Development of a three-dimensional model of sedimentary texture in valley-fill deposits of Central Valley, California, USA

Claudia C. Faunt · Kenneth Belitz · Randall T. Hanson

Abstract A three-dimensional (3D) texture model was developed to help characterize the aquifer system of Central Valley, California (USA), for a groundwater flow model. The 52,000-km^2 Central Valley aquifer system consists of heterogeneous valley-fill deposits. The texture model was developed by compiling and analyzing approximately 8,500 drillers' logs, describing lithologies up to 950m below land surface. The lithologic descriptions on the logs were simplified into a binary classification of coarse- and fine-grained. The percentage of coarse-grained sediment, or texture, was then computed for each 15-m depth interval. The model was developed by 3D kriging of the percentage of coarse-grained deposits onto a 1.6-km spatial grid at 15-m depth intervals from land surface down to 700m below land surface. The texture model reflects the known regional, spatial, and vertical heterogeneity in the aquifer system. The texture model correlates to sediment source areas, independently mapped geomorphic provinces, and factors affecting the development of alluvial fans, thus demonstrating the utility of using tcdrillers' logs as a source of lithologic information. The texture model is upscaled to a layered groundwater flow model for use in defining the hydraulic properties of the aquifer system.

Keywords USA · General hydrogeology · Geostatistics · Unconsolidated sediments

Received: 20 October 2008 / Accepted: 18 September 2009
Published online: 29 October 2009

Electronic supplementary material The online version of this article (doi:10.1007/s10040-009-0539-7) contains supplementary material, which is available to authorized users.

C. C. Faunt (✉) · K. Belitz · R. T. Hanson
US Geological Survey,
California Water Science Center, San Diego Projects Office,
4165 Spruance Road, Suite 200, San Diego, CA 92024, USA
e-mail: ccfaunt@usgs.gov
Tel.: +1-619-2256142
Fax: +1-619-225-6101

Introduction

For more than 50 years, California's Central Valley (Fig. 1) has been one of the most productive agricultural regions in the world. In an area of about 52,000 km^2, Central Valley produces over 250 different crops, which had an estimated value of 17 billion dollars in 2002 (Great Valley Center 2005, Fig. 1). The vast majority of crops is irrigated and relies on surface-water diversions and groundwater pumping. Approximately three-quarters of the irrigated land in California and one-sixth of the Nation's irrigated land is in Central Valley (Bureau of Reclamation 1994). About one-fifth of the Nation's pumped water is from its aquifers (Planert and Williams 1995). Because Central Valley contains so many communities, industries, and ecosystems that depend directly or indirectly on groundwater, and because competition for available water is intensifying, there is a need to quantify the region's water resources and the trends affecting them so that the potential for possible future water-use conflicts can be reduced or avoided. In response, the US Geological Survey (USGS) is assessing the availability and use of Central Valley's groundwater resources.

In order to understand the status of the groundwater system, the geologic framework, transmitting properties, and storage properties of the aquifer system are being assessed. The sand and gravel sediments underlying Central Valley make up the aquifer system. The primary purpose of this report is to assess the texture of the deposits in Central Valley (Fig. 1). Texture is defined as the percentage of coarse-grained sediment within a specified subsurface depth interval (Laudon and Belitz 1991). It is used as a basis for mapping the deposits. Although grain shape and sorting are often included as texture characteristics, they were not included as part of the texture classification used in this study. Statistical techniques used to analyze spatial correlations, commonly referred to as "geostatistics," were used to develop a spatial correlation model of the percentages of coarse-grained textures in Central Valley. The texture model developed in this study was evaluated in the context of regional geomorphology and depositional setting of Central Valley. This evaluation is summarized in the "Results and Discussion" section. The texture model was developed to provide information on the local-scale heterogeneity of the hydrogeologic framework and as a

 DOI 10.1007/s10040-009-0539-7

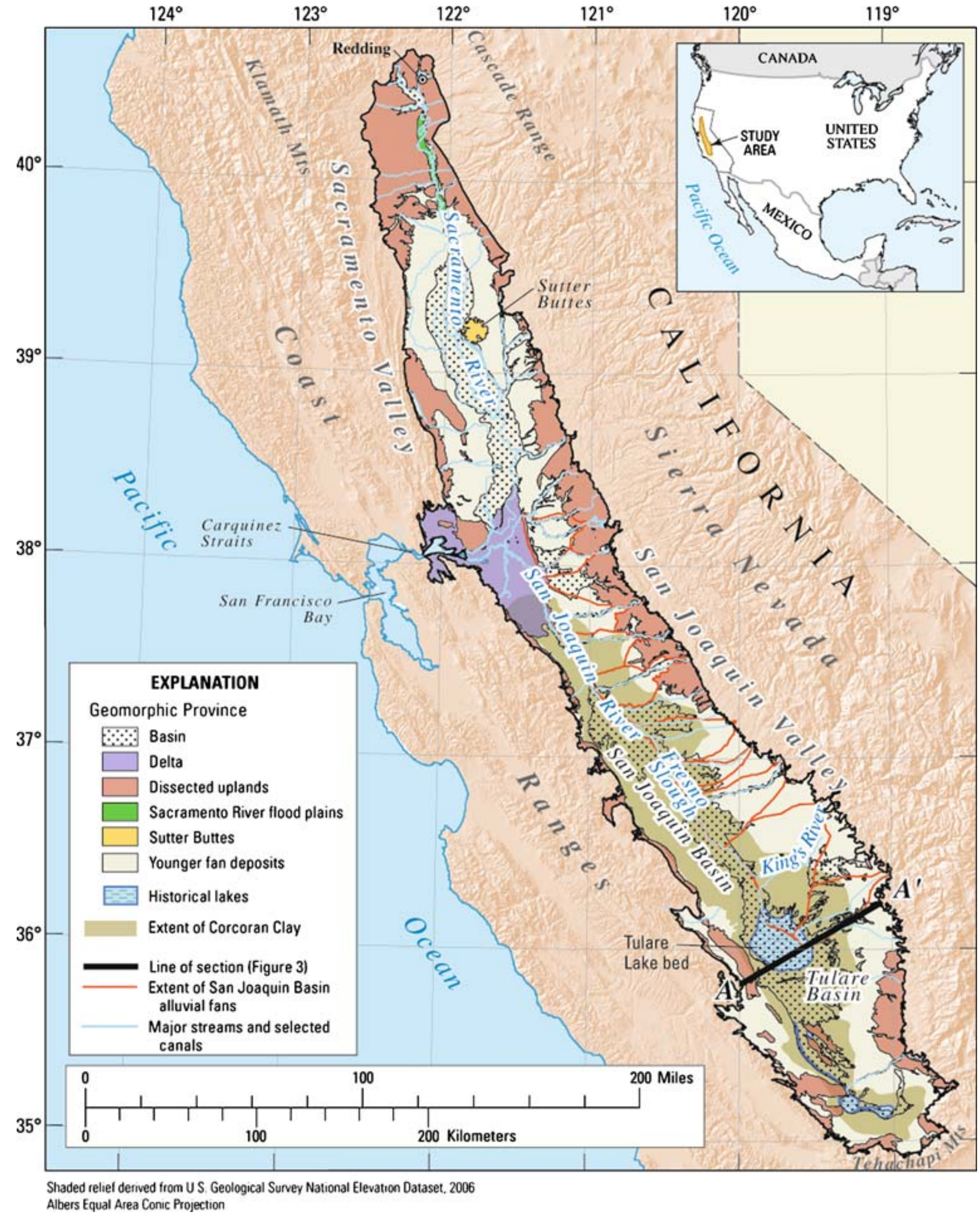


Fig. 1 Map of Central Valley showing major geomorphic provinces (modified from Davis et al. 1959; Olmsted and Davis 1961; Jennings 1977), alluvial fans of the San Joaquin Basin (Weissmann et al. 2005), and extent and thickness of Corcoran Clay (modified from Page 1986; Burow et al. 2004)

basis for estimates of hydraulic properties. The texture model may be used to assess vertical and lateral hydraulic conductivity and storage property distributions for a numerical groundwater flow model of the region.

Traditionally, assessing the geologic framework focuses on a description of the hydrogeologic or stratigraphic units that compose the aquifer system. For the purpose of estimating the groundwater storage capacity of the valley, Davis et al. (1959, 1964) were the first to extensively study the texture and volume of deposits in Central Valley. Although a number of stratigraphic deposits have been identified (Tuscan, Tehama, and Tulare formations), their spatial character as well as their lateral and vertical extent is poorly known. Because of the limited stratigraphic control, this study follows the methods used in several previous regional and site-specific investigations in the use of sediment texture as a continuous variable in Central Valley (Laudon and Belitz 1991; Belitz et al. 1993; Burow et al. 2004; C. Brush, US Geological Survey, personal communication, 2006; Phillips et al. 2007).

Recently, a variety of geostatistical approaches have been applied to specific areas within Central Valley, although these methods are too detailed or generally not applicable to a basin-scale approach. Phillips et al. (2007) used transition-probability geostatistical approaches (TProGS; Carle et al. 1998) to derive the spatial distribution of sedimentary hydrofacies in about 17 km^2 of the eastern San Joaquin Valley near the Merced River (Fig. 2a); Burow et al. (2004)

 DOI 10.1007/s10040-009-0539-7

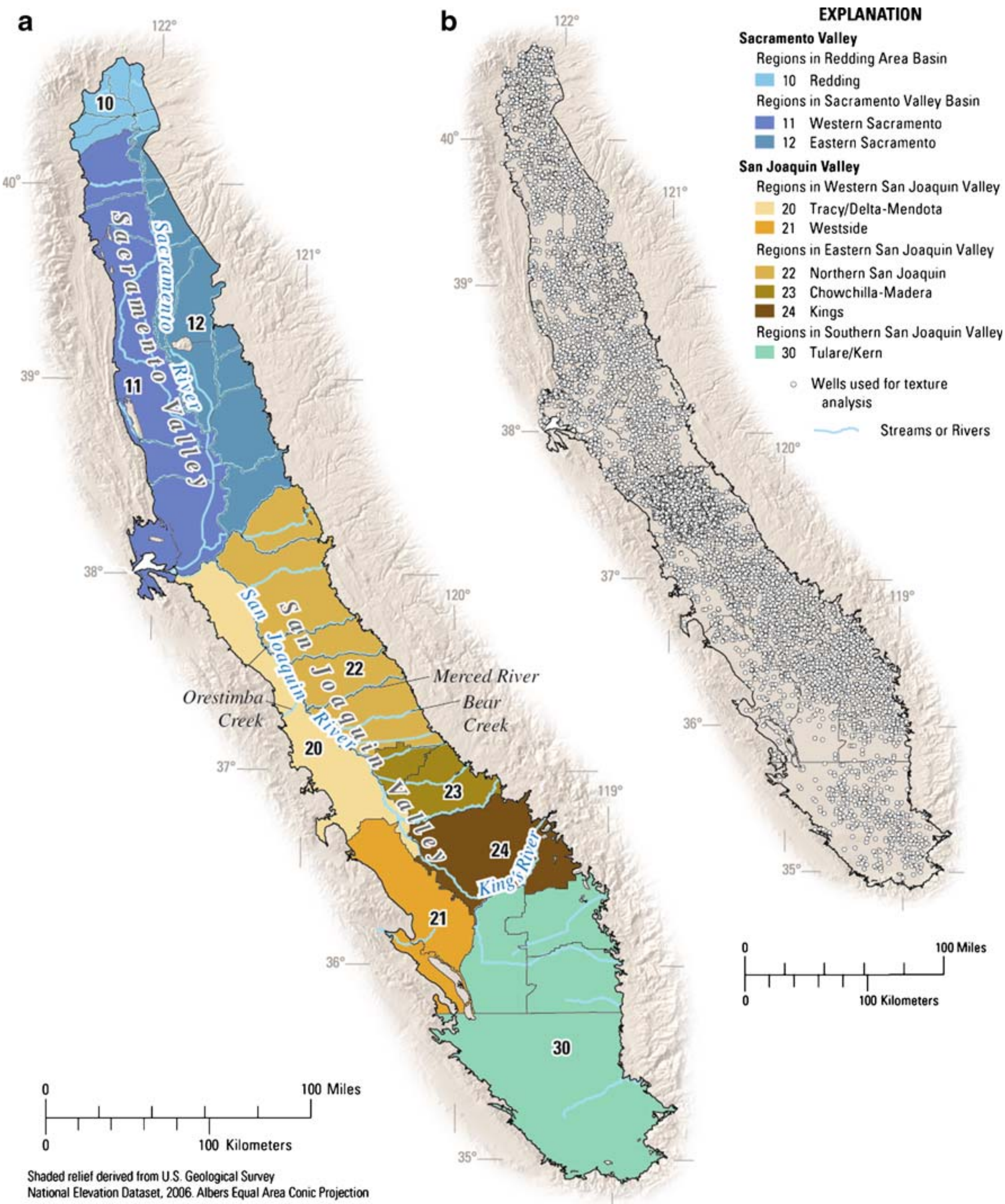


Fig. 2 **a** Map of Central Valley showing groundwater basins and subbasins, groups of basins and subbasins into spatial provinces and domains for textural analysis, and **b** distribution of wells used for mapping texture. Detailed description of the spatial provinces and domains are in Table 1. **c** Graph showing count of wells for each depth increment by domains

developed a 50-km^2 hydrofacies model near Modesto, and Weissmann et al. (2002) constructed a sequence stratigraphic model of the stream-dominated King's River alluvial fan by combining multiple adjacent individual TProGS realizations.

This study relies heavily on lithologic data from drillers' logs, which are frequently assumed to be poor sources of lithologic information. However, a number of previous studies in Central Valley have shown their utility if carefully used. Page (1986) utilized 685 geophysical logs to investigate the texture of deposits above the base of freshwater in the entire 52,000-km^2 area of Central Valley. Later investigations, particularly those by Laudon and Belitz (1991), show that drillers' logs can provide valid texture information if the logs are classified and screened on the basis of the degree of detail in the log. In addition to regional studies, different depth intervals at specific sites ranging from 1,300 to 2,600 km^2 in the west-central San Joaquin Valley have been studied (Prokopovich 1987; Belitz and Heimes 1990; Laudon and Belitz 1991; Belitz et al. 1993; C. Brush, US

 DOI 10.1007/s10040-009-0539-7

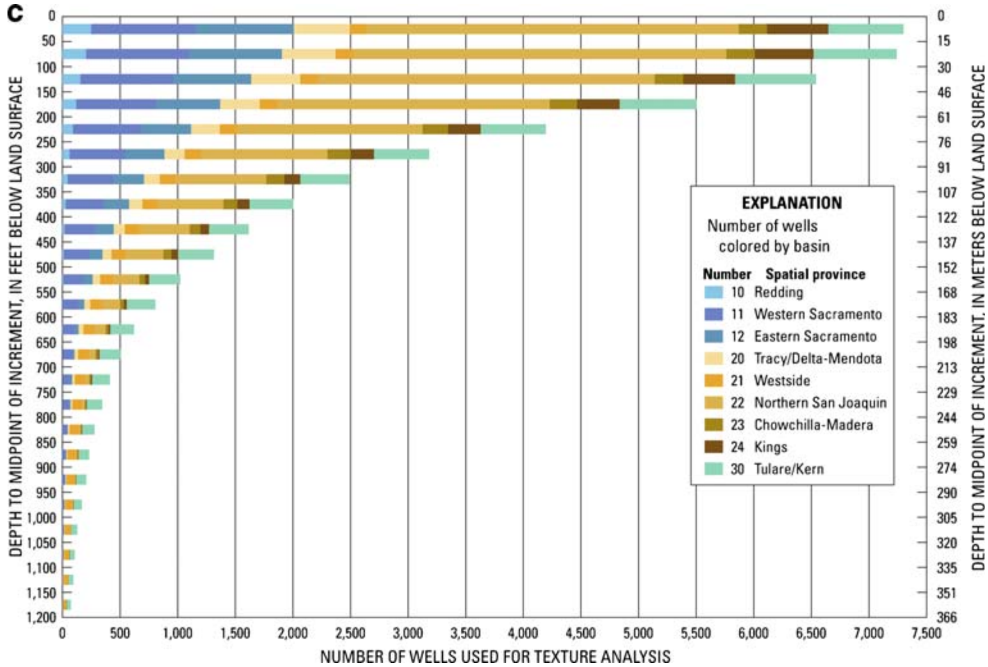


Fig. 2 (continued)

Geological Survey, personal communication, 2006). In the Brush (C. Brush, US Geological Survey, personal communication, 2006) study, they developed texture maps for the semi-confined aquifer above the Corcoran Clay (Fig. 1; further described in section Description of study area) for a 2,600 km^2 area in the western San Joaquin Valley. Burow et al. (2004) developed a 3D kriged estimate of the percentages of coarse-grained texture in the Modesto area in the eastern San Joaquin Valley. Although that study was based on more than 3,500 drillers' logs, it only covered an area of 2,350 km^2.

Description of study area

Central Valley, also known as the Great Valley of California, is one of the more notable structural depressions in the world. For convenience in discussion, the valley can be divided into two major parts: the northern one third is known as the Sacramento Valley, the southern two thirds as the San Joaquin Valley. The San Joaquin Valley is often split by topographic basins into the San Joaquin Basin and the Tulare Basin. The San Joaquin and the Sacramento Valleys meet in the delta area where the Sacramento and the San Joaquin Rivers converge (Fig. 1).

Many studies have been conducted summarizing the geology, geomorphology, and hydrogeology of Central Valley. Two comprehensive early reports on the geology and hydrogeology of the San Joaquin and Sacramento Valleys were done by Mendenhall et al. (1916) and Bryan (1923), respectively. Davis et al. (1959) wrote a comprehensive report on the San Joaquin Valley including a discussion of the diatomaceous clay that underlies a large part of the San Joaquin Valley. Repenning (1960) discussed the general stratigraphy of Central Valley. Olmsted and Davis (1961) wrote a comprehensive report on the geology, geomorphology, hydrogeology, and geologic history of the Sacramento Valley. Numerous other reports have also been written concerning specific areas or subjects within Central Valley.

Central Valley is virtually one large sediment-filled trough between the Coast Ranges and the Sierra Nevada. The Sierra Nevada, which forms the eastern side of the valley, is the eroded edge of a huge tilted block of crystalline rock. The valley fill overlies a westward-sloping surface of basement rocks that are the subsurface continuation of the Sierra Nevada. Throughout the history of the Sierra Nevada, the crestal elevations of the southern part of the range greatly exceed those of the northern part of the range (Farrar and Bertoldi 1988).

A huge volume of sediments of deep marine, shallow marine, deltaic, and continental origin fill Central Valley (Farrar and Bertoldi 1988). The sequence of valley fill deposits ranges in thickness from 0 along the western slopes of the Sierras on the eastern half of the valley to more than 16 km on the western edge of the valley (Wentworth et al. 1995). During and since marine deposition, sediments derived from erosion of igneous and metamorphic rocks and consolidated marine sediments in the surrounding mountains have been transported into the valley by streams. These continental sediments are as thick as 2,750 m at the southern end of the valley and have an average thickness of about 730 m (Planert and Williams 1995). The continental sediments consist mostly of basin-fill or lake deposits of sand and gravel interbedded and mixed with clay and silt. Depending upon location, deposits of fine-grained materials—mostly clay and silt—make up more than 50% of the thickness of the valley-fill sediments (Planert and Williams 1995).

 DOI 10.1007/s10040-009-0539-7

Olmsted and Davis (1961) and Davis et al. (1959) described geomorphic provinces of the Sacramento and San Joaquin Valleys, respectively. These geomorphic maps were combined with Jennings' (1977) map to develop a map of geomorphic provinces for the entire Central Valley (Fig. 1). The map shows the extent of the major alluvial fans in the valley as well as the dissected uplands and basins. Alluvial fans, some of which are over 300 m thick, have formed on all sides of Central Valley. Because the location and type of these provinces have been generally stable and continuous throughout the time of sediment deposition, the characteristics of these provinces relate to the character of the deposits.

Although the internal architecture of the deposits is not well understood, some general trends can be summarized from Page (1986). The sediments generally are characterized by two grain-size trends: (1) a downward fining trend in which grain sizes decrease and silt and clay content increases with depth and (2) a lateral trend in which sediments become finer-grained, and coarse-grained sand and gravel deposits become thinner with increasing distance from the sediment sources. The fine-grained detritus carried by streams is moved farther toward the valley axis, leaving the coarse-grained materials closer to the valley margins. The coarse-grained sediments in the fans are typically associated with large laterally migrating distributary stream channels. Over time, shifting stream channels cause the fans to coalesce, forming broadsheets of inter-fingering wedge-shaped lenses of gravel, sand, and finer detritus. The texture of these deposits relate to many geologic factors, including the texture of bedrock source materials, drainage basin area, elevation, and basin subsidence rate. These trends are similar to trends noted by Koltermann and Gorelick (1992) in an alluvial fan in a small coastal basin adjacent to Central Valley. Koltermann and Gorelick (1992) utilized large-scale process simulation to reconstruct the geologic evolution during the past 600,000 years. In this small basin and Central Valley, paleoclimatic trends induced fluctuations in stream flows and dominated the development of the sedimentary deposits.

Weissmann et al. (2005) recently looked at factors controlling sequence development of alluvial fans in the San Joaquin Valley (Fig. 1). They determined that the character of the fans is dependent on the fan's position in the basin and its drainage basin characteristics. In particular, four factors appear to control development of these fans: subsidence rates, ratio of degree of change in sediment supply to change in discharge, local base level changes, and basin width. These characteristics ultimately control the grain size and sorting of the deposits.

Textural analyses reported by Page (1986) and utilized by Williamson et al. (1989) also illustrate the fine-grained nature of the Sacramento Valley. A combination of mechanisms contribute to this fine-grained nature: (1) the drainage basins in the central and northern Sacramento Valley have lower elevations and a glacial system less significant than that farther south, and the Coast Ranges were higher, potentially creating a larger 'snow shadow' in the northern Sierra Nevada, prohibiting development of a substantial glacial system (Weissmann et al. 2005); (2) the largest glacial systems with substantial trunk glaciers were from Lake Tahoe southward (Weissmann et al. 2005); (3) there has been less subsidence in the Sacramento Valley compared with that in the Tulare Basin; and (4) a large part of the sediments in the Sacramento Valley were derived from fine-grained volcanic rocks (Olmsted and Davis 1961).

In the San Joaquin Valley, the texture varies from east to west. The Sierra Nevada is larger, higher and, because of their crystalline composition, generally more resistant to erosion than the Coast Ranges and provides a greater percentage of coarse-grained material to Central Valley. In general, the shale rich Coast Ranges yield finer-grained sediments in fans than the Sierra Nevada's on the eastern side of the valley. Near the valley axis, deposition in lacustrine and flood plain environments produced thick beds of clay and silt.

During the Pleistocene, as much as 19,000 km^2 in the San Joaquin Valley was covered by lakes that accumulated up to 50 m of diatomaceous clay, often referred to as the E-clay or the Corcoran Clay (Fig. 1; Farrar and Bertoldi 1988). The Corcoran Clay Member of the Tulare Formation of Pleistocene age is an extensive clay body and one of the few regionally mappable deposits in the valley. The three-dimensional (3D) thickness and extent of the Corcoran Clay defined by Page (1986) and later modified for the Modesto area by Burow et al. (2004) was used to define the area of the clay (Fig. 1). Except for the Corcoran Clay, the clays are generally not vertically extensive or laterally continuous. The Corcoran Clay divides the groundwater flow system of the western San Joaquin Valley into an upper semi-confined zone and a lower confined zone (Belitz and Heimes 1990). The coarser area below the Corcoran Clay is an exception to the general downward fining trend.

Overprinted on the spatial trends are climatic cycles, where fine-grained deposits are often interrupted by influxes of gravel during higher-energy wet periods. In parts of the San Joaquin Valley trough, Miller et al. (1971) mapped more than 150 m of Sierran sand below the flood-basin clays. According to Miller et al. (1971) and Laudon and Belitz (1991), the modern streams that deposited the flood-basin clays carry significantly less surface runoff from the Sierra Nevada now than when the Sierran sand was deposited.

Grain size and degree of sorting help determine the water-transmitting properties of aquifer sediments. Lateral and vertical variations in the texture of sediment affect the direction and magnitude of groundwater flow as well as the amount of compaction and ultimately subsidence. In Central Valley, trends in hydraulic conductivity parallel trends in grain size; the hydraulic conductivity of sediments generally decreases with depth and with increasing distance from sediment sources, or generally toward the valley axis (Page 1986). As expected, the most productive aquifers are within the coarse-grained deposits of alluvial origin. For the purpose of discussing the distribution of texture, Central Valley was split into nine regions based on groups of groundwater basins and subbasins (Fig. 2).

 DOI 10.1007/s10040-009-0539-7

First, the study area was split into its two dominant valleys, Sacramento and San Joaquin. The Sacramento Valley is influenced by volcanic activity and is generally finer grained, as is shown by the mean percentage of coarse grained deposits in Table 1, while the San Joaquin Valley is dominated by sediments eroded from the Sierra Nevada and the Coast Ranges. The Sacramento Valley was split into the major groundwater basins (California Department of Water Resources 2003): the Redding Area Basin on the north, and the Sacramento Valley Basin to the south (Fig. 2a). Although the Sacramento Valley Basin has been subdivided into 18 subbasins (California Department of Water Resources 2003), this amount of detail was not warranted and the subbasins within this basin were lumped into two domains, one east and one west of the Sacramento River.

The San Joaquin Valley is segregated like the Sacramento Valley into three major parts: the eastern and the western parts of the San Joaquin Valley that extend the length of the San Joaquin River and the Fresno Slough to the delta, and the southern more internally drained part. On the western side, the Tracy and Delta-Mendota subbasins were grouped into one region as were the Westside and Pleasant Valley sub-basins (Fig. 2a). Likewise, the eastern side of the valley was split into three regions that were groupings of groundwater sub-basins (Fig. 2a). These regions represent drainage basins from the Sierra Nevada that show a different geometry and distribution of stratigraphic sequences loosely based on work by Weissmann et al. (2005). The southern part, referred to here as the Tulare/Kern region in Fig. 2a, includes the four southern groundwater subbasins of the San Joaquin Valley Basin (California Department of Water Resources 2003). The Tulare/Kern region, surrounded on three sides by mountains, is internally drained.

Methods

The primary variable selected for the geostatistical analysis was the percentage of coarse-grained material defined over 15-m borehole composite intervals. The utilization of the percentage of coarse-grained deposits, or texture, was based on a methodology developed in earlier works by Page (1983, 1986), Laudon and Belitz (1991), and Burow et al. (2004). Textural data were compiled from drillers' logs of wells and boreholes drilled in Central Valley (Fig. 2).

Selection and compilation of existing well data

A database was constructed to organize information on well construction and subsurface lithology in the study area using the database design of Burow et al. (2004). Although more than 150,000 optically scanned drillers' logs were obtained from the California Department of Water Resources, this study did not attempt to utilize all of these logs. As was pointed out by Laudon and Belitz (1991), Belitz et al. (1993), and Burow et al. (2004), textural information in drillers' logs commonly is ambiguous and inconsistent because expertise, experience, and vocabulary of the describers vary greatly. As a result, an approach was devised to select a subset of good-quality logs that were spatially distributed throughout the valley. Two criteria were considered: specificity of location and degree of detail of geologic description. If the log lacked location information and had poor lithologic descriptions or was illegible it immediately failed and was skipped. Lithologic descriptors were subjectively evaluated on the basis of the amount of detail in the descriptions and the depth of the log. Although logs with abundant details were preferentially chosen, there was no attempt to condition the data or analyses to the high quality holes and all were treated equally once they were selected. The density of well logs collected was based on two qualitative criteria. If two "higher-quality" logs were available for a quarter township, the search was complete and the next quarter township was evaluated. If not, then up to four lesser-quality logs were chosen and then the next area was examined.

Although this process is not completely reproducible, the process could be replicated. The process resulted in a good spatial distribution of relatively good quality logs, however, deeper logs, if they existed, would have been useful during the geostatistical analyses. There was no attempt to identify the location of the deepest driller's logs. In addition, gaps in the digitized drillers' logs exist. There was no attempt to locate additional logs that would fill in these gaps.

Preliminary analysis of the drillers' logs indicated that this resulted in logs yielding sufficient detail to map the texture at 15-m depth intervals on a 1.6-km grid. A total of 15-m composite intervals were chosen based on the data distribution, density in the drillers' logs, and trends in the data. Ninety-five percent of the intervals were less than 15 m thick and the average thickness of the intervals was 4.7 m. On average, 20 intervals per hole were defined and more than 80% of these holes had ten or more different lithologic characteristics in each per hole.

Latitude-longitude locations were derived from the township, range, section numbers, and their divisions given on the drillers' logs. The location was calculated to the center of the most detailed part of the township/range information. If more than one point was available for a given location, the subsequent points were randomly located within the most detailed township/range designation.

Burow et al. (2004) had developed a database from about 3,500 drillers' logs in the 2,350 km^2 Modesto area. Therefore, this area was not redigitized and their more detailed database was used where it existed. As a result, the data density for this region, which covers only about 5% of Central Valley, is much higher than the rest of the valley. In this study, the sediment descriptions and depth intervals were entered into the database exactly as they appeared on the drillers' log. As discussed later, these wells are part of a separate domain and kriged as a separate entity.

The database of existing wells constructed for this 52,000-km^2 study area contains information from 8,497

DOI 10.1007/s10040-009-0539-7

Table 1 Distribution of statistical properties for the portion of coarse-grained deposits of the Central Valley by domain, including variogram and variogram models[a]

Valley	Spatial province	Spatial province number[b]	Domain	Area (km^2)	Number of samples	Mean[e]	Variance	Variogram models[c,d]			Model 1: exponential				Model 2: Gaussian			
								Mean[e]	Anisotropy/rotation (degrees)[f]	Nugget	Sill	1	2	Vert.	Sill	1	2	Vert.
Sacramento	Redding	10	Redding	3,151	1,010	39	1,348	44	0	400	725	1,500	4,500	150	250	30,000	100,000	200
	Western Sacramento Valley	11	Western Sacramento	18,606	6,423	25	820	27	10	350	375	5,000	6,500	110	100	40,000	200,000	700
	Eastern Sacramento Valley	12	Eastern Sacramento	13,662	4,632	32	1,069	34	15	400	500	6,000	8,500	120	150	50,000	150,000	140
San Joaquin	Tracy/Delta-Mendota	20	Tracy/Delta-Mendota above Corcoran Clay	6,325	1,466	45	1,029	46	20	300	700	5,000	18,000	250				
			Tracy/Delta-Mendota Corcoran Clay absent	2,681	433	29	820	29	20	0	825	5,000	2,500	75				
	Westside	21	Westside above Corcoran Clay	4,455	1,343	30	982	29	47	300	680	6,000	9,000	160				
			Westside Corcoran Clay absent	2,027	481	33	1,012	33	47	410	600	5,200	12,000	150				
	Northern San Joaquin	22	Northern San Joaquin above Corcoran Clay	4,566	4,470	51	876	46	31	500	375	140,000	10,000	180				
			Northern San Joaquin Corcoran Clay absent	12,531	8,931	34	936	34	31	100	650	1,000	1,100	75	175	20,000	50,000	100
	Chowchilla-Madera	23	Chowchilla-Madera above Corcoran Clay	1,982	330	37	691	39	35	0	675	9,000	6,000	70				
			Chowchilla-Madera Corcoran Clay absent	2,575	1,119	36	878	35	35	350	450	6,500	6,500	175				
	Kings	24	Kings: above Corcoran Clay	2,630	1,157	46	577	46	30	300	275	8,000	12,000	65				
			Kings: Corcoran Clay absent	5,421	1,560	47	837	45	30	300	475	12,000	9,000	140				
	Tulare/Kern	30	Tulare/Kern: above Corcoran Clay	14,723	2,562	43	1,042	40	28	150	625	3,500	2,500	100	265	50,000	90,000	600
			Tulare/Kern: Corcoran Clay absent	13,200	2,775	41	1,314	40	28	370	600	5,000	7,500	200				
	Corcoran Clay	N/A	Inside extent of Corcoran Clay	34,681	374	26	874	20	33	0	875	6,000	6,000	0	3,000	60,000	200,000	60,000
			Below Corcoran Clay	34,681	4,685	35	1,138	37	33	275	440	1,900	1,200	110	415	55,000	170,000	135

[a] All values in feet unless noted otherwise. 1 foot = 0.3048 m

[b] Numbers are used to correlate with Fig. 2

[c] Variogram calculation parameters: slicing height 15.23 m; lag 2,000 m; tolerance 1,000 m

[d] Variogram model parameters: *1* primary horizontal range (applies in the direction of anisotropy); *2* secondary horizontal range; *Vert.* vertical range

[e] Values are percentages

[f] Angles are in degrees from north counter-clockwise

DOI 10.1007/s10040-009-0539-7

drillers' logs. This represents about 5% of the total number of wells drilled in this region and a little over one-third of the total wells drilled in the 2,350-km^2 Modesto region. Although the database does not include all well records, the data provides a representative sample of the variety of the existing wells. Well depths range from 4 to 950 m below land surface, with a median depth of 98 m. An example of the upper portion of one drillers' log is shown in Fig. 3.

Data density throughout the study region varies based on the availability of data. This variable sample density does not appear to bias the statistics. The dense data for the Modesto region are separated for statistical analyses. Although wells may be preferentially drilled in areas of high texture, calculation of the mean appears to relatively low. The data were not declustered prior to the geostatistical modeling.

Classification of texture from drillers' logs and regularization of well data

Each lithologic log was divided into a discrete binary texture classification of either "coarse grained" or "fine grained" intervals on the basis of the description in the log. In this study, coarse-grained sediment is defined as consisting of sand, gravel, pebbles, boulders, cobbles, or conglomerate. Fine-grained sediment is defined as consisting principally of clay, lime, loam, mud, or silt. These definitions of "coarse grained" and "fine grained" are similar to those originally defined by Page (1986) and later used by Laudon and Belitz (1991), Belitz et al. (1993) and Burow et al. (2004). For use in statistical and geostatistical analysis, the percentage of coarse-grained texture was calculated over 15-m depth increments in the 8,497 logs in the database (Fig. 3). This regularized data set consists of 46,878 data values of percentage of coarse-grained texture, referred to in this report as "texture values," from 8,497 drillers' logs. General statistical analyses were computed to examine spatial changes in percentage of coarse-grained deposits (count, mean, and standard deviation), both laterally and with depth. The global mean percentage of coarse-grained texture is 36%, with a standard deviation of 32%.

The graph in Fig. 2b shows that the majority of the 46,878 texture values were for depths less than 60 m; the maximum number of texture values was 7,300 for the first 15 m. Many of the well-log values entered into the database are not continuous from the ground surface to the bottom of the borehole. Thus, none of the depth intervals include texture values for all 8,497 logs. For depth increments shallower than 150 m, there are at least 1,300 texture values available within each of the nine study domains. For deeper depths >340 m, fewer than 100 texture values exist for a given depth interval. Only 129 logs had texture values for depths greater than 300 m, and only 16 drillers' logs had data for intervals at depths greater than 550 m. Analysis of the sample variance for each depth increment indicated that the variability of the average percentage of coarse-grained texture increased with increasing depth for depths greater than 90 m. For depth intervals with fewer than approximately 1,000 texture values (>170 m), the number of drillers' logs is likely insufficient to represent the average percentage of coarse-grained texture at a given depth.

Geostatistical modeling approach

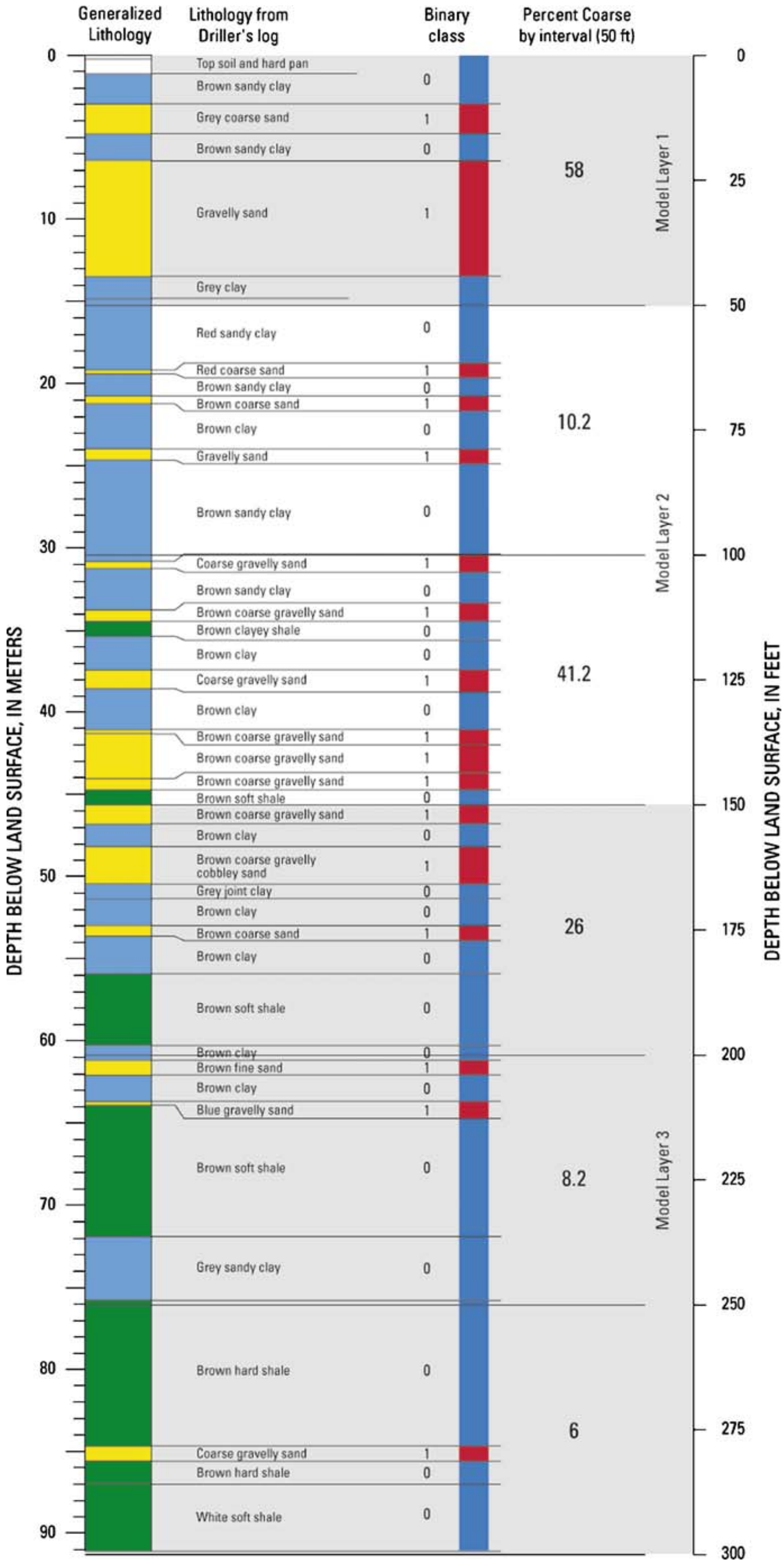
Geostatistics is a set of applications and statistical techniques used to analyze spatial and (or) temporal correlations of variables distributed in space and (or) time (Isaaks and Srivastava 1989). An advantage of using geostatistical models instead of simple spatial interpolation methods such as inverse-distance weighted interpolation, is that the geostatistical model provides the best linear unbiased estimate and provides a set of weights that minimize estimation error (Journel and Huijbregts 1978). In addition, the model is fitted to the observed spatial correlation structure, whereas simple interpolation methods are based on an assumed spatial correlation structure. Furthermore, anisotropy in the spatial correlation structure can be modeled by combining several different models aligned along the principal axis of anisotropy to form a nested set of models.

A number of geostatistical methods exist. One of the most commonly used and referenced is some form of kriging. Other methods that incorporate more geologic principals have recently been developed (Koltermann and Gorelick 1992; Webb 1994; Carle and Fogg 1996; Carle et al. 1998). Large-scale process simulations have been used to reconstruct the sedimentary record in alluvial basins (Koltermann and Gorelick 1992; Webb 1994). These simulations account for the dynamics of river flooding, sedimentation, subsidence, land movement that result from faulting, and sea level changes. Carle and Fogg (1996) and Carle et al. (1998) developed and applied TProGS approaches to simulate the distribution of hydrofacies in continental sediments. TProGS is a stochastic approach to modeling the distribution of facies that allows introduction of geologic reasoning (Carle et al. 1998; Weissmann et al. 1999; Weissmann and Fogg 1999; Ritzi 2000; Fogg et al. 2001). Both process simulations and TProGS account for connected hydrofacies with high permeabilities that form preferential flow paths. These connected hydrofacies are critical factor in hydrogeological investigations involving assessment of contaminant movement and remediation.

TProGS worked well for the small size models of the King's River fan (170 km$^{2)}$ and the Merced River (17 km^2) and the Modesto (50 km^2) areas. Although several of these models had a few depositional environments, developing and combining models with numerous

Fig. 3 Diagram showing the process of interpreting the texture from the driller's descriptions. The original drillers' intervals are identified, the binary classification of coarse (*1*) or fine (*0*), and the regularization over the 15-m depth intervals to develop the percentage of coarse-grained deposits. In addition, the correlation of the 15 m texture lattice with the flow-model grid is shown ▶

 DOI 10.1007/s10040-009-0539-7



DOI 10.1007/s10040-009-0539-7

depositional environments may be difficult and time consuming. In addition, the extent, number, and nature of the depositional environments for the entire Central Valley are poorly known. For this study, process simulations and the TProGS method were determined to be unwieldy for the entire Central Valley.

The geostatistical method, ordinary kriging, was employed in this study. The method used is similar to those used by Burow et al. (2004). The depositional environments, as well as the magnitude, type, and distribution of data were used to determine the geostatistical approach and variables. Although estimation variance is an important piece of information for this study and future data gathering, little focus is placed on it in this article.

Modeling of the entire Central Valley using a single 3D variogram could not be done without violating the stationarity condition. To allow more locally customized variograms, the area was split up into zones of interpreted different depositional environment. This procedure of subdividing an aquifer complex into units of apparent stationarity is in essence equivalent to traditional stratigraphic delineation. In a regional basin-fill aquifer complex it is, however, difficult to correlate stratigraphic units. These zones discussed in more detail in the next section.

Regions and domains

Because of the large size of Central Valley and multiple depositional environments, the study area was split spatially into the nine regions discussed previously (Fig. 2). Data analyses indicated that the regions needed to be subdivided again. The mean vs. the standard deviation of the texture data was evaluated for the presence or absence of "stationarity" (Journel and Huijbregts 1978) and to identify and remove any proportional effect. Two criteria were used to identify and remove any proportional effect: groundwater subbasins and position relative to the Corcoran Clay (above, below, and outside). The Sacramento Valley was divided into domains equivalent to the three parts based on groundwater basins: the Redding basin and the two groups of subbasins east and west of the Sacramento River.

The subdivision of the San Joaquin Valley is complex because it is divided laterally and vertically (Table 1). Laterally, the domains consist of groupings of similar groundwater subbasins (Fig. 2a). However, the hydrogeology of the San Joaquin Valley is dominated by the Corcoran Clay. Therefore, where this clay exists, the regions were subdivided above and outside the extent the Corcoran Clay (Table 1). This resulted in two more domains: the Corcoran Clay and the area below the clay. Thus, to assure stationarity within a domain, 17 domains were identified (9 spatial provinces and divisions of the 6 southern provinces into the domains within, above, below, and where the Corcoran Clay is absent) (Fig. 2b; Table 1).

Geostatistical model of coarse-grained texture

Because present-day land surface represents a depositional horizon, the spatial correlation model was developed using depth below land surface as the z axis. Because the domains were constructed to represent geologic and stratigraphic areas, Euclidean distances were used in the calculation of the variograms. The texture data at wells represent point values within these domains. Textural end members were constrained during gridding by capping the low and high values at the possible values (0 and 100). Punctual kriging, as opposed to block kriging was used. Block kriging would represent an average for the 15 m thick blocks. Because the groundwater model will aggregate these blocks at unknown intervals, punctual estimates were calculated prior to aggregation into model layers. This will allow the use and examination of various ranges and (or) averages in texture values within each model cell.

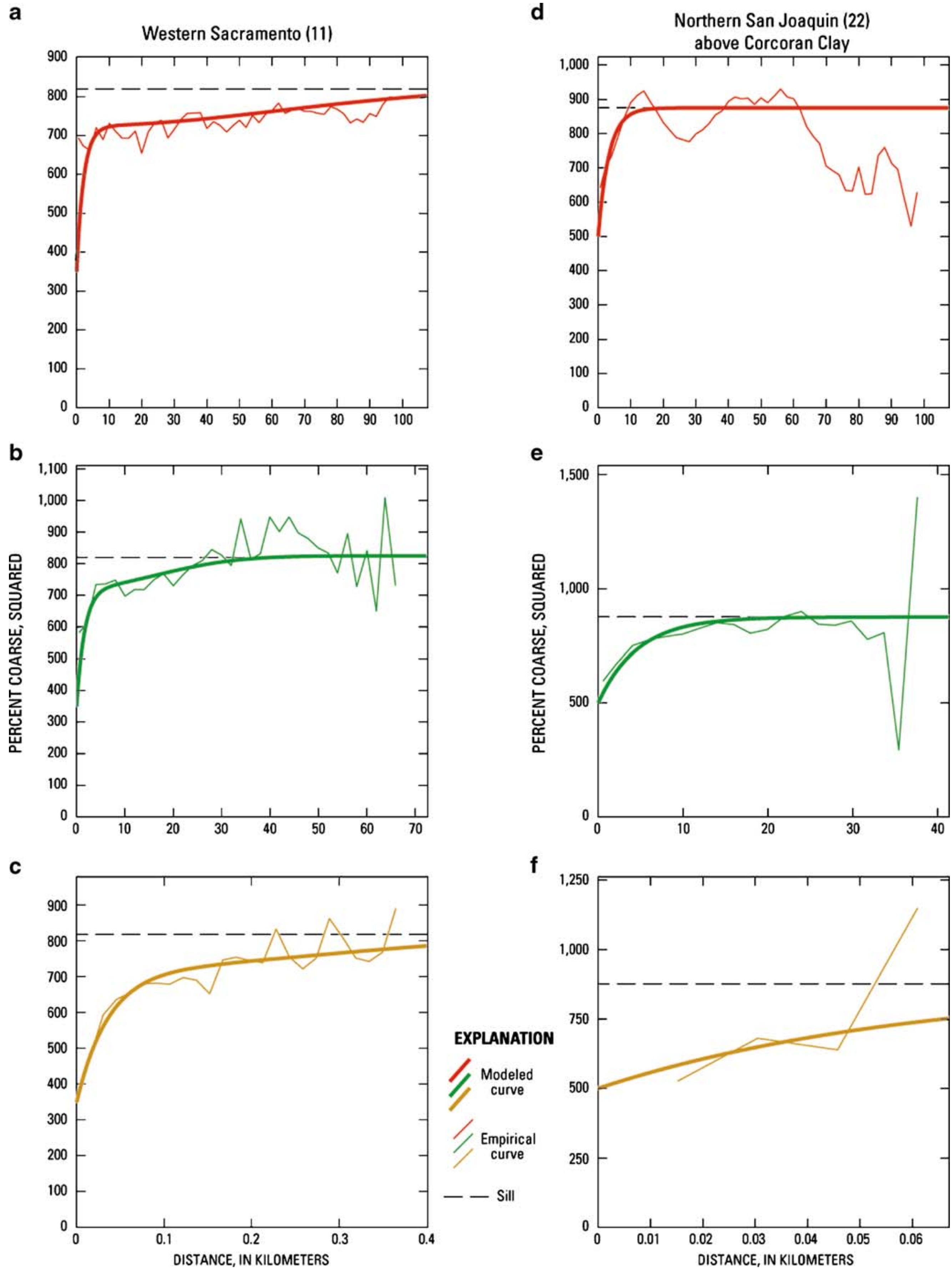
3D variograms for each of the seventeen domains (Table 1) were developed. The variogram models for each domain were defined using nested structures; each model included a nugget, an exponential variogram model, and often a nested Gaussian variogram model. Any of a number of different models could have been chosen. The choice of variogram models was based on those models that fit the data most precisely in the portion of the variogram to be used. A moving neighborhood was used with at least two nearest neighbors and an optimum of four nearest neighbors. The majority of search distances used for interpolation were less than half the range of the variograms. Because these distances used for interpolation were a small fraction of the total ranges, they did not create issues from any potential hole effects or unbounded extrapolations.

Figure 4 shows an example of the set of variograms for 2 of the 17 domains. One example is from the Sacramento Valley (Fig. 4a–c) and one is from the San Joaquin Valley (Fig. 4d–f); one has one and one has two nested models. The Western Sacramento area (area 11) illustrates the nested variogram with the nearest data fitted with the nugget and exponential. Because the larger distance pairs appear to gradually increase without bound, the farther data was fitted with the Gaussian variogram. The actual interpolation of the sediments did not need to use these larger distance pairs. Similarly, the Northern San Joaquin (area 22) was fitted with a nugget and exponential variogram and the ranges and interpolation distances do not encounter the hole effect shown in the experimental variogram data at about 12 km between distance pairs. In addition, the hole effect appears to be most pronounced in the direction that is parallel to the sedimentary fabric.

Anisotropy was set along the trend of the valley axis, parallel to the main river channel, and perpendicular to this axis, for the tributaries and fans, for each domain. Therefore, the anisotropy of the domains are almost north–south in the Sacramento Valley and are oriented

Fig. 4 Graphs showing the variograms in each of the three directions for two domains (11 and 22 see Fig. 2): Western Sacramento: **a** major axis 350°, **b** secondary axis 80°, and **c** vertical axis and Northern San Joaquin above Corcoran Clay: **d** major axis 329°, **e** secondary axis 59°, and **f** vertical axis ▶

 DOI 10.1007/s10040-009-0539-7



DOI 10.1007/s10040-009-0539-7

more northwest–southeast, like the valley axis, in the San Joaquin Valley. Reflecting the geometry and depositional environment of Central Valley, the variograms typically have a horizontal range in the hundreds of kilometers along the axis of the valley and tens of kilometers perpendicular to the valley axis, and a much smaller vertical range of 50–250 m (Table 1). Although nugget values range from 0 to 50% of the sill, the nugget is typically about one third of the sill. The largest variance is in the northern and southern domains (Redding and Tulare/Kern outside the extent of the Corcoran Clay), where streams enter the valley from three directions.

Texture was estimated at the nodes (points) of a 3D grid. The grid is oriented with the long axis roughly parallel to Central Valley axis and has a uniform cell spacing of 1,600 m in the x and y directions consisting of 98 cells in the x-direction and 441 in the y-direction. The vertical discretization is defined by 15 m depth increments, starting with the midpoint of the first increment at 7.5 m below land surface and extending 46 grid layers in the vertical direction to 700 m below land surface. Because areas outside the basin boundary (Fig. 1) were not estimated, the discretization defined a total of 20,533 grid cells in the lateral direction and a total of 944,518 grid cells for the entire 3D estimation grid.

Using the 3D variogram models described above and in Table 1, textural values for 15 m depth intervals for each cell center were estimated by 3D kriging for each domain. The 17 domain models were then merged to form one model at 15-m depth increments for the entire Central Valley. Because data points for the entire model area were used for estimation within each domain, a smooth transition usually occurs from one domain to the next. The exception to this smooth transition occurs in areas of sparse data in the deeper portions of the system. An octant search was used during kriging and the closest at least two and optimally four texture values selected according to the variogram distance. The spatial dimensions of the search neighborhood were not constrained; therefore, for locations of the estimation grid having densely spaced and relatively deep boreholes with continuous drillers' logs, the effective search neighborhood was relatively small. For locations of the estimation grid which contain sparsely spaced drillers' logs, the effective search neighborhood expanded vertically and laterally until at least two texture values were reached. Although the estimation neighborhood used at least two values for each kriged estimate, most estimates in the corners, lower layers, and along the boundaries of the grid are extrapolated rather than interpolated values. As is indicated by the nugget and range of the variograms, the assumption that, in heterogeneous alluvial sediments, texture at a point is related to texture at surrounding points several kilometers away may not always be valid. Therefore, in areas of sparse data, the texture maps should be regarded as only showing general trends and averages. Conversely, in areas where nearby data are variable and there is a significant relative nugget in the variogram model, the 3D kriging may produce smoothed estimates. These results occur because the kriging algorithm used aims to find a least-squares estimate of the expected value. As a result, the more data that are included in the estimate, the smoother the estimate will be.

Kriging was done at points instead of volumes. One consequence of this method is that layers do not correspond to the Corcoran Clay boundary. Points allow membership in a volume and the ability to map the texture within the Corcoran Clay. Where the Corcoran Clay is thin and therefore underrepresented by the 15-m depth increments, the texture distribution within the Corcoran Clay showed some gridding artifacts that parallel the depth and thickness of the Corcoran Clay. These artifacts could be the result of imperfect mapping of the depth to the Corcoran Clay, the regularized 15-m incremented data banding in and out of the Corcoran Clay, and/or misidentification and/or generalization of the extent and thickness of the Corcoran Clay on Page's (1986) map. To better represent the spatial pattern of texture within the Corcoran Clay, the 3D boundary defined by Page (1986) and later modified by Burow et al. (2004) was used to segregate points thought to represent the clay. These points were used to develop a two-dimensional (2D) kriged map of the percentage of coarse texture in the Corcoran Clay.

Three-dimensional model of percentage of coarse-grained texture

The grid used for the groundwater flow model is the same as the texture grid in the lateral direction, but included 10 layers rather than 46 layers. In general, the groundwater-flow model layers range from 15 to 125 m thick, increasing with depth (Table 2). Where the Corcoran Clay exists, the layers were morphed to allow the explicit representation of the clay by layers 4 and 5 (Fig. 5). In order to complete this representation, the relative thicknesses of layers 1 through 3 above the clay were also modified. If necessary, any additional thickness was added to layer 3 as necessary to reach the depth of the top of the Corcoran Clay (Fig. 5). The texture value for each layer could be set by taking the minimum, maximum, or

Table 2 Central Valley groundwater flow model: layer thicknesses and depths

Layer	Thickness (m)	Depth to base (m) outside Corcoran Clay	Refer to
1	15	15	Fig. 6a
2	30	46	–
3	46	91	Fig. 6b
4	Variable[a]	92	Fig. 6c
5	Variable[a]	92	Fig. 6c
6	60	152	Fig. 6d
7	76	229	–
8	91	320	–
9	107	427	Fig. 6e
10	122	549	–

[a] Layers 4 and 5 represent Corcoran Clay where it exists; elsewhere there is a 0.3-m thick phantom layer. (They are kept only to keep track of layer numbers)

 DOI 10.1007/s10040-009-0539-7

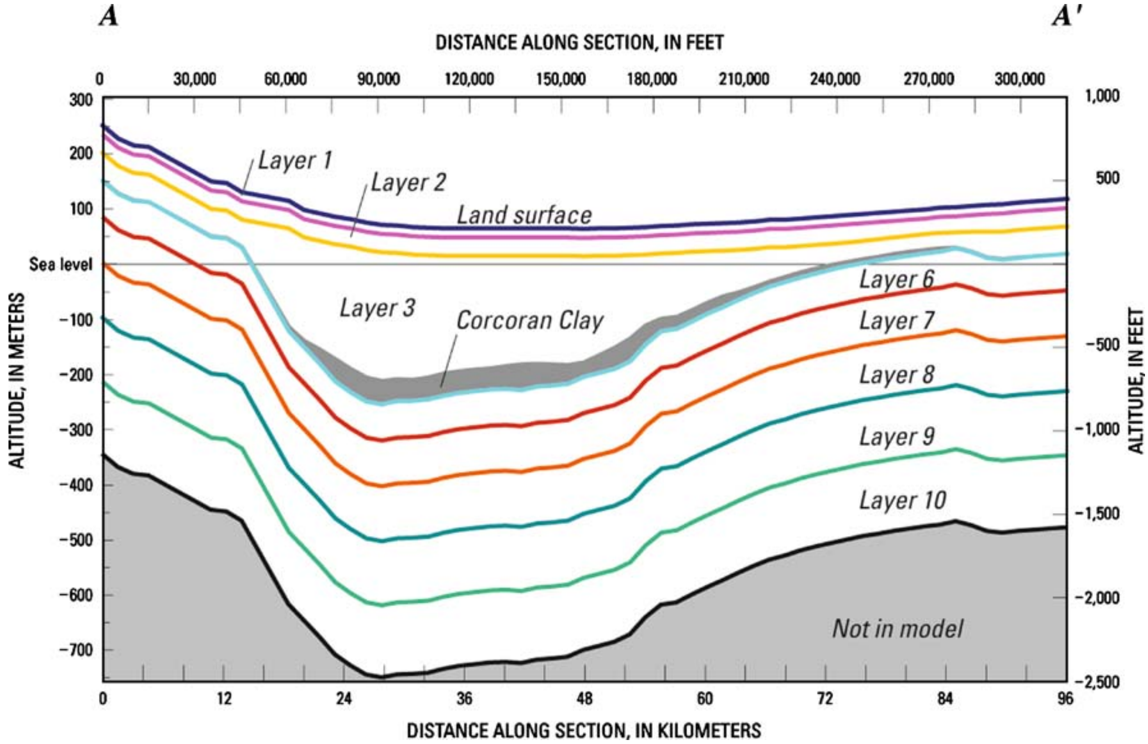


Fig. 5 Generalized hydrogeologic section (*A–A′*) indicating the vertical discretization of the numerical model of the groundwater flow system in Central Valley, California. Line of section is shown on Fig. 1

averaging the percent coarse value for the appropriate model layer (Fig. 3). In this representation, the percent coarse values were averaged vertically within each model cell. Because layer 1 of the texture model is identical to that of the texture lattice, the percent coarse values are identical. Likewise, layers 4 and 5 within the Corcoran Clay correspond to the 2D kriged values. Layers 4 and 5 are identical and are replicated in the groundwater flow model to allow for more accurate calculation of storage properties and subsidence. Outside of the area of the Corcoran Clay, layers 4 and 5 do not exist and are considered phantom layers and are kept only to keep track of numbering.

Results and discussion

The mean percentage of coarse-grained deposits indicates a prevalence of fine-grained texture throughout the region (Table 1). This tendency was previously identified by Page (1986), Belitz et al. (1993), and Burow et al. (2004). The spatial patterns of the percentage of coarse-grained texture are shown in texture maps (Fig. 6) and oblique views of the model (Fig. 7). Figure 6 shows five representative layers in the texture model. The figure shows that as the data density decreases with depth so does the detail in the layers of the model. Layers 4 and 5 are identical and represent the Corcoran Clay. As expected, the texture is generally very fine-grained (Fig. 6c). In layer 9, the highest texture values occur in the southwestern portion of the study area, yet there are no data at those locations. These values are a result of interpolation from data predominantly in the overlying layers.

The 3D kriged estimates of percentage of coarse-grained texture show significant heterogeneity in the texture of the sediments (Figs. 6 and 7). Table 1 summarizes the statistical analysis of thee texture in the 17 domains. It can also be related to the geomorphic provinces and alluvial fan morphology of the Sacramento River (Fig. 8). In the next section, the general textural modeling results are described for each of the domains and discussed in relationship to published descriptions.

The Redding domain is the coarsest (sample mean of 39%, kriged mean of 45%) of the three northern areas making up the Sacramento Valley region. Going deeper in the Redding domain, the western part of this small basin becomes coarser. Most of the area in the eastern and western Sacramento domains, including the delta, is predominantly fine-grained (Williamson et al. 1989; Figs. 6 and 7); the eastern Sacramento Valley domain is coarser grained (sample mean of 32%, kriged mean of 34%) than the western domain (sample mean of 25%; kriged mean of 27%). The fine-grained nature of the Sacramento Valley reflects a number of factors, including more fine-grained volcanic-derived sediments and the lack of glacially driven deposits in the Sacramento Valley (Williamson et al. 1989). Except for the drainage basins draining Tahoe, the northern Sierra Nevada water sheds have a much lower average elevation and did not have coarse alluvial deposition like the glaciated drainage basins (Weissmann et al. 2005). This resulted in a higher percentage of fine-grained texture. In addition, the lack of subsidence in the Sacramento Valley may have resulted in

 DOI 10.1007/s10040-009-0539-7

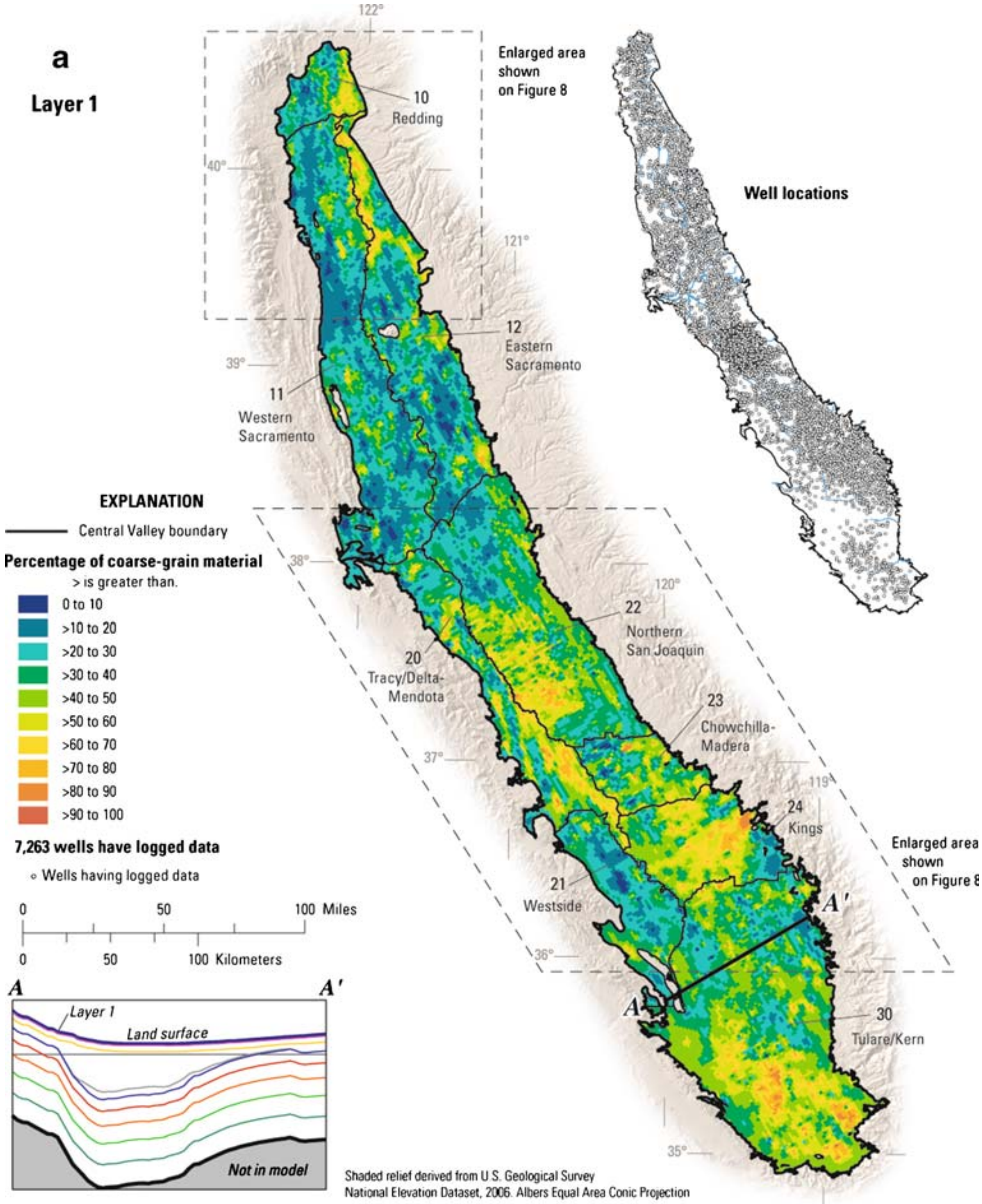


Fig. 6 Maps showing kriged distribution of coarse grained deposits for layers **a** *1*, **b** *3*, **c** Corcoran Clay, **d** *6*, and **e** *9* of the groundwater flow model. *Inset* shows distribution of wells used in that depth interval

most of the sediments being removed from the individual drainage basins (Weissmann et al. 2005). However, some coarse-grained isolated deposits are in the shallow part of the Sacramento Valley (layer 1; Figs. 1 and 6a) along the channel of the Sacramento River and the distal parts of the fans off the Cascade Range, the northern Sierra Nevada, and the American River drainage basin. The coarsest deposits correlate with the Sacramento River channel and flood-plain before it widens out into more of a basin-type province (Fig. 8). Hence, the southernmost Sacramento Valley is similar to the northern San Joaquin Valley and the fan character is similar to that of the Tuolumne or Stanislaus River fans (Fig. 6). Although somewhat smoothed with depth, both of the Sacramento domains remain relatively fine grained with depth with some coarser areas along the western edge of the Sierras. These areas most likely represent older alluvial fans off the Sierras (Figs. 6 and 7; Weissmann et al. 2005).

Texture in the San Joaquin Valley and the Tulare Basin is punctuated by the distribution of the Corcoran Clay domain. In contrast to the texture of the overlying and underlying domains (Table 1), the Corcoran Clay domain has zones of very fine grained texture in most areas and on average it is the finest grained domain (sample mean of 26%, kriged mean of 19%) in the San Joaquin Valley (Fig. 6c). Although the Corcoran Clay domain has large continuous extents of very fine-grained sections, on average the western Sacramento Valley is finer than the Corcoran Clay. Despite the overall fine-grained nature of this deposit, the drillers' logs digitized and kriged as part of this study indicate some coarse-grained areas within areas previously defined as part of the Corcoran Clay

 DOI 10.1007/s10040-009-0539-7

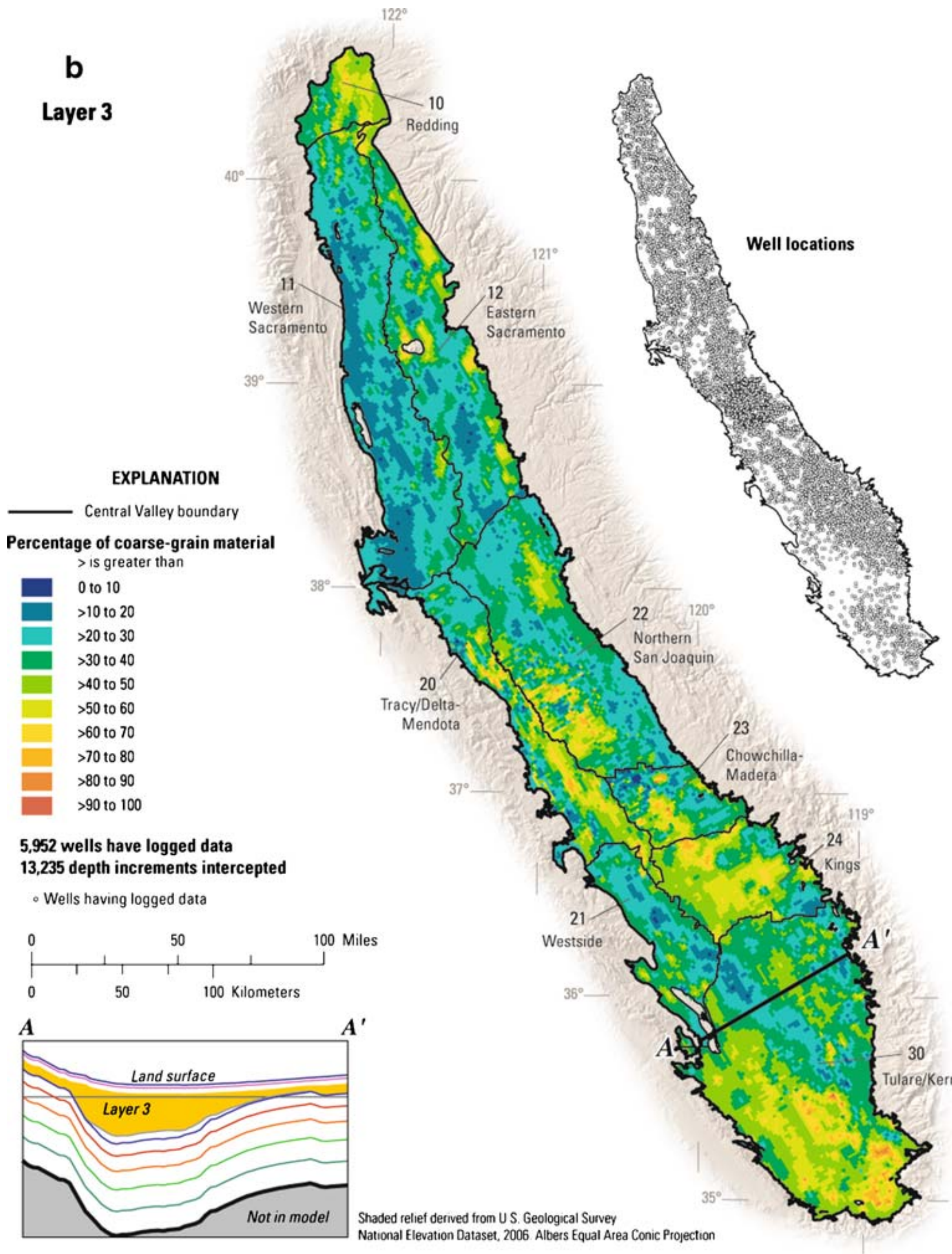


Fig. 6 (continued)

(Page 1986; Burow et al. 2004). These coarser areas are generally where the Clay is thin and may partly be the result of regularizing texture over the 15-m depth intervals. Many of these thin coarser areas are not laterally extensive and are along the edges of the clay. A more extensive coarser area is along the northern part of the clay along the Merced River, Bear Creek, and Orestimba Creek. Adjacent to the border between the Kings and the Westside domains, the clay is particularly thin and consistently coarser grained across the clay from east to west. South of the Tulare Lake bed (Fig. 1), the clay is thin and, except for a few bands, is not very fine-grained in this model (Figs. 2, 6c, and 7). In this area, it is possible that the wells reach as deep as Tertiary sediments. Before the Corcoran Clay existed, this area was probably alluvial/deltaic, as the southern seaway was open as late as late Pliocene when the Coast Ranges were uplifted (Weissmann et al. 2005). As a result, the sediments are interbedded. The Pleistocene sediments may be thick here because of basin subsidence combined with the narrowness of the valley that may have forced the Kern River to deposit its sediment near the mountain front (Weissmann et al. 2005).

Below the Corcoran Clay, the mean grain size is larger than that in (or, for) the domain of the Corcoran Clay. Except for the Westside domain, the domains below the Corcoran Clay are finer grained than the domains above. Although the area below the Tulare Lake bed is thought of

 DOI 10.1007/s10040-009-0539-7

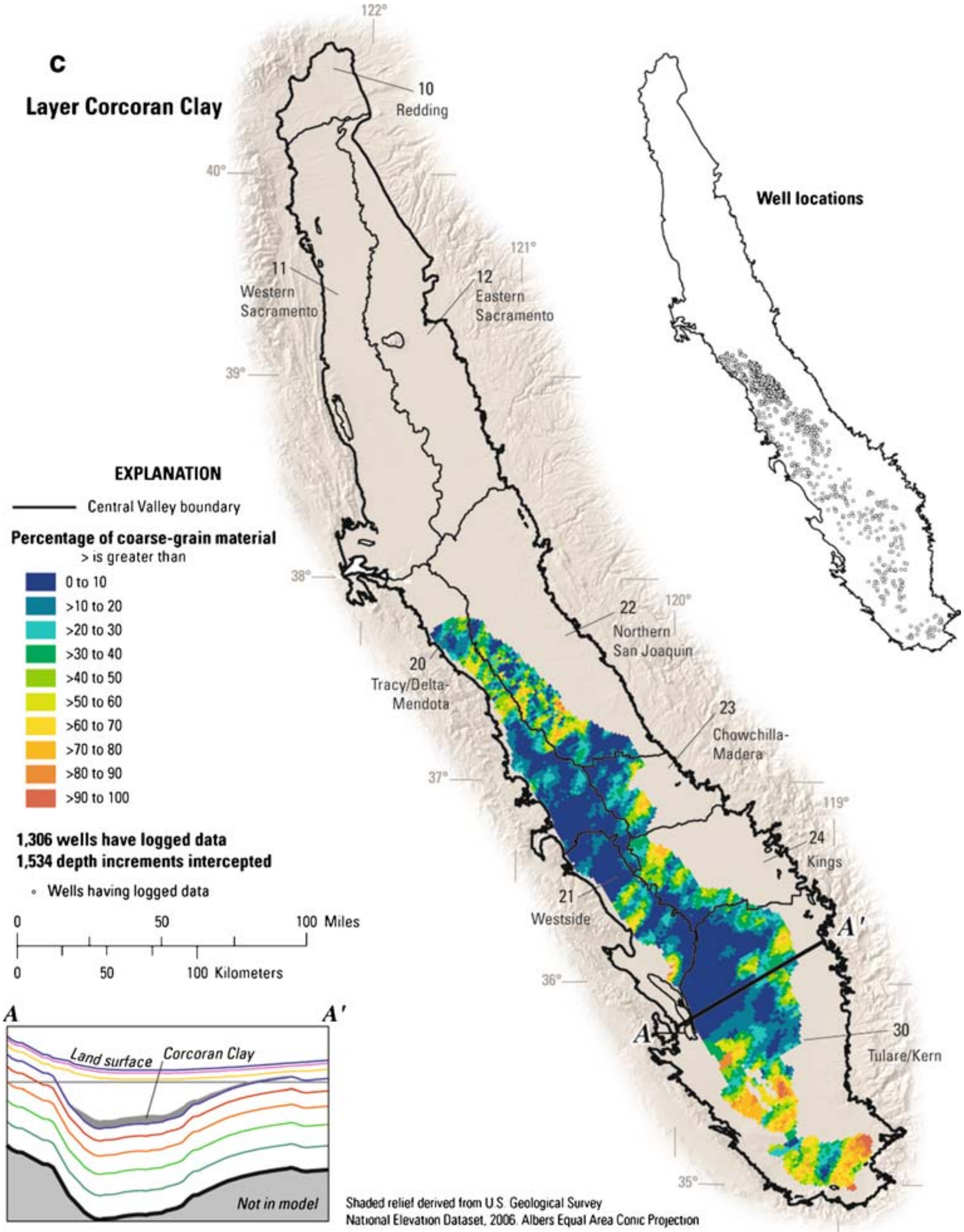


Fig. 6 (continued)

as a clay plug, the nine wells identified in this study that extend below the base of the Corcoran Clay near the Tulare Lake bed show alternating series of sands and clays (coarse and fine-grained sequences). As a result, the texture model of the lower layers (Figs. 4e and 6) shows a relatively coarse-grained area in the southern part of Central Valley.

In the San Joaquin Valley, above and beyond the extent of the Corcoran Clay, areas of coarse-grained texture are more widespread than the areas of fine-grained texture and are concentrated along the major rivers and alluvial fans. The domains of the eastern San Joaquin Valley (Northern San Joaquin, Chowchilla-Madera, and Kings) suggest a complex spatial structure in the shallow Pleistocene sediments, which are the dominant water-bearing units. This spatial structure can be attributed to the effects of the east–west alignment of the tributary rivers and the fans (Fig. 8) along the Sierra foothills bounding the eastern edge of the valley combined with the asymmetry of the north–south aligned San Joaquin River dominating the central part of the area. At least in the shallow parts of the system, the alignment of the river channels and the physiography of the valley played an important role in the depositional history (Burow et al. 2004). The deeper Tertiary sediments may not reflect the orientation of the streams, especially in the northern San Joaquin Valley where the Tertiary sediments are much shallower. As a result, although not done as a part of this study, the

 DOI 10.1007/s10040-009-0539-7

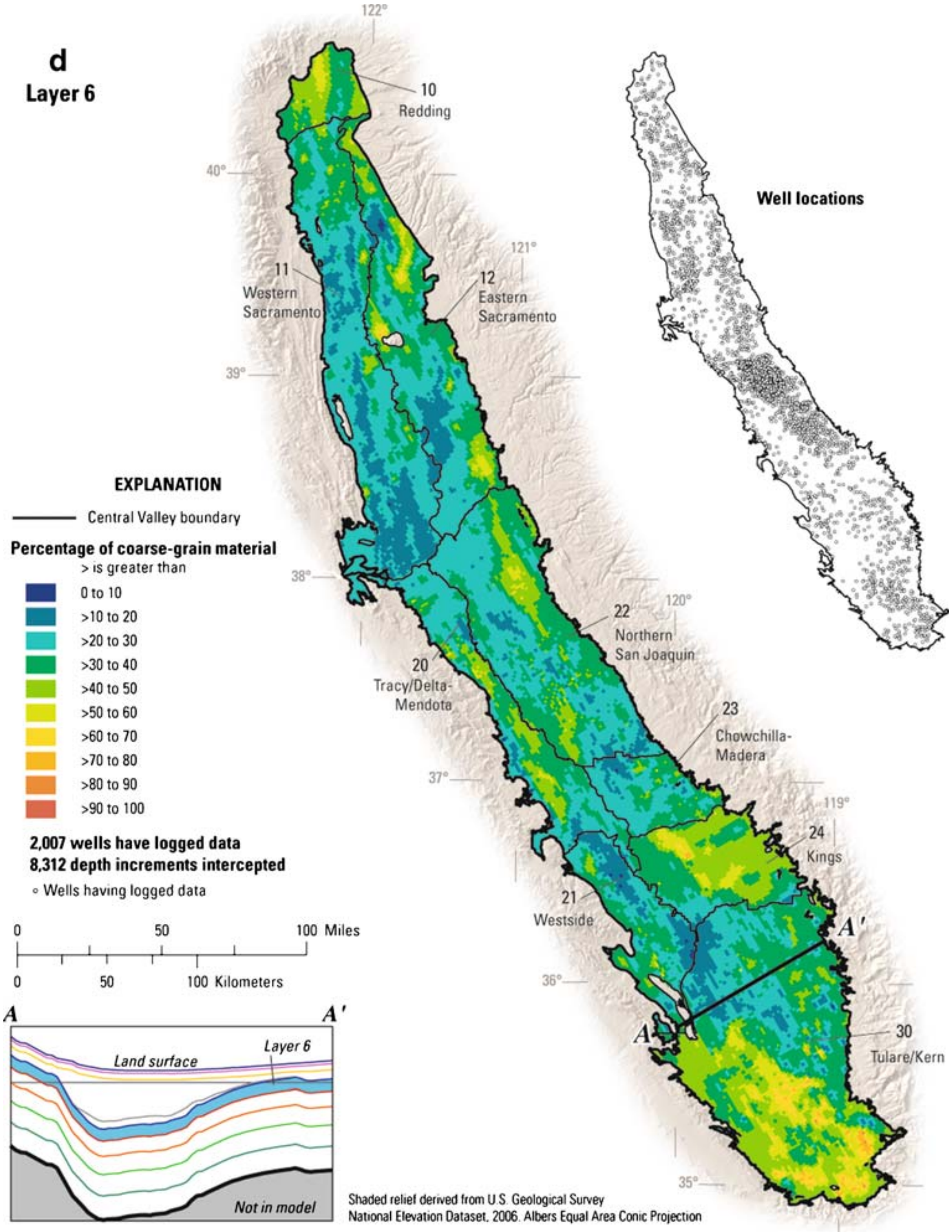


Fig. 6 (continued)

anisotropy angle could be varied with depth. This might remove some of the “striping” evident in the model (Fig. 6a). Likewise, although the depth intervals are consistent depths from the land surface, they represent potentially different depositional environments from north to south because of the differences in basin subsidence rates. For example, the coarse-grained sediments at 150 m below land surface in the Kern basin are probably Pleistocene sediments, whereas the sediments at 150 m below land surface in the Modesto/Merced area are probably Tertiary in age and are more fine grained because of the difference in environment (Bartow 1991; Weissmann et al. 2005). The southern seaway also may have changed the course of the rivers, and some of them may have been oriented more north-south. During Pliocene and older ages, it is thought that the San Joaquin Valley drained to the south, thus affecting orientation of streams and location of fluvial/deltaic deposits in the south (Bartow 1991).

The coarse-grained areas are prevalent in many of the fans in the Sierra foothills and the San Joaquin River channel along the axis of the valley (Figs. 6 and 7). Generally, the fine-grained texture zones are in the proximal inter-channel and distal floodplain areas. Along the valley axis, the coarsest deposits lie west of the San Joaquin present day channel and the river may have shifted to the east.

In the northern part of the Northern San Joaquin domain, dissected uplands along the Sierra Nevada are

DOI 10.1007/s10040-009-0539-7

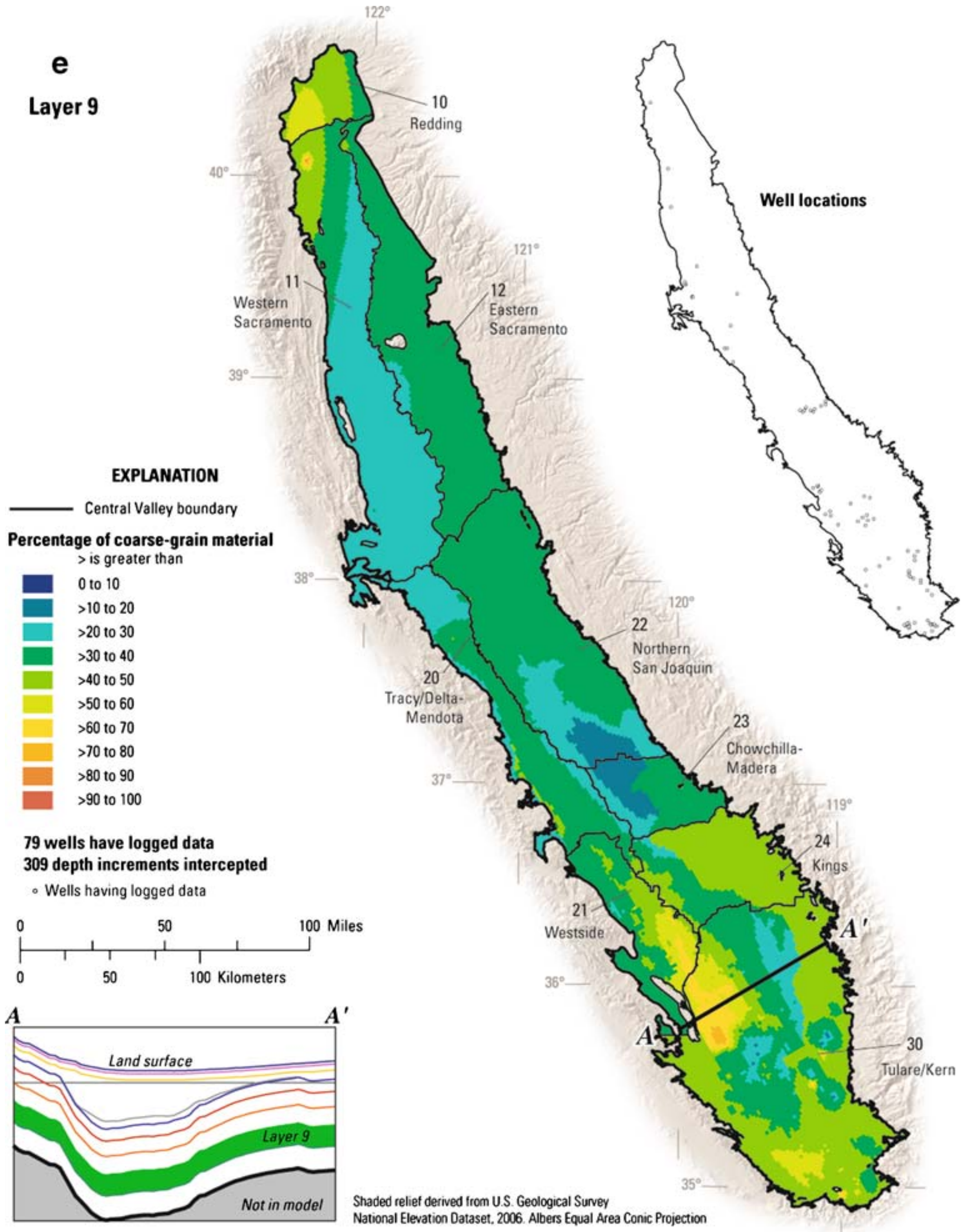


Fig. 6 (continued)

generally fine-grained. The Calaveras and Mokelumne River fans formed in a narrow part of the basin near the valley outlet (Fig. 8). The Calaveras fan (Figs. 6 and 8) is not connected to glaciated parts of the Sierra Nevada, serving to limit the supply of readily available coarse-grained sediments (Weissmann et al. 2005). These fans exemplify these characteristics with their fine-grained texture. Conversely, as the Stanislaus and Merced Rivers leave the finer-grained, dissected uplands, the texture becomes coarser toward the valley axis where they meet the San Joaquin River. Although these rivers connect to glaciated parts of the Sierra Nevada (like the very coarse-grained Kings River fan to the south), their drainage basins are at lower elevations and smaller and their outlets have a lower subsidence rate (Weissmann et al. 2005). Likewise, the Tuolumne River's drainage basin is about the same size and elevation as that of the Kings River; however, its outlet has a lower subsidence rate (Weissmann et al. 2005). As expected, the Stanislaus, Merced, and Tuolumne River fans are moderately coarse-grained, but not as coarse-grained as the Kings River fan. In addition, areas south of each of these three present-day channels are coarser grained, possibly indicating that the rivers have migrated north. In the southern-most part of the Northern San Joaquin domain (the Merced basin south of Bear Creek), the basin geomorphic province reaches farther east and the texture model demonstrates this with finer-grained deposits.

 DOI 10.1007/s10040-009-0539-7

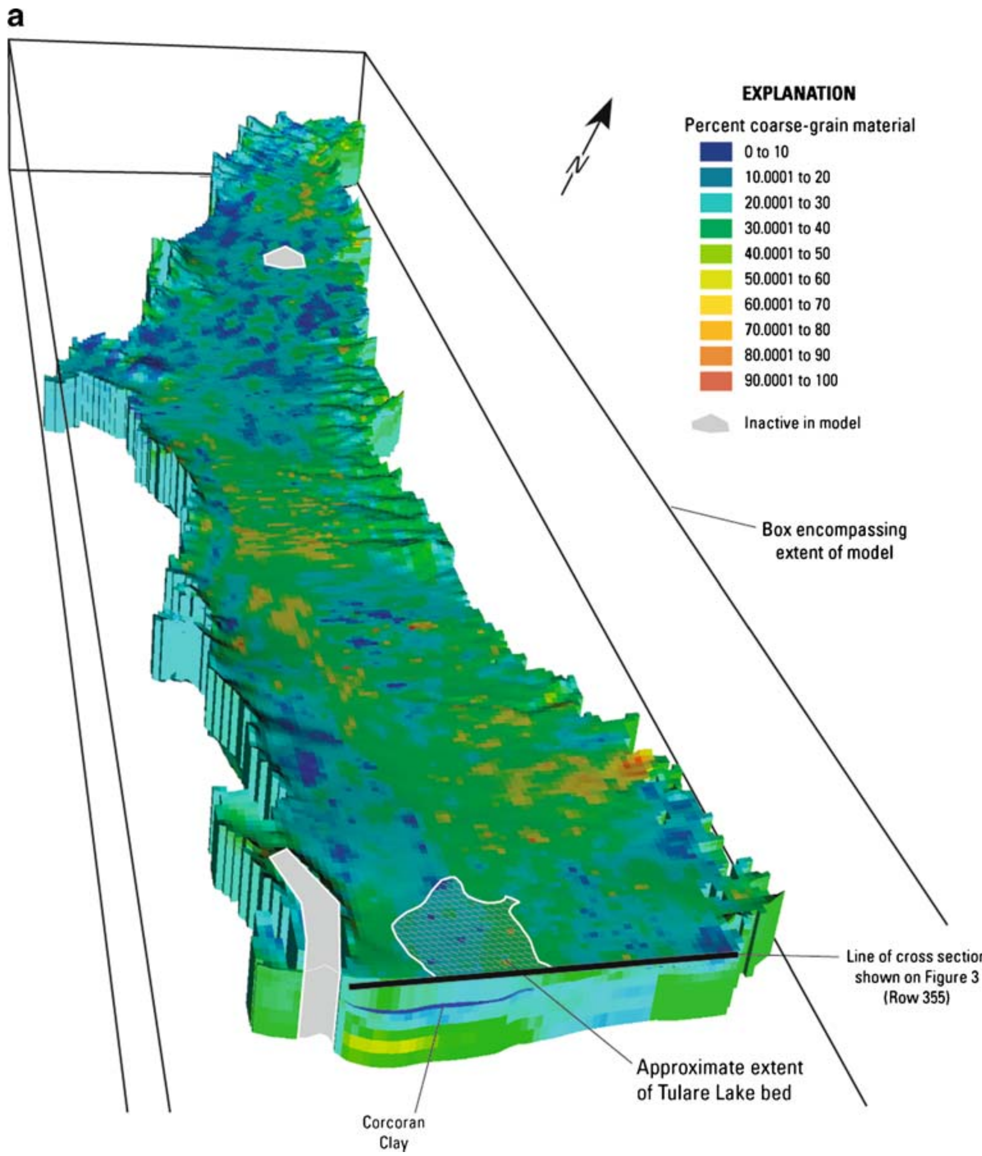
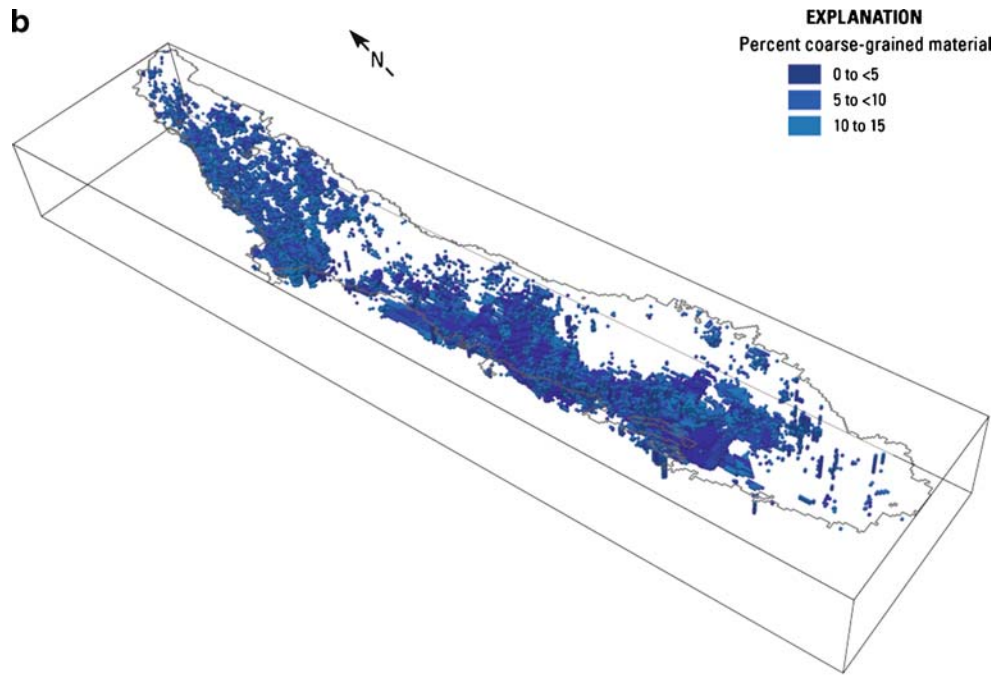


Fig. 7 **a** Block diagram of texture model with cutaway in south. **b** Block diagram showing the extreme fine-grained (0–15%) portion of the texture model. **c** Block diagram showing the coarser-grained (50–100%) portion of the texture model

The Chowchilla-Madera domain, dominated by the Chowchilla River fan and Fresno River fan (Figs. 6 and 8) is generally fine-grained. These fans, along with some minor fans and the Calaveras fan to the north, have drainage basins that tap only nonglaciated parts of the Sierra Nevada (Weissmann et al. 2005). These fans did not experience large changes in the supply of sediment to the drainage basin relative to the amount of water discharging from the basin (Weissmann et al. 2005), and therefore they did not develop the deep incised valleys and appear to have thin sequences and relatively moderate grain sizes throughout their extent. As expected, visually there is a correlation between the extent of the basin geomorphic province in this domain and the finer-grained texture.

In the Kings domain, the San Joaquin River fan (on the southern boundary of the Chowchilla-Madera domain) and Kings River fan are much coarser grained than the river fans to the north, especially near their apex (Figs. 6a and 8). Both fans are connected to glaciated parts of the Sierra Nevada (Weissmann et al. 2005). These glaciated sections provide an abundance of coarse-grained sediments to the basin. The San Joaquin River fan (between the Fresno and Kings River) is similar in character to the Tuolumne River fan. It was developed in an area having relatively low subsidence rates, has a deep modern incised valley, and connects to the axial San Joaquin River (Weissmann et al. 2005). As a result, it is relatively coarse grained, particularly near the river channel. It is finer grained in the basin geomorphic province outside the active channel to the southwest. The Kings River fan is an example of fan development in a wide part of the valley having high subsidence rates (Weissmann et al. 2005). As a result, this fan has relatively thick deposits with vertical stacking and is one of the coarsest-grained areas in Central Valley, particularly near its apex. The texture data in layers 2 and 3 show coarse-grained deposits, some greater than

DOI 10.1007/s10040-009-0539-7



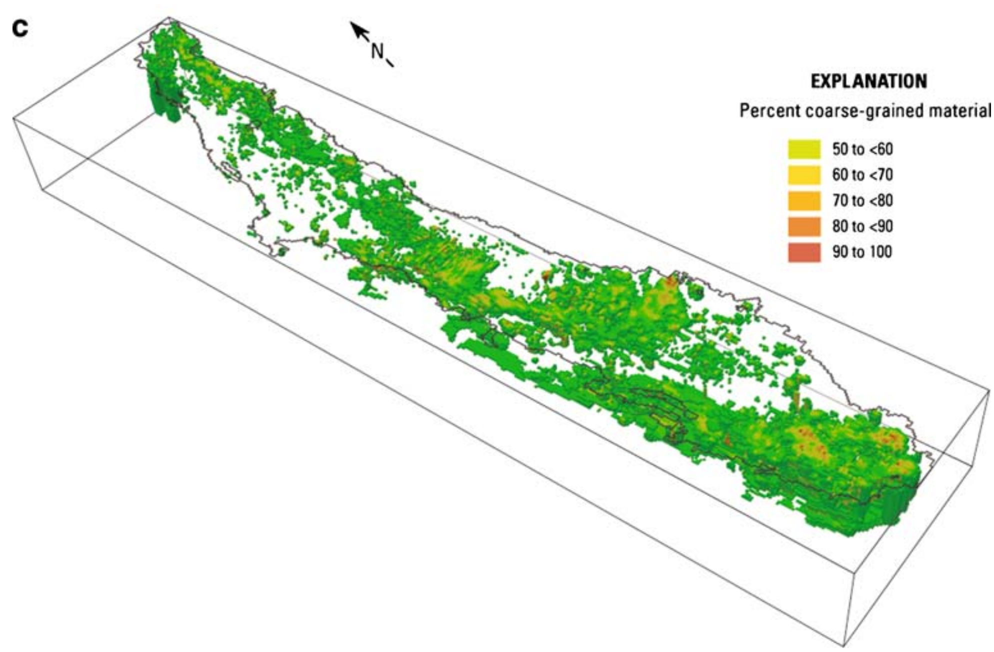


Fig. 7 (continued)

70% coarse, north of the present day Kings River and south of the current San Joaquin River (Figs. 6b and 8), indicating that these rivers may have changed their course, migrating to the south and north respectively. In contrast to the Kings River fan, the Kaweah River fan, which drains into the subsided area of the Tulare Lake Basin, is generally fine grained (Fig. 8); both fans have some coarse-grained deposits near their respective apex. This finer-grained nature may be related to the fact that the fan has a significantly smaller drainage basin with a lower contributing basin elevation. In addition, although its drainage basin was glaciated, it never had a large trunk glacier like fans in the Kern, Kings, San Joaquin, Merced, and Tuolumne drainage basins; rather, it had a series of separate, small glacial systems in tributary streams (Matthes 1960).

Most of the southern parts of the Tulare/Kern domains show a predominance of coarse-grained areas in the upper seven layers of the model (Figs. 6 and 7). The coarse-grained deposits have been utilized for artificial recharge sites and water banks. The Tulare Lake bed in the north northwestern part of the domain above and within the Corcoran Clay is predominantly fine-grained (Figs. 6a–c and 8).

 DOI 10.1007/s10040-009-0539-7

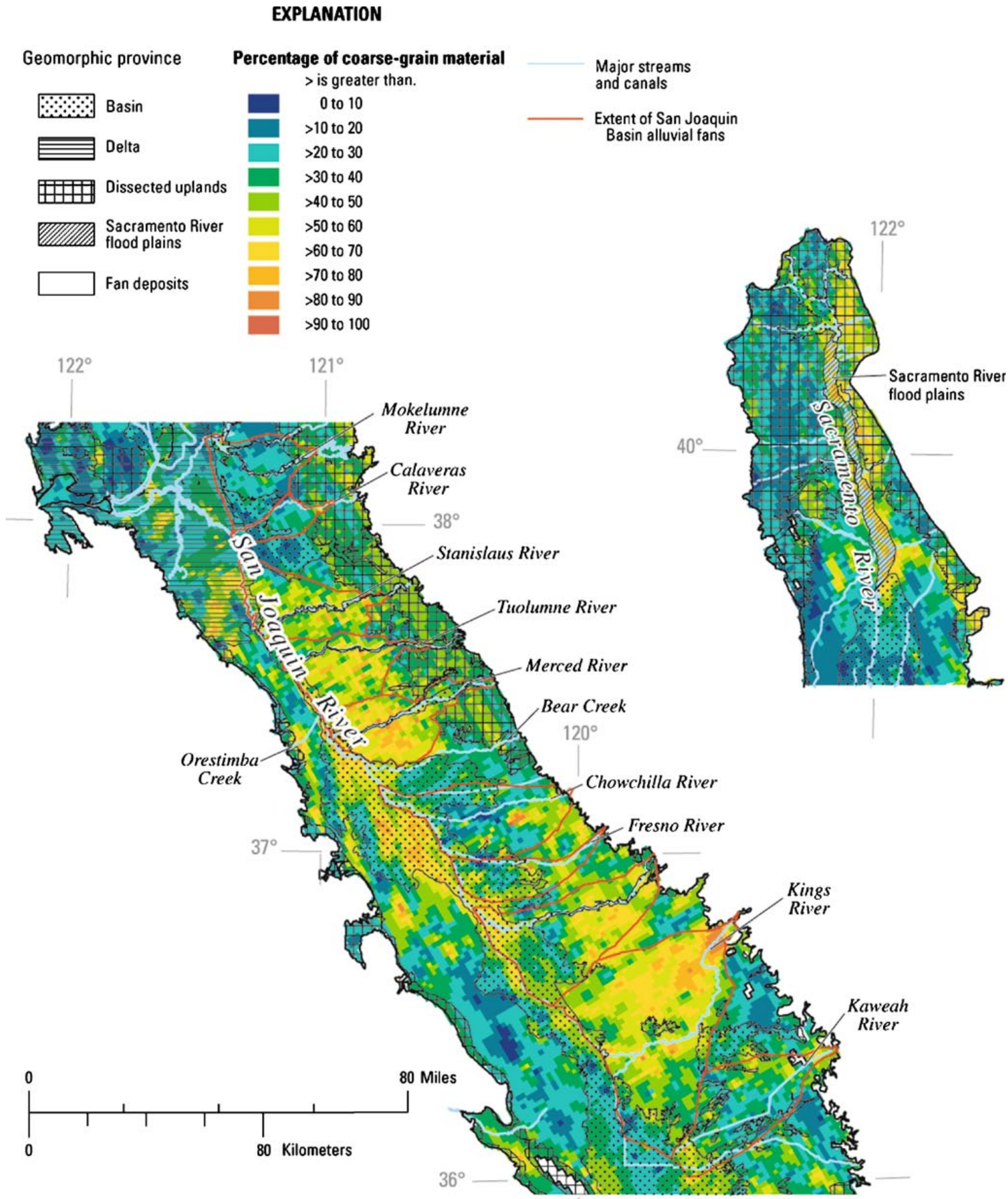


Fig. 8 Map showing distribution of percentage of coarse grained deposits for the upper 15 m for the Sacramento and San Joaquin Valleys (see dashed areas in Fig. 6a). In the San Joaquin Valley, the distribution is overlain with the major geomorphic provinces and alluvial fans (modified from Davis et al. 1959; Olmsted and Davis 1961; Jennings 1977; Weissmann et al. 2005)

DOI 10.1007/s10040-009-0539-7

In comparison to the eastern San Joaquin Valley domains and the Tulare/Kern domains, the domains in the western San Joaquin Valley (Tracy/Delta-Mendota and Westside regions) are finer-grained (Fig. 6). These finer textures reflect the source material: shales and marine deposits in the Coast Ranges. These rocks usually yield finer-grained sediments than the granitic rocks that are the sediment source for the fans on the eastern side of the Valley. The Westside domains, both above and outside the Corcoran Clay, and the northern part of the Tulare/Kern domains are especially fine-grained. Except for the Corcoran Clay and the area around the delta, the Westside domains are among the finest-grained areas in Central Valley. This finer-grained nature may be attributed to flashy debris-flow-fan type deposits from small drainage basins characteristic of this part of Central Valley and/or the fact that the area is internally drained with no outlet for exporting the finer-grained deposits (Fig. 8). It is interesting to note that this fine-grained area dominates the area in Central Valley underlain by tile-drains. In addition, this area has the largest amount of pumping-induced subsidence recorded in the valley (Williamson et al. 1989).

Despite this predominance of fine-grained deposits, coarse textures do exist in the Westside region. The western edge of the Westside, Tracy, and Delta-Mendota regions are coarser grained along the alluvial fans of the Coast Range, and coarse deposits are evident below 15 m (Fig. 6b) below land surface along the along the San Joaquin River. These coarser deposits correspond to the area identified by Laudon and Belitz (1991) as the Sierran Sands. Above the Corcoran Clay, the Tracy/Delta-Mendota domain is generally fine grained near the delta and gets coarser to the southeast, particularly along the San Joaquin River. Similar trends continue farther below the land surface until an abrupt break at the Corcoran Clay.

Hydraulic properties

The hydraulic properties of an aquifer system govern the transmission and storage of groundwater in the system. In this study, equivalent horizontal and vertical hydraulic conductivities are assumed to be correlated to sediment texture (the fraction of coarse-grained sediment). This assumption is based on the spatial correlation between saturated hydraulic conductivity and grain-size distributions in geologic media (Sumners and Weber 1984; Russo and Bouton 1992). A method for estimating hydraulic conductivity based on this assumption has been applied successfully in previous groundwater-flow models of the central western San Joaquin Valley (Phillips and Belitz 1991; Belitz and Phillips 1995; C. Brush, US Geological Survey, personal communication, 2006) and northeastern San Joaquin Valley (Burow et al. 2004; Phillips et al. 2007). Faunt and others (2009) utilize the texture properties from this study and this method to estimate hydraulic conductivity and storage properties in a groundwater model of Central Valley. The method uses the estimated sediment texture for each flow model cell and horizontal and vertical hydraulic conductivity estimates for each textural end member.

In this method, the power mean can be useful for defining hydraulic conductivity values (Desbarats 1991). A power mean is a mean of the form:

$$M^p(x) = \left(\frac{1}{n}\sum_{k=1}^{n} x_k^p\right)^{1/p},$$

where

x is the value being averaged (such as hydraulic conductivity)
p is the averaging power-mean exponent
n is the number of elements being averaged, and
x_k is the kth element in the list.

The horizontal hydraulic conductivity ($K_{h,i}$) was calculated as the weighted arithmetic mean (p=1) of the hydraulic conductivities for each cell (i) of the coarse-grained (K_c) and fine-grained (K_f) lithologic end members and the distribution of sediment texture:

$$K_{h,i} = \left[K_c F_{c,i} + K_f F_{f,i}\right]$$

where

$F_{c,i}$ is the fraction of coarse-grained sediment in a cell, estimated from sediment texture data, and
$F_{f,i}$ is the fraction of fine-grained sediment in a cell (1 – $F_{c,i}$).

Because K_f is much smaller that K_c, the arithmetic mean largely is influenced by the K and fraction of the coarse-grained end member.

Vertical hydraulic conductivity between layers $\left(K_{v,k+1/2}\right)$ can be calculated as the p^{th} weighted power mean of the hydraulic conductivities of the coarse-and fine-grained lithologic end members:

$$K_{v,k+1/2} = \left[F_{c,k+1/2}K_c^p + F_{f,k+1/2}K_f^p\right]^{1/p},$$

where

k represents the layer
$F_{c,k+1/2}$ is the fraction of coarse-grained sediment between layer midpoints, and
$F_{f,k+1/2}$ is the fraction of fine-grained sediment between layer midpoints.

The harmonic mean is a weighted power mean with p=−1.0. Belitz et al. (1993) represented the vertical conductivities with the weighted harmonic mean. The geometric mean is a weighted power mean with p=0.0. Phillips and Belitz (1991) determined that vertical conductivities could be calculated using either weighted

 DOI 10.1007/s10040-009-0539-7

harmonic or weighted geometric means. Both the harmonic and geometric means more heavily weight the fine-grained end members and, as a result, the vertical hydraulic conductivities are much lower than the horizontal hydraulic conductivities. Vertical conductivities can be defined as power means in which p varies between −1.0 (the harmonic mean) and 0.0 (the geometric mean). Dimitrakopoulos and Desbarats (1993) determined that the value of p depends, to some extent, on the size and thickness of the grid blocks used to discretize the model domain; smaller grid cells result in smaller values of p.

The Sacramento and San Joaquin Valleys have somewhat different depositional environments and textural compositions that may affect the end-member K values and the value of p. The Sacramento Valley is much finer grained, has a strong volcanic influence, and, as a result, possibly has less layering of fine-grained deposits than does the San Joaquin Valley. Conversely, the San Joaquin Valley is known to have numerous lenticular clay deposits (Page 1986; Williamson et al. 1989).

In addition to hydraulic conductivity, storage properties can be estimated from the percentage of coarse-grained deposits. Porosity values for can be estimated for the coarse- and fine-grained end members. The products of these porosity values and the respective cell-by-cell average coarse- and fine-grained fractional aggregate thicknesses can be summed and multiplied by the compressibility of water to yield an aquifer-system specific storage value for each cell. Specific yield can be estimated using a relationship such as linear, between end members of specific yield and the fractions of coarse-grained deposits.

The elastic and inelastic skeletal storage coefficients can be calculated as the product of the estimated elastic- and inelastic-specific storage values for coarse- and fine-grained materials and the aggregate thicknesses of those materials. The elastic skeletal storage coefficient of the coarse-grained deposits can be estimated from the product of the aggregate thickness of coarse-grained deposits and the difference between an estimated elastic specific storage and the specific storage representing the compressibility of water (Hanson 1988). Likewise, the elastic skeletal storage coefficient of the fine-grained deposits can be estimated as the product of the skeletal specific storage and the aggregate cell-by-cell thickness of the fine-grained deposits. The composite aquifer-system elastic skeletal storage coefficient is the sum of the elastic skeletal storage coefficients for the coarse-grained and fine-grained deposits. The inelastic skeletal storage coefficient can be estimated as the product of the inelastic specific storage and the aggregate cell-by-cell thickness of the fine-grained deposits for each layer.

Summary and conclusions

Central Valley comprises sediments derived from the major rivers and their tributaries that drain the Sierra Nevada from the east and the Coast Ranges from the west. The hydrologic system in Central Valley is complex, in part, because of the heterogeneous nature of the hydrogeologic setting. Although fine-grained deposits are spread throughout the valley-fill and one mappable clay body, the Corcoran Clay, the valley deposits can be thought of as one large heterogeneous aquifer system.

A database digitized from approximately 8,500 drillers' logs was compiled to organize information on subsurface lithology in the study area. Well depths range from 4 to 950 m below land surface, with a median depth of 98 m. Texture was used as a basis for constructing a 3D spatial-correlation model of the deposits in Central Valley. The model is on 1.6-km grid spacing, congruent with a groundwater flow model being developed and 15-m depth intervals. The procedure for creating the texture model involved a number of steps. First, drillers' logs were entered into a database with their complete lithologic description categorized. The primary description was then coded according to the simplified classification scheme defined above and the percentage of coarse-grained sediment was computed for each of the 15-m depth intervals noted in every log. Next, general statistical analyses were computed to examine changes in percentage of coarse-grained deposits (count, mean, and standard deviation) spatially and with depth. These analyses, along with plots of mean vs. standard deviation, indicated an absence of stationarity for Central Valley as a whole. The Corcoran Clay significantly influences hydrology in Central Valley and is often considered to be the dominant definable hydrogeologic unit in Central Valley (Williamson et al. 1989). As a result, Central Valley was subdivided spatially, as well as vertically within the horizontal extent of the Corcoran Clay (Fig. 1), 3D variograms were constructed with the primary axis of each domain oriented parallel to the Valley axis (Table 1). These variograms were then used to develop a 3D model of percentage of coarse-grained deposits for each of the domains. These domain models were then merged to form one texture model for the entire Central Valley.

The texture model based on drillers' logs agrees with the independently mapped geomorphic provinces (modified from Davis et al. 1959; Olmsted and Davis 1961; Jennings 1977) as well as the factors affecting the development of alluvial fans (Weissmann et al. 2005). The texture distribution reflects the source material: volcanic materials contribute to a fine-grained texture in the Sacramento Valley, the shales and marine deposits of the Coast Ranges contribute to the fine-grained texture of the western San Joaquin Valley, and the granitic rocks of the Sierra Nevada provide coarse-grained materials to the eastern San Joaquin Valley and southeastern Sacramento Valley. The model also indicates that the regional lateral spatial structure is affected by zones of coarse-grained texture correlated to the position of the main river channels for the shallow depths. The textural distribution is also related to differences in alluvial and fluvial depositional environments between channel, interfan, and basin geomorphic provinces combined with subsidence rates, valley

 DOI 10.1007/s10040-009-0539-7

width and the spacing, alignment, and tributary source area of the main tributaries to the Sacramento and San Joaquin River. Fans along the eastern San Joaquin Valley connected to the glaciated parts of the Sierra Nevada, particularly those with large drainage basins and high subsidence rates, have relatively coarse-grained deposits.

The types of depositional environments and changes in these environments over time are reflected in the texture model. For example, a decrease in runoff and an increase in aridity can be interpreted as the result of a transition from glacial to interglacial conditions and may be seen as a change from coarse to fine-grained deposits in the texture model. Assuming hydraulic conductivity is correlated to texture, the kriged results imply significant heterogeneity in the hydrogeologic framework.

The hydraulic properties of an aquifer system govern the transmission and storage of groundwater in the system. Hydraulic conductivities can to be correlated to sediment texture (the fraction of coarse-grained sediment). A method for estimating hydraulic conductivity based on this assumption has been developed. The method uses the estimated sediment texture for each cell and horizontal and vertical hydraulic conductivity estimates for each textural end member. The power mean can be used for defining hydraulic conductivity values. In addition to hydraulic conductivity, storage properties can be estimated from the percentage of coarse-grained deposits.

References

Bartow JA (1991) The Cenozoic evolution of the San Joaquin Valley, California. US Geol Surv Prof Pap 1501, 40 pp

Belitz K, Heimes FJ (1990) Character and evolution of the ground-water flow system in the central part of the western San Joaquin Valley, California. US Geol Surv Water Suppl Pap 2348, 28 pp

Belitz K, Phillips SP (1995) Alternative to agricultural drains in California's San Joaquin Valley: results of a regional-scale hydrogeologic approach. Water Resour Res 31(8):1845–1862

Belitz K, Phillips SP, Gronberg JM (1993) Numerical simulation of ground-water flow in the central part of the Western San Joaquin Valley, California. US Geol Surv Water Suppl Pap 2396, 69 pp

Bryan K (1923) Geology and ground-water resources of Sacramento Valley, California. US Geol Surv Water Suppl Pap 495, 285 pp

Bureau of Reclamation (1994) The Central Valley Project overview: Bureau of Reclamation History Program research on historic reclamation projects. http://www.usbr.gov/dataweb/html/cvpintro.html. Cited 15 April 2009

Burow KR, Shelton JL, Hevesi JA, Weissmann GS (2004) Hydrogeologic characterization of the Modesto area, San Joaquin Valley, California. US Geol Surv Sci Invest Rep 2004-5232, 54 pp

California Department of Water Resources (2003) California's groundwater, Bulletin 118, update 2003. California Department of Water Resources, Sacramento, CA, 246 pp

Carle SF, Fogg GE (1996) Transition probability: based indicator geostatistics. Math Geol 28:453–476

Carle SF, Labolle EM, Weissmann GS, Vanbrocklin D, Fogg GE (1998) Conditional simulation of hydrofacies architecture: a transition probability/Markov approach. In: Fraser GS, and Davis JM (eds) Hydrogeologic models of sedimentary aquifers. Concepts in Hydrogeology and Environmental Geology no. 1, SEPM, Tulsa, OK, pp 147–170

Davis GH, Green JH, Olmsted FH, Brown DW (1959) Groundwater conditions and storage capacity in the San Joaquin Valley, California. US Geol Surv Water Suppl Pap 1469, 287 pp

Davis GH, Lofgren BE, Mack S (1964) Use of ground-water reservoirs for storage of surface water in the San Joaquin Valley, California. US Geol Surv Water Suppl Pap 1618, 125 pp

Desbarats AJ (1991) Spatial averaging of hydraulic conductivity in three-dimensional heterogeneous porous media. Math Geol 24 (3):249–267

Dimitrakopoulos R, Desbarats AJ (1993) Geostatistical modeling of grid block permeabilities for 3D reservoir simulators. Reservoir Eng 8:13–18

Farrar CD, Bertoldi GL (1988) Region 4, Central Valley and Pacific Coast Ranges. In: Back W, Rosenshein JS, Seaber PR (eds) Hydrogeology: geology of North America, vols O-2. Geological Society of America, Boulder, Colorado, pp 59–67

Faunt, CC, Hanson, RT, Belitz, K, Schimid, W, Predmore, SP, Rewis, DL, McPherson KR (2009) Numerical model of the hydrologic landscape and groundwater flow in California's Central Valley, chap. C. In: Faunt CC (ed) Groundwater availability of the Central Valley Aquifer, California. US Geol Surv Prof Pap 1776, pp 121–212. http://pubs.usgs.gov/pp/1766/PP_1766.pdf. Cited 1 August 2009

Fogg GE, Carle S, Green CT (2001) A connected network paradigm for the alluvial aquifer system. In: Dongxiao Z, Winter CL (eds) Theory, modeling and field investigation in hydrogeology. GSA Special Publication, A special volume in honor of Shlomo P. Neuman's 60th birthday, GSA, Boulder, CO, 252 pp

Great Valley Center (2005) State of the Great Central Valley: assessing the region via indicators: the economy (2005): State of the Great Central Valley Indicators Series, Great Valley Center, Modesto, CA, 49 pp. http://www.greatvalley.org/pub_documents/2005_1_18_13_59_43_indicator_econ05_report.pdf. Cited 15 April 2009

Hanson RT (1988) Aquifer-system compaction, Tucson Basin and Avra Valley, Arizona. US Geol Surv Water Resour Invest Rep 88–4172, 69 pp

Isaaks EH, Srivastava RM (1989) An introduction to applied geostatistics. Oxford University Press, New York

Jennings CW (1977) Geologic map of California, 1:750, 000. California Division of Mines and Geology, Sacramento, CA

Journel AG, Huijbregts CJ (1978) Mining geostatistics. Academic Press, New York, 600 pp

Koltermann CE, Gorelick SM (1992) Paleoclimatic signature in terrestrial flood deposits. Science 256(5065):1775–1782. doi:10.1126/science.256.5065.1775

Laudon J, Belitz K (1991) Texture and depositional history of Late Pleistocene-Holocene alluvium in the central part of the western San Joaquin Valley, California. Bull Assoc Eng Geol 28(1):73–88

Matthes FE (1960) Reconnaissance of the geomorphology and glacial geology of the San Joaquin Basin, Sierra Nevada, California. US Geol Surv Prof Pap 329, 62 pp

Mendenhall WC, Dole RB, Stabler H (1916) Ground water in San Joaquin Valley, California. US Geol Surv Water Suppl Pap 398, 310 pp

Miller RE, Green JH, Davis GH (1971) Geology of the compacting deposits in the Los Banos-Kettleman City subsidence area, California. US Geol Surv Prof Pap 497-E, 45 pp

Olmsted FH, Davis GH (1961) Geologic features and ground-water storage capacity of the Sacramento Valley, California. US Geol Surv Water Suppl Pap 1497, 287 pp

Page RW (1983) Geology of the Tulare formation and other continental deposits, Kettleman City area, San Joaquin Valley, California, with a section on ground-water management considerations and use of texture maps. US Geol Surv Water Resour Invest Rep 83–4000, 24 pp

Page RW (1986) Geology of the fresh ground-water basin of the Central Valley, California, with texture maps and sections. US Geol Surv Prof Pap 1401-C, 54 pp

Phillips SP, Belitz K (1991) Calibration of a textured-based model of a ground-water flow system, western San Joaquin Valley, California. Ground Water 29(5):702–715

 DOI 10.1007/s10040-009-0539-7

Phillips SP, Green CT, Burow KR, Shelton JL, Rewis DL (2007) Simulation of multiscale ground-water flow in part of the northeastern San Joaquin Valley, California. US Geol Surv Sci Invest Rep 2007–5009, 43 pp

Planert M, Williams JS (1995) Groundwater atlas of the United States: segment 1, California, Nevada. US Geological Survey Hydrologic Atlas 730-B, 1 atlas, US Geological Survey, Reston, VA, 28 pp

Prokopovich NP (1987) Textural composition of near-surface alluvium in west-central San Joaquin CA. Bull Assoc Eng Geol 24(1):59–81

Repenning CA (1960) Geologic summary of the Central Valley of California with reference to disposal of liquid radioactive waste. US Geol Surv Open-File Rep 61-127, 69 pp

Ritzi RW Jr (2000) Behavior of indicator variograms and transition probabilities in relation to the variance in lengths of hydrofacies. Water Resour Res 36:3375–3381

Russo D, Bouton M (1992) Statistical analysis of spatial variability in unsaturated flow parameters. Water Resour Res 28(7):1911–1925

Sumners WK, Weber (1984) The relationship of grain-size distribution and hydraulic conductivity: an alternate approach. Ground Water 22(4):474–475

Webb EK (1994) Simulating the three-dimensional distribution of sediment units in braided-stream deposits. J Sediment Res 64b (2):219–231. doi:10.1306/D4267F96-2B26-11D7-8648000102C1865D

Weissmann GS, Fogg GE (1999) Multi-scale alluvial fan heterogeneity modeled with transition probability geostatistics in a sequence stratigraphic framework. J Hydrol 226:48–65

Weissmann GS, Carle SF, Fogg GE (1999) Three-dimensional hydrofacies modeling based on soil surveys and transition probability geostatistics. Water Resour Res 35:1761–1770

Weissmann GS, Mount JF, Fogg GE (2002) Glacially driven cycles in accumulation space and sequence stratigraphy of a stream dominated alluvial fan, San Joaquin Valley, California, USA. J Sediment Res 72:270–281

Weissmann GS, Bennett G, Lansdale AL (2005) Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA. In: Harvey A, Mather A, Stokes M (eds) Alluvial fans: geomorphology, sedimentology, dynamics. Geol Soc Lond Spec Publ 251, pp 169–186

Wentworth CM, Fisher GR, Levine P, Jachens RC (1995) The surface of crystalline basement, Great Valley and Sierra Nevada, California: a digital map database. US Geol Surv Open-File Rep 95-0096, 16 pp

Williamson AK, Prudic DE, Swain LA (1989) Ground-water flow in the Central Valley, California: US Geol Surv Prof Pap 1401-D, 127 pp

 DOI 10.1007/s10040-009-0539-7