Three-dimensional geologic modeling of the Santa Rosa Plain, California

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ABSTRACT

New three-dimensional (3D) lithologic and stratigraphic models of the Santa Rosa Plain (California, USA) delineate the thickness, extent, and distribution of subsurface geologic units and allow integration of diverse data sets to produce a lithologic, stratigraphic, and structural architecture for the region. This framework can be used to predict pathways of groundwater flow beneath the Santa Rosa Plain and potential areas of enhanced or focused seismic shaking.

Lithologic descriptions from 2683 wells were simplified to 19 internally consistent lithologic classes. These distinctive lithologic classes were used to construct a 3D model of lithologic variations within the basin by extrapolating data away from drill holes using a nearest-neighbor approach. Subsurface stratigraphy was defined through the identification of distinctive lithologic packages tied, where possible, to high-quality well control and to surface exposures. The 3D stratigraphic model consists of three bounding components: fault surfaces, stratigraphic surfaces, and a surface representing the top of pre-Cenozoic basement, derived from inversion of regional gravity data.

The 3D lithologic model displays a west to east transition from dominantly marine sands to heterogeneous continental sediments. In contrast to previous stratigraphic studies, the new models emphasize the prevalence of the clay-rich Petaluma Formation and its heterogeneous nature. Isopach maps of the Glen Ellen Formation and the 3D stratigraphic model show the influence of the Trenton Ridge, a concealed basement ridge that bisects the plain, on sedimentation; the thickest deposits of the Glen Ellen Formation are confined to north of the Trenton Ridge.

INTRODUCTION

Sonoma County is in the northern part of the San Francisco Bay region of northern California, an area that has undergone rapid population growth and accelerated urbanization in response to economic expansion over several decades. Approximately half of the population of Sonoma County resides on the Santa Rosa Plain (Fig. 1), a northwest-trending topographic and structural low. Water supply in this area is provided by a combination of surface water delivered via aqueduct from the Russian River and groundwater from beneath the Santa Rosa Plain. The Santa Rosa Plain is known to be underlain by four Miocene and younger formations, each of which has distinct aquifer properties, including: (1) Miocene–Pleistocene gravels that have been referred to in part as the Glen Ellen Formation (Fox, 1983); (2) dominantly marine sands of the Miocene and Pliocene Wilson Grove Formation; (3) various types of Miocene and Pliocene volcanic rocks; and (4) dominantly fine-grained continental sediments of the Miocene and Pliocene Petaluma Formation (Fig. 1). Although the outcrop distribution of each of these formations has been mapped (e.g., Blake et al., 2002; Wagner et al., 2006; Graymer et al., 2007), the degree of subsurface interfingeriing and overlapping age relations of the Miocene and Pliocene marine and nonmarine units have only recently been recognized and have important significance for the hydrogeologic system. The large increase in population and concomitant changes in land use within Sonoma County requires a reassessment of the hydrogeologic system, including the thickness, extent, and three-dimensional (3D) distribution of each of these important aquifers.

The distribution, subsurface extent, and interfingering relations between the four principal formations reflect the geomorphic development of the basins that underlie the Santa Rosa Plain, the history of uplift and subsidence, tectonic activity, including offset along major basin-bounding faults, and the interaction between continental and marine sedimentation. The complexity in stratigraphic and structural relations across faults bounding the Santa Rosa Plain makes it difficult to project the geology exposed in the uplands surrounding the plain directly to the subsurface, making 3D subsurface analysis from well data essential. An understanding of the extent and 3D geometry of these formations bears on an understanding of basin evolution, the timing of movement of faults the bound and transect the basins that underlie the Santa Rosa Plain, and the relation to volcanism in the nearby Sonoma volcanic field.

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Figure 1. Simplified geologic map (modified from Saucedo et al., 2000; Graymer et al., 2006) of the Santa Rosa Plain and surrounding highlands. The Santa Rosa Plain is bound on the west by the Sebastopol fault and on the east by the Rodgers Creek and Healdsburg faults. The buried Trenton Ridge separates the northern Windsor Basin from the southern Cotati Basin. Drill holes used in this study are classified by total depth. Two drill holes with high-quality lithologic and biostratigraphic data (Powell et al., 2006) are labeled: OR—Occidental Road well; SR—Sebastopol Road well.
Studies of the Santa Rosa Plain that have focused on water availability (Cardwell, 1958; California Department of Water Resources, 1975, 1982) used drill-hole data to develop geologic cross sections and to help estimate the transmissivity of various rock types. However, these previous subsurface interpretations largely were based on limited borehole information from a small number of oil and gas wells and water wells, augmented by projection of surface exposures to the subsurface. Since these water availability studies, much new work has been conducted, including new geologic maps published by the California Geologic Survey (Wagner and Bortugno, 1982; Bezore et al., 2003; Clahan et al., 2003; Wagner et al., 2003, 2006) and geologic maps and other studies published by the U.S. Geological Survey (USGS) (Blake et al., 2002; Graymer et al., 2007; McPhee et al., 2007; McLaughlin et al., 2008; Langenheim et al., 2010). There have also been studies on exposed basin-margin stratigraphy and structure (Fox, 1983; Davies, 1986; Allen, 2003), stratigraphic data from oil and gas wells (Wright and Smith, 1992; Ziegler et al., 2005), and detailed biostratigraphic and chronostratigraphic analysis of surface exposures and drill cuttings (Powell et al., 2004, 2006). This paper provides integration of these data sets with existing and new well data to develop a modern context for subsurface analysis of the Santa Rosa Plain.

In this paper we define the subsurface stratigraphy and lithologic heterogeneity of the four principal aquifer units using compiled drill-hole data from the Santa Rosa Plain. A 3D model of lithologic variations within the basins that underlie the Santa Rosa Plain is developed by extrapolating data away from drill holes using a 3-dimensional gridding process (Rockware Earth science and GIS software: www.rockware.com). Subsurface stratigraphy is defined through the identification of distinctive lithologic packages, tied, where possible, to high-quality well control. Available subsurface data provided sufficient detail to allow us to confidently distinguish major stratigraphic boundaries and enough internal detail within these units to develop a reliable subsurface geologic model. Faults are incorporated as discontinuities in structure contour and isopach maps of the principal units; however, interbasin structural complexities such as folding and thrust faulting are not explicitly considered by these models. This structural complexity is partly accommodated in the model through integration of unit interfingering and facies relations changes. These 3D subsurface models provide new insight into the configuration of the basin-fill sediments, the relative importance and lithologic character of each of the four principal basin-filling units, and a suitable hydrogeologic framework for groundwater resource assessments of the Santa Rosa Plain.

**GEOLOGIC SETTING OF SANTA ROSA PLAIN**

The southern part of the Santa Rosa Plain is covered by Quaternary alluvial deposits (Fig. 1). The northern part features low, slightly dissected exposures of late Pliocene and Quaternary (Pleistocene and Holocene) fluvial, lacustrine, and alluvial plain deposits that have in part been referred to as the Glen Ellen Formation (Fox, 1983), along with younger alluvium within stream channels (Graymer et al., 2007) (Fig. 1). The highlands to the east of the Santa Rosa Plain are underlain by various types of Miocene and Pliocene volcanic rocks, in part interbedded with the largely nonmarine and estuarine strata of the Petaluma Formation; both of these units unconformably overlie Mesozoic rocks (Fig. 1). This eastern margin of the Santa Rosa Plain is highly deformed and cut by major right-lateral strike-slip faults. West of the Santa Rosa Plain, a broad, low topographic area is underlain by Miocene to Pliocene, locally felsiclastic marine sandstone formerly known as the Merced Formation (Cardwell, 1958), now referred to as the Wilson Grove Formation (Fox, 1983). These marine strata dip gently northeastward beneath the Santa Rosa Plain and unconformably overlie Mesozoic rocks (Fig. 1). Interfingering of marine sandstone with transitional marine and nonmarine deposits is inferred to occur beneath the Santa Rosa Plain based on exposures at Meacham Hill immediately southwest of the Santa Rosa Plain (Powell et al., 2004). However, this transition zone is obscured by younger deposits beneath most of the plain. Cross sections that accompanied previous groundwater resource assessments of the Santa Rosa Plain (Cardwell, 1958; California Department of Water Resources, 1975, 1982) portray most of the plain as being underlain by Glen Ellen Formation as much as ~300 m thick, underlain, in turn, by an unspecified thickness of Wilson Grove Formation beneath the western half of the plain, and flanked by Neogene volcanic rocks on the east. The Petaluma Formation was inferred beneath the Petaluma Valley, but not to the north in the Santa Rosa Plain. We recognize significantly different stratigraphic relations and distributions between the Glen Ellen, Wilson Grove, and Petaluma Formations.

The Santa Rosa Plain is bounded and transected by major faults, including the active northwest-striking, right-lateral Rodgers Creek–Healdsburg fault zone bounding the east side of the plain. The west and southwest side of the plain is bounded by a system of poorly defined Pliocene and younger normal faults, here generalized as the Sebastopol fault (Fig. 1). Inversion of gravity data indicates that the Santa Rosa Plain is underlain by two main structural basins, the Cotati Basin to the south and the Windsor Basin to the north (Fig. 1). These depositional troughs are 2–3 km deep and filled with Tertiary and younger deposits (McPhee et al., 2007; Langenheim et al., 2010). These two basins are separated by a shallow west-northwest–striking bedrock ridge (the Trenton Ridge) that bisects the Santa Rosa Plain (McPhee et al., 2007; Williams et al., 2008; Langenheim et al., 2010) (Fig. 1). The Windsor Basin to the north is ~9 × 12 km, centered near the town of Windsor, and is located near many of the thickest outcrops of the Glen Ellen Formation in the Santa Rosa Plain. The Cotati Basin to the south is larger, 10 × 18 km, and 2.5–3 km deep. The Cotati Basin has a complex shape that suggests the presence of structurally controlled subbasins. The Glen Ellen Formation is also considerably thinned within much of the Cotati Basin, as the basin fill is dominated by the Wilson Grove and Petaluma Formations.

**Description of Principal Stratigraphic Units of the Santa Rosa Plain**

**Quaternary to Pliocene–Pleistocene nonmarine units (Glen Ellen Formation)**

The Pliocene–Pleistocene (younger than 3.2 Ma) Glen Ellen Formation was first described by Weaver (1949) as exposures of poorly sorted clays, sands, gravels, and cobbles near the town of Glen Ellen in the upper Sonoma Valley. Exposures of similar rocks have since been mapped through most of the Santa Rosa Plain, especially to the north and west of Santa Rosa. The unit consists of heterogeneous mixtures of tuffaceous clay, mud, bouldery to pebbly gravel, and sand and silt deposits with interbedded conglomerates. These sediments were deposited in a variety of nonmarine environments, including coalescing alluvial fans, fan deltas, streams, and lakes. Cardwell (1958) referred to many of these deposits as Glen Ellen Formation, but this terminology has been largely abandoned with the recognition of the existence of a number of other named and unnamed gravel-dominated sequences that overlap in age and are derived from several different local source areas (McLaughlin and Sarma-Wojcicki, 2003; McLaughlin et al., 2005). We retain the use of the term “Glen Ellen” to describe these diverse deposits in this study, mostly for consistency with earlier reports concerning the Santa Rosa Plain.

For our study we have combined all late Pliocene and younger nonmarine deposits in
Western end point of profile: 122° 50.53' W; 38° 30.13' N
Eastern end point of profile: 122° 47.89' W; 38° 31.1' N

Figure 2. Characteristics of Pliocene–Pleistocene gravels (Glen Ellen Formation). (A) Surface exposure 5 km northwest of Santa Rosa. Height of outcrop is ~2 m. (B) Well profile showing typical lithologic logs from drill holes. Wells are hung from land surface; depth below land surface is in meters.
the subsurface into a Glen Ellen unit, including the surficial Quaternary deposits, because the younger surficial deposits are typically thin and difficult to differentiate in drill logs. Outcrop exposures of this unit typically consist of gently to moderately tilted sections of stratified, but poorly sorted heterogeneous mixtures of gravels and sands interbedded with more consolidated conglomerates (Fig. 2A). The unit is generally poorly sorted to unsorted, and unconsolidated to weakly cemented and consolidated. Although no drill-hole or outcrop data document such a thickness, the unit has been interpreted to be as thick as 1000 m (Cardwell, 1958; California Department of Water Resources, 1975). Typical drill-hole lithologic descriptions of this unit (Fig. 2B) are notable for their overall heterogeneity, generally recording relatively thin beds (<5 m) of coarse and fine units, interspersed with coarse gravel intervals. Several nonwelded tuffs occur in parts of this unit.

**Late Miocene and Pliocene Wilson Grove Formation**

The Pliocene and Late Miocene Wilson Grove Formation is exposed over a broad area on the west side of the Santa Rosa Plain, extending from Petaluma in the south to the Russian River on the north, and from the west edge of the Santa Rosa Plain westward to the Pacific Ocean coastline between Bodega and Tomales Bays (Fig. 1). The formation consists of consolidated to weakly consolidated deposits of massive or thick-bedded, gray to buff, fine-grained to very fine grained fossiliferous sand or sandstone (Fig. 3). The unit includes local beds of mollusk and gastropod shell hash, pebble to boulder conglomerate, and local pumiceous tuff (Fox, 1983; Blake et al., 2002; Powell et al., 2004). The Wilson Grove Formation has a maximum exposed thickness of ~150 m; well logs indicate as much as 300 m thickness. The Wilson Grove Formation is marine, deposited in dune, littoral, and shelf settings. Distal western parts of the formation that are inset into the Mesozoic rocks may represent the head of a submarine canyon (Allen, 2003; Powell et al., 2004). The formation interfingers with the Petaluma Formation in exposures near the town of Cotati and at Meacham Hill immediately southwest of the Santa Rosa Plain. Interfingering of marine facies rocks with transitional marine and nonmarine deposits is inferred to occur beneath the Santa Rosa Plain as well.

Outcrop and drill-hole data suggest that the Wilson Grove Formation can be divided into three distinct marine environments represented by lateral variations in lithology (Powell et al., 2004). The first environment includes fine-grained marine sandstones (Fig. 3B) that were
probably deposited in water depths characteristic of upper bathyal or outer shelf settings (Powell et al., 2004) and most commonly occur well to the west of the Santa Rosa Plain. The second environment includes well-sorted fine- to medium-grained sandstone (Fig. 3A) deposited in shallow-marine settings. This facies represents much of the exposed Wilson Grove Formation, especially north of Sebastopol (Fig. 1).

The third environment is represented by a transitional marine and/or continental facies commonly composed of medium- to coarse-grained, angular sandstone beds interbedded with very well rounded pebble conglomerate beds (Fig. 3C). The transitional unit is interbedded with local well-sorted, well-rounded, and polished cobble to pebble gravel (pea gravel) that increases in abundance at the eastern and southeastern extent of outcrop (e.g., south and east of Sebastopol).

Compared to overlying Quaternary and Pleistocene units and to interfingered facies of the Petaluma Formation, the Wilson Grove Formation is distinguished in drillers’ lithologic logs by its overall homogeneous sorting, presence of shells, and massive bedding. Drillers typically described the finer-grained marine sand of the

Figure 3 (continued). (D) Well profile showing typical lithologic logs from drill holes. Wells are hung from land surface; depth below land surface is in meters. Drillers typically describe the fine-grained marine facies of the Wilson Grove Formation as clay and sand.
Wilson Grove Formation as clay or clay and sand (Fig. 3D). The presence of fossil shells serves as an important marker in the recognition of the Wilson Grove Formation in the subsurface. Although shells are infrequently described in the Petaluma Formation, the Petaluma is generally considerably finer grained, typically consisting of a silty to clayey mudstone, and is usually easily distinguished from the Wilson Grove Formation in drillers’ descriptions. The Wilson Grove Formation is mostly poorly cemented; some beds are cemented with calcium carbonate and iron and are reported by drillers as hard ledges. The unit contains beds of soft white tuff as much as 3 m thick in outcrop west of Sebastopol; some of these tuff beds have been identified as the Late Miocene Roblar tuff (Sarna-Wojcicki, 1992; Bezore et al., 2003), an important time-stratigraphic marker.

Neogene Volcanic Rocks

Volcanic rocks exposed in the general vicinity of the Santa Rosa Plain and present within the basin fill include the 3–8 Ma Sonoma Volcanics, the 8.5–9.5 Ma Tolay Volcanics, and the 10.6–11.2 Ma Burdell Mountain Volcanics (Wagner et al., 2005). The Sonoma Volcanics dominate the east side of the Santa Rosa Plain. These volcanic rocks are well exposed to the east of the Rodgers Creek–Healdsburg fault zone and are complexly imbricated by faulting along the southwest side of the fault zone, where they project beneath, and probably correlate with, volcanic units in the subsurface of the Santa Rosa Plain (McLaughlin et al., 2005, 2008).

The Tolay Volcanics and the Burdell Mountain Volcanics are exposed in outcrops to the southeast and southwest of the Petaluma Valley, respectively, and have been intercepted in the subsurface in the valley based on 40Ar/39Ar dates from oil and gas wells (Wagner et al., 2005). The Tolay Volcanics also are exposed in the fault-bound anticline at Meacham Hill that separates the Santa Rosa Plain from the Petaluma Valley to the south (Fig. 1), and are present in the uplifted southeast corner of Cotati Basin north and northwest of the town of Rohnert Park (Clahan et al., 2003; Wagner et al., 2005). Several drill holes in the vicinity of Cotati intercept volcanic rocks at depth that may represent buried equivalents of these older volcanic units.

All of the volcanic units include a wide variety of volcanic rock types including basaltic, andesitic, dacitic, and rhyodacitic flows, flow breccias, avalanche or talus breccia, tuffs, and several andesitic to rhyodacitic tephra units (Figs. 4A, 4B). Many of the units have relatively limited lateral extent and appear to have erupted from local volcanic vents. The older volcanics are interbedded with the Petaluma or Wilson Grove Formations, whereas the younger parts of the Sonoma Volcanics overlie the Petaluma Formation and are interbedded with, or underlie, the Pliocene–Pleistocene Glen Ellen Formation (Wagner et al., 2005). Drillers typically have distinguished volcanic rocks, although they may not have reliably noted the degree of welding in tuffaceous units. The term “volcanic conglomerate” was often used by drillers due to its typical association with sections of volcanic rocks. We interpret this unit to be volcanic in origin, consisting of flow breccia or volcanic agglomerate, rather than sedimentary conglomerate dominated by volcanic rock clasts. In places, volcanic rocks directly overlie Mesozoic rocks. The thickness of the volcanic rocks is highly variable and, in general, water wells do not penetrate the entire thickness of the formation (Fig. 4C). For the purpose of the subsurface lithologic and stratigraphic modeling of the Santa Rosa Plain, and in the absence of age or stratigraphic control, the various volcanic rocks are not differentiated as separate packages, and therefore are combined in a single unit as Neogene volcanic rocks in the 3D models.

Pliocene and Miocene Petaluma Formation

The Pliocene and Miocene Petaluma Formation is dominated by deposits of moderately to weakly consolidated silty to clayey mudstone (Fig. 5A), with local beds and lenses of poorly sorted sandstone (Fig. 5B). The Petaluma Formation is as thick as 900 m in outcrop (Weaver, 1949) and as thick as 1200 m in the subsurface in Petaluma Valley (Morse and Bailey, 1935; Allen, 2003). The unit is intercalated with Neogene volcanic rocks (andesitic to rhyolitic) around the margins of the Santa Rosa Plain that have radiometric ages ranging from ca. 5.0 to ca. 10 Ma (Wagner et al., 2005). The Petaluma Formation consists of transitional marine and nonmarine sediments that were deposited in estuarine, lacustrine, and fluvial depositional settings (Allen, 2003; Powell et al., 2004). The upper part of the Petaluma Formation is contemporaneous with the Wilson Grove Formation. Where the two formations interdigitate, they represent an oscillating Miocene–Pliocene shoreline (Powell et al., 2004).

Petaluma Formation deposits interpreted from drill-hole lithologic data mostly consist of monotonous sequences of clay with occasional interbeds of sand, probably representing distributary channels and gravel bars (Fig. 5C). The Petaluma Formation is more diverse texturally than the Wilson Grove Formation. The Petaluma Formation contains more clayey layers, and is finer grained and generally less permeable, with sandy and coarser-grained units being more poorly sorted than coarse units found in the Wilson Grove Formation. The Petaluma Formation is predominantly finer grained than the Glen Ellen Formation. Although coarse gravely facies exist in the Petaluma Formation, these coarse beds are thinner (usually <10 m), more poorly sorted, and usually interbedded with fine-grained clay that lacks a gravel component (Fig. 5C).

Pre-Miocene Rocks, Undivided

Pre-Miocene rocks (Eocene? and Cretaceous–Jurassic) consist largely of Franciscan mélangé of the Central belt, Eocene and older rocks of the Franciscan Coastal belt, the Jurassic Coast Range Ophiolite, and the Cretaceous and Jurassic Great Valley Group (Blake et al., 1984, 2002; McLaughlin and Ohlin, 1984). This unit forms the base of active groundwater flow.

Pre-Miocene rocks are characterized by a variety of consolidated rock types, including penetratively sheared shale (mélange matrix), graywacke, blocks of blueschist, chert, greenstone, thinly interbedded shale and sandstone, and mafic to ultramafic ophiolitic rocks. Drillers typically recognize serpentinite; other rock types are given a variety of descriptions (Table 1). All of these consolidated rock types are assigned to a single general lithologic class, i.e., undifferentiated basement. The top of pre-Miocene rocks was picked in a drill hole at the highest occurrence of one of the above-described consolidated rocks, especially where additional intervals of similar rocks occurred below. In rare cases, intervals that could be interpreted as part of the Cenozoic section were reported underlying undifferentiated basement. In these cases, the drill-hole intercepts were compared to the interpreted depth to high-density geophysical basement (Langenheim et al., 2006, 2010; McPhee et al., 2007) to help guide subsurface stratigraphic interpretation.

METHODOLOGY FOR USE OF DRILL-HOLE DATA

Drill-hole data were compiled from a variety of sources, including USGS water resources reports (Cardwell, 1958) and drill-hole compilations (Valin and McLaughlin, 2005), oil and gas exploration holes (California Department of Conservation Division of Oil, Gas, And Geothermal Resources, www.conservation.ca.gov/ dog [July 2008]), data provided by local water agencies, and water wells drilled by independent entities and compiled as proprietary data by the California Division of Water Resources (CDWR). Drill-hole data in USGS water resources reports (Cardwell, 1958) typically are summaries derived from the original CDWR records. We used the original CDWR data, even
Figure 4. Characteristics of the Neogene volcanics. (A) Surface exposure east of Santa Rosa, showing rhyolite lava flow. Height of exposure is ~5 m. (B) Surface exposure north of Santa Rosa, showing pumice-rich, reworked nonwelded tuff. (C) Well profile showing typical lithologic logs from drill holes. Wells are hung from land surface; depth below land surface is in meters. Note that only one well intercepts pre-volcanic basement.
Figure 5. Characteristics of the Petaluma Formation. (A) Surface exposure east of Petaluma, showing mudstones. (B) Surface exposure southeast of Petaluma, showing thick sandstone within a lens-shaped channel deposit. (C) Well profile showing typical lithologic logs from drill holes. Wells are hung from land surface; depth below land surface is in meters.
<table>
<thead>
<tr>
<th>Lithology class</th>
<th>Typical drillers' description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>Boulders; cemented gravel; gravel; loose rock; rock [if surrounded by clay and/or gravel and is &lt;5 ft (~1.5 m) thick]; rubble</td>
<td></td>
</tr>
<tr>
<td>Conglomerate</td>
<td>Alluvial deposits; clayey sand and gravel; clayey sand with minor gravel or streaks of gravel; gravel and, with, or with streaks of clay; gravel with sand and clay; sand and gravel; sand and gravel with clay; sand and rock; silty gravel; surface and boulders</td>
<td></td>
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<tr>
<td>Sand and gravel</td>
<td>In some cases this unit may be volcanic in origin, not sedimentary.</td>
<td></td>
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<tr>
<td>Sand (sandstone) and gravel</td>
<td>Cemented sand and gravel; sandstone and gravel</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>Adobe; clay sandstone; loam; quicksand; sand and clay; sand and shale; soil; silt; sticky sand; surface; topsoil</td>
<td></td>
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<tr>
<td>Clay, sand, and gravel</td>
<td>Clayey sand with ledges; sandstone and clay; sandy rock</td>
<td></td>
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<tr>
<td>Clay, sand, and trace gravel</td>
<td>Clayey sand with ledges; sandstone and clay; sandy rock</td>
<td></td>
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<tr>
<td>Clay and gravel</td>
<td>Clay and boulders; clay sand and gravel; sand and clay; clay and gravel; shale and gravel; shale and gravel; clay and gravel; clay and (with) rock; clayey sand and gravel; embedded clay or gravel; gravel and clay; gravel clay; gravelly clay; hardpan</td>
<td></td>
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<tr>
<td>Clay and trace gravel</td>
<td>Clay and little gravel; clay and boulders; clay and some gravel; clay and streaks gravel; clay with gravel stringers</td>
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<tr>
<td>Clay and sand</td>
<td>Basin deposits; clay and sand; clay and shale; clay and silt; mud; mudstone; sand clay (brown, blue, green, orange and yellow); sandy clay; silt; silty clay; shale; shale and sand</td>
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</tr>
<tr>
<td>Clay and sand (sandstone)</td>
<td>Clay and sandstone; gray rock when surrounded by shale; sandy claystone; siltstone</td>
<td></td>
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<tr>
<td>Clay</td>
<td>Clay, typically described as black, blue, brown, gray, green, tan, or yellow</td>
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<tr>
<td>Clay, sand and limestone</td>
<td>Clay and limestone; shale and limestone</td>
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<tr>
<td>Volcanic conglomerate</td>
<td>Conglomerate and volcanic rock; volcanic conglomerate</td>
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<tr>
<td>Basalt</td>
<td>Andesite; basalt; basalt and cinders; basalt and lava; basalt and sand; basalt boulders; black ash; black volcanic rock; cinders; dionite; lava rock; porous volcanic rock</td>
<td></td>
</tr>
<tr>
<td>Ash and/or tuff</td>
<td>Altered ash; ash (blue, brown, gray, red, white, yellow); ash-flow tuff; broken rock; clay and ash; lava ash; fractured rock; multicolored rock; pumice rock; rock (red or black, or when surrounded by rocks that are described as volcanic); rock or sandstone (when surrounded by ash or tuff); shattered rock; tuff; tuff and basalt; volcanic ash; volcanic clay; volcanic rock</td>
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<tr>
<td>Undifferentiated basement</td>
<td>All units that underlie an interval described as serpentinite; serpentinite; basalt and serpentinite; basalt and shale; black rock with quartz; blue and/or green rock; rock (red or black, or when surrounded by graywacke, shale and/or serpentinite; oily; rock with quartz and blue or green rock, shale or clay; green and blue rock or clay; serpentinite; shale with serpentinite</td>
<td></td>
</tr>
<tr>
<td>No data</td>
<td>No data, rock [when not surrounded by volcanic units and &gt; 5 ft (~1.5 m) thick]</td>
<td>Only units at depth are considered. When an interval at shallow depth is described by any of these terms other than serpentine and the underlying intervals are not described as basement, this zone is not described as undifferentiated basement. Although undifferentiated basement is only used at depth in a drill hole, on rare occasion Franciscan Formation is thrust over Glen Ellen Formation, such as along the Trenton fault near the Russian River.</td>
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if it was later published by the USGS, because these data included information from all downhole intervals, rather than summaries or generalizations of subsurface lithologic data.

A digital database of lithologic information from drill holes was compiled by manually entering lithologic data from the above sources. We culled the immense number of records obtained from CDWR by selecting ~10 representative drill holes from each of the 36 sections within a township and range, or ~10 holes within each ~1.6 km² (i.e., square mile) of the study area. In parts of the study area where the population density is low, our drill-hole distribution is correspondingly less. The drill holes that were used represented those that contained the greatest amount of detail in the description of each interval, had a large number of downhole intervals described (as opposed to a single long interval of “sand and gravel” or “alluvium”), were representative of downhole lithology of nearby holes, and represented a distribution of holes that were not clustered but were approximately equally distributed over the study area. The study area includes an area encompassed by three ranges in the east-west direction (R7W, R8W, and R9W) and five townships in the north-south dimension (T5N, T6N, T7N, T8N, and T9N). In all, 2683 drill holes were compiled within this area (Fig. 1).

When available, we selected drill holes with the most detailed logs that were at least 100 m deep, but most important, we selected holes that could be definitively located. Total drill-hole depths vary from 6 to 1811 m; only 25 holes are >250 m in total depth (Fig. 6). The deepest holes were drilled for oil and gas exploration. The average or mean total depth is 102 m and the median is 90 m.

All of the 2683 wells in this final compilation were located to either a specific street address, to the center of a quarter-quarter section, or to the center of a county assessor’s parcel. Of the wells placed at a specific street address, 1883 were located using address geocoding in a geographic information system, and 435 were located using mapping resources available on the internet. Of the remaining wells, 295 were located to the center of a quarter-quarter section, 54 were located at the center of a county assessor’s parcel, and 10 were located using drillers’ written descriptions. Wells that could only be located to the nearest section were deleted and not used in this study. Wells with fragmentary street addresses or addresses that could not be found to exist in Census Bureau data or internet geocoding services were likewise deleted. Wells that could only be located by assessor’s parcel number were deleted if the parcel information listed on the log did not appear in the parcel data from the Sonoma County Assessor’s records.

**Interpretation of Drillers’ Lithologic Descriptions**

Drillers’ descriptions vary from detailed lithologic descriptions collected by an onsite geologist at the time of the drilling, to brief summaries at 10 ft increments, to, most commonly, generally short phrases that accompany a significant lithologic change. Typically, descriptions range from between 1 and 10 words that describe a change recognized by the driller as they penetrate a different unit; for example, descriptions may include information on grain size, presence or absence of gravel and/or large rocks, degree of consolidation, rock type, and/or abrupt color changes. This study relies heavily on lithologic information from water well data, which are usually assumed to be poor sources of geologic and lithologic information. However, some previous studies have shown that drillers’ logs can provide valid geologic information if the logs are classified and screened on the basis of the degree of detail provided (Laudon and Belitz, 1991; Sweetkind and Drake, 2007; Faunt et al., 2010).

In an attempt to evaluate the reliability of drillers’ logs and their usefulness in characterizing the subsurface, we selected 186 drill holes for analysis in four sections (25, 26, 35, 36) located in the southeast corner of T7N R9W, northeast of Sebastopol (Fig. 1); 40 drill holes would have been selected in these four sections for the 3D subsurface modeling. By examining in detail a dense concentration of drill holes in an area where the geology was relatively constant over a small area, we hoped to evaluate differences in the drill-hole lithologic descriptions related to different drilling companies and their methods, rather than real variability in the geology. The selected 186 wells were completed

![Figure 6. Frequency distribution of total drilled depth, in meters, for drill holes used in the Santa Rosa Plain subsurface mapping. Inset diagram shows frequency distribution for the holes drilled to 350 m or deeper.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/6/3/237/3339091/237.pdf)
by 18 different drilling contractors; ~92 of the holes were drilled by a single company. Most of the holes are shallow. With the exception of 2 holes drilled to a depth of ~450 m, the average depth is ~50 m.

We counted the number of downhole intervals in each of the 186 drillers’ logs and the number of unique descriptive phrases to quantify the level of detail present in the logs. For example, if a driller described four intervals as clay, sand, clay, and sand, respectively, that would constitute only two unique descriptive phrases in four downhole intervals. There is no observed correlation between the number of downhole intervals and the total depth of a drill hole ($r^2 = 0.05$) (Fig. 7A). Deeper holes do not necessarily have more downhole intervals than shallower holes. This result indicates that holes are described based on the units intersected rather than some random criteria, such as equally spaced description intervals. In addition, there is no correlation between the number of unique descriptive phrases and the total depth of a drill hole ($r^2 = 0.0817$) (Fig. 7A). Deeper holes do not necessarily have more unique descriptive phrases used than shallow holes. However, there is a significant correlation between the number of downhole intervals and the number of unique descriptive phrases ($r^2 = 0.70$) (Fig. 7B). The more subdivisions the driller made, the greater the number of descriptive units used. This indicates that descriptions tend to be unique and not repeated in a single drill hole.

As another test of evaluating the internal consistency of drill-hole data, we compiled the lithologic units described in all of the 186 holes at 25 ft (~7.5 m) depth intervals (Fig. 7C). The compiled drillers’ descriptions were simplified to the same 19 units used in the 3D modeling of the entire Santa Rosa Plain (Table 1). We normalized the data from each depth interval so that the numbers of lithologic keywords are reported as percent of the total for that depth interval (Fig. 7C). Based on detailed lithologic descriptions (Powell et al., 2006) from the nearby Occidental Road and Sebastopol Road drill holes (Fig. 1), the subsurface geology in the four sections was expected to consist of an upper sequence of clayey to pebbly silt, sand, and gravel of dominantly nonmarine distal fluvial, lacustrine, and deltaic deposits (the Glen Ellen Formation and correlative strata) overlying a lower sequence of silt, sand, and pebbly sand with mollusks of dominantly shelfal marine affinities (the Wilson Grove Formation). The expected geology is borne out with reasonable consistency by the 186 drillers’ lithologic logs. High in the section, clay and sandy gravel dominate the lithologic descriptions, the section as a whole is poorly sorted, and no shells are identified (Fig. 7C). A wide variety of lithologic descriptions was used, but this is to be expected of the Glen Ellen Formation and equivalents, and does not necessarily indicate inconsistency between drillers’ descriptions. Below the 150 ft (~45 m) interval, sands and shells dominate the lithologic descriptions, consistent with the interpreted Wilson Grove Formation (Fig. 7C). It is important that few other lithologic categories are described, lending confidence to the drillers’ overall interpretation.

Once the initial selection criteria of selecting deep holes with enough descriptive subdivisions in the lithologic log to be useful and reliable locations were met, the drill-hole lithology data, or drillers’ nomenclature, then were simplified. If the physical characteristics of the major rock formations exposed at the surface are mapped, these geologic criteria can be used to help interpret and standardize the various descriptions submitted by numerous well drillers. By combining observations made at surface exposures with known or inferred facies relations, alluvial units can be distinguished from fine-grained marsh and/or palustrine deposits, proximal coarse-grained deposits can be distinguished from fine-grained distal deposits, and interfingering of major lithologic packages can be recognized in the subsurface data. This technique was used to simplify the drillers’ descriptions (Table 1).

### Interpretation of Stratigraphy from Drill-Hole Data

Because one of the overall goals of this exercise was to create a geologic framework suitable for groundwater resource assessment, the complex Neogene stratigraphy was simplified to four principal units: Glen Ellen Formation, Wilson Grove Formation, Petaluma Formation, and Neogene volcanics, all underlain by a generalized unit, called undifferentiated basement, that includes all pre-Cenozoic rocks. When numerous drillers’ logs were viewed and interpreted together, it became clear that each of the principal stratigraphic units had a reasonably distinct mappable character in the subsurface such that they could often be distinguished from each other. Assignment of stratigraphic tops was fundamentally lithology based and, as such, was rock-stratigraphic rather than being a true stratigraphic assignment based on timelines or sequence boundaries.

Mappable lithologic sequences were identified in well data by analyzing numerous serial cross sections across the Santa Rosa Plain and making stratigraphic interpretations based on rock type, bedding and sorting characteristics, stratigraphic succession, and an understanding of the relationship between the mapped geologic units and their lithologic characteristics. Stratigraphic tops were picked interactively by viewing lithologic logs from 10–20 wells in a profile. Contacts were picked in an iterative fashion from numerous cross sections of varying orientations with combinations of wells examined to eliminate spurious picks and maximize the consistency of the stratigraphic interpretation. Subsurface interpretation began with wells spudded in known outcrop or correlations to higher quality data to condition the rest of the data set.

Map relations show that over most of its outcrop area the Wilson Grove Formation unconformably overlies pre-Cenozoic rocks, so the unit could be confidently assigned in the subsurface. Some complexities arose in the far southwest part of the study area where volcanic rocks, probably related to the Tolay or Burdell Mountain Volcanics, were reported near the base of the penetrated section in several wells. Based on known facies and age variations within the Wilson Grove Formation (Powell et al., 2004) and Petaluma Formation (Davies, 1986; Allen, 2003), we initially made stratigraphic picks of a number of subdivisions of each formation based on grain size, sorting, and bedding characteristics. This fine-scale subdivision was effective where well data could be tied to outcrop control, especially for the Wilson Grove Formation. However, such fine-scale subdivision was difficult to maintain throughout the Cotati Basin, where the units interfingered but outcrop control was lacking.

In a similar fashion, subsurface stratigraphic picks of the Glen Ellen Formation were first assigned in drill holes in the Windsor Basin near outcrops of the formation. The unit was identifiable as a relatively thin bedded, heterogeneous package that contained gravels with a clayey or fine-grained matrix, a unit often called clay and gravel by the drillers. The Glen Ellen Formation was readily identified to the north and east of the Trenton fault, but was more difficult to identify to the south, where both the Wilson Grove and Petaluma Formations are more gravel rich. Heterogeneous, gravel-rich sediments that overlie volcanic rock on the east side of the Windsor Basin, near the city of Santa Rosa, and in Rincon Valley were also assigned to the Glen Ellen Formation.

For wells drilled on or near an outcrop of volcanic rocks, we selected the first intercept of volcanic rocks as the top of the Neogene volcanics unit. In certain areas, the volcanic units are interbedded with sediments and in those cases this entire interval was called Neogene volcanics.

The Petaluma Formation was consistently described by drillers as being mostly monotonous sequences of clay with occasional
Figure 7. Plots showing statistical analysis of drillers' lithologic descriptions. (A) Number of intervals and number of descriptive phrases versus total depth. (B) Number of intervals versus number of descriptive phrases. (C) Normalized frequency of lithologic units occurring in 25 ft (~7.5 m) intervals.
interbeds of sand or gravel bars. We initially attempted to identify the following three subdivisions within the Petaluma Formation: (1) Petaluma Upper, assigned to intervals of Petaluma Formation near Santa Rosa above thick sequences of Sonoma Volcanics; (2) Petaluma Middle, assigned to most of the unit beneath the Santa Rosa Plain; and (3) Petaluma Lower, assigned where there were significant amounts of volcanic rocks, typically basalts in the section, that were inferred to be older volcanic units such as the Tolay Volcanics. However, due to structural complexity and lack of correlateable horizons, we eventually abandoned attempts to subdivide the Petaluma Formation.

3D MODELING RESULTS

3D Lithologic Model

Drillers’ descriptions were simplified to a small number of internally consistent lithologic classes (Table 1) for all 2683 drill holes. When these drill-hole data were viewed together, the 19 lithologic units derived from the drillers’ descriptions fell into distinct spatial groupings (Fig. 8A) that were amenable to stratigraphic classification with some confidence. The standardized subsurface lithologic data were then used to construct a 3D lithologic model of the study area (Fig. 8B). Interpreted drill-hole lithologic data were numerically interpolated between drill holes by using a cell-based, 3D gridding process using the RockWorks 3D modeling software package (Rockware, Earth Science and GIS software: www.rockware.com). In this method, a solid modeling algorithm is used to extrapolate numeric codes that represent a lithologic class. Grid nodes between drill holes are assigned a value that corresponds to a lithologic class based on the relative proximity of each grid node to surrounding drill holes. The interpolation routine looks horizontally from each drill hole in search circles of ever-increasing diameter. Initially, the algorithm assigns a lithology class to grid nodes immediately adjacent to each drill hole, at a vertical discretization defined by the modeler. Then the interpolation moves outward from the drill hole by one node and assigns the next circle of grid nodes a lithology class. The interpolation continues in this manner until the program finds a cell that is already assigned a lithology class (presumably interpolating toward it from an adjacent drill hole), in which case it skips the node assignment step.

A strength of the 3D gridding process is that the interpolated data in the resulting 3D grid have the appearance of stratigraphic units, with aspect ratios that emphasize the horizontal dimension over the vertical (Fig. 8B). Also, the method preserves the local variability of the lithology in each drill hole with no smoothing or averaging. Thus, where data are abundant, local lithologic variability is incorporated. One limitation of this type of numerical interpolation is the sensitivity to the distribution of the data, where values from an isolated drill hole tend to extrapolate outward to fill an inordinate amount of the model area. The effect is particularly noticeable where a small number of deep drill holes are interspersed with shallower holes. Data from the deepest drill holes in this case tend to overextrapolate over the entire model area. A second limitation of this method is that it is purely deterministic and data based. Alternatively, it may be possible to use a stochastic approach where the drill-hole data are used as a guide to predict subsurface lithologic variability (e.g., Weissmann et al., 1999). Such an approach would have the benefit of being able to incorporate depositional process and facies relationships by evaluating the tendency of specific lithologic units to be adjacent to each other in specific geologic environments. Because of the large-scale nature of the Santa Rosa Plain, the presence of multiple depositional environments, and resource limitations, stochastic modeling approaches were not applied.

Faults were not explicitly included in the creation of the 3D lithologic model, owing to the limitations of the software package used. However, the interpolation methods used here produce lithologic variations that approximate fault truncations of lithologic units where data density is high.

Cell dimensions for the 3D interpolation were 250 m in the horizontal dimensions and 10 m in the vertical dimension. The vertical discretization was chosen as a compromise between preserving geologic detail, such that thin geologic units are not averaged out, and computational efficiency, such that model runs could be completed in a reasonable time. The model ranges in elevation from 400 m to ~400 m, for a total thickness of 800 m, before being trimmed at the surface and base. We trimmed the resulting model at the top using a digital elevation model (DEM) to represent land surface elevations and at the base by a grid of the top of the geophysically modeled high-density geophysical basement that represents the elevation of pre-Miocene rocks (Langenheim et al., 2006, 2010; McPhee et al., 2007).

For the 3D lithologic model presented here, strata were assumed to be horizontal. The assumption of horizontality is likely more valid for the younger, upper parts of the basin fill than for the deeper parts of the alluvial section. Seismic reflection profiles across the eastern side of the Windsor Basin (Williams et al., 2008) show a progressive increase in reflector dip beneath ~100–200 m. Several more complicated models were constructed that incorporated stratatal tilt or folding. However, the 3D gridding approach is very sensitive to the choice of dip or the magnitude and style of the fold chosen as a bounding surface; none of the more complicated models yielded results that were higher quality than the simple horizontal model.

An initial test of the strength of the subsurface 3D lithologic model is to compare the mapped surface geology to that predicted at land surface by the 3D model. The density of drill-hole lithologic data is greatest at the surface, so resolution of the resultant model should be highest. When the solid lithologic model is trimmed with a DEM, the resulting upper model surface compares favorably to the geologic map; for example, compare the general distribution of sand and volcanic-rock lithologic classes in Figure 8B with the map distribution of Wilson Grove Formation and Neogene volcanics, respectively, in Figure 1. The sand-dominated marine deposits in the south and west, the fine-grained basin-axis deposits capped by younger, coarser and thinner alluvial fans, and the volcanic highlands to the north and east are all well expressed in the 3D model (Fig. 8B). Although no faults were used in the construction of the lithologic model, due to the density of well data the contacts between lithologic units are relatively abrupt and are coincident with the major basin-bounding faults (Figs. 8B, A1–2, and A1–4).

3D Stratigraphic Model

In order to tie the basin-fill lithology to a stratigraphic context and to mapped surface exposures, we created a 3D stratigraphic model of the Santa Rosa Plain. In contrast to the 3D lithologic model, which used just a single type of data, interpreted drill-hole lithologic data, to populate a 3D volume, the 3D stratigraphic model was built using multiple geologic data sets including geologic maps, surface traces of faults, interpreted subsurface stratigraphic contacts from drill-hole data, and the results of geophysical models. The 3D stratigraphic model, built using EarthVision (Dynamic Graphics, Inc., http://www.dgi.com/) and Rockworks 3D (Rockware Earth science and GIS software: www.rockware.com) geologic mapping software consists of three bounding components: fault surfaces, stratigraphic surfaces, and a modeled surface representing the top of Pre-Cenozoic rocks.

Fault surface traces were generalized from published geologic maps (McLaughlin et al.,
Cylinders represent the location of drill holes; colors represent lithologic units intercepted downhole. Drill holes are hung from their collar elevation at land surface. Land surface is transparent; as a result, the drill holes have the appearance of hanging in space. Faults are shown as vertical “ribbons” decorated with parallel black lines.

Vertical sections cut through the solid volume 3D lithology model. Sections are hung from land surface. Land surface is transparent; as a result, the sections have the appearance of hanging in space. Tops and bottoms of each section appear irregular because the model was clipped at the top by a digital elevation model and at the base by the modeled elevation of pre-Cenozoic bedrock.

Figure 8. Perspective views of drill-hole lithologic data and resultant three-dimensional (3D) lithology model. View is from above and the southwest, looking northeast. UTM—Universal Transverse Mercator. (A) Perspective views of drill-hole lithologic data. (B) Perspective 3D view of vertical sections cut through the solid volume 3D lithology model. For a fully interactive 3D image, see Supplemental Figure 1 in Appendix 2.

1Supplemental Figure 1. Zipped file containing a RockPlot3D (http://www.rockware.com/downloads/trialware.php#R [February 2010]) image of the three-dimensional (3D) lithologic model. This 3D image corresponds to Figure 8B and presents vertical sections cut through the 3D solid lithologic model in three dimensions. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00513.S1 or the full-text article on www.gsapubs.org to view Supplemental Figure 1.

Geosphere, June 2010
A limited number of faults was included in the framework model to bound the major basin elements, including (Fig. 1) a combined Bennett Valley–Maacama fault trace that offsets Neogene volcanics to the east of the Santa Rosa Plain, a combined Rodgers Creek–Healdsburg fault trace that generally bounds the eastern side of the Santa Rosa Plain, a generalized trace of the Sebastopol fault that bounds the western side of the Santa Rosa Plain, a generalized fault that bisects the Santa Rosa Plain and approximates the Trenton Ridge as a single structure, and a generalized trace of the Bloomfield fault that offsets the Wilson Grove Formation to the southwest of the Cotati Basin. All faults are presumed vertical for this study; this is probably an acceptable simplification for the major faults with strike-slip motion, but may be less applicable to faults bounding the Trenton Ridge, which have been interpreted as being reverse faults with gentle dip (Fox, 1983) or steep dip (Williams et al., 2008). These faults were incorporated into the structure contour and isopach maps of each of the major units, serving to bound and truncate contoured thickness and unit extents.

Stratigraphic surfaces are derived from stratigraphic information from wells, described in the previous section, along with point data derived by combining the mapped geology and a DEM. A generalized hydrogeologic map (Fig. 1) was constructed by merging geologic map data from several sources (Saucedo et al., 2000; Blake et al., 2002; Graymer et al., 2007) to portray four distinct Cenozoic formations (Pliocene–Pleistocene gravels, the Wilson Grove Formation, Neogene volcanic rocks, and the Petaluma Formation) and a fifth unit representing undifferentiated pre-Cenozoic rocks. The 3D geometry of outcrops of each of the five units was defined by intersecting the hydrogeologic map with a DEM, resulting in x, y, z coordinate locations within each outcrop area that were exported for use as input data in the stratigraphic modeling. Where possible, interpreted stratigraphic surfaces were tied to high-quality well control where biostratigraphic information was available (Powell et al., 2006), or tied to previously identified formation picks in wells (Valin and McLaughlin, 2005).

The surface representing the top of the geophysically modeled high-density geophysical basement was derived from inversion of regional gravity measurements (Langenheim et al., 2006, 2010; McPhee et al., 2007), as constrained by outcrop data and well data. This surface is inferred to represent the elevation of pre-Miocene rocks. This depth-to-basement inversion takes advantage of the large density contrast between dense pre-Cenozoic rocks (predominantly composed of Mesozoic rocks of the Franciscan Complex and the mafic Coast Range Ophiolite) and less dense Quaternary–Tertiary sedimentary rocks and Neogene volcanics. The inversion method allows the density of bedrock to vary horizontally as needed, whereas the density of basin-filling deposits is specified by a predetermined density-depth relationship (Jachens and Moring, 1990). The resulting model of depth to pre-Cenozoic bedrock for the Santa Rosa Plain defines both the overall basin geometry and the configuration of subbasins that are bounded by internal faults. Locally, the modeled depth to geophysical basement from the gravity inversion may not exactly match the depth to pre-Cenozoic rocks observed in every drill hole because of the resolution of the grid model from the inversion or in areas of large gravity gradients.

The 3D geologic framework of the Santa Rosa Plain was constructed by standard subsurface mapping methods of creating isopach maps (Fig. 9) and structure contouring for each of the four principal stratigraphic units. The structural elevation of stratigraphic tops and thickness for each of the four major units were contoured from map and well data using simplified fault traces to bound contoured regions. Data were contoured using an inverse distance algorithm with a moderate smoothing routine. Data were considered to be sufficiently numerous that no prefiltering, regridding, or declustering of the original data was done prior to contouring. Attempts at contouring the data using a pre-kriging routine were computationally intensive and did not provide significantly different results.

One challenge in creating the isopach maps is that few of the wells, being for the most part shallow water wells, penetrated the entire thickness of a formation. To provide some 3D control on unit thickness, the modeled depth-to-basement surface was used to define unit thickness where it could be reasonably inferred that the stratigraphic unit would be expected to directly overlie pre-Cenozoic rocks. For example, where the Wilson Grove Formation crops out to the west of Sebastopol, the base of the unit is exposed and is nearly everywhere unconformable on pre-Miocene rocks with no intervening units. So, for the Wilson Grove Formation to the west of the Sebastopol fault, the modeled depth-to-basement surface was used to define the base of the formation (Fig. 10). This method was also used for the Neogene volcanics in wells that penetrated a thick sequence of volcanic rocks uninterrupted by sediments. The base of the volcanic section is rarely exposed in outcrop near the Santa Rosa Plain. However, volcanic rocks unconformably overlie pre-Cenozoic rocks east of Napa Valley. In cases where the base of the Neogene volcanics was forced to the elevation of the depth-to-basement model, the 3D mapping incorporates uncertainty that is inherent in the depth-to-basement model. Specifically, the variation of density with depth in the volcanic units can dramatically influence the model results. For wells in the center of the Santa Rosa Plain where the top of the Petaluma Formation was interpreted, the base of the Petaluma Formation was defined as the elevation of the depth-to-basement surface, forcing the formation to be very thick and fill the deepest parts of the basins. This method forces any older Cenozoic rocks that might be present beneath the Petaluma Formation and Neogene volcanics to be included in those units.

The Glen Ellen Formation was a special case where wells, especially in the Windsor Basin, did not penetrate the entire thickness of the formation, but some other unit would be expected to underlie it. The formation therefore could not be reasonably expected to extend down to the pre-Cenozoic rocks. In order to contour the formation, the thickness was arbitrarily picked at ~15 m below the base of wells that bottomed in the Glen Ellen Formation. In areas where the entire thickness of the formation was not penetrated, these data give a minimum thickness to the Glen Ellen Formation.

Computer-generated isopach maps were reviewed to identify anomalous data points. These data points were evaluated and, in many cases, reinterpreted to create more consistent isopach trends. Isopach maps were filtered to remove extremely thin parts of units, and thicknesses of 2 m or less typically were set to zero. Isopach maps were hand-edited in selected places to remove outliers that were well outside the main part of the unit. The final grids used to create the 3D framework represent a hybrid approach that combines (1) unit thickness that incorporates the depth-to-basement model, as described above, with (2) unit thickness defined by interactive assignment of stratigraphic tops from well data. In places the grids show abrupt transitions where the regions in which the two methodologies were used abut each other.

The 3D stratigraphic framework was constructed initially in EarthVision and later in Rockworks 3D modeling packages by importing gridded surfaces to define the top and base of each stratigraphic horizon that were then stacked in stratigraphic sequence to form a 3D digital solid. The 3D stacking was guided by rules that controlled stratigraphic onlap, truncation of units, and minimum thickness. Stacked grid models for the upper and lower surfaces of each of the stratigraphic units are then displayed on multiple 3D cross section fence panels (Fig. 11).
Figure 9. Isopach maps of the four principal aquifer formations, Santa Rosa Plain. (A) Glen Ellen Formation map. (B) Wilson Grove Formation. (C) Neogene volcanics. (D) Petaluma Formation. A and B are contoured at different intervals than C and D.
3D Subsurface Mapping of Textural Classes

In addition to building a 3D geologic framework of stratigraphic units, it is important to assess geologic factors that could affect conductivity and storage properties of the aquifer system for characterization of groundwater flow. Lateral and vertical variations of sediment texture, including grain size, sorting, and bedding, may affect the direction and magnitude of groundwater flow and the amount of compaction and potential subsidence. A 3D portrayal of sediment texture was developed from the 3D lithology model to help characterize grain-size variations of the aquifer system. Textural classes still need to have a stratigraphic context, however, because each formation largely represents a distinct depositional setting and would be expected to have different permeability characteristics than surrounding units. The combination of texture and stratigraphy was accomplished by sampling the 3D texture and stratigraphy models and imprinting this geologic information onto nodes in a predefined grid. Through this operation, these discretized stratigraphic and textural data are preserved in a form amenable for guiding assessment of vertical and lateral hydraulic conductivity and storage property distributions for the Santa Rosa Plain.

A 16 layer scheme of grids was devised for the study area as required by the anticipated discretization of a planned groundwater flow model; the flow model is being constructed in California State Plane feet coordinates; as a result the texture model was constructed in feet, rather than in metric units. The tops and bottoms...
Figure 11. Perspective views of multiple vertical sections cut through solid volume three-dimensional (3D) stratigraphy model of the Santa Rosa Plain. UTM—Universal Transverse Mercator. DEM—digital elevation model. (A) View from southeast. (B) View from northwest. For a fully interactive 3D image, see Supplemental Figure 2 in Appendix 2.

EXPLANATION

- Glen Ellen Formation
- Wilson Grove Formation
- Neogene volcanics
- Petaluma Formation
- Undifferentiated basement

View is from the southeast looking to the northwest from an elevation 30 degrees above the horizon. Vertical exaggeration is 4x. Colors appear variable due to the effects of illumination from above and northeast.

View is from the northwest looking to the southeast from an elevation 45 degrees above the horizon. Vertical exaggeration is 4x. Colors appear variable due to the effects of illumination from above and northeast.
of the 16 layers are parallel to the land surface as defined by a DEM. Within each layer, grid cells were 660 ft (~198 m) in the x, y dimension and of a thickness defined for each layer. The top 4 layers are 50 ft (~15 m) thick, the next 8 layers are 100 ft (~30 m) thick, and the bottom 4 layers are 500 ft (~150 m) thick, such that the base of the model volume is 3000 ft (~900 m) below land surface. This discretization scheme created 26,376 grid cells in each layer; a total of 422,016 cells composed the model domain.

Textural classes were defined by grouping the lithologic classes used in constructing the 3D lithologic model. Textural classes were based on the percentage of coarse-grained lithologic classes and on degree of sorting; the relative proportion of clay matrix was considered an important variable. Resultant texture classes (Table 2) included coarse grained, intermediate, and fine grained; volcanic rocks did not fit into this scheme and were retained as two additional classes. Using this classification, three texture models were constructed with grid cells 660 ft (~198 m) in the x and y dimension and vertical discretizations of 50 ft, 100 ft, and 500 ft (~15, ~30, and ~150 m) thickness, respectively. Using a geographic information system (GIS), each grid cell for each of the 16 layers was attributed with texture class by intersecting the layering scheme with the classified data from a textural model. Layers 1–4 [each 50 ft (~15 m) thick] were populated with texture by sampling the texture model with 50 ft vertical discretization; layers 5–12 [each 100 ft (~30 m) thick] were populated with texture by sampling the texture model with 100 ft (~30 m) vertical discretization; and layers 13–16 [each 500 ft (~150 m) thick] were populated with texture by sampling the texture model with 500 ft (~150 m) vertical discretization. Stratigraphic units were assigned a numeric code (Table 3). Using a GIS, each grid cell for each of the 16 layers was attributed with stratigraphic unit by intersecting the layering scheme with the 3D stratigraphic framework and assigning the stratigraphic unit that the centroid of each cell is within.

Numeric values for textural class and stratigraphic unit were added to create a new combined attribute called “strat_text” (Tables 4 and 5). This attribute combines stratigraphy and texture class such that gravels in the Petaluma Formation can be distinguished from gravels in the Glen Ellen Formation or Wilson Grove Formation. Because each formation largely represents a distinct depositional setting, and gravels may have different sorting characteristics and presence of fine matrix, this distinction is of use in identifying permeability differences between units. The results of sampling the 3D solid volume texture and stratigraphy models and combined attribute strat_text are shown for layers 1–5 (Plate 1), layers 6–10 (Plate 2), and layers 11–16 (Plate 3).

### TABLE 2. DESCRIPTION OF TEXTURE CLASSES

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<th>Texture number</th>
<th>Descriptor</th>
<th>Lithologic classes* included in texture class</th>
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</thead>
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<tr>
<td>1</td>
<td>Coarse grained</td>
<td>Conglomerate; sandstone and gravel; gravel; sand and clay; clay, sand, and gravel; sand and gravel; sand; sandstone</td>
</tr>
<tr>
<td>2</td>
<td>Intermediate</td>
<td>Clay and gravel</td>
</tr>
<tr>
<td>3</td>
<td>Fine grained</td>
<td>Clay and sand; clay; sandstone and clay; clay and trace gravel; clay and sandstone; clay, sand and trace gravel</td>
</tr>
<tr>
<td>4</td>
<td>Tuff</td>
<td>Ash and/or tuff</td>
</tr>
<tr>
<td>5</td>
<td>Basalt</td>
<td>Basalt</td>
</tr>
<tr>
<td>0</td>
<td>No classified</td>
<td>Undifferentiated basement; volcanic conglomerate; shells; undefined</td>
</tr>
<tr>
<td>98</td>
<td>No data</td>
<td>Areas where layer is above of below the texture model</td>
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</tbody>
</table>

*Lithologic classes from three-dimensional lithology model.

### TABLE 3. NUMERIC CODES USED FOR STRATIGRAPHIC UNITS

<table>
<thead>
<tr>
<th>Numeric code</th>
<th>Stratigraphic unit</th>
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</thead>
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<td>1000</td>
<td>Glen Ellen Formation and equivalents and Quaternary alluvial deposits</td>
</tr>
<tr>
<td>2000</td>
<td>Wilson Grove Formation</td>
</tr>
<tr>
<td>3000</td>
<td>Neogene volcanics</td>
</tr>
<tr>
<td>4000</td>
<td>Petaluma Formation</td>
</tr>
<tr>
<td>5000</td>
<td>Mesozoic basement rocks, undivided</td>
</tr>
</tbody>
</table>

### TABLE 4. NUMERIC CODES USED FOR STRATIGRAPHIC UNITS

<table>
<thead>
<tr>
<th>Stratigraphic unit (numeric code)</th>
<th>Texture class (texture number)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coarse grained (1)</td>
</tr>
<tr>
<td>Glen Ellen (1000)</td>
<td>1001</td>
</tr>
<tr>
<td>Neogene volcanics (3000)</td>
<td>3001</td>
</tr>
<tr>
<td>Petaluma Formation (4000)</td>
<td>4001</td>
</tr>
<tr>
<td>Basement, undivided (5000)</td>
<td>5000</td>
</tr>
</tbody>
</table>

Sweetkind et al.
basins that underlie the Santa Rosa Plain, and the relation to volcanism in the nearby Sonoma volcanic field. Without strict age control on many of the wells, analysis of basin evolution depends upon interpretations of lithologic patterns tied to a limited number of wells with age control and relatively rare deep well penetrations into the basin.

Structural Controls on Depositional Trends and Thickness in the Glen Ellen Formation

The contoured thickness of the Glen Ellen Formation (Fig. 9A) shows distinctly greater thickness in the Windsor Basin, to the north of the Trenton Ridge, than in the Cotati Basin to the south. Stratigraphic maps of the shallowest layers (Plate 1) highlight the dominance of the Pliocene–Pleistocene gravels (Glen Ellen Formation) and the confinement of the thickest deposits to north of the Trenton Ridge. Beneath Pleistocene fans of the Cotati Basin the Glen Ellen Formation is thin and irregularly distributed, but in the Windsor Basin the formation is at least 165 m thick. Between 100 and 150 ft (~30–45 m) below land surface, the Pliocene–Pleistocene gravels are interpreted to exist only north of the ridge (Plate 2). The thickest deposits appear to occupy sinuous depocenters that have general northeast-southwest trends (Fig. 9A).

Paleoflow data and the distribution of chemically fingerprinted obsidian clast suites show that Glen Ellen gravels in the Windsor and Cotati Basins were deposited by separate west-flowing, interfingering fluvial systems. Paleoflow directions collected from the Glen Ellen Formation indicate deposition in west-southwest–flowing fluvial systems that were nearly orthogonal to the Rodgers Creek–Healdsburg and Maacama fault zones (McLaughlin et al., 2005), consistent with the isopach trends. Obsidian pebbles in gravels of the Glen Ellen Formation within the Windsor Basin came from a 2.8 Ma obsidian source area in northwestern Napa Valley (McLaughlin et al., 2005). In contrast, gravels in the Cotati Basin contain obsidian clasts that correlate to 4.5 Ma volcanic source areas in northwestern Sonoma Valley and the volcanic uplands to the east of Santa Rosa (McLaughlin et al., 2005). This suggests that drainage across the Rodgers Creek–Healdsburg fault zone from northwestern Sonoma Valley into the Windsor Basin was blocked by the Trenton Ridge during the deposition of these gravels between 3 and

<table>
<thead>
<tr>
<th>strat_text code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>Glen Ellen Formation without a texture assignment; assigned as the texture most typical of the formation, and thus assumed to be similar to 1001 (Glen Ellen coarse gravels).</td>
</tr>
<tr>
<td>1001</td>
<td>Coarse-grained Glen Ellen Formation; dominantly gravel and sand + gravel as relatively thin beds.</td>
</tr>
<tr>
<td>1002</td>
<td>Intermediate-grained Glen Ellen Formation; poorly sorted mixtures of clay and gravel, as relatively thin beds.</td>
</tr>
<tr>
<td>1003</td>
<td>Fine-grained Glen Ellen Formation, typically as clay or clay, sand and gravel, as relatively thin beds.</td>
</tr>
<tr>
<td>1004</td>
<td>Ash or tuff defined by borehole data in the texture model, but within the Glen Ellen Formation in the three-dimensional (3D) stratigraphic model. Likely to be Neogene volcanics; common in Rincon Valley and Valley of the Moon where selection of top of Neogene volcanics is complicated by interbedding of sedimentary and volcanic rocks.</td>
</tr>
<tr>
<td>1005</td>
<td>Basalt defined by borehole data in the texture model, but within the Glen Ellen in the 3D stratigraphic model.</td>
</tr>
<tr>
<td>2000</td>
<td>Wilson Grove Formation without a texture assignment; assigned as the texture most typical of the formation, so assumed to be similar to 2001 (Wilson Grove mostly coarse grained).</td>
</tr>
<tr>
<td>2001</td>
<td>Coarse-grained Wilson Grove Formation, dominantly thick beds of medium-grained sandstone and sand + gravel.</td>
</tr>
<tr>
<td>2002</td>
<td>Intermediate-grained Wilson Grove Formation; relatively minor distribution, often occurs where Wilson Gove and Petaluma Formations interfinger.</td>
</tr>
<tr>
<td>2003</td>
<td>Fine-grained Wilson Grove Formation; typically as thick beds of very fine-grained sandstone with shells; drillers typically call the lower marine facies of the Wilson Grove clay.</td>
</tr>
<tr>
<td>2004</td>
<td>Ash or tuff defined by borehole data in the texture model, but within the Wilson Grove in the 3D stratigraphic model. Includes two rock types; in the vicinity of Freestone, WSW of Sebastopol, unit is dominantly a nonwelded ash 10-15' thick, at least some of which is the nonwelded Roblar tuff of the Neogene volcanics. In the southwestern part of the model domain, near Bloomfield and Two Rock, unit includes older volcanics, probably Burdell Mountain Volcanics, below the Wilson Grove Formation.</td>
</tr>
<tr>
<td>2005</td>
<td>Code would correspond to basalt defined by borehole data in the texture model, but within the Wilson Grove in the 3D stratigraphic model; this combination does not occur in any cell.</td>
</tr>
<tr>
<td>3000</td>
<td>Neogene volcanics without a texture assignment; assigned as the texture most typical of the formation, so assumed similar to 3004 (Neogene volcanics as ash and/or tuff).</td>
</tr>
<tr>
<td>3001</td>
<td>Neogene volcanics in which texture model assignment is coarse grained. In places, especially north of the city of Santa Rosa, top of volcanics was chosen at first intercept of volcanic rock, even if there were sedimentary rocks beneath it. Thus, the Neogene volcanics hydrogeologic unit may include sedimentary rocks where they are interbedded with volcanics. This classification can also arise as a model artifact; where borehole data are sparse, horizontal extrapolation of texture values may populate cells with a coarse-grained attribute whereas the irregular grid that defines top of volcanics may define the cell as being within Neogene volcanics.</td>
</tr>
<tr>
<td>3002</td>
<td>Neogene volcanics in which texture model assignment is intermediate grained.</td>
</tr>
<tr>
<td>3003</td>
<td>Neogene volcanics in which texture model assignment is fine grained.</td>
</tr>
<tr>
<td>3004</td>
<td>Neogene volcanics in which texture model assignment is ash and/or tuff.</td>
</tr>
<tr>
<td>3005</td>
<td>Neogene volcanics in which texture model assignment is basalt.</td>
</tr>
<tr>
<td>4000</td>
<td>Petaluma Formation without a texture assignment; assigned as the texture most typical of the formation, so assumed similar to 4003 (Petaluma mostly fine grained).</td>
</tr>
<tr>
<td>4001</td>
<td>Coarse-grained Petaluma Formation, dominantly sand and sandy gravels that occur as lenses or channels.</td>
</tr>
<tr>
<td>4002</td>
<td>Intermediate-grained Petaluma Formation, poorly sorted mixtures of clay and gravel that occur as lenses or channels.</td>
</tr>
<tr>
<td>4003</td>
<td>Fine-grained Petaluma Formation, often present as thick, monotonous intervals.</td>
</tr>
<tr>
<td>4004</td>
<td>Ash or tuff defined by borehole data in the texture model, but within the Petaluma in the 3D stratigraphic model. Common near the contact of the Neogene volcanics and the Petaluma Formation, where the texture model may have horizontally extrapolated tuff lithology into cells assigned as Petaluma; also present in the lower model layers where Petaluma may be interfingered with Neogene volcanics or older volcanics such as Tolay Volcanics.</td>
</tr>
<tr>
<td>4005</td>
<td>Basalt defined by borehole data in the texture model, but within the Petaluma Formation in the 3D stratigraphic model.</td>
</tr>
<tr>
<td>5000</td>
<td>All Mesozoic basement, as defined by the 3D hydrogeologic framework model, was assigned a single value, without any textural classes.</td>
</tr>
</tbody>
</table>
Plate 1. Maps showing discretized results from three-dimensional (3D) stratigraphy model, solid volume 3D texture class model, and attribute strat_text (see text) for layers 1–5. Thin horizontal and vertical lines portray the grid cell discretization, which consists of 168 rows and 157 columns of cells 660 ft (~198 m) on a side. The locations of drill holes that are deep enough to penetrate the upper surface of each layer, and thus serve as a point of geologic information for that layer, are shown on the stratigraphy maps. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00513.SP1 or the full-text article on www.gsapubs.org to view the large-format file of Plate 1.
Plate 2. Maps showing discretized results from three-dimensional (3D) stratigraphy model, solid volume 3D texture class model, and attribute strat_text (see text) for layers 6–10. Thin horizontal and vertical lines portray the grid cell discretization, which consists of 168 rows and 157 columns of square cells 660 ft (~198 m) on a side. The locations of drill holes that are deep enough to penetrate the upper surface of each layer, and thus serve as a point of geologic information for that layer, are shown on the stratigraphy maps. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00513.SP2 or the full-text article on www.gsapubs.org to view the large-format file of Plate 2.
Plate 3. Maps showing discretized results from three-dimensional (3D) stratigraphy model, solid volume 3D texture class model, and attribute strat_text (see text) for layers 11–16. Thin horizontal and vertical lines portray the grid cell discretization, which consists of 168 rows and 157 columns of square cells 660 ft (~198 m) on a side. The locations of drill holes that are deep enough to penetrate the upper surface of each layer, and thus serve as a point of geologic information for that layer, are shown on the stratigraphy maps. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00513.SP3 or the full-text article on www.gsapubs.org to view the large-format file of Plate 3.
l Ma. Paleoflow from northwestern Sonoma Valley was instead diverted southwestward, to the Cotati Basin side of the Trenton Ridge.

Seismic reflection profiles across the eastern side of the Windsor Basin (Williams et al., 2008) show a progressive increase in reflector dip beneath ~100–200 m, indicating active growth of the ridge within relatively young sediments. The ridge appears to affect sedimentation patterns, resulting in differing stratigraphic packages within the Windsor and Cotati Basins, the Windsor Basin being dominated at shallow depths (Plate 1) by the Glen Ellen Formation, and the Cotati Basin being dominated by the Petaluma Formation.

Identifying the Marine-Continental Transition

Interfingering of marine sandstone of the Wilson Grove Formation with transitional marine and nonmarine deposits of the Petaluma Formation is inferred to occur beneath the Santa Rosa Plain’s irregular northwest-trending boundary (Allen, 2003; Powell et al., 2004). Where the two formations interfinger, they represent an oscillating Miocene–Pliocene shoreline (Powell et al., 2004). The 3D stratigraphic model (Fig. 11; see stratigraphy column in Plates 1, 2, and 3) clearly highlights the location of the transition from the dominantly marine sands of the west to more heterogeneous, poorly sorted continental sediments. This transition consists of an irregular northwest-trending boundary, regardless of the formation in which the interval was interpreted.

The stratigraphic-texture maps between 150 and 500 ft (~45–150 m) below land surface (Plates 1 and 2) contain sufficient drill-hole data to highlight the lithologic variability within the Petaluma Formation and its overall heterogeneous nature. Although individual drill holes are often dominated by clay-rich sediment, the 3D distribution of data shows lenticular packages of spatially restricted sand and gravel deposits that may represent channels deposited in an overall estuarine environment. Allen (2003) cited ostracode and diatom data associated with the mudstones and diatomites as suggestive of deposition in fresh to brackish water (lagoonal?) settings. Local lenses of lignite are associated with the lagoonal to estuarine strata, suggesting deposition in a large river delta, embayment, or lagoon (Allen, 2003). Gravels of the Petaluma Formation are, in places, dominated by clasts derived from Franciscan Complex, Coast Range Ophiolite, and Great Valley Sequence sources. More commonly, 30–50% of gravel clast suites are derived from Tertiary volcanic sources to the east and/or the southeast, consistent with paleoflow data that suggest that nonmarine Petaluma gravels were deposited in a northwest–flowing fluvial system (Allen, 2003).

Relative Absence of Volcanic Rocks

The relative absence of volcanic rocks is a striking aspect of the subsurface maps of the Santa Rosa Plain, considering the area’s proximity to the Sonoma volcanic field to the east. Although many of the water wells are too shallow to penetrate a volcanic section at depth, even the rare deeper holes within the basin penetrate relatively few volcanic rocks. Two wells situated on the west side of the Santa Rosa Plain within the Cotati Basin penetrated 840 ft and 1070 ft (~252 m, ~321 m), respectively, of 5.8 Ma to ca. 4.5 Ma sedimentary section without intercepting volcanic rocks (Powell et al., 2006). Two oil exploration wells situated in the same part of the Cotati Basin penetrated 1460 ft and 2075 ft (~438 m, ~622 m), respectively, of sedimentary rocks without hitting volcanic rocks (California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, www.conservation.ca.gov/dog [July 2008]). The only oil exploration well within the Santa Rosa Plain to intercept volcanic rocks was at the south end of the Cotati Basin. This well penetrated the entire thickness of Petaluma Formation, which was interbedded with Tolay volcanic rocks before intersecting Mesozoic rocks at a depth of 5520 ft (~1656 m) (Wright, 1992).

The relative absence of volcanic rocks is consistent with the relatively quiet aeromagnetic signature from shallow sources over much of the basin (Langenheim et al., 2010). The relative absence of volcanic rocks within the basin may be due to the relatively localized nature of volcanism, where volcanic rocks are dominated by flows of generally limited spatial extent.

In the far southwest part of the study area, volcanic rocks described as basalts were reported near the base of the penetrated section in several wells. Neogene volcanic rocks are known to underlie the Wilson Grove Formation to the southeast and southwest of the Petaluma Valley (Bezore et al., 2002, 2003) and have been intercepted in the subsurface in the Petaluma Valley in oil and gas wells (Wagner et al., 2005). These rocks are probably related to the Tolay Volcanics or possibly the Burdell Mountain Volcanics. Volcanic rocks are not known to be present beneath the Wilson Grove Formation farther to the north near Sebastopol. The presence of volcanic rocks at the base of the marine section in the southwest part of the study area suggests that west-northwest–striking faults such as the Bloomfield fault may have a component of dextral offset such that these older volcanic rocks are offset to the northwest from localities farther to the southeast (e.g., McLaughlin et al., 1996).

Generalized Depositional History of the Santa Rosa Plain

In contrast to previous stratigraphic interpretations (Cardwell, 1958; California Department of Water Resources, 1975, 1982), the drill-hole lithology data and resulting 3D lithologic model emphasize the lateral extent of clay-rich Petaluma Formation throughout the deeper parts of the basins that underlie the Santa Rosa Plain (Figs. 8 and 11). Previous studies have generally interpreted Wilson Grove Formation and Neogene volcanic rocks to underlie the Santa Rosa Plain. The interpreted subsurface extent of the Petaluma Formation is surprising given that, in contrast to Petaluma Valley to the south, outcrops of the Petaluma Formation are uncommon.
around the margins of the Santa Rosa Plain. The formation crops out to the east of the Santa Rosa Plain, where it is involved within the Rodgers Creek fault zone, and is exposed in the core of fault-bounded Meacham Hill anticline at the southern boundary of the Santa Rosa Plain; no Petaluma Formation crops out to the west or northwest of the Santa Rosa Plain where the Wilson Grove Formation unconformably overlies pre-Cenozoic rocks (Fig. 1).

Both the Cotati and Windsor Basins appear to contain Petaluma sediments (Plate 2) at depth, although the two basins are now separated by the Trenton Ridge. The Petaluma Formation is inferred to have been deposited within a single large basin that was subsequently segmented by the Trenton Ridge. The Petaluma Formation was deposited over a protracted time period during which strike-slip displacement propagated northward associated with northwestward movement of the Mendocino triple junction and the development of the San Andreas and related fault systems (Allen, 2003). Strike-slip offset in the North Bay is interpreted to have undergone a major reorganization ca. 9 Ma whereby slip was transferred from a proto-Hayward fault southwest of the Santa Rosa Plain, to faults on the east side of the Santa Rosa Plain (McLaughlin et al., 1996). This displacement transfer was accomplished across a major right step in the strike-slip system, which resulted in the extensional opening of the early Santa Rosa Plain basin. In this scenario, there was initially a single basin filled largely by deposition from a west-northwest-flowing, Miocene–late Pliocene fluvial to marine depositional system and also demonstrated the dominance of the marine-continental transition in some detail. Tentative 3D framework modeling allowed us to map stratigraphic units, and deep in the section facies transitions, where there is significant dip to stratigraphic units, and deep in the section where drill-hole data are scarce.

The compilation of drill-hole data and resultant 3D framework modeling allowed us to map the marine-continental transition in some detail and also demonstrated the dominance of the Petaluma Formation within most of the basins that underlie the Santa Rosa Plain. Structural facies transition is located very close to the western structural margin of the basin as defined by the gravity inversion. It appears that the western margin of the basin must have remained relatively high in order to prevent marine transgression into the Petaluma depocenter. Consistent with this interpretation, the thickness and facies patterns within the Wilson Grove Formation have been interpreted to suggest that the marine sands gradually lapped onto and buried preexisting paleotopographic highs of Franciscan basement (Powell et al., 2004).

CONCLUSIONS

This study relies heavily on lithologic information from water well data, usually assumed to be poor sources of geologic and lithologic information. However, our analysis and resulting 3D modeling show that drillers’ logs can provide valid lithologic information if the logs are carefully classified and screened. Although lacking time control, the 3D lithologic interpolation and identification of stratigraphic units work reasonably well where the units are relatively homogeneous and drill-hole data are abundant. Construction of 3D lithologic, stratigraphic, and textural models of the Santa Rosa Plain has resulted in several new interpretations regarding the thickness, extent, and 3D distribution of the important geologic units in the Windsor and Cotati Basins.

Interpretation of numerous drillers’ logs from the Santa Rosa Plain has allowed for the delineation of the principal stratigraphic units, each of which had a reasonably distinct mappable character in the subsurface. Drillers’ descriptions tend to use unique, albeit simple, lithologic nomenclature to describe each downhole interval, and do not tend to repeat these descriptions in a single hole. Careful classification and screening of these data produced a surprisingly clean lithologic data set. Although lacking time control, the 3D lithologic interpolation and identification of stratigraphic units work reasonably well where the units are relatively homogeneous and drill-hole data are abundant. The models break down in the vicinity of rapid facies transitions, where there is significant dip to stratigraphic units, and deep in the section where drill-hole data are scarce.

The southernmost cross section, A–A′′′′ (Fig. A1-2) crosses the south end of the study area in Petaluma Valley, south of the Santa Rosa Plain. This section is south of the region where stratigraphy was interpreted (Fig. A1-1C), so modeled stratigraphy is not shown on the section. However the sandy and sand and clay lithologic units on the west half of the section (Figs. A1-2A, A1-2B) are typical of the Wilson Grove Formation, and the eastern half of the section is dominated by fine-grained units characteristic of the Petaluma Formation. In general pattern, the modeled lithology is very similar to the previously published interpretation (Fig. A1-2C). The nature of the contact between the two major units cannot be determined from the lithologic model alone, but it is likely fault related. No gravelly lithologic units characteristic of the Glen Ellen Formation are evident in the shallow subsurface. Volcanic units appear at depth in the lithology model on the east side of the section, where they are interbedded within the Petaluma Formation. Sonoma Volcanics were interpreted to occupy the deepest portion of the basin in the previously published interpretation (Fig. A1-2C), based on the existence of outcrops of volcanic rocks to the south of Petaluma Valley; the lithologic models suggest that Neogene volcanic rocks do not project as far north as this section line.

Cross-section line B–B′′′′ traverses the southern end of the Santa Rosa Plain, extending through the town of Rohnert Park in a southwest-northeast trend (Fig. A1-1A). On the west (Fig. A1-3A), a relatively thin section of sandy and sand and clay lithologic

APPENDIX 1

3D Lithologic and Stratigraphic Model Results Compared to Published Cross Sections

A groundwater resources evaluation of Sonoma County (California Department of Water Resources, 1975, 1982) included 12 geologic cross sections depicting inferred geology beneath the Santa Rosa Plain. Eight of the cross-section lines crossed the entire county (California Department of Water Resources, 1975); the remaining four sections were confined to the southern half of the Santa Rosa Plain (California Department of Water Resources, 1982). It is clear that these sections were constructed on the basis of geologic map and well data, but the specific data sources used for each section are unknown. In order to make comparisons with these earlier interpretations and to directly compare the results of the 3D subsurface lithologic and stratigraphic models, we cut vertical profiles through our solid models of lithology and stratigraphy along the same lines of section as seven of the previously published cross sections (Fig. A1-1).

End points and section bends from the published cross sections were located in a GIS by georeferencing the index maps from the published reports. Cross sections were constructed through both the 3D solid volume lithologic and stratigraphic models along these same lines of section (part B in Figs. A1-2–A1-8). The original published cross sections were digitized (part C in Figs. A1-2–A1-8) and then scaled to match the cross sections from our models. Each cross section illustration also includes lithologic logs from all drill holes within 500 m on either side of the section line (part A in Figs. A1-2–A1-8); drill holes were projected onto the section perpendicular to the trend of the section line. The drill-hole data provide a convenient display of the density of the subsurface data and the strength (and limitations) of the numerical interpolation.
**Figure A1-1.** (A–C) Index geologic map showing the trace of previously published geologic cross sections and perspective views of vertical sections cut through three-dimensional (3D) solid volume lithology and stratigraphy models along the same lines of section. All three images have the same viewpoint from the south (185°) looking to the north from an elevation of 35° above the horizon. Colors appear variable due to the effects of illumination in the 3D views. UTM—Universal Transverse Mercator.

**A** Index geologic map showing cross section locations

**B** Perspective 3D view of vertical sections cut through 3D lithology model

**C** Perspective 3D view of vertical sections cut through 3D stratigraphy model
Figure A1-2. (A) Drill-hole lithologic data. (B) Three-dimensional (3D) solid volume lithology model results. (C) Comparison to previously published geologic cross-section A–A′. Lithologic logs are shown for all drill holes within 500 m on either side of the section line; drill-hole data projected onto the section may not necessarily match the land surface elevation and/or the lithologic modeling results portrayed along the line of section.
Figure A1-3. (A) Drill-hole lithologic data. (B) Three-dimensional (3D) solid volume lithology model results. (C) Comparison to previously published geologic cross-section B′-B′′. Lithologic logs are shown for all drill holes within 500 m on either side of the section line; drill-hole data projected onto the section may not necessarily match the land surface elevation and/or the lithologic modeling results portrayed along the line of section.
units characteristic of the Wilson Grove Formation is truncated against the structurally complex Meacham Hill anticline (Clahan et al., 2003), as suggested by the irregular Petaluma Formation–Neogene volcanics contact in the stratigraphic model (Fig. A1-3B), but not captured by the horizontal interpolation of the 3D lithologic model except as an abrupt transition to clay-rich Petaluma Formation. East of the Sebastopol fault, the published section (Fig. A1-3C) interprets a dipping section that includes the Wilson Grove and Glen Ellen Formations. In this location both the Wilson Grove and the Petaluma Formations become gravelly, representing a transition to a more continental facies (Powell et al., 2004), mapped as gravel of the Cotati Formation (Fox, 1983; Clahan et al., 2003). In the stratigraphic model these sandy and gravelly facies were assigned to the Petaluma Formation (Fig. A1-3B), although they are known to be transitional. On the east side of the sections both the Rodgers Creek and Bennett Valley faults are expressed as abrupt change in lithologic packages and the appearance of the Neogene volcanics. Again the 3D lithologic model does not incorporate the structural complexity associated with these faults and implied by the irregular top of the Petaluma Formation (Fig. A1-3B), except as abruptly terminating local packets of lithology that cannot be extrapolated very far.

Section C–C′ is >38 km long and crosses the central part of the Santa Rosa Plain in a southwest-northeast–trending direction through the city of Santa Rosa (Fig. A1-1A). The west end of the section is dominated by sandy and sand and clay lithologic units (Fig. A1-4A) characteristic of the Wilson Grove Formation (Fig. A1-4B). Volcanic units appear at the base of the Wilson Grove section on the west, where they probably represent buried Tolay or Burdell Mountain Volcanics, and near the top of the section, where they represent ash, welded tuff including outcrop of Roblar tuff (Sarna-Wojcicki, 1992).

The marine-continental facies transition between Wilson Grove Formation and Petaluma Formation is evident from the lithologic model (Fig. A1-4A) beneath the tiepoint with section A2–A2′ (Fig. A1-4B), to the east of the Sebastopol fault. The top of the Wilson Grove Formation is offset in an east-side-down manner by the Sebastopol fault. The steeply dipping black line that transects the sandy lithology of the Wilson Grove Formation near the Sebastopol fault (Fig. A1-4B) is the Wilson Grove–Petaluma contact as derived from the 3D stratigraphic model. The location and orientation of this contact between the two formations are obtained via the method by which the base of the Wilson Grove Formation was forced to honor the depth-to-basement surface beneath outcrops of the formation. Basinward, where the Wilson Grove Formation is covered, the base of the formation climbs steeply because the transition zone between the Wilson Grove Formation and Petaluma Formations was always coded as Petaluma Formation when picking stratigraphic tops from the well data. For the stratigraphic model, where units must maintain a prescribed stacking order, the base of the Wilson Grove Formation must climb high in the section to overlie the Petaluma Formation. However, the lithology model clearly shows that the Wilson Grove Formation extends some distance eastward into the basin to the transition between the two formations.

The fine-grained units typical of the Petaluma Formation fill most of the center of the basin (Fig. A1–4B), an interpretation not consistent with that of older cross sections (Fig. A1-4C). Intervals interpreted as Petaluma Formation include locally thick but discontinuous gravel packages. To the northeast of the Trenton Ridge, the Glen Ellen Formation shows a distinct thickening and the underlying Petaluma Formation alternates with intervals of Neogene volcanics. Volcanic units predominate east of the Rodgers Creek fault, along with a thick interval of Glen Ellen Formation in Rincon Valley to the east of the city of Santa Rosa, near the trace of the Bennett Valley fault.

Section line D–D′ crosses the north-central part of the Santa Rosa Plain on a southwest-northeast trend, nearly parallel to section C–C′ (Fig. A1-1A). On the west end of the section, a relatively thin section of sand and sand and clay lithologic units characteristic of the Wilson Grove Formation overlies the basement rocks (Fig. A1-5A). This depositional unit projects east beyond the Sebastopol fault and is truncated at the northwest end of the Trenton Ridge, where to the northeast the basin fill is primarily clay-dominated units of the Petaluma Formation capped by relatively thick, gravel-dominated Glen Ellen Formation (Fig. A1-5B). This section transects the Windsor Basin, where the Glen Ellen Formation has been shown to be as thick as 160 m in certain drill holes. It is likely that the stratigraphic model, based on numerous shallow water wells, underestimates the thickness of the Glen Ellen Formation here. Neogene volcanics dominate to the east of the Rodgers Creek fault, and continue eastward to the Maacama fault, where they are faulted against basement rocks (McLaughlin et al., 2004). The overall geometry is similar between the sections cut through the 3D models and the previous published section (Fig. A1-5C), however, the published section describes the basin-filling clay section as Glen Ellen Formation, rather than Petaluma Formation, and the published section infers that the Wilson Grove Formation might extend beneath the entire basin, an interpretation that does not appear to be supported by the subsurface data and how the stratigraphic units were selected from the lithology packages.

Cross-section line A2–A2′ extends from the southern end of the Santa Rosa Plain to the southeast of the town of Rohnert Park (Fig. A1-1A). Drill-hole data and the resultant 3D lithologic model (Fig. A1-7A) portray a clay-rich section with discrete lenses and sand and gravel. The published cross section (Fig. A1-7C) infers that the Wilson Grove Formation is present at depth along the entire section line; the 3D stratigraphic model includes the discontinuous sandy facies within the Petaluma Formation (Fig. A1-7B), with only thin intervals of overlying Glen Ellen and Wilson Grove Formation sediments. The section trends northwest along the west side of the basin, parallel to the trend of the facies transition between the Wilson Grove Formation and the Petaluma Formation. It is likely that the lenses of sand and gravel material may represent interfingerings of the two facies; such transitional intervals were routinely coded as Petaluma Formation when picking stratigraphic tops from the well data. The published cross section (Fig. A1-7C) suggests that the Sebastopol fault is crossed at the north end of the section, an interpretation that does not appear to be supported by the available lithologic data.

Cross-section line D2–D2′ trends generally west to east across the southernmost part of the basin, through the town of Rohnert Park (Fig. A1-1A). The line intersects the Rodgers Creek fault on the east side (Fig. A1-8). West of the fault, the Glen Ellen Formation is interpreted to overlie a thick section of the Petaluma Formation (Fig. A1-8B). The discontinuous gravels within the Petaluma probably represent a part of the continental-marine transitional facies known to occur at the south end of the basin. In the published section Fig. A1-8C), the Wilson Grove Formation is projected at depth in the center of the basin, offset by the Sebastopol fault; this interpretation is not apparent from the available lithologic data or the results of the 3D modeling.
Figure A1-4. (A) Drill-hole lithologic data. (B) Three-dimensional (3D) solid volume lithology model results. (C) Comparison to previously published geologic cross-section C–C'. Lithologic logs are shown for all drill holes within 500 m on either side of the section line; drill-hole data projected onto the section may not necessarily match the land surface elevation and/or the lithologic modeling results portrayed along the line of section.
Figure A1-5. (A) Drill-hole lithologic data and lithology model. (B) Three-dimensional (3D) solid volume lithology model results. (C) Comparison to previously published geologic cross-section D–D′. Lithologic logs are shown for all drill holes within 500 m on either side of the section line; drill-hole data projected onto the section may not necessarily match the land surface elevation and/or the lithologic modeling results portrayed along the line of section.
Figure A1-6. (A) Drill-hole lithologic data. (B) Three-dimensional (3D) solid volume lithology model results. (C) Comparison to previously published geologic cross-section H–H'''''. Lithologic logs are shown for all drill holes within 500 m on either side of the section line; drill-hole data projected onto the section may not necessarily match the land surface elevation and/or the lithologic modeling results portrayed along the line of section.
Figure A1-7. (A) Drill-hole lithologic data. (B) Three-dimensional (3D) solid volume lithology model results. (C) Comparison to previously published geologic cross-section A2–A2'. Lithologic logs are shown for all drill holes within 500 m on either side of the section line; drill-hole data projected onto the section may not necessarily match the land surface elevation and/or the lithologic modeling results portrayed along the line of section.
A Drill-hole lithologic data and lithology model

B Lithology and stratigraphy models

C Published interpretation

Figure A1-8. (A) Drill-hole lithologic data. (B) Three-dimensional (3D) solid volume lithology model results. (C) Comparison to previously published geologic cross-section D2–D2’. Lithologic logs are shown for all drill holes within 500 m on either side of the section line; drill-hole data projected onto the section may not necessarily match the land surface elevation and/or the lithologic modeling results portrayed along the line of section.
APPENDIX 2

3D Images of the Lithologic and Stratigraphic Model Results Using the Rockworks 3D Viewer—Rockplot3D

This appendix contains two supplemental files of dynamic three-dimensional images of certain statistic two-dimensional views included as figures in the main paper. The diagrams were created in the Rockworks 3D modeling software package (Rockware Earth science and GIS software: www.rockware.com) and are viewable and able to be manipulated using the Rockworks 3D viewer, RockPlot3D (available as a free software download at www.rockware.com/downloads/trialware.php#R [February 2010]).

RockPlot3D is a 3D display tool that is used for display of 3D objects, such as stratigraphic and solid models. RockPlot3D permits interactive movement of the display (rotate, zoom, pan) and easy viewing of image objects. A number of interactive tools, i.e., zoom, rotate, turn items on and/or off, are included, as well as print and export features. The 3D viewer comes with extensive help documentation; the short discussion here is meant to help the reader to quickly begin using the viewer to access the supplemental figures included in this appendix, and is not a substitute for the help menu.

In order to view Supplemental Figures 1 and 2 (see footnotes 1 and 2), users will have to perform the following general steps.

1. Download and install the RockPlot3D Viewer, from the RockWare website (http://www.rockware.com/downloads/trialware.php#R [February 2010]).
2. Unzip the supplemental 3D files and save them to a folder on the user’s computer.
3. Launch RockPlot3D and open the 3D files from within the viewer.

System Requirements

Minimum system requirements include the following: IBM-compatible computer running Windows 2000, NT, XP, or Vista, 512 MB of RAM (1GB recommended), Pentium III or newer CPU (1.4 GHz or faster recommended), 75 MB of free disk space for program installation, and display set to >800 x 600 pixels. Supports most Windows-supported peripherals. Neither Windows98 nor Windows ME are supported.

Unzipping the Supplemental 3D Files

RockPlot3D cannot open a ZIP-format file. To access the contents of the ZIP files, you will need to have a software program capable of extracting files from the ZIP archive. Many Windows-based machines have the utility WinZip, which decompresses a file and places it in the folder of your choice. Right-click or double-click on each of the zipped archives to Open WinZip, select Extract from the Actions pull-down menu or click the Extract toolbar button; WinZip then lets you choose the folder where you’d like to place the extracted files. Place all of the files in a directory of your choice.

Installing RockPlot3D

2. Choose Save, when prompted, and save the file to your computer’s desktop.

Recommended Procedure When Viewing Files in RockPlot3D

When the supplemental 3D file opens, it will not have the viewpoint or vertical exaggeration of the figure shown in the paper. Once opened, the user in encouraged to set the viewpoint using the command View>Custom View and enter in the compass bearing and the angle from horizon as described in this appendix for each figure. Enter the settings, click on the Apply button, then click on the close button. Then use the command View>Dimensions to set the vertical exaggeration specified for each figure in this appendix; alternatively, you could also use the vertical exaggeration button. At this point the 3D image will have a viewpoint and vertical exaggeration equal to that shown in the static image in the body of the paper. Then use the zoom and pan tools to zoom in to the diagram and view different parts.

Once the initial viewpoint has been set as a reference, feel free to change vertical exaggeration and/or use the rotate tool to view the diagram from different viewpoints. This tool is rather sensitive and takes a certain amount of practice. Be cognizant of the axis labels (up, down, north, south, east, west) in order to keep track of the view direction. One easy “fix” is to revert to a preset viewpoint using, for example, the command View>Dimensions to set the vertical exaggeration to 6.

In the left window, under the data list, the following data sets are part of this image.

Draped 100K topo: a 1:100,000-scale USGS topographic map draped on a regional-scale DEM (Graham and Pike, 1998) (this layer is provided for locational reference and is not shown in Fig. 1).

In the left window, under the list of linked files, the following data sets are part of this image.

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