

Detailed laboratory testing of construction and foundation materials should be done. Compaction and remolded triaxial shear tests should be done on core materials. Relative density or compaction, in the absence of any other data, is perhaps the single most important item to be used in judging a soil's dynamic stability.

## **Regional Geology**

The proposed projects are in the western foothills along the edge of the Sacramento Valley. The rocks underlying the damsites are part of the Great Valley geologic province, which is mostly sandstone, mudstone, and conglomerate of the Cretaceous GVS.

### **Geomorphic Provinces**

The Great Valley geologic province is bound on the west by the Coast Ranges province, to the north by the Klamath Mountains province, to the northeast by the Cascade Range province, and to the east by the Sierra Nevada province. The location of the various geologic provinces in Northern California is shown in Figure 3. Figure 4 shows the North American geologic time scale.

### **Great Valley Province**

The projects lie along the western edge of the Great Valley province, a 400-mile-long by 60-mile-wide sedimentary basin positioned between the Sierra Nevada, Klamath Mountains, Cascade Range, and Coast Ranges.

Along the west side of the Sacramento Valley, rocks of the Great Valley province include Upper Jurassic to Cretaceous marine sedimentary rocks of the GVS, fluvial deposits of the Tertiary Tehama, Quaternary Red Bluff, Riverbank, and Modesto formations, and Recent alluvium.

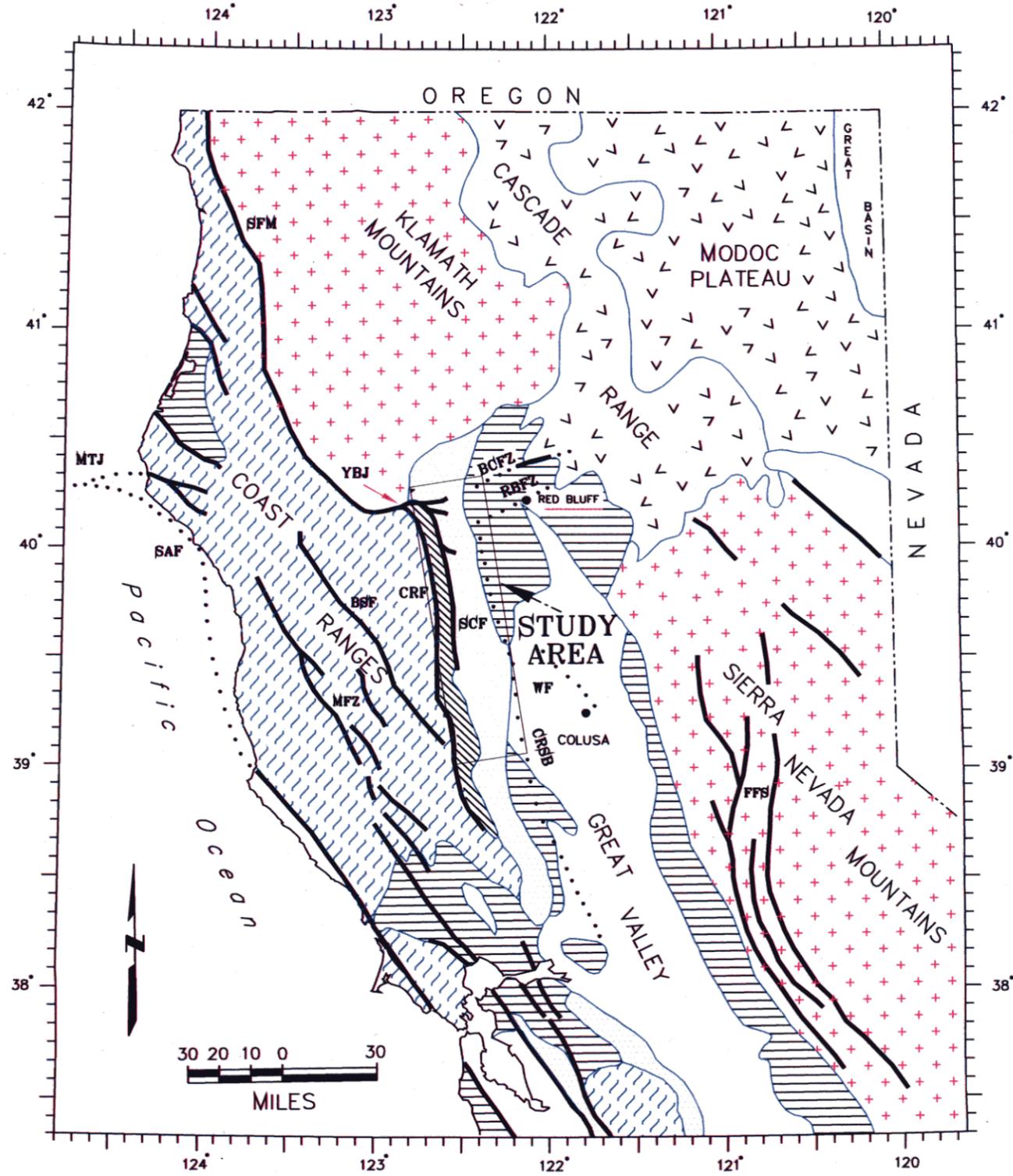
Rocks of the GVS form an asymmetric south-plunging syncline, with a steeply dipping western limb and a gently dipping eastern limb. The west side has eroded to form a series of northwest-trending, east-dipping ridges of sandstone and conglomerate separated by valleys underlain by siltstone and mudstone. Water gaps in the sandstone and conglomerate ridges form the damsites for all four proposed projects.

The basement of the GVS is believed to be basaltic ocean floor consisting of flows, dikes, gabbroic plutonic rocks, and serpentinites and is commonly referred to as the Coast Ranges ophiolite. The ophiolite is middle Jurassic in age and is believed to be the oceanic basement of a forearc basin. Most of the ophiolite is fragmented and stratigraphically thin. The contact with the overlying sedimentary rocks is believed to be depositional in some places but faulted by the Stony Creek fault in other areas.

The GVS formed from sediments deposited within a submarine fan in the forearc basin environment along the continental edge. Sources of the sediments were the Klamath Mountains and the Sierra Nevada to the north and east. Limited lateral extent and the grading of one unit into another are characteristic of this type of depositional environment.

# NORTHERN CALIFORNIA

## LEGEND



### GEOLOGIC UNITS

-  Quaternary Sedimentary Deposits
-  Quaternary and Tertiary Volcanic Rocks of the Cascade Range and Modoc Plateau.
-  Tertiary Sedimentary Deposits
-  Upper Jurassic/Cretaceous Sedimentary Rocks of the Great Valley
-  Upper Jurassic/Cretaceous Sedimentary Rocks of the Coast Ranges
-  Upper Jurassic to Cretaceous Mafic to Ultramafic Rocks
-  Mesozoic - Paleozoic Metamorphic and Granitic Rocks of the Klamath and Sierra Nevada Mountains.
-  Geologic Contact
-  Fault- Dotted where Concealed

### FAULTS

- SAF San Andreas Fault
- CRF Coast Range Fault
- SFM South Fork Mountain Fault
- SCF Stony Creek Fault
- BCFZ Battle Creek Fault Zone
- MFZ Maacama Fault Zone
- FFS Foothills Fault System
- YBJ Yolla Bolly Junction
- RBFS Red Bluff Fault Zone
- CRSB Coast Range-Sierran Block Boundary
- WF Willows Fault
- MTJ Mendocino Triple Junction
- BSF Bartlett Springs Fault

STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
**DEPARTMENT OF WATER RESOURCES**  
NORTHERN DISTRICT

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**FAULT AND SEISMIC HAZARDS - PHASE I**  
RED BANK, THOMES-NEVILLE, SITES, AND COLUSA PROJECTS

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**Regional Geologic Map**

# NORTH AMERICAN GEOLOGIC TIME SCALE

GEOLOGICAL SOCIETY OF AMERICA

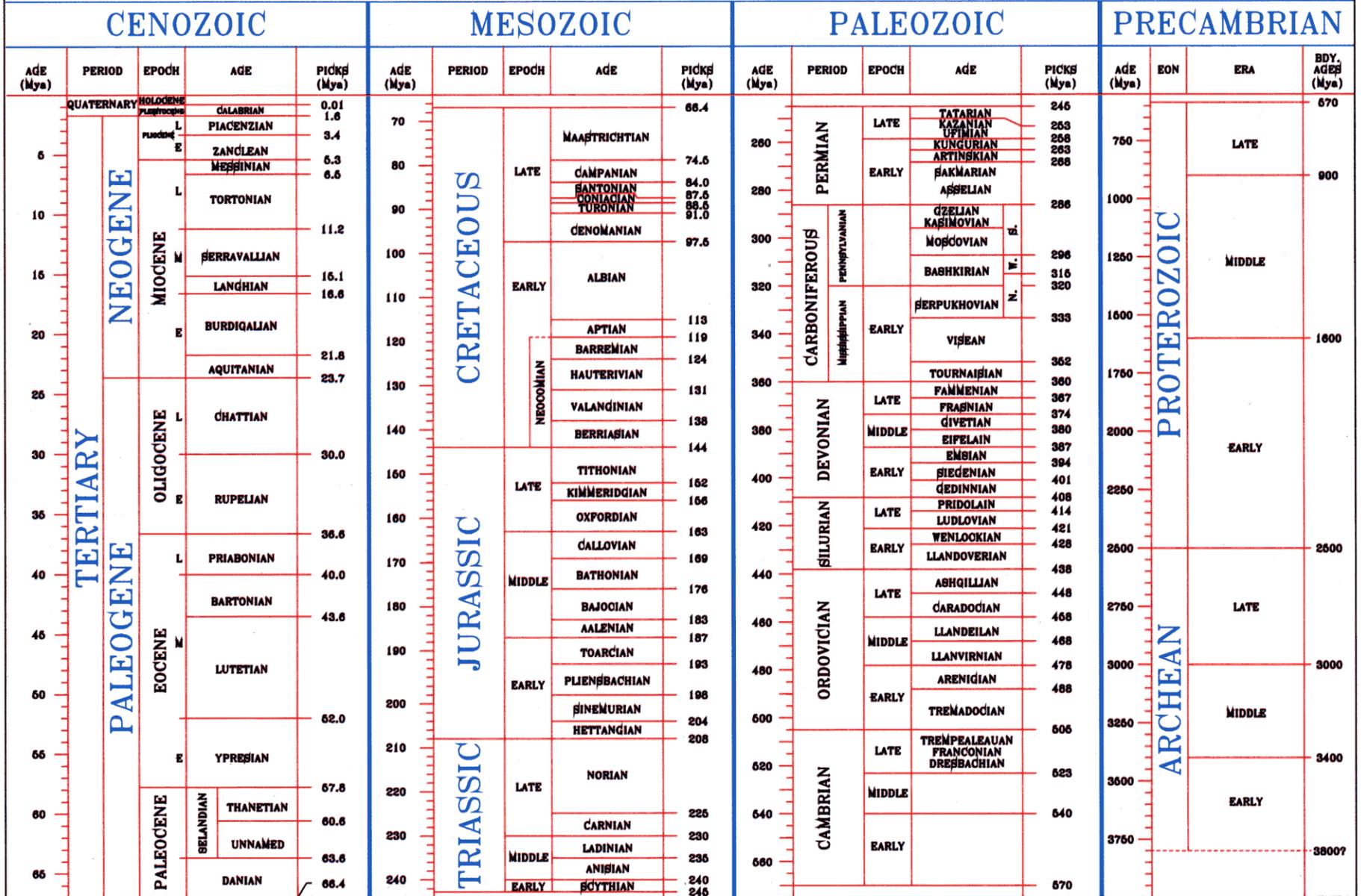


Figure 4. North American Geologic Time Scale.

The mudstones of the GVS are typically dark gray to black. Generally the mudstones are thinly laminated and have closely spaced and pervasive joints. When fresh, the mudstones are hard, but exposed units weather and slake readily. Mudstones generally underlay the valleys because of the minimal resistance to weathering and erosion.

The sandstones are light green to gray. They are considered to be graywackes in some places because of the percentage of fine-grained interstitial material. Sandstone beds range from thinly laminated to massive. In many places the sandstones are interlayered with beds of conglomerates, siltstones, and mudstones. Massive sandstones are indurated with widely spaced joints, forming the backbone of most ridges.

The conglomerates are closely associated with the massive sandstones and consist of lenticular and discontinuous beds varying in thickness from a few feet to over 100 feet. Conglomerate clasts range in size from pebbles to boulders and are composed primarily of chert, volcanic rocks, granitic rocks, and sandstones set in a matrix of cemented sand and clay. The conglomerates are similar to the sandstones in hardness and jointing.

Tertiary and Quaternary fluvial sedimentary deposits unconformably overlie the GVS. The Pliocene Tehama formation is the oldest. It is derived from erosion of the Coast Ranges and Klamath Mountains and consists of pale green to tan, semiconsolidated silt, clay, sand, and gravel. The Nomlaki tuff member occurs near the bottom of the Tehama and has been age-dated at about 3.3 million years. The Nomlaki is a slightly pink to gray dacitic pumice and lapilli tuff outcropping as a single massive bed about 30 feet thick. Along the western margin of the valley the Tehama is generally thin, discontinuous, and deeply weathered.

The Quaternary Red Bluff formation consists of reddish poorly sorted gravel with thin interbeds of reddish clay. The Red Bluff is a broad erosional surface, or pediment, of low relief formed on the Tehama formation between 0.45 and 1 million years ago. Thickness varies up to about 30 feet. The pediment is an excellent datum to assess Pleistocene deformation because of its original widespread occurrence and low relief. Red Bluff outcrops occur just east of the damsites.

Recent alluvium is a loose sedimentary deposit of clay, silt, sand, gravel, and boulders. Deposits include landslides, colluvium, stream channel deposits, floodplain deposits, and stream terraces. Quaternary alluvium is the major source of construction materials. Colluvium, or slope wash, consisting mostly of soil and rock, occurs at the face and base of a hill. Landslide deposits are similar but more defined and generally deeper. Landslides occur along the reservoir rim but are generally small, shallow debris slides or debris flows. These deposits may be incorporated as random fill in dam construction.

Stream channel deposits generally consist of sand and gravel. Construction material uses include concrete aggregate, filters, and drains. Floodplain deposits are finer grained and consist of clay and silt. Floodplain deposits may be used for the impervious core and for random fill.

The stream terraces form flat benches adjacent to and above the active stream channel. Up to nine different stream terrace levels have been identified. Terrace

deposits consist of several to ten feet of clay, silt, and sand overlying a basal layer of coarser alluvium containing sand, gravel, cobbles, and boulders. Four terrace levels have been given formational names by the USGS (Helley and Harwood 1985): the Upper Modesto, Lower Modesto, Upper Riverbank, and Lower Riverbank, ranging in age from 10,000 to several hundred thousand years old.

Terraces are valuable for evaluating the age and activity of faults that trend across them. A number of investigators have applied soil-stratigraphic, relative, and absolute age dating techniques, together with geomorphic analysis, to date and correlate terrace deposits. Evidence of faulting across the terrace deposits constrains the time of last movement.

### **Coast Ranges Province**

The Coast Ranges are located just west of the reservoir projects. The Coast Ranges are underlain by a collection of accretionary wedges of the Mesozoic-Cenozoic Franciscan complex, a Cenozoic forearc basin consisting of marine sedimentary deposits. The Franciscan increases in age and metamorphic grade inland and consists of a mixture of marine sedimentary, igneous, and metamorphic rocks ranging in age from Jurassic to Tertiary. The assemblage of graywacke, metagraywacke, shale, chert, schist, limestone, mafic and ultramafic metamorphic and igneous rocks is pervasively deformed by folds, faults, and zones of extensive shearing. The Coast Ranges fault, the Coast Ranges ophiolite, and the Stony Creek fault separate the Coast Ranges from the Great Valley province to the east.

### **Klamath Mountains Province**

Rocks of the Klamath Mountains province occur northwest of the Great Valley province, about 10 miles from the Red Bank Project. The province is about 70 miles wide and extends northward into Oregon. Geologically it is similar to the Sierra Nevada, ranging in age from Paleozoic to Jurassic. It consists of several well-defined mountain ranges, including the Trinity, Marble, Scott, and Salmon Mountains. These mountains comprise a series of arcuate metamorphic terranes of different age and stratigraphy separated by major faults. Large bodies of intrusive rocks, such as the Shasta Bally Batholith, occur in the province.

The variety of terranes and structural features can be related to pre-Cretaceous subduction. The faults between the terranes are probably old subduction zones where two crustal plates converged, and the terranes are melanges or fragments of individual plates.

### **Cascade Range Province**

The Cascade Range is a long sequence of volcanoes and volcanic rocks stretching from about Mt. Lassen to Alaska. Rocks of the Cascades vary in age from Eocene to Recent and consist of ash, tuffs, flows, mudflows, breccias, agglomerates, dikes, and sills. Along with the igneous rocks are associated volcanically derived sedimentary rocks.

The Cascade Range is a volcanic arc, a product of subduction of the Gorda and Juan de Fuca plates beneath the North American plate. The migration of the

Mendocino triple junction northward along the coast results in the gradual extinction of volcanic activity to the south. Intermediate- to deep-focus earthquakes from Red Bluff north have been correlated to the subduction of the Gorda plate (Cockerham 1984; Walter 1986).

### **Sierra Nevada Province**

The Sierra Nevada are about 400 miles long, extending from Southern California to just south of Lassen to the north. The Sierra Nevada are diverse in composition and age, but consist mostly of igneous and metamorphic rocks.

The mountains are complex, with structural deformation dating back 300 million years. Like the Klamath Mountains, both the lithology and structures are related to subduction and accretion of a variety of different terranes. About 10 mya in the early Pliocene time period, the compressional tectonic regime was replaced by an extensional regime (associated with tectonics in the Basin and Range provinces) that continues to the present. The west-northwest-directed extension is responsible for the uplift and tilting of the Sierra Nevada and the seismicity along the Chico monocline.

### **Regional Plate Tectonic Setting**

Plate tectonics have played a major role in the geologic development of California. From the late Jurassic to mid-Tertiary periods, the eastern Pacific lithosphere (Farallon plate) was subducted beneath the western margin of the North American continental plate. This resulted in the coeval formation of an arc-trench system that included an accretionary prism, a forearc basin, and a magmatic arc. The Franciscan complex, the GVS, and the Klamath Mountains-Sierra Nevada represent these terrains.

Throughout the Cretaceous time period, sediments from the magmatic arc were deposited by submarine currents in the forearc basin. These sediments now make up the GVS on which the proposed dams would be founded. At the same time, sediments and volcanic rocks, now the Franciscan complex, were scraped from the subducting ocean floor and accumulated as an accretionary wedge seaward of the GVS. As subduction ceased during the late Tertiary period, uplift became more rapid, and the transition to a strike-slip regime of the San Andreas fault system began in Southern California. Figure 5 is a cross-sectional drawing showing the California area during the middle Cretaceous period.

Since the late Tertiary period, the Mendocino triple junction has been migrating northward along the coastline, leaving the San Andreas transform fault in its wake. In a rigid plate model, one consequence of the northward migration of the triple junction is that the North American plate slides off the Gorda plate, leaving in its wake a void that is filled by upwelling asthenosphere, often referred to as a “slabless window” or “slab gap.” Seismic refraction-reflection profiles indicate partial melt and/or metamorphic fluids at the base of the crust or in the upper mantle south of the Gorda plate (Beaudoin, et al., 1997). Other supporting evidence for a slabless window includes gravity and magnetic data, teleseismic P-wave delay studies, shear-wave velocities, and changes in volcanism. The slabless

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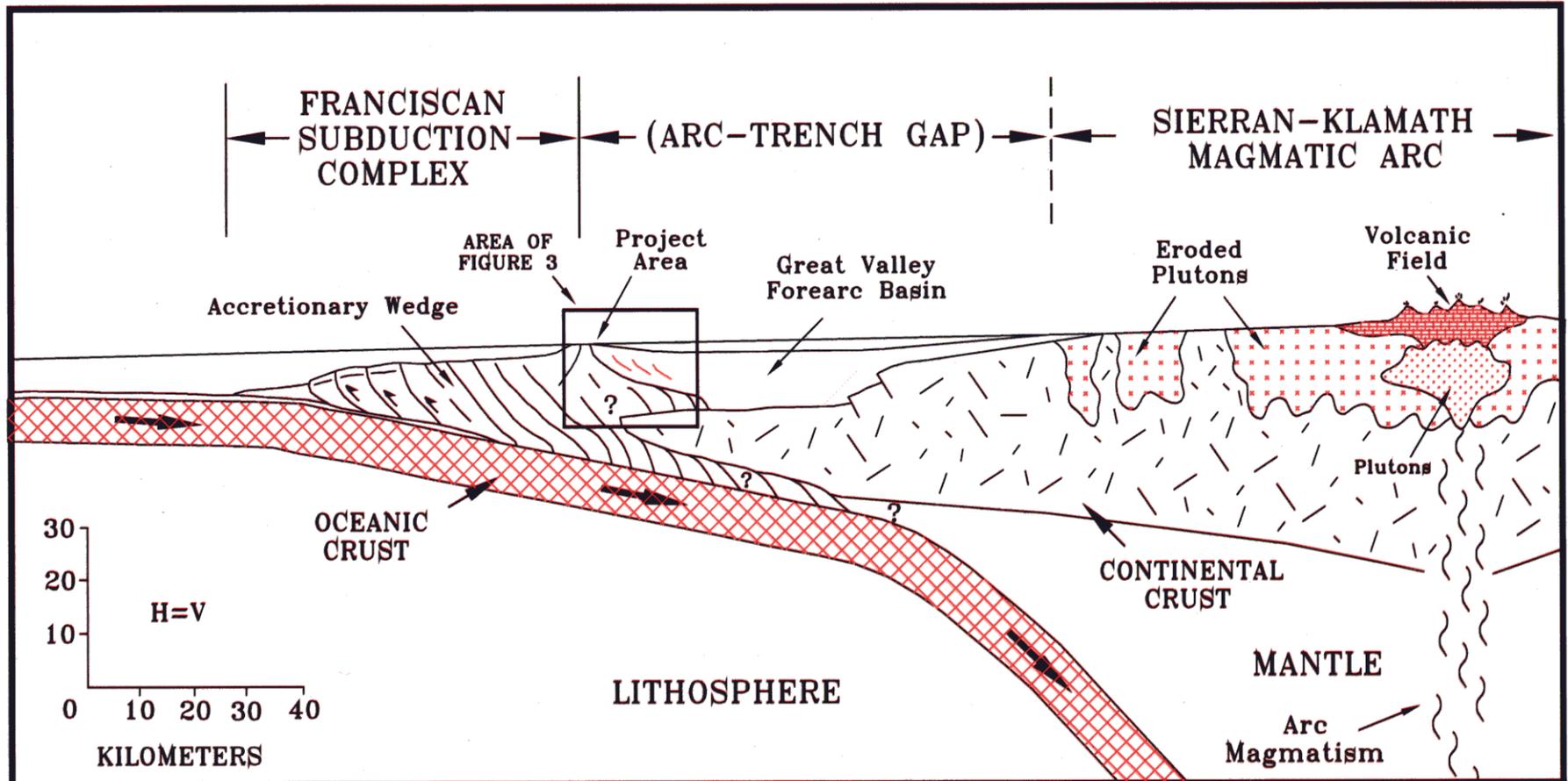


FIGURE 5. Schematic profile of subduction system across northern California during the late Mesozoic, (modified from Dickinson and Seeley, 1979).

window is probably the reason for the region's volcanic and geothermal activity, such as the Geysers, Mt. Konocti, and Clear Lake volcanics.

Subduction of oceanic lithosphere still occurs north of Cape Mendocino above the Mendocino triple junction among the Pacific, North American, and Gorda plates. Here the Gorda plate is moving under the North American continental plate in a northeast direction at an average rate estimated at about 3.5 cm per year, as evidenced by the 150-mile-long zone of intermediate focus earthquakes dipping eastward below the North American plate.

As described by Atwater (1970), the Juan de Fuca and Gorda plates are remnants of the larger Farallon plate. The Pacific plate is on the opposite side of the spreading center, several hundred miles off the coast. Subduction of the Farallon plate here has caused most of the deformation from the Cretaceous period to the present. As the San Andreas fault zone evolved, the triple junction migrated slowly northward. During this period, the Great Valley experienced several episodes of uplift and subsidence, until the early Miocene when the valley emerged from the sea and was subjected to fluvial erosion and deposition (Harwood 1984). At the same time, volcanic eruptions were occurring along the northern Sierra Nevada, damming streams and filling narrow valleys.

Extensional forces from backarc spreading reached their peak during this period. These forces are responsible for the upward tilting of the Sierra Nevada and the large expansion of the Great Basin to the east during the Tertiary.

Strong evidence suggests that as the Mendocino triple junction migrated northward, structures in the valley began to show compressive deformation and faulting in a similar progressive pattern (Harwood 1984). This is evident from the age of faulting, folding, and volcanic activity ranging from 2.5 mya near Sutter Buttes to 0.5 mya near the Battle Creek fault. Figure 6 shows the current position of the plates.

The stress regime in the Sacramento Valley is a result of its position between the right lateral transform tectonism of the San Andreas fault to the west and the crustal extension of the Basin and Range provinces to the east. The direction of stress may vary but, in general, the direction of maximum compression is northeast-southwest.

Evidence of this stress regime is a series of northwest trending folds and faults along the western Sacramento Valley. The faults dip steeply east, with reverse and minor left-lateral movement. In the north and northeastern valley, the structural trend shifts, and structures are oriented in an east to northeast direction. The faults typically dip steeply to the south with normal offset and a minor right-lateral component.

The relationship among the Coast Ranges, Great Valley, and Sierra Nevada is explained by the process of tectonic wedging. In this process, the Franciscan rocks of the Coast Ranges were metamorphosed to blueschist grade in a subduction zone and then were thrust upward and eastward as a wedge onto the Klamath-Sierra Nevada basement. As it moved, the wedge progressively peeled up and carried before it, in imbricate fashion, a slab of Coast Ranges ophiolite and several slabs of the GVS. This thrusting greatly shortened the original distance across the basin in which the GVS was deposited (Wentworth, et al., 1984).

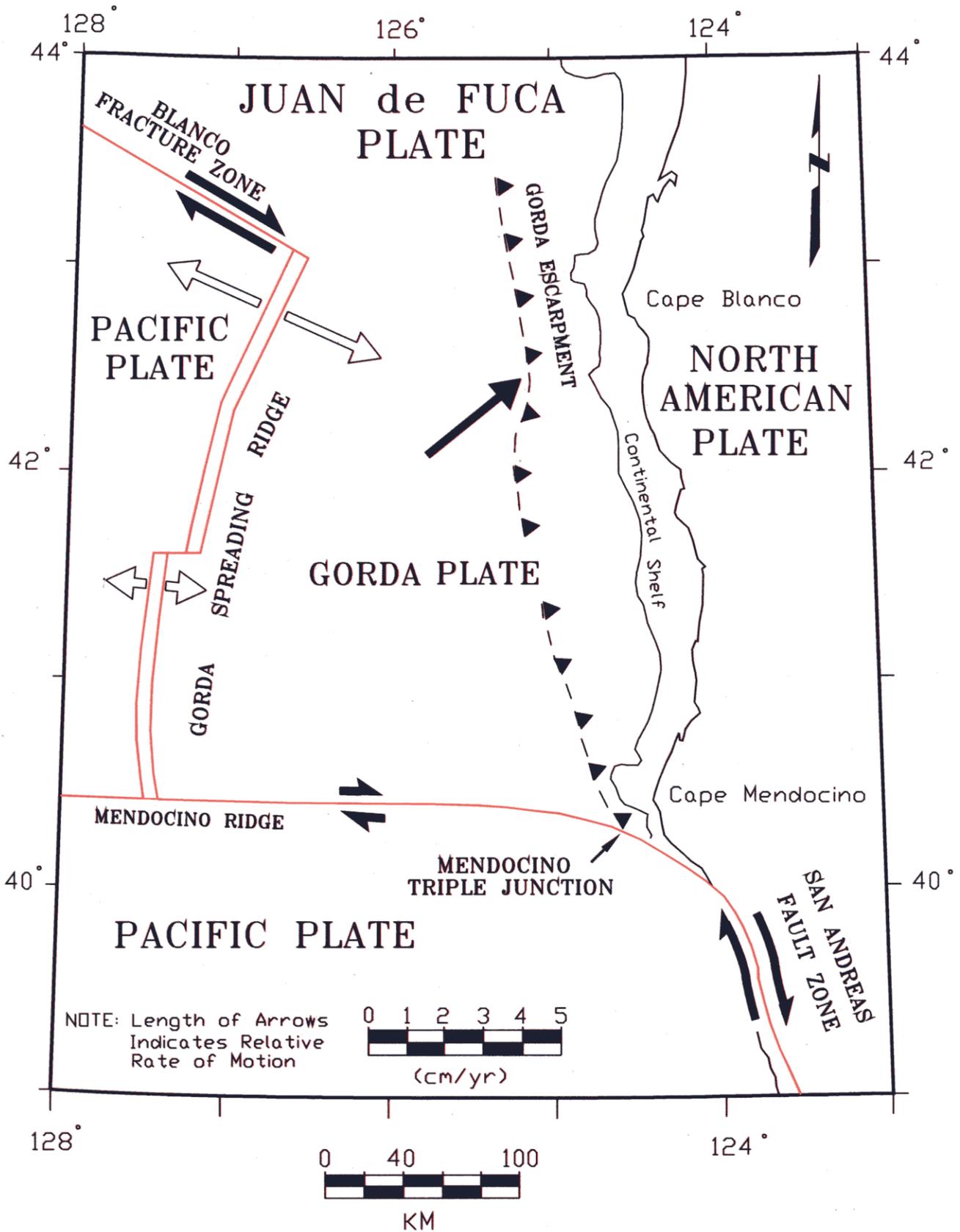


FIGURE 6. Mendocino Triple Junction and Plate Boundaries

Recent studies indicate that folding and faulting along the west side of the Sacramento Valley are active and represent the shallow expression of deeper thrusting. Evidence also suggests that this seismically active zone, called the Coast Ranges-Sierra Nevada block boundary or the Great Valley fault, extends the full length of the greater Central Valley.

### **Local Seismotectonic Setting**

The project area lies near the boundaries of three tectonic stress provinces (Zoback and Zoback 1989). Stress provinces are areas affected by the same stress regime, resulting in roughly similar faulting.

The San Andreas transform stress province is characterized by NW-SE tension and NE-SW compression. The province extends along the northern Coast Ranges, as far east as the central part of the Great Valley, and as far north as Cape Mendocino.

The Cordilleran stress province encompasses the eastern part of the Great Valley, the Sierra Nevada, and the Basin and Range to the east. The province is characterized by WNW-ENE-trending minimum principal stress (extension).

The Pacific Northwest stress province extends northward from the general area of Red Bluff. The province is characterized by roughly east-west compression resulting from the underthrusting of the Gorda plate beneath the North American plate. Both strike-slip and thrust faulting have occurred here.

### **San Andreas Transform Stress Province**

The Red Bank, Thomes-Newville, Sites, and Colusa Projects all lie along the eastern edge of the San Andreas transform stress province. The stress is caused by right lateral movement between the Pacific and North American plates, estimated to be about 37 to 41 millimeters per year. Most of this motion occurs along three major right-lateral strike-slip fault systems. These are the San Andreas to the west, the Maacama, and the Bartlett Springs fault systems. The amount of movement decreases from the west to the east, with about 75 percent of the motion accommodated along these three faults in the northern Coast Ranges, and the remainder in the Great Valley and the Sierra Nevada to the east. The 2 to 5 mm component of plate motion perpendicular to the plate boundary is probably accommodated primarily by thrust and reverse faulting along the Great Valley margin (Great Valley fault).

In this general area, WLA (1997) divides the stress province into the northern Coast Ranges and the CRSNBZ seismotectonic provinces.

The eastern extents of the northern Coast Ranges seismotectonic province include, from south to north: the Green Valley, Cordelia, Hunting Creek, and Bartlett Springs faults. WLA (1997) believes these faults to represent the easternmost extent of major strike-slip faulting in the northern Coast Ranges. The Bartlett Springs fault lies about 18 miles southwest of the town of Sites and 25 miles southwest of Newville.

The CRSNBZ seismotectonic province lies east of the northern Coast Ranges. The eastern extent of the province lies along the Willows and Corning faults near the center of the Sacramento Valley. The province is a complex region of contractional deformation characterized by uplift, folding, and thrust faulting. Quaternary deformation is present in places such as the Dunnigan Hills, Rumsey Hills, and the Corning domes. Compressive deformation along the CRSNBZ is also responsible for the uplift and tilting of the east-dipping strata of the GVS. Patterns of historical seismicity and microearthquakes show that the thrust faults are active (Wong, et. al., 1988; Unruh and Moores 1992; and WLA 1997).

### **Cordillera Extensional Stress Province**

The eastern Great Valley and the Sierra Nevada physiographic provinces lie within the Cordillera extensional stress province (Zoback and Zoback 1989). This province is characterized by WNW-ENE trending tensile stress. Both normal and strike-slip faulting are common. The tensile stresses in this province have caused such features as the Chico monocline, the westward tilting of the Sierra Nevada, and the Basin and Range features to the east.

### **Pacific Northwest Stress Province**

The southern extent of this province is in the general area of Cape Mendocino, and includes the Klamath Mountains and most of the Cascade Range. Both strike-slip and thrust faulting are common. The state of stress is probably mostly related to underthrusting of the Gorda plate under the North American plate. The Red Bank Project is on the boundary between this stress province and the San Andreas transform stress province.

## **Regional Faulting And Structures**

In general, south of Red Bluff, regional faults strike to the northwest, roughly parallel to the San Andreas fault. Fault plane solutions for the Sacramento Valley and Coast Ranges in this area are variable and do not show consistent right-lateral movement. Faulting along the CRSNBZ also have a large component of east-west thrusting.

North of Red Bluff, faults strike to the east and northeast, roughly parallel to the Gorda plate subduction direction. The following discussion of faulting includes only those faults that may affect the proposed west side projects, either from seismic events or ground breakage.

Numerous smaller faults strike perpendicular to the regional faults and the regional structural trend. These are called cross, tear, or transverse faults. Most of the damsites and saddle damsites have these faults in the foundation area. They are believed to be late Cretaceous in age, and none of these faults have shown any evidence, to date, of Quaternary movement.

The faults represent weaknesses in the foundation where present. Typically the faults need to be excavated deeper than the rest of the foundation, then filled with concrete. Faults also are seepage corridors and require more grout. Because of the inherent weakness of faults, landslides are also common along fault surface traces.

## **Gorda Plate-Cascadia Subduction Zone**

The Pacific Northwest coast from the Mendocino triple junction northward to Alaska is a subduction zone where the Gorda plate to the south and the Farallon plate to the north are descending beneath the North American plate. The Cascade Range is a continental volcanic arc resulting from the collision zone and the melting of the downgoing plate. Worldwide, these subduction zones are marked by seismicity to include large or great ( $M > 7.5$ ) earthquakes having thrusting focal mechanisms. South of the Mendocino triple junction, the San Andreas right lateral transform fault mechanism is operational.

The Cape Mendocino area exhibits intense activity, as expected in a zone where three plates join. Most of the larger magnitude seismicity appears to be associated with the Mendocino fracture zone, San Andreas fault, and other related faults. The triple junction is too far away from the proposed projects to affect the designs and specifications.

Cockerham (1984) presented seismic data suggesting the subduction of a 180-km-long slab of the Gorda plate beneath Cape Mendocino. The slab would extend eastward to the vicinity of Red Bluff. The plate dips about 10 degrees for a length of 120 km to depths of 30 to 35 km, then steepens to 25 degrees and plunges to depths of 60 km.

Most of the world's strongest earthquakes occur along active subduction zones. Recent examples include the M8.3, 1964 Alaskan earthquake and the M8.1, 1985 Mexican earthquake. These are the result of locking in the zone of contact between the descending and overriding plates, with a longer period of locking resulting in a larger release of energy during an earthquake. However, not all subduction zones produce great earthquakes; and the differences between those generating great earthquakes, and those that do not, appear to be systematic. There have been no large-thrust earthquakes in the subduction zone in historical times. Explanations for this include the cessation of subduction, aseismic convergence, and locking, which is most likely based on similarities with other subduction zones in other parts of the world that have experienced great historical earthquakes.

These similarities include the lack of an active backarc basin, an absence of seismicity at depths greater than 100 km, the presence of a shallow, sediment-choked trench, a shallow-dipping Benioff zone, smooth topography of the subducted slab, and seismic quiescence over a significant time span. In addition, an empirical relationship between convergence rate, age of subducted crust, and maximum earthquake magnitude for major subduction zones suggests that the Cascadia subduction zone may be strongly locked and capable of producing great earthquakes (USBR 1986).

CDMG (1996, Web site) assumes that large earthquakes occur every few hundred to 1,000 years as inferred from paleoseismic information. The entire zone was modeled as a combination of an M9 occurring along the entire length from California to Washington about every 500 years and an M8.3 rupture along the California portion of the zone about every 335 years.

The Gorda plate extends underneath the continental plate as shown in Figure 7. In a zone that extends from about Weaverville to Red Bluff, several earthquakes have had focal depths between 45 and 55 km. Walter (1986) and Cockerham

(1984) have associated these events with the southeastern edge of the underthrusting Gorda plate. Further east, several events 50 to 80 km deep are grouped along a northwestern trend. It is theorized that these deeper events could be related to isolated failures within the same plate (HMT 1983).

American Indian stories tell of a quake in this general area in 1700, and major quakes normally come every 300 to 500 years, hence the prediction of the Big One by 2200. "It's going to be bigger than the San Francisco earthquake, bigger than 1906," Stephen Walter of USGS said (Ralph Jennings in Record Searchlight article on Shasta Shaker).

A major earthquake related to Gorda plate subduction is a concern for the Red Bank Project. This is because the edge of the plate is directly underneath the project or somewhat to the south at depth. Walter (1986) described the seismic characteristics of Gorda plate subduction, including shallow earthquakes to the west and increasing depth of focii to the east. Recently USGS outlined the possibility of an M8+ occurring near the Red Bank Project at an approximate depth of 35 to 55 km or about 25 to 35 miles.

### **San Andreas Fault System**

The San Andreas fault extends almost the entire length of the state. In Northern California, the system consists of three subparallel right lateral strike-slip faults, the San Andreas, Maacama, and Bartlett Springs faults. The total width of the system is about 100 km. Freymuller and Segall (1997) used Global Positioning System measurements along all three faults over a period of four years to determine a relative motion of 3.9 centimeters between the North American plate and the Pacific plate. They further divide the slip rate to 2 cm for the San Andreas, 1.2 to 1.5 cm for Maacama, and 0.7 to 0.9 cm for Bartlett Springs.

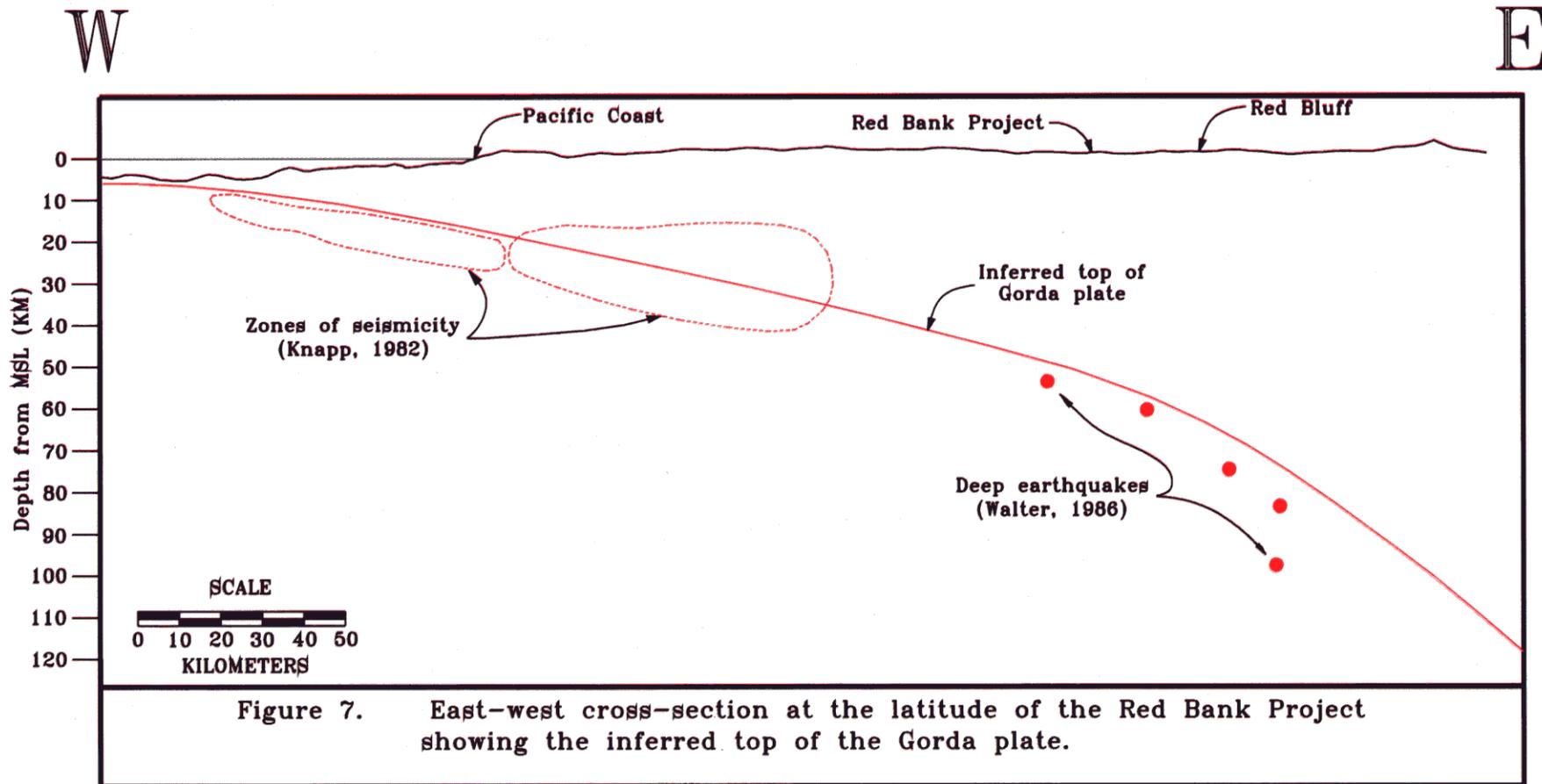
#### **San Andreas Fault**

The San Andreas fault lies about 80 miles west of the project area. HMT (1983) assigned the following seismic parameters to the Corps' Cottonwood Creek project: an M8.3 resulting in a peak horizontal ground acceleration of 0.07g, a peak ground velocity of 12 cm per second, and a duration of five seconds. CDMG (1996) assigned an M7.6 and a recurrence interval of 210 years to the north coast segment of the great San Francisco earthquake of 1906.

#### **Maacama Fault**

The Maacama is generally considered a splinter fault of the San Andreas and part of the Hayward fault subsystem. No major historical earthquakes have been associated with this fault, although it has a sizable creep rate of about 7 mm per year near Ukiah (USGS 1996), but most of the fault must be locked according to Freymueller and Segall (1997).

Seismic refraction-reflection profiles from the Mendocino triple junction seismic experiment (Beaudoin, et al., 1997) across the Coast Ranges show breaks in these reflections correlate to this Maacama fault and the Bartlett Springs fault, suggesting that these faults extend at least to the mantle.



### **Bartlett Springs Fault**

The Bartlett Springs fault is believed to be a northward extension of the Green Valley fault. No historic major earthquakes have occurred on the Bartlett Springs fault, but creep rates of about 8 mm per year on the Calaveras fault suggest that this may continue to the north. USGS (1996) assigned an  $M_w$  of 7.1, a slip rate of 6 mm per year, and an effective recurrence time of 230 years to this fault.

As stated previously, seismic refraction-reflection profiles from the Mendocino triple junction seismic experiment (Beaudoin, et al., 1997) across the Coast Ranges show breaks in these reflections correlate to the Maacama fault and this Bartlett Springs fault, suggesting that these faults extend at least to the mantle.

### **Coast Ranges-Sierra Nevada Block Boundary**

Recent work by numerous researchers indicates an active tectonic boundary between the Sierra Nevada basement and the Coast Ranges lies buried beneath the entire western edge of the greater Central Valley from Bakersfield to Red Bluff. This system of faults is generally referred to as the Great Valley thrust fault system or the Great Valley fault.

Activity along this complex zone is characterized by both reverse and thrust faulting, and is considered to be the source of the two 1892 Winters-Vacaville earthquakes ( $M_L$  6-7), and the 1983 Coalinga earthquake ( $M_L$  6.7). Many small to moderate earthquakes have also occurred along the full length of the boundary. These include an  $M$ 5.8 in 1866 and an  $M$ 5.9 in 1881 west of Modesto, and an  $M$ 6 in 1889 near Antioch. The deeper faulting manifests itself on the surface as the deformation of younger deposits. The anticlines at Corning and Dunnigan Hills are thought to be shallow expressions of deeper thrusting along this boundary (Wentworth and Zoback 1990).

Since no definitive surface faulting exists, the analysis of microseismic data becomes an important tool to define the extent and seismic potential. Wong, et al. (1988), believes that an  $M_L$  7 earthquake could possibly occur anywhere along the boundary. WLA considers this too conservative, with an  $M$ 6.5 to  $M$ 6.75 more likely.

The Working Group on Northern California Earthquake Potential and other workers have divided the Great Valley fault into about 14 segments that act, and are independent of each other. The segments of interest to this study are designated GV01, with the source centered at the Sites anticline, and GV02 outside the project area to the south, centered on the Cortina thrust (USGS 1996).

It is not clear whether there are additional segments to the north of GV01. Luce (1993), in his masters thesis, outlined nine segments from the Battle Creek fault zone on the north, to Coalinga on the south. Caltrans also assumes that the boundary zone extends north to the Battle Creek fault zone, and this seems the most logical.

The idea of “characteristic earthquakes” is that major faults tend to rupture along discrete segments rather than along their entire length (Schwartz and Coppersmith 1984). Segmentation of the fault is based on bends, stepovers, and truncations of major structural features associated with faulting. Based on experience with the Coalinga earthquake, this segmentation distinctly limits the

extent of ruptures and the magnitude of the tremors. Figure 8 shows this segmentation. GV01 has been assigned an Mw of 6.7 with a recurrence interval of 8,300 years and a slip rate of 0.1 mm per year. GV02 has an Mw of 6.4 with a recurrence interval of 6,000 years and a slip rate of 0.1 mm per year (USGS 1996). These moment magnitudes do not include the possibility that more than one segment may rupture at once. The USGS also assigns a slip rate of 1.5 mm per year to all segments except for GV01 and 02, to which they assign a slip rate of 0.1 mm. This increases the recurrence interval from about 500 years to about 8,000 years.

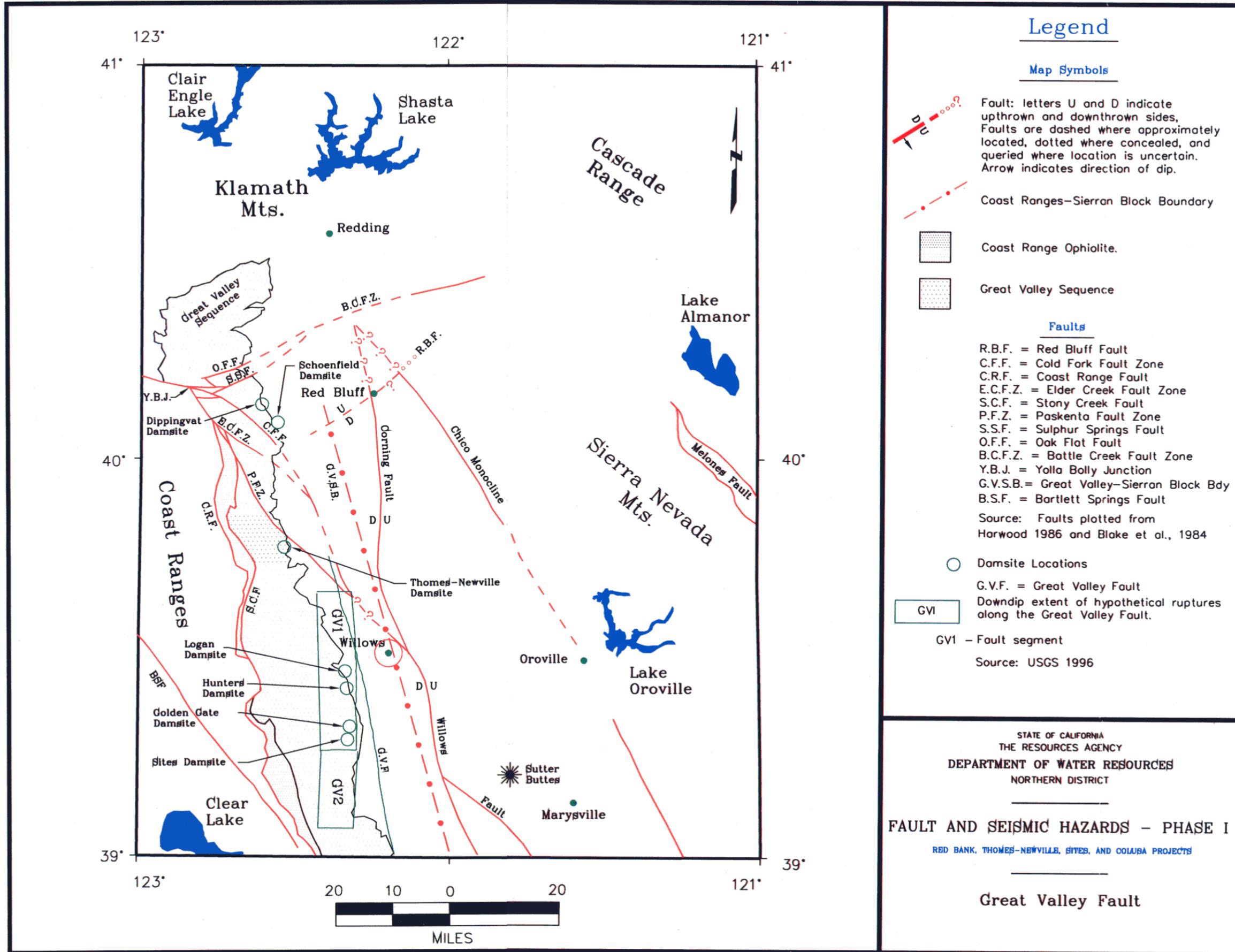
Earthquakes along this zone could potentially affect all of the proposed projects. Figure 8 shows the distance between the proposed structures and a potential earthquake. The worst case scenario is that an earthquake may occur directly underneath the damsite at depths ranging from 5 to 15 km, with the dam on the upthrown block of a thrust fault, resulting in directivity effects. Accelerations and consequent damages are generally much higher on the upthrown side.

### **Salt Lake Fault, Sites Anticline, and Fruto Syncline**

The Sites anticline is associated with the adjacent Fruto syncline that extends a distance of about 45 miles from an area near the town of Sites to near the town of Newville to the north. The anticline is a tight fold with steeply dipping and locally overturned strata on both limbs. Based on analyses of seismic reflection data, WLA (1997) interprets the anticline as a fault-propagation fold developed above one or more blind-thrust faults. The faults are truncated by a subhorizontal detachment at a depth of about 3 miles.

The Salt Lake fault is a high-angle thrust fault that developed adjacent to the axis of the doubly plunging Sites anticline (DWR 1978). Salt water springs, gas seeps, and possible sag ponds along the fault trace are suggestive of recent fault activity. In several locations, however, the fault is concealed by an unbroken Pliocene Tehama formation, suggesting that the latest movement occurred prior to this time.

Based on the work done by the WLA and the Working Group on Northern California Earthquake Potential in 1996, it is probable that the Salt Lake fault, the Sites anticline, and the Fruto syncline are features related to the Great Valley fault. The fault trends within one mile of most of the Thomes- Newville, Sites, and Colusa Project damsites, and possibly crosses the upstream edge of the Sites Dam site. The Sites anticline (Kirby 1943) and the Fruto syncline (Chuber 1961) are flexures extending in the northwest direction from the general area of Sites about 40 miles north to Newville, and possibly as far as Paskenta. It was generally believed that the folds and attendant faulting (Salt Lake fault and numerous transverse faults) in the middle Cretaceous sediments were formed as a result of east-west compression prior to Pliocene (Tehama formation) deposition (Chuber 1961). It is now, however, considered possible that deformation along this zone may be an active process, caused by deep thrusting along the CRSNBZ (see section on the Coast Ranges-Sierra Nevada block boundary).



**Legend**

**Map Symbols**

Fault: letters U and D indicate upthrown and downthrown sides, Faults are dashed where approximately located, dotted where concealed, and queried where location is uncertain. Arrow indicates direction of dip.

Coast Ranges-Sierran Block Boundary

Coast Range Ophiolite.

Great Valley Sequence

**Faults**

- R.B.F. = Red Bluff Fault
  - C.F.F. = Cold Fork Fault Zone
  - C.R.F. = Coast Range Fault
  - E.C.F.Z. = Elder Creek Fault Zone
  - S.C.F. = Stony Creek Fault
  - P.F.Z. = Paskenta Fault Zone
  - S.S.F. = Sulphur Springs Fault
  - O.F.F. = Oak Flat Fault
  - B.C.F.Z. = Battle Creek Fault Zone
  - Y.B.J. = Yolla Bolly Junction
  - G.V.S.B. = Great Valley-Sierran Block Bdy
  - B.S.F. = Bartlett Springs Fault
- Source: Faults plotted from Harwood 1986 and Blake et al., 1984

Damsite Locations

G.V.F. = Great Valley Fault  
Downdip extent of hypothetical ruptures along the Great Valley Fault.

GVI - Fault segment

Source: USGS 1996

STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

**FAULT AND SEISMIC HAZARDS - PHASE I**  
RED BANK, THOMES-NEWVILLE, SITES, AND COLUSA PROJECTS

**Great Valley Fault**

Field inspections during this investigation along the trace of these three features suggest that the zone is more complex, with numerous smaller folds, faults, and shears along a wide area of deformation. Hints of this complexity can be seen along creek exposures on Sites, Funks, and Logan Creeks.

There also appears to be a bedding, dip, and strike discontinuity between the middle and early Cretaceous sedimentary rocks. Exposures are poor and more work needs to be done in the area to determine the true character of this zone.

WLA (1997) surveyed three geomorphic fluvial terrace profiles across the Sites anticline. They found no evidence for systematic uplift or tilting evident on surfaces dating back to the last 30,000 years. The Sites anticline also lacks the pronounced geomorphic expression similar to Dunnigan Hills and Rumsey Hills, two actively growing anticlines in the southwestern Sacramento Valley.

WLA also performed aerial and field reconnaissance of the Salt Lake fault. They observed undeformed colluvium draping the escarpment and fault traces at numerous locations. Terraces crossed by the fault appear to be undeformed. For these reasons, WLA concluded that the fault is not active.

### **Coast Ranges Fault**

This fault is the structural contact between the Franciscan complex to the west and the Coast Ranges ophiolite to the east. In general, the fault is within 10 miles of the proposed damsites. The fault generally dips steeply. It is one of the longer faults in the State, extending from south of Colusa Reservoir to near the Oregon border. The fault may have originated in the Cretaceous period as a result of east-dipping subduction and subsequently accommodated crustal attenuation. However, there is little agreement about the fault's current activity and recent displacement history.

At the surface, it appears to be a high-angle, west-side-up reverse fault. However, recent research suggests that it probably has, over time, moved under compression, extension, and right lateral strike-slip (Jayko 1987; Wentworth, et al., 1984; Platt 1986; Krueger and Jones 1989).

Phipps and Unruh (1992) believe the fault to have been a subduction fault that has locally been reactivated as a thrust and, possibly, a normal fault. They also believe the fault to be allocthonous, that is, separated from its deep-seated roots. The fault has been cut and folded by later thrusts and by strike-slip faults.

This fault is generally considered a Mesozoic and early Tertiary feature. A part of the fault northwest of Lake Berryessa shows evidence of Quaternary displacement. It is uncertain whether the Coast Ranges fault is active. Near the Red Bank Project, HMT (1983) found no evidence of movement since the deposition of the Nomlaki 3.3 mya. WLA (1997) also found no evidence for late Quaternary activity.

### **Stony Creek Fault**

The Stony Creek fault is east of and runs parallel to the Coast Ranges fault. It is also the contact that separates the Coast Ranges ophiolite from the GVS to the east. This contact is believed to be both depositional and faulted, showing both normal and reverse movement. In most places, the fault is near-vertical. This fault is only of concern because of its proximity to the proposed structures.

Past investigations (ESA 1980; DWR 1982; USBR 1981) studying movement along this fault have been inconclusive. Evidence from these studies suggests that at least some of the segments have been inactive for at least the last 130,000 years and, most likely, the last 250,000 years. WLA (1997) concluded that the fault is not active.

Outcrops of the fault trace along roadcuts near Grindstone Creek indicate that the contact is sharp and well defined, suggesting that not much movement has occurred. The USGS (1996) does not consider it a potential source of M6+ earthquakes.

### **Corning and Willows Faults**

The Corning fault is not expressed at the surface but is based on well data and the overlying deformation, including the Corning domes and the Greenwood anticline. Pleistocene deformation and the association of microearthquakes suggest that the fault may be an active steeply east-dipping reverse fault (Wong, et al., 1988). Near its southern end, the Corning fault is interpreted to trend NW-SE and either splay off from or terminate against the Willows fault (Harwood and Helley 1987). The closest approach of the Willows fault to any of the damsites is 12 miles from the Sites Dam site.

The Willows fault appears to be a steeply dipping reverse fault with the east side up. It is probably the most extensive fault within the valley and appears to be a major tectonic boundary dividing the Sacramento Valley into two late-Cenozoic structural provinces. North of Willows, the fault changes to a northwest strike and appears to splay into the Paskenta, Cold Fork and Elder Creek faults (Wong, et al., 1988).

### **Northern Transverse or Tear Faults, and Other Minor Faults**

From south to north there are a number of minor faults, some of which are transverse to the regional structure. These include the Paskenta, Black Butte, Elder Creek, Cold Fork, Sulphur Spring, and Oak Flat faults.

The faults near the Red Bank Project are believed to be tear faults associated with subduction and the westward rotation of the Klamath Mountains. Wentworth and Zoback (1984) believe that the faults break the GVS but do not root in the deeper basement rocks.

The Paskenta fault consists of a number of subparallel faults that trend west-northwest. To the east, the fault disappears under the Pliocene Tehama formation, suggesting that the last movement occurred prior to that time (DWR 1978).

The Elder Creek fault zone originates west of the Red Bank Project, then strikes southeast, branching out to form a series of bifurcating fault segments. Displacement is largely left-lateral strike-slip (Bailey and Jones 1973) with GVS rocks displaced tens of miles west. Harwood and Helley (1987) projected the Willows fault to the south and the Cold Fork fault to the north into the Elder Creek fault zone. There has been no evidence of Quaternary movement documented for this fault zone but the Willows fault has recent seismic activity associated with it.

The Cold Fork fault is about 6 miles north of the Elder Creek fault zone and is similar in form, trend, and displacement. The fault consists of numerous splays

that trend northwest, crossing both the Sulphur Spring and Oak Flat faults. There is no evidence of Quaternary displacement along this fault.

The Sulphur Spring fault is a few miles north of the Dippingvat Dam site. It trends from the Stony Creek fault northeast about 10 miles to the contact point between the GVS and the Tehama formation. Movement is right lateral, with significant displacement of both the GVS and the basal Tehama units. Bailey and Jones mapped several thousand feet of offset in the Nomlaki tuff (3.3 million years old). HMT excavated several trenches across traces of the fault and concluded that movement along the fault ceased by more than 100,000 years ago, but more likely 1.2 mya.

The Oak Flat fault is about 2 miles north of, and parallel to the Sulphur Spring fault. It is also about the same length and shows right lateral movement, but does not displace the Pliocene Tehama. This suggests that the last movement was older than 3.3 mya.

### **Battle Creek Fault Zone**

This fault zone consists of a number of parallel faults that end near the town of Cottonwood to the west and extend northeast about 22 miles toward Mt. Lassen. The fault is associated with an east-west trending zone of seismicity and folding (Inks Creek fold system), separating the Sacramento Valley proper from the Redding basin.

Movement is predominantly normal with the south side down, but with a smaller component of right lateral strike-slip (Helley, et al., 1981). Interpretation of deep seismic lines (HMT 1984) indicates vertical basement displacements of about 150 feet near the west end to 1,300 feet on the east. The fault is Quaternary in age, but it is not known whether it is active. The age of latest displacement increases toward the east with the most recent movement believed to be greater than 0.42 mya (Harwood and Helley 1987).

### **Foothills Fault System**

Located about 50 miles to the east of the project along the western flank of the Sierra Nevada, the Foothills fault system is believed to be a low activity fault with a slip rate of less than 0.1 mm per year. An M5.7 occurred on this fault zone (Cleveland Hills fault) near Oroville in 1974. An MCE of 6.5 was assigned by Caltrans in 1996 to this fault; an earthquake of this magnitude should have minimal effects on the proposed structures.

This system is composed of generally minor and younger normal displacement faults superimposed on a wider zone of older high-angle reverse faults.

### **Mt. Lassen and Related Earthquakes**

Seismicity is associated with Mt. Lassen volcanic activity, including earthquakes associated with eruptive activity, aftershocks, and swarms. The largest earthquakes are in the M5-6 range with intensities of MM VII. These earthquakes are too far away to affect the designs of the project dams.

## **Other Regional Structures**

Other regional structures besides faults include folds and joints. Regional folds generally trend in the same northwest direction as the regional faults. Some of the folds, such as Corning and Dunnigan Hills, are probably the surface expression of deeper movements along faults. Regional folds are consistent with a compressive stress regime oriented about N75E.

The largest structure is the synclinal fold of the Sacramento Valley. On the west side, the Cretaceous mudstone, sandstone, and conglomerate dip moderately to steeply east and strike northwest. On the east side, similar beds dip to the west and strike in about the same direction.

The Chico monocline occurs along the east side of the valley between Chico and Red Bluff. Along the east side, beds dip shallowly to the west, but at the axis of the monocline, the beds dip more steeply toward the center of the valley. The axis is also displaced by numerous faults trending parallel to the axial plane.

Jointing is pervasive in the GVS but is generally not present in rocks younger than the Cretaceous. The Cretaceous mudstones are generally the most jointed. Jointing sets in three directions, and spacings from less than an inch to about a foot are common. The joint directions are perpendicular to each other with one set parallel to the bedding and the other two sets perpendicular to the bedding and to each other. The pervasive jointing causes the exposed mudstone outcrops to slake readily.

The Cretaceous sandstones and conglomerates vary in joint spacing depending mostly on the thickness of the individual beds. Joint directions are similar to the mudstones. The massive units have joint spacings ranging from a few feet to several tens of feet or more.

## **Seismicity**

The seismicity of the western Sacramento Valley foothills has been recorded by a number of different agencies over the last 100 years. These agencies include the University of California, Berkeley, the California Department of Conservation, USGS, and DWR. The accuracy in the measurements of the epicenters, focii, and magnitude has improved over the years as more instruments with greater sensitivity and accuracy have been installed. The older data were recorded with instruments located several hundred miles away. Consequently, the plotted locations of seismic events may be off by tens of miles.

Earthquakes as small as M1 and M2 have been recorded in the project area since the installation of the Northern California Seismic Network beginning in 1975 (Attachment A). The appendix includes an analysis of earthquake activity to date. DWR, in 1991, as part of the Red Bank Project, worked with USGS to install four additional seismic stations in the area. Accuracy in the plotting of epicenters with the data from these stations can be within several miles for relatively small earthquakes occurring close by. USGS provided DWR with an analysis of the data recorded to date by the network.

According to USGS, the number of earthquakes recorded by the network is typically three or less and often zero per month.