeled F1) that projects updip to the surface trace of the Los Osos fault at horizontal distance 6,600 ft. Fault F1 has an apparent dip of approximately 75 degrees and cuts the crest of an antiformal fold in the layered reflective fabric at approximately –1,500 ft (–460 m). If it is assumed that Fault F1 strikes parallel to the map trace of the Los Osos fault, then the true dip is approximately 79 degrees. Another planar discontinuity (labeled F2) cuts the folded reflectors in the north-dipping limb of the antiform in footwall of the Fault F1. We interpret this discontinuity to be a fault, possibly a splay of the more steeply dipping trace to the south that has broken into the footwall. Based on reflector truncations, we interpret the presence of another fault (F3) with an apparent dip of approximately 75 degrees to the south and/or west that projects to the surface near horizontal distance 4,000 ft, approximately 2,500 ft (760 m) south of the surface trace of the Los Osos fault (Figure 5-25).

Imaging of the faults at very shallow depths (i.e., less than ~500 ft) is hampered by what appears to be horizontal layered reflectors. We interpret these features to be processing artifacts because they extend south of the fault into the Irish Hills, where the seismic line was acquired directly on deformed Franciscan bedrock with no overlying deposits to produce a shallow layered reflective fabric.

5.3.3 Northern Part of Seismic Line 204

The northern reach of vibroseis Line 204 is approximately 3 km long and trends approximately due north across the Irish Hills range front (Figure 5-23; see Section 5.1.2 for discussion of the southern reach of vibroseis Line 204). The northern reach of Line 204 crosses the queried map trace of the Los Osos fault and extends partly into southwestern Los Osos Valley.

Based on reflector truncations in the Franciscan Complex at depth, we interpret two south-dipping faults beneath the north end of the line that appear to merge upward and project toward the northern Irish Hills range front (Figure 5-26). The steeper of the two faults (labeled F1) has an apparent dip of approximately 75 degrees and is associated with truncation of a bright reflector package in the depth range of –6,500 to –9,000 ft (–1,981 to –2,743 m) to the north in the footwall. The shallower of the two faults (labeled F2) has an apparent dip of approximately 60 degrees and is associated with pronounced discordance between a north-dipping reflective fabric in the hanging wall against subhorizontal to gently south-dipping reflectors in the footwall.

The two south-dipping faults appear to merge or intersect at a depth of approximately –3,000 ft (–914 m) beneath horizontal distance 5,100 ft and project up toward a north-facing monoclinal fold in the Franciscan reflective fabric along the range front. The monocline in the Franciscan reflectors coincides with a monocline mapped within a distinct metagraywacke unit in the Franciscan Complex (Figure 5-23). Line 204 crosses the southern contact of the metagraywacke with metavolcanics at about horizontal distance 4,500 ft (Figure 5-26). We trace this contact to depth along the base of a layered reflective package that we associate with the metagraywacke. The contact passes through a monoclinal fold in the northern Irish Hills and flattens northward beneath Los Osos Valley. The north-facing limb of the monocline in the seismic data coincides with a prominent north-facing dip slope in the metagraywacke along the range front. We tentatively interpret the dip slope and monocline to have formed by reverse fault-propagation folding above the south-dipping faults or fault zone beneath the range front.

5.3.4 Discussion

Our interpretation of the seismic-reflection data suggests that the Los Osos fault becomes a blind or buried fault beneath the north-central and northwestern Irish Hills, and that it may die out westward beneath a west-plunging anticline.

As shown on Plate 1, the Los Osos fault is mapped in the northeastern Irish Hills as a zone of surface faulting along the range front (Figure 5-23). Here, the mapped surface trace is associated with interpreted south-dipping faults in seismic-reflection Lines 138-149 and 150 that appear to extend to or approach the surface (Sections 5.3.1 and 5.3.2). In the north-central Irish Hills, the geologic map shows a dashed and queried trace of the Los Osos fault, indicating that a well-expressed surface trace is not present. The geologic mapping is consistent with the interpretation of vibroseis Line 204 that the range front here is a fault-propagation fold above the tip of a blind, south-dipping fault (Section 5.3.3). In the northwestern Irish Hills near Line 103-104 (Figure 5-22), the dotted map trace of the Los Osos fault along the physiographic range front approximately coincides with a northward gradient in the elevation of the basement surface that may reflect offset across a relatively shallow south-dipping reverse fault or uplift and northward tilting above the tip of a deeper blind reverse fault (see discussion in Section 5.2.7).

These relationships suggest that a laterally continuous and integrated surface trace of the Los Osos fault is limited to the northeastern and north-central Irish Hills, with the fault tip plunging westward to become a blind structure beneath the northwestern range front of the Irish Hills, and possibly dying out several kilometers west of Line 204. This would account for the large west-plunging antiform in the top Franciscan contact in the northwestern Irish Hills (Figure 5-12), as well as the synformal fold in the basement surface that we depict in the structure contour map of the basement surface along the range front.

We note that the dotted trace of the Los Osos fault crosses Line 103-104 in the vicinity of the Edna B fault trace, which is interpreted to be a Neogene normal fault that has been reactivated as a reverse fault since deposition of the Miguelito Member of the Pismo Formation. It is possible that the tip of the blind Los Osos fault is present below the depth of imaging at the north end of Line 103-104 and is primarily responsible for range-front uplift by fault-propagation folding, as suggested by the panel of north-dipping Pismo Formation bordering the northern Irish Hills east of Line 103-104. In this model, the reverse reactivation of the Edna B fault and folding of its hanging wall interpreted in Line 103-104 may be secondary deformation that accommodates a component of shortening in the hanging wall of the deeper Los Osos fault.

5.4 San Luis Bay Fault Zone

Three seismic lines cross the map trace or traces of the San Luis Bay fault zone in the southern Irish Hills (Figure 5-27), as follows:

- AWD Line 112-140 (southern aprt)
- AWD Line 113
- AWD Line 114

Each of these lines is discussed in detail below. While AWD Line 112-140 was previously discussed in Section 5.1.3, key features imaged in this line in the vicinity of the San Luis Bay fault zone are described below in greater detail.

5.4.1 Southern Part of Line 112-140

Line 112-140 is approximately 9 km long and extends north-northwest approximately from Point San Luis to the axis of the Pismo syncline (Figure 5-27). A comprehensive discussion of Line 112-140 is presented in Section 5.1.3 of this report. The following discussion focuses exclusively on the southern part of Line 112-140, where it crosses the primary map trace of the San Luis Bay fault zone (Figures 5-1 and 5-7).

The southern part of Line 112-140 images steeply north-dipping discontinuities in layered reflectors within Mesozoic rocks north of Point San Luis (Figure 5-7) that project updip to the San Luis Bay fault and possibly associated structures south of the San Miguelito fault zone (Figures 5-7 and 5-27). Specifically, Fault F1 on Figure 5-7 projects updip to the main trace of the San Luis Bay fault zone mapped through the low saddle on San Luis Hill. Fault F1 displaces a subhorizontal change in reflector character within the Mesozoic rocks (possibly a structural contact between the Cretaceous sandstone and underlying Franciscan Complex; Section 5.1.3) in a north-side-up sense. Fault F2 also dips north, is located 1,250 ft (380 m) north of Fault F1, and projects to a mapped fault that juxtaposes Franciscan Complex on the north with Cretaceous sandstone to the south. Because the Franciscan Complex is a structurally lower unit than the sandstone, Fault F2 exhibits north-side-up structural separation.

Fault F3 is located south of Fault F1 and is interpreted to be a north-dipping structure that juxtaposes distinctly north-dipping packages of reflectors in the footwall with south-dipping structures in the hanging wall. A splay in the footwall of Fault F3 is interpreted to underlie an antiformally folded package of reflectors at –1,500 to –3,000 ft (–457 m to –914 m) approximately below horizontal distance 2,000 ft (Figure 5-7). No faults are mapped in the Cretaceous sandstone in the vicinity of horizontal distance 1,000 ft, updip of Fault F1; the structural contact between the Franciscan Complex and Cretaceous sandstone exposed in the sea cliffs north of Point San Luis is not mapped as being offset, indicating that this structure does not reach the surface and likely terminates below the

Franciscan-Cretaceous structural contact at depth (i.e., at or below –750 ft, or –229 m); Figure 5-7).

5.4.2 Seismic Line 113

Seismic Line 113 is approximately 1.9 km long and extends north-northeast from the coast across the San Luis Bay fault zone west of the point where it splays into two distinct traces (Figure 5-28; see discussion in Section 2.4.5). From south to north, Line 113 crosses the northern splay of the San Luis Bay fault zone known as the Olson fault or Olson Hill deformation zone, then crosses two splays of the unnamed fault zone to the north that juxtaposes Franciscan Complex rocks to the north with Cretaceous sandstone to the south (Figure 5-27).

Line 113 images a south-dipping interface at approximately –2,500 ft (–760 m), north of horizontal distance 2,000 ft, that separates reflectors of different dip (Figure 5-28). Above approximately –2,500 ft, reflectors generally dip moderately or steeply north. Reflectors below the interface dip toward the south, particularly in the central and northern parts of the line (Figure 5-28). Reflective fabric at approximately –2,000 to –4,000 ft below horizontal distance 1,700 ft in the southern part of the line dips moderately to steeply north; this fabric is abruptly juxtaposed with packages of moderately south-dipping reflectors in the same depth range along a steeply north-dipping interface (Figure 5-28). Below approximately –5,500 ft (–1,675 m), the reflectors appear to reverse dip across a synformal hinge coincident with the north-dipping interface. We interpret the reflector juxtaposition as occurring across a steeply north-dipping fault (Fault F1; Figure 5-28). The interpreted fault projects toward the map trace of the Olson splay of the San Luis Bay fault, but reflector offsets associated with the updip projection of Fault F1 cannot be confidently inferred above a depth of approximately –750 ft. The reflector pattern imaged in the southern part of Line 113 may have developed by the Mesozoic rocks first being folded into a synform and subsequently offset along a north-dipping reverse fault that cut the core of the synform and displaced south-dipping reflectors in the northern limb against the southern limb.

Based on reflector discontinuities and dip discordances in the Mesozoic rocks, we interpret the presence of a subvertical to very steeply north-dipping fault (Fault F2; Figure 5-28) that projects updip to the southern splay of the unnamed fault zone at approximately horizontal distance 2,800 ft. It is possible that this fault extends to the surface; however, the upper 300–500 ft (91–152 m) of the reflection data are obscured by strong subhorizontal reflectors that likely are associated with acoustic ringing in the bottom of the stream valley in which the data were acquired, rather than true geologic structure (D. O'Connell, pers. comm., 2014). Map relations show that the northern splay of the unnamed fault zone juxtaposes Franciscan Complex rocks to the north with Cretaceous sandstone to the south. This structure may be questionably imaged as a steeply north-dipping alignment of reflector truncations (Fault F3; Figure 5-28) that displaces the south-dipping interface up to the north.

5.4.3 Seismic Line 114

Seismic Line 114 is approximately 2.3 km long and extends north-northeast from the coast in the southern Irish Hills (Figure 5-27; also, see discussion in Section 2.3.5). From south to north, Line 114 crosses the northern splay of the San Luis Bay fault zone at the southern tip of the line, then crosses two splays of the unnamed fault zone that juxtaposes Franciscan Complex rocks to the north with Cretaceous sandstone to the south, and, finally, crosses the basal Tertiary section where two splays of the San Miguelito fault zone offset Tertiary rocks (Figure 5-27).

The reflective fabric in the southern part of the line (horizontal distance 0 to ~2,000 ft) at approximately –1,000 to –4,000 ft (–305 to –1,219 m) dips moderately to steeply north; and this fabric is abruptly juxtaposed with packages of moderately south-dipping reflectors in the same depth range along a steeply north-dipping interface (Figure 5-29). Below approximately –4,500 ft (–1,370 m) depth, the reflectors appear to smoothly reverse dip across a synformal hinge roughly coincident with the north-dipping interface. Assuming the change in reflector dip represents true rock structure and is not a processing artifact, we interpret the reflector juxtaposition to occur across a steeply north-dipping fault (Fault F1; Figure 5-29). The interpreted fault projects updip to the southern unnamed fault splay, just north of the map trace of the Olson splay of the San Luis Bay fault (Figure 5-27).

Based on reflector discontinuities and dip discordances in the Mesozoic rocks, we interpret the presence of a subvertical to very steeply north-dipping fault (Fault F2; Figure 5-29) that projects updip to the northern splay of the unnamed fault zone at approximately horizontal distance 3,300 ft. Map relations show that the northern splay of the unnamed fault zone juxtaposes Franciscan Complex rocks to the north with Cretaceous sandstone to the south, which is an apparent north-side-up map relationship.

We tentatively interpret a third steeply north-dipping fault (labeled F3 on Figure 5-29), also based on lateral reflector truncations. This fault projects up to the ground surface at horizontal distance along the seismic line of 4,300 ft, where there is no fault mapped at the surface. Fault F3 may be a fault entirely within Franciscan basement (or it may not exist).

At the north end of Line 114, two subvertical faults (labeled F4 and F5) are interpreted beneath two splays of the San Miguelito fault zone mapped at the surface (Figure 5-29). The base of the Tertiary section is interpreted north of horizontal distance 5,500 ft based primarily on surface mapping, strike and dip data, and an apparent vertical change in reflector amplitude. However, because the quality of reflectors on the shallow portion of this line is poor, the top of Mesozoic basement on Line 114 is highly uncertain.

Geologic mapping indicates that Fault F4 juxtaposes the basal Tertiary section (Rincon and Vaqueros Formations) with Obispo Formation and, based on the map pattern, is steeply dipping (Figure 5-27). Fault F4 is interpreted based on reflector truncations and angular discordances below –1,500 ft (–457 m) elevation (Figure 5-29). We infer from the geologic mapping that Fault F4 extends to the surface; however, the upper 1,500 ft of the reflection data at this location are obscured by strong shallow subhorizontal reflectors that are likely artifacts. The top of Mesozoic basement is shown as offset (<200 ft, or <61 m) down to the north across Fault F4. However, this offset is based primarily on geologic map relationships that suggest limited north-side-down displacement of the basal Tertiary section; offset seismic reflectors are not imaged.

Fault F5 in Line 114 is interpreted beneath the central splay of the San Miguelito fault zone and is mapped within the Obispo Formation (Figures 8-1 and 8-3). This steeply-north-dipping fault is mapped beneath horizontal distance 6,800 ft and is interpreted based on a poor alignment reflector truncations below –1,500 ft (–457 m). At shallow depths, the subhorizontal reflectors do not appear to be offset across or truncated against the interpreted fault. We therefore query Fault F5 at shallow depths. Similar to Fault F4, we infer north-side-down vertical separation (~400 ft, or 122 m) across Fault F5, based primarily on surface mapping; this offset is highly uncertain.

5.5 Discussion: Downdip Geometry of Major Faults in the Irish Hills

Six geologic cross sections were drawn through the DCPP site vicinity to provide an integrated interpretation of the surface geology documented by the PG&E (2014) geologic mapping study, as well as the deeper structure of the Irish Hills interpreted from analysis of the reflection data (Figures 5-30 through 5-35). The primary objectives of these cross sections are to test the feasibility of the seismic interpretation by incorporating bedding dips measured at the surface, assess a reasonable subsurface geometry of the key stratigraphic units and faults, and project geologic relationships below the resolution depth of the reflection data to the base of the seismogenic crust.

Three of the cross sections were drawn at 1:24,000 scale and traverse the entire Irish Hills, focusing on the structure of the Pismo syncline and the geometry of faults bounding the Irish Hills, such as the Los Osos and San Luis Bay fault zones (Figures 5-30, 5-31, and 5-32). Three additional cross sections were drawn at 1:12,000 scale in the direct vicinity of the DCPP to specifically assess the subsurface geology at the site (Figures 5-33, 5-34, and 5-35), with emphasis on using surface bedding orientation data (PG&E, 2014; Plate 1) to infer the thickness of the Obispo Formation beneath the southern Irish Hills in the vicinity of the DCPP.

The 1:24,000-scale cross sections presented here focus on the ONSIP team’s preferred interpretation of the seismic data beneath the Pismo syncline. Our approach in developing the subsurface interpretations in the sections follows the criteria and recommendations of Elliott (1983), who describes “balanced” cross sections as both “viable” and “admissible.” According to Elliott (1983), a “viable” cross section is one that can be retro-deformed (i.e., the major fold and fault deformation depicted in the section can be sequentially restored to a plausible pre-deformed geometry that preserves 2D line length and area of stratigraphic units). Elliott (1983) considers an “admissible” cross section to be one in which the geologic structures depicted can also be observed in the field (i.e., styles of faulting and folding that have not been mapped or otherwise observed in the area where the cross section is drawn should not be invoked arbitrarily to solve structural problems at depth). Although a viable and admissible cross section may be incorrect, a cross section that does not satisfy these criteria cannot possibly be correct (Elliott, 1983). Therefore, a cross section that is both admissible and viable, and which incorporates additional subsurface data (e.g., well logs, seismic-reflection interpretations, constraints from potential field data) represents a geologic interpretation that is robust and limits the set of reasonable alternative interpretations (Elliott, 1983). We acknowledge that the cross sections presented herein are not unique, and that other "balanced" interpretations are possible.

The cross-section lines were drawn perpendicular to regional structural trends (within practical limits) using ArcMap 10.2. Topographic profiles for the sections were generated using the 3D Analyst tool in ArcGIS and exported to Adobe Illustrator CC for cross-section construction. Lithologic contacts, structural data (bedding orientations), and other pertinent geologic information were transferred to the topographic profiles in Adobe Illustrator. Where the cross sections are oblique to bedding strike, apparent dip of bedding was calculated using the method developed by Satin (1960). Down-plunge projection methods were used to infer structure and lithology at depth; regional plunge (oriented 274/04 degrees strike/dip) was calculated on a π diagram of bedding orientations from the geologic map (e.g., Marshak and Mitra, 1988). Fold geometries were conserved by projecting axial surfaces to depth. Bedding thickness was preserved between inferred subsurface faults, as these structures are interpreted to be growth faults that accommodated subsidence during deposition of the major lithologic units in this basin. Only the major Neogene stratigraphic units (i.e., Obispo, Monterey, and Pismo Formations) are depicted in these sections, and Mesozoic units (e.g., Franciscan Complex, Cretaceous sandstone) are generalized simply as "Mesozoic basement."

The cross-section interpretations of the Pismo syncline depict the Neogene extensional basin as asymmetric and deepest adjacent to the northern basin margin (Figures 5-30, 5-31, and 5-32). The majority of net subsidence was accommodated by strands of the Edna fault system, and in particular by the blind Edna C fault in the central part of the Irish Hills. The blind, north-dipping faults beneath the southern limb of the Pismo syncline are interpreted to dip less steeply than the Edna C fault, and thus are subordinate and antithetic to the Edna fault system. The key role of the Edna C fault in accommodating asymmetric subsidence of the ancestral basin, especially during deposition of the Obispo Formation, is illustrated in a fence diagram that joins the three cross sections together (Figure 5-36).

In our interpretation, both the south-dipping Edna system and the antithetic north-dipping faults converge downward and merge into a single master fault zone in the upper 30,000 ft (~9 km) depth. The steep dips of the faults and narrow, deep Obispo-age basin recall models for negative flower structures. The ancestral basin geometry may thus be the structural expression of local transtensional deformation in this region during early Miocene. Other observations consistent with this hypothesis include the right-stepping en echelon relationship between the Edna A and B normal faults, and the possible connection of these faults by a southwest-dipping relay ramp. If this interpretation is correct, then it suggests that the early Miocene basin formed under sinistral (left-lateral) transtensional boundary conditions.

The Pismo syncline formed by uplift and broad folding after deposition of the Edna and Miguelito Members of the Pismo Formation. Stratigraphic and structural relations in the San Luis Range to the southeast of the Irish Hills (Hall, 1973a, 1973b) suggest that the Pismo syncline was growing prior to deposition of the Squire Member of the Pismo Formation, so the initial folding occurred in latest Miocene to Pliocene time.

The majority of the present structural relief in the central and southern Irish Hills associated with folding is represented by the southern limb of the Pismo syncline. Relative to the present stratigraphic level of the Pismo Formation exposed north of the Edna C fault, the stratigraphically lowest exposures of Obispo Formation in the southern Irish Hills have been uplifted approximately 8,500 ft (2,591 m); compare Figure 5-31 with Figure 5-37). In contrast, there is low relative structural relief across the northern limb of the Pismo syncline. These observations require a mechanism or structure for the uplift and northward tilting of the southern limb of the Pismo syncline; however, no potentially causative structures were imaged in the 2011 ONSIP reflection data. The possibility that other unidentified structures are present beneath the Irish Hills represents remaining uncertainty that must be considered in evaluating the tectonics of this region.

During folding of the Pismo syncline, some of the normal faults associated with the Neogene extensional basin were reactivated as reverse or thrust faults, typically forming small anticlines in the hanging walls. Examples of these relationships are well documented in the geologic map of the Irish Hills and include anticlines mapped in the hanging walls of the A and B strands of the Edna system along the northern margin of the Pismo syncline. Antiformal folds in the Pismo and Monterey Formations are interpreted in the hanging walls of blind Neogene normal faults on Line 103-104. In developing the cross sections, we observed that anticlines with along-strike length of several kilometers are associated with the blind Edna C fault and antithetic north-dipping faults beneath the southern limb of the Pismo syncline. In general, the anticlines mapped at the surface are in the hanging walls of the blind normal faults, and the synclinal axis at the base of the forelimbs of the folds is the surface projection of the faults at depth. We propose that most of the secondary folds in the Pismo syncline are probably associated with blind normal faults of the Neogene basin (Figures 5-30, 5-31, and 5-32). We acknowledge that other interpretations are possible, including development of folds by out-of-syncline thrusting along the limbs of the Pismo syncline. In this alternative model, the thrust faults underlying the folds are very shallowly rooted because they splay upward from bedding plane detachments in the Pismo Formation.

The cross section across the eastern Irish Hills (C-C′; Figure 5-32) depicts the Los Osos fault zone as a range-front structure that dips moderately to steeply south. Using dips derived from analysis of the seismic data to project the fault downward, we find that it may intersect the base of the seismogenic crust (~12 km depth) in the vicinity of the Edna fault zone. The downdip projection of the steeply north-dipping San Luis Bay fault zone also intersects the base of the seismogenic crust near the Edna fault zone (Figure 5-32). These relationships are similar to those observed in analogue sandbox models of transtensional basins that are subsequently inverted under transpression. Specifically, Ustaszewski et al. (2005) found that in models of oblique rift basins formed under transtensional conditions, the primary basin-bounding normal faults form a negative flower structure that roots into the principal displacement zone at the base of the physical model (Figure 5-37). When the deformation is reversed and the model basins are subjected to transpressional boundary conditions, shortening is accommodated by both reactivation of the normal faults as reverse faults and development of thrust faults that root from or near the principal displacement zone and verge outward from the older extensional basin (Figures 5-37 and 5-38).

As discussed in Section 5.3.4, the Los Osos fault zone may be a blind or buried fault beneath the north-central and northwestern Irish Hills (Figures 5-31 and 5-30, respectively). Total displacement on the fault may decrease or die out westward beneath a west-plunging, basement-involved anticline, the northern limb of which is expressed by tilting along the range front south of western Los Osos Valley. We show this interpretation on Figure 5-36 by depicting the Los Osos fault as a blind structure west of cross section B-B″. In this model, distributed shortening above the blind tip of the Los Osos fault has reactivated the upper part of the Edna B fault in the northwestern Irish Hills, accounting for the interpreted post–Pismo Formation reverse slip on this structure (Figure 5-30).

We selected cross section B-B″ as a representative example of the Irish Hills geology from which to develop a restored section (see Woodward et al., 1989, for an overview of methodology). The restoration assumes that negligible out-of-plane motion has occurred, which may not be correct given the transpressional mechanism we interpret for shortening in the Irish Hills. Cross section B-B″ was retrodeformed using the equal area method augmented with line-length conservation to provide a further test of the geologic strength of the subsurface interpretations presented herein (Figure 5-37). Using both line length and area balancing yields a relatively robust restoration, as an infinite number of solutions can be derived by only maintaining constant area without regard to line length (Mitra and Namson, 1989). Line lengths of lithologic contacts and the area of Neogene basinal unit polygons were quantitatively evaluated using the "patharea filter" plug-in for Adobe Illustrator (www.telegraphics.com.au); these data were used to ensure that area and line length were conserved (within 10%) during the palinspastic restoration. Differences in the area of lithologic unit polygons in the restored section relative to the unrestored section were calculated using the equation

$$(A_1 - A_0 / A_0) \times 100 \qquad (5\text{-}1)$$

where A_1 is the area of the restored section and A_0 is the area of the unrestored section. To simplify the interpreted restoration, lithologic contacts between basinal strata were assumed to be horizontal prior to late Cenozoic shortening.

Restored section B-B″ (Figure 5-37) suggests that the magnitude and loci of subsidence varied during deposition of the Neogene stratigraphic section. Maximum subsidence during deposition of the Obispo Formation was localized directly adjacent to the Edna C fault and accommodated by complementary slip on the north-dipping blind Fault 0 and Fault 1 (Table 5-1), which effectively formed an "inner graben" within the Obispo-age basin. The thickness of combined Obispo Formation and older Rincon and Vaqueros Formations in the hanging wall of the Edna C fault is estimated to be approximately 6,000 ft (1,829 m), compared to 3,000 ft or less (≤914 m) directly to the west in blocks bounded by the north-dipping Faults F2, F3, and F4 (Table 5-1). Note that the southern margin of the ancestral basin must have been south of the modern Irish Hills to account for the thickness of exposed Obispo Formation near the coast, south of north-dipping Fault 4 (Figure 5-36).

In contrast, variations in thickness of the Monterey Formation indicate that the blind, north-dipping normal faults were less active in Monterey time, with the majority of subsidence accommodated primarily along the strands of the Edna system and presumably a complementary north-dipping structure south of the present Irish Hills. In this interpretation, the Edna A fault formed the northern structural boundary of the Monterey-age basin, thus accounting for the map relations showing that the Monterey Formation is missing from the hanging wall of the Edna B fault. The basin broadened northward in Pismo time, as basal Pismo Formation was deposited north of the Edna A fault directly on Franciscan basement rocks and occupied accommodation space formed by the activity of (presently blind) normal faults in western Los Osos Valley north of the Edna B strand.

The detailed cross sections in the southern Irish Hills near the DCPP (Figures 5-33, 5-34, and 5-35) interpret the Obispo Formation to be approximately 4,000 ft thick (1,219 m), based on projecting bedding dips to depth and honoring map relations that indicate that the stratigraphic section is not repeated or thickened by thrust faulting. Note that the Obispo Formation is interpreted to be approximately 2,000 ft thick (610 m) beneath the southern limb of the Pismo syncline, based on interpretation of the top of basement in Lines 112-140 (Figure 5-7) and 141-142 (Figure 5-11). If the thickness of the Obispo Formation at depth is faithfully rendered in the cross sections through the southern Irish Hills, and if the interpretation of the seismic-reflection data is correct, then some mechanism is required to explain the difference in stratigraphic thickness of the Obispo Formation between the central and southern Irish Hills. The cross sections attribute the thickness difference to the presence of a blind, south-dipping normal fault approximately underlying Green Peak in the southern Irish Hills that was active during deposition of the Obispo Formation. As shown on the basement structure contour map (Figure 5-12), this fault is interpreted to terminate to the east against the San Miguelito fault zone, and to extend southwest into the offshore region where it is presumably truncated against the Shoreline fault. If the Mesozoic basement is significantly shallower beneath the DCPP than approximately 1,500–2,000 ft (457–610 m; FCL, 2014b), then a mechanism other than a blind normal fault is required to explain the apparent thickness of greater than 4,000 ft (>1,219 m) of Obispo Formation exposed in the southern Irish Hills.

6.0 RESULTS AND CONCLUSIONS

The key conclusions of the analysis of the 2011 2D seismic-reflection data are summarized as follows:

- The Pismo syncline in the central and southern Irish Hills is the deformed remnant of a Neogene extensional basin.
- Structures of the Edna fault zone, including the well-mapped strands exposed in the central Irish Hills and a previously unrecognized blind strand (herein called the Edna C fault), dip steeply south and comprise the northern structural margin of the Neogene extensional basin. In particular, the Edna C fault accommodated the majority of south-side-down displacement of the basement surface beneath the northern limb of the Pismo syncline.
- A series of previously unknown blind, north-dipping normal faults is present beneath the southern limb of the Pismo syncline. These structures, which are secondary and antithetic to the Edna C fault, localized subsidence in the vicinity of the modern syncline axis during deposition of the Obispo Formation.
- The San Miguelito fault zone is a subvertical to steeply south-dipping structure that locally juxtaposes Obispo Formation to the north with Franciscan Complex basement to the south. These faults are interpreted to be elements of the southern structural margin of the Neogene basin that originally were moderately to steeply north-dipping normal faults, and which were rotated to their present orientation by uplift and northward tilting of the southern limb of the Pismo syncline.
- Blind, south-dipping normal faults of the Neogene extensional basin are present in the subsurface of western Los Osos Valley north of the Irish Hills and are associated with a local gravity low in this region.
- The normal faults of the Neogene extensional basin locally were reactivated as reverse faults during uplift and folding of the Pismo syncline. Examples of folds in the hanging walls of faults with Neogene normal separation are well mapped and documented along exposures of the Edna fault zone. Anticlines formed by fault-propagation folding in the hanging walls of blind normal faults in the central and southern Irish Hills are the surface expression of late Cenozoic reactivation of these structures to accommodate regional shortening.
- Based on seismic imaging of the upper 5,000 ft (~1,525 m) of the crust, the San Luis Bay fault is interpreted to be a steeply north-dipping fault with north-side-up structural separation that obliquely crosses the southeastern Irish Hills and probably terminates to the west against the Shoreline fault in the offshore region. The imaging quality and depth resolution of reflection data from the southwestern Irish Hills are relatively low, and interpretations of the San Luis Bay fault zone in the data are very uncertain.
- Moderately to steeply south-dipping faults that project updip to the northern front of the Irish Hills are interpreted in seismic lines that cross the boundary between the Irish Hills and Los Osos Valley. In the northeastern Irish Hills, the interpreted

faults project updip to mapped surface traces of the Los Osos fault. In the central Irish Hills, the interpreted faults project updip to a monoclinal fold mapped in a Franciscan Complex metagraywacke unit. No surface trace of the Los Osos fault is recognized along this reach of the northern Irish Hills, suggesting that the Los Osos fault is blind here and that range-front deformation is characterized by fault-propagation folding rather than surface faulting.

- Total displacement on the Los Osos fault may decrease or die out westward beneath a west-plunging, basement-involved anticline, the northern limb of which is expressed by tilting along the range front south of western Los Osos Valley. In this model, distributed shortening above the blind tip of the Los Osos fault has reactivated the upper part of the Edna B fault in the northwestern Irish Hills, accounting for the interpreted post–Pismo Formation reverse slip this structure.
- Both the Los Osos and San Luis Bay faults dip beneath the central Irish Hills toward the root zone of the ancestral Edna fault system. This geometry is similar to faults produced in analogue sandbox models of transtensional basins subsequently deformed by transpression and shortening (Ustaszewski et al., 2005). Specifically, the primary basin-bounding normal faults (e.g., the Edna fault zone) form as a negative flower structure in a transtensional regime that roots into the principal displacement zone at the base of the physical model. When the deformation is reversed and the model basins are subjected to transpressional boundary conditions, shortening is accommodated by both reactivation of the normal faults as reverse faults (e.g., reverse reactivation of the Edna faults and related antithetic north-dipping structures) and development of reverse faults that root from the principal displacement zone and verge outward from the older extensional basin (e.g., the Los Osos and San Luis Bay fault zones).

Table 6-1 summarizes the range of downdip geometries for each of these fault zones based on the constraints provided by the seismic-reflection data, geologic mapping, structure contour maps, and available borehole data. The table includes the depth range of the interpretation, average fault strike, apparent dip, and estimated true fault dip and dip direction. The strike of each fault was estimated from geologic maps (Plate 1) or structure contour maps (Figures 5-12, 5-13, and 5-14). Apparent dips were measured on seismic lines, and, in some cases, a range of fault dips is reported. The average dip represents the dip of the fault measured along the total depth of the seismic line. Estimated true dip (δ) was calculated using the apparent dip (α) and the angle between the fault strike and apparent dip line (β) using the following equation from Suppe (1985):

$$\delta = \arctan(\tan\alpha / \sin\beta) \tag{6-1}$$

We note that the fault dips determined from analysis of the reflection data are specific to the depth range for which the given source and acquisition parameters permit imaging and resolution. For AWD lines discussed in this report, the maximum depth of imaging is approximately 6,000 ft (1,830 m); AWD depth resolution may vary ±1,000 ft (±305 m) depending on local conditions. For the vibroseis lines discussed in this report, the maximum depth of imaging is approximately 12,000 ft (~3,660 m).

Table 6-1. Principal Fault Strike and Dip Information from Interpretation of 2011 Seismic-Reflection Data

Fault	Seismic Line	Depth Range of Interpretation	Strike	Apparent Dip[2]	Estimated True Dip[3]
Los Osos	AWD Line 150	0 to –7,500 ft (0 to –2,285 m)	~N60°W	75°SW	78°–79°SW
Los Osos	AWD Line 138-149	–500 to –7,000 ft (–152 to –2,130 m)	~N60°W	58°–70°SW	76°–82°SW
Los Osos	Vibroseis Line 204 north	–2,000 to 12,000 ft (–600 to –3,650 m)	~N90°E (~E-W)	55°–75°SW 58°–72°SW (avg.)	55°–75°S 58°–72°S (avg.)
Edna A	Vibroseis Line 141-142 north	1,000 to –12,000 ft (300 to 3,650 m)	~N68°W	68°–80°S 73°S (avg.)	68°–80°S 73°S (avg.)
Edna A	AWD Line 204	0 to –7,500 ft (0 to –2,285 m)	~N58°W	72°–78°SW 76°SW (avg.)	80°–83°SW 82°SW (avg.)
Edna A	Vibroseis Line 204 west	0 to –8,100 ft (0 to –2,470 m)	~N58°W	66°–76°SW 70°(avg.)	76°–82°SW 78°(avg.)
Edna A	AWD Line 103-104	0 to –7,500 ft (0 to –2,285 m)	~N58°W	64°–80°SW 74°SW (avg.)	64°–80°SW 74°SW (avg.)
Edna B	Vibroseis Line 141-142 north	1,000 to –14,500 ft (–300 to –4,420 m)	~N64°W	67°–72°S 72°S (avg.)	67°–72°S 72°S (avg.)
Edna B	AWD Line 204	0 to –8,000 ft (0 to –2,440 m)	~N40°W to N60°W	80°–86°S 83°S (avg.)	81°–87°S 84°S (avg.)
Edna B	Vibroseis Line 204 west	0 to –10,500 ft (0 to –3200 m)	~N40°W to N60°W	77°S	79°
Edna B	AWD Line 103-104	0 to –7,500 ft (0 to –2,285 m)	~N35°W	60°S	60°
Edna C	Vibroseis Line 141-142 north	1,000 to –12,500 ft (–300 to –3,800 m)	~N68°W	73°S	73°
Edna C	AWD Line 103-104	0 to –7,500 ft (0 to –2,285 m)	~N65°W	75°	75°
San Miguelito	AWD Line 112-140	0 to –5,000 ft (0 to –1,520 m)	~N66°W	88°S	88°
San Miguelito	AWD Line 114	0 to –4,000 ft (0 to –1,220 m)	~N66°W	90°	90°
San Luis Bay	AWD Line 112-140	0 to –8,000 ft (0 to –2,440 m)	~N85°W	71°N	72°
San Luis Bay	AWD Line 113	0 to –8,000 ft (0 to –2,440 m)	~N77°E	65°–85°N 72°N (avg.)	65°–85°N 72°N (avg.)

[1] Strike of faults was estimated from geologic maps (Plate 1) or structure contour maps (Figures 5-12, 5-13, and 5-14).

[2] Apparent dip was measured on the seismic line. Average dip represents the dip of the fault measured along the total depth of the seismic line.

[3] True dip (δ) was calculated using the apparent dip (α) and the angle between the fault strike and apparent dip line (β) using the equation $\delta = \arctan(\tan\alpha / \sin\beta$; Suppe, 1985).

As discussed in Section 5.3, the east-west- to northwest-striking Los Osos fault in the northern Irish Hills is interpreted as a steeply south- to southwest-dipping fault in AWD Lines 138-149 and 150 and vibroseis Line 204 (Figure 5-23). The apparent dip of the fault in AWD Lines 138-149 and 150 ranges from 58 to 75 degrees; the true dip is estimated to be between 76 and 82 degrees (Table 6-1; Figures 5-24 and 5-25). The apparent dip and true dip of the Los Osos fault interpreted from Faults F1 and F2 in vibroseis Line 204 are identical and are estimated to range from 55 to 75 degrees (with an average dip of 58°–72°; Table 6-1; Figure 5-26).

As discussed in Section 5.5, the west-northwest-striking Edna fault zone is interpreted as a steeply south-southwest-dipping fault zone in vibroseis Lines 141-141 and 204 west and AWD lines 103-104 and 204 (Figure 5-1). The fault zone includes three separate strands: Edna A, Edna B, and Edna C. The average strike of each fault strand was estimated from either the mapped fault trace on the geologic maps or the structure contour maps (Figure 5-12). The apparent dip of Edna A ranges from 64 to 80 degrees (70°–76° average dip), and the true dip ranges from 64 to 83 degrees (73°–82° average dip; Table 6-1). The apparent dip of Edna B ranges from 67 to 86 degrees (72°–83° average dip), and the true dip ranges from 67 to 87 degrees (72°–79° average dip). The apparent and true dip of Edna C ranges from 73 to 75 degrees.

As discussed in Section 5.5, the west-northwest-striking San Miguelito fault zone in the northern Irish Hills is interpreted as a steeply north- to south-dipping fault in AWD Lines 112-140 and 114 (Figure 5-27). The apparent dip of the fault zone in AWD Line 112-140 is 88 degrees dipping to the south; based on the high angle of intersection (60°), the true dip is also estimated to be 88 degrees (Table 6-1; Figure 5-7). On the alternative interpretation of Line 112-140 (Figure 5-8), the San Miguelito fault zone is interpreted to dip 88 degrees north rather than south, suggesting that the fault zone may be vertical or nearly so. Both interpretations are permissible, given the uncertainty of the seismic data, and both generally agree with the steep dip (80°N) reported by Hall (1973b). Similarly, the apparent dip and true dip of the fault zone in AWD Line 114 are estimated to be subvertical, although the strands of the fault zone in AWD Line 114 are poorly constrained and largely inferred (Figure 5-29).

As discussed in Section 5.4, the west-northwest-striking San Luis Bay fault is interpreted as a steeply north-dipping fault in AWD Lines 112-140 and 113 (Figure 5-27). The apparent dip and true dip of the fault in AWD Line 112-140 are estimated to be 71 degrees and 72 degrees, respectively (Table 6-1). On Line 113, the apparent dip and true dip of the fault are estimated to be between 65 and 85 degrees north, with an average true dip of 72 degrees north (Figure 5-28). We note that the true fault dip measured on Line 112-140 (72°N) agrees with the average true dip measured on Line 113 (72°N).

7.0 LIMITATIONS

Given the objective of imaging faults and other relevant geologic structure in the subsurface, there are limitations of the seismic-reflection data and other data relevant to the interpretations and conclusions of this study, as follows:

- **Depth of Imaging.** The maximum depth of imaging for seismic lines acquired using an AWD source is approximately 6,000 ft (~1,830 m) and approximately 12,000 ft (3,657 m) for lines acquired using a vibroseis source. The downdip geometries of faults and other geologic features interpreted in the seismic-reflection data are uncertain below these depth limits.
- **Poor Correspondence Between Surface Geology and Shallow Reflective Structure.** Many of the seismic lines cross Neogene stratigraphic units with well-mapped and documented bedding orientations. Systematic comparison of the dip of shallow reflectors with mapped surface bedding dips along the seismic lines reveals that moderate to steep bedding dips typically are not imaged in the reflection data. This is likely due to the physical limitations of seismic methodology to image reflections from steeply dipping features, as well as the crooked geometry of many of the acquisition lines that further complicates the processing and recovery of reflections from complex and steeply dipping structure. In practice, poor correspondence between surface geology and shallow reflective structure made it difficult to confidently project surface faults, stratigraphic contacts, and other features into the subsurface.
- **Subdued Reflectivity of Neogene Stratigraphic Units.** In general, Neogene marine stratigraphic units in the Irish Hills are characterized by moderate to poor layered reflectivity in the seismic lines. We did not observe clear, distinguishing reflective characteristics in the data that allowed us to confidently and consistently identify a particular stratigraphic unit in the subsurface, and this limited our ability to correlate units among seismic lines.
- **Origin of Reflectivity in the Franciscan Complex.** In general, the Franciscan Complex rocks are significantly reflective. In some cases, the reflectivity exhibits coherent and laterally continuous structure, and we use this reflectivity to assess the presence and absence of faults with the criteria outlined in Section 4.0. The exact origin of the reflectivity of the Franciscan Complex is unknown, however. Speculatively, the reflectivity may arise from a foliation that developed in the Franciscan rocks during subduction and deformation within an accretionary prism. This foliation may have subsequently been tilted and folded, giving rise to antiformal and synformal folds imaged in some of the seismic lines that cross Franciscan rocks. We did not observe a simple correlation between reflectivity and map patterns of alternating lithologies in the Franciscan Complex, however, and thus our understanding of the origin and significance of the reflectors is incomplete.
- **Well Data.** Details and limitations of the oil and gas exploration well data available for this report are described in Appendix E of PG&E (2014). Some of the limitations of the well data were as follows:

- Uncertain well locations.
- Incompletely logged and described holes.
- Different interpretations of “Franciscan basement” and Neogene stratigraphy among the various drillers and operators who logged the holes.
- Changes in the state of knowledge regarding stratigraphy in the region between the time the wells were drilled and the present.
- Poor correlation between bedding dips indicated by dipmeter data from the Honolulu-Tidewater 1 well and reflectors in adjacent seismic-reflection lines.

8.0 IMPACT EVALUTION

Impacts to other Geosciences reports and documents are not known at this time.

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VERIFICATION SUMMARY REPORT

Item	Parameter	Yes	No*	N/A*
1	Purpose is clearly stated and the report satisfies the Purpose.	X		
2	Data to be interpreted and/or analyzed are included or referenced.	X		
3	Methodology is appropriate and properly applied.	X		
4	Assumptions are reasonable, adequately described, and based upon sound geotechnical principles and practices.	X		
5	Software is identified and properly applied. Validation is referenced or included, and is acceptable. Input files are correct.	X		
6	Interpretation and/or Analysis is complete, accurate, and leads logically to Results and Conclusions.	X		
7	Results and Conclusions are accurate, acceptable, and reasonable compared to the Data, interpretation and/or analysis, and Assumptions.	X		
8	The Limitation on the use of the Results has been addressed and is accurate and complete.	X		
9	The Impact Evaluation has been included and is accurate and complete.	X		
10	References are valid for intended use.	X		
11	Appendices are complete, accurate, and support text.			X

* Explain "No" or "N/A" entries. (For example, Items 3 thru 7 would be N/A for a data report that simply presents the collected data.)
Item 11 is N/A because there are no Appendices in this report.

My comments listed below are tied to numbered paragraphs of the revised technical report. Comments marked by an asterisk * merit a response from the ONSIP team; ones not marked by an asterisk are editorial and require no response. Following my comments is Table 1, the comment resolution form for the review of the technical report. Table 1 contains the starred items with responses from the ONSIP team. I have reviewed the team's revisions to the text and concur that they adequately resolve the issues.

Verifier (ITR): Robert S. Yeats
(name/signature)

6/24/2014
(date)

ITR Comments on the revised Draft ONSIP Technical Report GEO.DCPP.TR.14.03 Dated 10 June 2014

1.0 Purpose: It would be useful here to point out that the onshore 2012 seismic lines not included in this analysis are in the vicinity of DCPP. We did not review the 2012 seismic data.

2.0 Data: In par. 1, Fig. 1-1 describes the hills east of U.S. Highway 101 as San Luis Range, not Edna Hills.

2.1 Seismic Reflection Data: Give reference describing AWD and Vibroseis because some people reviewing this report, including California legislators, are not geophysicists. Cite Fugro 2014 a, b. I favor expanding your non-technical explanation, keeping it to a single paragraph. The reason is that the seismic lines did not show as much as expected, and you simply wanted to tell a reviewer that it was state of the art, and you gave it your best shot. The hilly topography and landowner issues explain why you couldn't shoot all the ONSIP lines in 3D.

2.2.2.1 Franciscan Complex. Include mélange in the description, as the report on the surface mapping did. One explanation for the reflectors in the Franciscan is that they are low-angle thrusts dating from the accretionary-prism period. I think it is very unlikely that these reflectors are primary with the possible exception of the ophiolite block east of the southern end of line 112-140.

2.2.2.4.1 Rincon Formation. I don't think you have evidence for an unconformity between Vaqueros and Rincon. This problem is complicated because the Vaqueros is dated by megafossils and the Rincon is dated by microfossils (Saucesian and Zemorrian): comparing apples to oranges.
*Russ Graymer attributes the "great thickness" as repetition of the Rincon by reverse faulting in the Honolulu Tidewater well, but you are correct to point out that part of this thick section could be Obispo. Either way, an interpretation by fault repeat in the well is more likely than a local basin. I reviewed Appendix E, the Sowers report, and the well file. In Appendix E, samples from 5400 to 5600 contain Zemorrian faunas, and samples from 6420 to 10,180 have Saucesian faunas, consistent with Obispo. Kris McDougall of USGS examined the microfaunas and agreed with the older-over-younger interpretation. Note the change in dip at 5440 feet and the presence of fracturing and slickensides; at shallower depths, the dips are steep to S, but immediately below, dips are to NE. Appendix E showed another dip change associated with slickensides at 9000 feet, within the "second Rincon shale." An interpretation of the alternation between shale and tuff (Rincon and Obispo) that is stratigraphic is less likely based on interpretation of the outcrop by Hall and associates. Shale is subordinate in the Obispo as compared with tuff; volcanigenic strata are subordinate in the Rincon. Repeat of the section by reverse faulting strengthens Graymer's argument for reverse faulting in the Pismo syncline to explain the anomalous thickness in the well as opposed to a local basin, unlike any observed elsewhere in outcrop.
It was pointed out that Graymer's presentation at SSHAC had not been through USGS peer review, but I think the data discussed above for the Tidewater well stands on its own, whether Graymer presented it or not. More below in discussion of dip changes in the synclinorium.

2.2.2.4.2. Obispo Formation. Last paragraph: Cole and Stanley, 1998 not in references. Corbató is misspelled; he has an accent over the last o.

2.2.2.4.3. Monterey Formation. Are you sure that the Monterey includes Delmontian? Almost certainly, Delmontian microfossils would be in the San Miguelito Member. The Keller and *Barron* reference is shown as Keller and *Brown* in the references.

2.2.2.4.4. Pismo overlies older strata with angular unconformity also in SE Irish Hills, where it rests on rocks as old as Ks and JKf. Top of p. 9, show Pismo Formation (undivided). The reason that only the lower two Pismo members are important is that the upper three are too shallow to show on the ONSIP lines. In the last paragraph, Montaña is misspelled.

*2.2.2.5. Surficial deposits. This section should include a brief discussion of the marine terrace deposits (Qm on Plate 1), the analysis of which permitted the determination of uplift rates on the W and SW margins of Irish Hills, including close to DCPP. Qm is too shallow to appear on ONSIP lines, but their interpretation bears on uplift rates and therefore to analysis of Irish Hills faults. You already included the Qm references in this report.

*2.3.1. Pismo syncline. I disagree with your interpretation that the increased apparent thickness of pre-Monterey in Tidewater well is stratigraphic and not structural repetition, as discussed above. Graymer makes a convincing case for structural repetition in the Tidewater well based not only on this repetition but also the steep dips in the Pismo synclinorium. Dips greater than 60° are too steep to be attributed to drape over underlying normal faults; they most likely represent contraction. You can determine how much contraction by a cross section through the syncline, picking an arbitrary Pismo marker and using the dips to determine the shortening. There are no normal-fault-plane solutions from Hardebeck (2010) in the Irish Hills, only strike slip and reverse faulting.

*The best argument for your interpretation are the v's showing a south dip on the Edna A fault in the geologic map east of the Tidewater well and extending as far east as the Townsend Gunter well; strata on the north side are older. Note that the narrow belt of Monterey also dips south and is sub-parallel to the Edna A fault, suggesting that the Edna A fault there is a bedding fault. The south-dipping contact of Tertiary with basement also shows on the Clarence Hall map in USGS I-1097, although it is farther west than on the ONSIP map. Rather than showing a steep Edna A fault cutting across bedding, as in your cross sections, this contact and the steep dips of anticlines and synclines in the synclinorium could be due to bending moment during folding, analogous to folding a thick telephone book and noting that pages in the concave center of this fold would be folded secondarily.

I do not ask you to accept the Graymer interpretation, but only to cover your bases and consider it as one of the working hypotheses in forming the structure of the Irish Hills. See my discussion of the 112-140 line, which discusses the Tidewater well.

*2.3.2. Edna fault zone. If the Edna fault branches from the Los Osos fault, as shown in Fig. 2-1, that argues that the Edna fault is also a reverse fault. However, the map pattern of Edna A parallel to Monterey outcrop favors a bedding fault for Edna A, but not B or C.

2.3.4. Los Osos fault. Cite also Lettis et al. (2004). The uplifted Qm is restricted to S of Los Osos fault, indicating that the uplift rate on Qm S of fault is a minimum for total vertical separation. You could say that the ONSIP lines support the interpretation you give in the last paragraph.

3.0. Methodology and 4.0 Assumptions sections are useful in light of the subsequent description of individual seismic lines. The reader needs to know what the team went through to come up with the interpretation, and the quality of the seismic lines and attendant uncertainty meant that this was not a walk in the park. For the record, I had my say on interpreting the seismic lines in the first ITR report, and because of the cramped time schedule for the ITR review, I don't see any need to review this further, although I add further comments.

5.1.2. Line 204. This description considers uncertainties and, although the early normal fault interpretation is retained, a late reverse fault reactivation is considered, including a comparison of anticline with surface anticlines to E.

The absence of Monterey N. of Edna B could be due to pre-Pismo erosion. If this happened, it should show stratigraphic evidence: coarse clastics at N end. The disappearance of Monterey occurs at N end of Edna A. Could the Edna Member of Pismo Fm. be an expression of stratigraphic evidence of disappearance of Monterey northward?

5.1.3. Line 112-140. The interpretation of unusual thickness in Tidewater well favors a local thickening of Obispo or Rincon over faulting, although both interpretations of this seismic line have faults in well. (See also discussion above.) Only reverse faulting would require an apparent thickening, an interpretation supported by Sowers' well data report, which shows repeats of Rincon and two repeats of Obispo (second and third tuffs). She reports dips of 70-85 in Monterey and 73-82 in "second Rincon shale." See also Appendix E.

5.1.5. Synthesis. Edna A fault shown as high angle, although the outcrop between Tidewater and Gunter wells requires the fault to be parallel to bedding. Edna B and C faults, by cutting across stratigraphy at high angle, could be entirely different from Edna A.
*The synthesis considers only normal faulting and stratigraphic thickening in Tidewater well. Include the alternate interpretations even if the ONSIP team adopts the normal fault interpretation.

*5.1.5.1. Show outcrop control as well as well control.

5.2. Cambrian block should be Cambria felsite block.
Los Osos fault discussion. In general, the offsets defining faults on ONSIP lines appear more convincing for the Los Osos fault than for others in the Irish Hills. See, for example, faults F1 and F2 in line 138-149. In line 204, the S-dipping events at horizontal 5000-6000 and vertical between 2000 and 5000 could be fault-plane reflections. As stated in the original ITR report, the structural style of the Los Osos fault is consistent with its expression at the surface, both of which reduce the perceived earthquake hazard (at least the deformation rate) on the Los Osos fault, as discussed by Lettis and Hall (1994).

5.5. Downdip geometry. No change from discussion in original ITR report. You report your interpretation as the ONSIP team's preferred interpretation. I expressed my reservations elsewhere, recognizing that the ONSIP team must come up with a final interpretation, even when there are significant uncertainties. Your report has discussed the uncertainties.

*One interpretation introduced here is that the anticlines in the Pismo syncline are the surface expression in the hanging wall of normal faults at depth, and the synclines are the surface expression of the faults themselves. When the stress field changes to contraction, the faults are reactivated as reverse faults. This should be discussed as alternate interpretations, as suggested above.

*The balanced cross section approach assumes dip slip normal to line of section. The "admissible" argument is one in which the structures depicted can also be observed in the field, and the styles of faulting and folding are not invoked arbitrarily to solve structural problems at depth in the subsurface. But the cross sections presented with predominantly normal faults merging downward into a master fault are not based on structures apparent from the surface map, only from the possible correlation of events offset by faults that are themselves highly interpretive.

*The 3 regional cross sections show the assumed normal faults and dipping formation contacts that do not appear to result from normal offset. One way to see this is to use the top of basement together with added control based on altitude of mapped basement contacts on the map together with the controls on top basement altitudes from ONSIP sections where this is possible. Does this result in the mapped structure?

*Cross section C-C', which includes the Tidewater well, shows Tmo (actually Tmo + Tr and Tvaq) as a local basin, repeated in sections A-A' and B-B' with no evidence, just extending along strike. These sections, at least B-B', show an anticline just S of well and syncline just to N, but very small displacements on each fault except Edna C fault.j Figs. 5-38 and 5-39 explain this by making the folds younger than the normal faults.

*The basin is interpreted as asymmetric, deepest near the N margin of basin. This could be correct, but it would be better to illustrate it with isopachs of the Obispo, where most of the subsidence of the Pismo basin is recorded.

6.0. Results and conclusions. This is a synthesis of the conclusions based on the data, rationale, and assumptions described earlier. I commented in the original ITR report on those assumptions where they were made in the text and so I see no reason to comment further here.

7.0. Limitations. This section is very important and is most effectively shown at the end, even though some of the points were made earlier in the text.
It would have been much more effective to have had these discussions at the second ITR meeting, rather than through exchanges of emails or critiques of the final ONSIP report. An advantage of having an ITR is that it builds in a set of independent eyes to make sure that alternate hypotheses are presented, such as a more general interpretation of reverse faulting and a more detailed analysis of the Honolulu Tidewater well. Such an analysis allows for a more thorough assessment of the uncertainties of the ONSIP study, with implications for the assessment of earthquake hazard to DCPP.

The short time allowed for the ITR report, particularly the short time for interaction between the ITR and the ONSIP team, made it difficult because as ITR, I knew that there was a very short time line, and this made it difficult to have the interaction called for in evaluating the ONSIP project. I hope that this interaction will be possible at the next SSHAC meeting. Although I have raised some basic issues on structural interpretation, I want to close with the statement that I believe that the ONSIP team report meets the high standards of an update on the seismic hazards to what will be the only nuclear power plant on the West Coast. I have presented alternatives for the ONSIP team to consider, but as long as ONSIP builds in the alternate working hypotheses discussed here, I agree as ITR to abide by their decision on approval of the final report.

Table 1. Comment Resolution Form for the Review of ONSIP Technical Report GEO.DCPP.TR.14.03

Page #	Section	Paragraph	Document Text	PG&E Response	Comment Resolution	Comment Resolution Date
2	2.2.2.4.1 Rincon Formation		*Russ Graymer attributes the "great thickness" as repetition of the Rincon by reverse faulting in the Honolulu Tidewater well, but you are correct to point out that part of this thick section could be Obispo. Either way, an interpretation by fault repeat in the well is more likely than a local basin. I reviewed Appendix E, the Sowers report, and the well file. In Appendix E, samples from 5400 to 5600 contain Zemorrian faunas, and samples from 6420 to 10,180 have Saucesian faunas, consistent with Obispo. Kris McDougall of USGS examined the microfaunas and agreed with the older-over-younger interpretation. Note the change in dip at 5440 feet and the presence of fracturing and slickensides; at shallower depths, the dips are steep to S, but immediately below, dips are to NE. Appendix E showed another dip change associated with slickensides at 9000 feet, within the "second Rincon shale." An interpretation of the alternation between shale and tuff (Rincon and Obispo) that is stratigraphic is less likely based on interpretation of the outcrop by Hall and associates. Shale is subordinate in the Obispo as compared with tuff; volcanigenic strata are subordinate in the Rincon. Repeat of the section by reverse faulting strengthens Graymer's argument for reverse faulting in the Pismo syncline to explain the anomalous thickness in the well as opposed to a local basin, unlike any observed elsewhere in outcrop. It was pointed out that Graymer's presentation at SSHAC had not been through USGS peer review, but I think the data discussed above for the Tidewater well stands on its own, whether Graymer presented it or not. More below in discussion of dip changes in the synclinorium.	We have revised Section 5.1.5 to explicitly discuss the relationships in the Tidewater well cited here by the ITR. The revisions are briefly summarized as follows: 1) We acknowledge that the "Rincon-Obispo" section in the Tidewater well could be repeated by faulting. 2) We explicitly cite Dr. Graymer's SSHAC presentation as an example of this class of models. 3) We acknowledge the data and relationships in the well cited by the ITR. We also discuss alternative explanations for these relationships that do not require 4,000 ft of thrust repetition. We conclude that the data do not provide conclusive evidence for an extensional basin or thrust repetition, and state that this contributes to uncertainty in our preferred model.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14

Page #	Section	Paragraph	Document Text	PG&E Response	Comment Resolution	Comment Resolution Date
3	*2.2.2.5. Surficial deposits	1	This section should include a brief discussion of the marine terrace deposits (Qm on Plate 1), the analysis of which permitted the determination of uplift rates on the W and SW margins of Irish Hills, including close to DCPP. Qm is too shallow to appear on ONSIP lines, but their interpretation bears on uplift rates and therefore to analysis of Irish Hills faults. You already included the Qm references in this report.	We have modified the text as suggested by the ITR.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14
3-4	*2.3.1. Pismo syncline	2	I disagree with your interpretation that the increased apparent thickness of pre-Monterey in Tidewater well is stratigraphic and not structural repetition, as discussed above. Graymer makes a convincing case for structural repetition in the Tidewater well based not only on this repetition but also the steep dips in the Pismo synclinorium…I do not ask you to accept the Graymer interpretation, but only to cover your bases and consider it as one of the working hypotheses in forming the structure of the Irish Hills. See my discussion of the 112-140 line, which discusses the Tidewater well.	As noted above, we have modified Section 5.1.5 and 5.5 to explicitly acknowledge Dr. Graymer's model as a valid alternative hypothesis.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14
4	*2.3.2. Edna fault zone	3	If the Edna fault branches from the Los Osos fault, as shown in Fig. 2-1, that argues that the Edna fault is also a reverse fault. However, the map pattern of Edna A parallel to Monterey outcrop favors a bedding fault for Edna A, but not B or C.	1) We believe that the map relations show that the Los Osos fault branches from the Edna fault, rather than vice versa. 2) Map relations show that the Edna A fault cuts progressively down section east of the Tidewater well, which is not consistent with the hypothesis that the fault is confined to a bedding plane within a single stratigraphic horizon.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14
5	5.1.5. Synthesis.	4	*The synthesis considers only normal faulting and stratigraphic thickening in Tidewater well. Include the alternate interpretations even if the ONSIP team adopts the normal fault interpretation.	As noted above, we have modified Section 5.1.5 to explicitly acknowledge Dr. Graymer's model as a valid alternative hypothesis.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14

Page #	Section	Paragraph	Document Text	PG&E Response	Comment Resolution	Comment Resolution Date
5	*5.1.5.1.	4-6	Show outcrop control as well as well control.	The figure has been revised to show locations of top basement exposures in the Irish Hills.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14
6	5.5. Downdip geometry.	2	*One interpretation introduced here is that the anticlines in the Pismo syncline are the surface expression in the hanging wall of normal faults at depth, and the synclines are the surface expression of the faults themselves. When the stress field changes to contraction, the faults are reactivated as reverse faults. This should be discussed as alternate interpretations, as suggested above.	In the revision of Section 5.5, we present the model that secondary folds in the Pismo syncline are related to bedding-parallel and out-of-syncline thrusts as an alternative hypothesis.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14
6		3	*The balanced cross section approach assumes dip slip normal to line of section. The “admissible” argument is one in which the structures depicted can also be observed in the field, and the styles of faulting and folding are not invoked arbitrarily to solve structural problems at depth in the subsurface. But the cross sections presented with predominantly normal faults merging downward into a master fault are not based on structures apparent from the surface map, only from the possible correlation of events offset by faults that are themselves highly interpretive.	We interpret the south-down stratigraphic separations on the Edna fault as evidence for Miocene normal faulting; likewise, the north-down separations across the San Miguelito fault zone. Per the definition discussed in the report, we believe that normal faulting is an “admissible” deformation style for use in developing cross sections of the Irish Hills.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14
6		4	*The 3 regional cross sections show the assumed normal faults and dipping formation contacts that do not appear to result from normal offset. One way to see this is to use the top of basement together with added control based on altitude of mapped basement contacts on the map together with the controls on top basement altitudes from ONSIP sections where this is possible. Does this result in the mapped structure?	We agree with the ITR’s summary of what the cross sections show. The structure depicted on the cross sections is consistent with geologic map data, well data and our interpretations of the seismic reflection data. The cross sections also are consistent with the structure contour maps.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14

Page #	Section	Paragraph	Document Text	PG&E Response	Comment Resolution	Comment Resolution Date
6		5	*Cross section C-C', which includes the Tidewater well, shows Tmo (actually Tmo + Tr and Tvaq) as a local basin, repeated in sections A-A' and B-B' with no evidence, just extending along strike. These sections, at least B-B', show an anticline just S of well and syncline just to N, but very small displacements on each fault except Edna C fault.j Figs. 5-38 and 5-39 explain this by making the folds younger than the normal faults.	The intent of the cross sections is to show continuity and/or variations in structures interpreted in the seismic lines along strike. All three cross sections are consistent with interpretations of adjacent seismic lines.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14
6-7		6	*The basin is interpreted as asymmetric, deepest near the N margin of basin. This could be correct, but it would be better to illustrate it with isopachs of the Obispo, where most of the subsidence of the Pismo basin is recorded.	We believe that the interpretation of basin asymmetry is best illustrated on the cross sections. The only seismic line that images to the base of the Obispo Formation across the Pismo syncline is line 141-142. As acknowledged in the report, our interpretation of the top of basement beneath the Pismo syncline axis is highly uncertain in this line. None of the other lines provide any constraints on the base of the Obispo Formation beneath the syncline axis. Consequently, we believe that any isopach map of Obispo Fm thickness based on the seismic data would be highly uncertain and interpretative at best, and would not provide any independent data to assess basin asymmetry.	The ITR agrees that the PG&E response adequately addresses the comment.	6/18/14