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Seismic Hazards Associated with active Deformation within the Camarillo Fold Belt, Western Transverse Ranges, Southern California

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Introduction

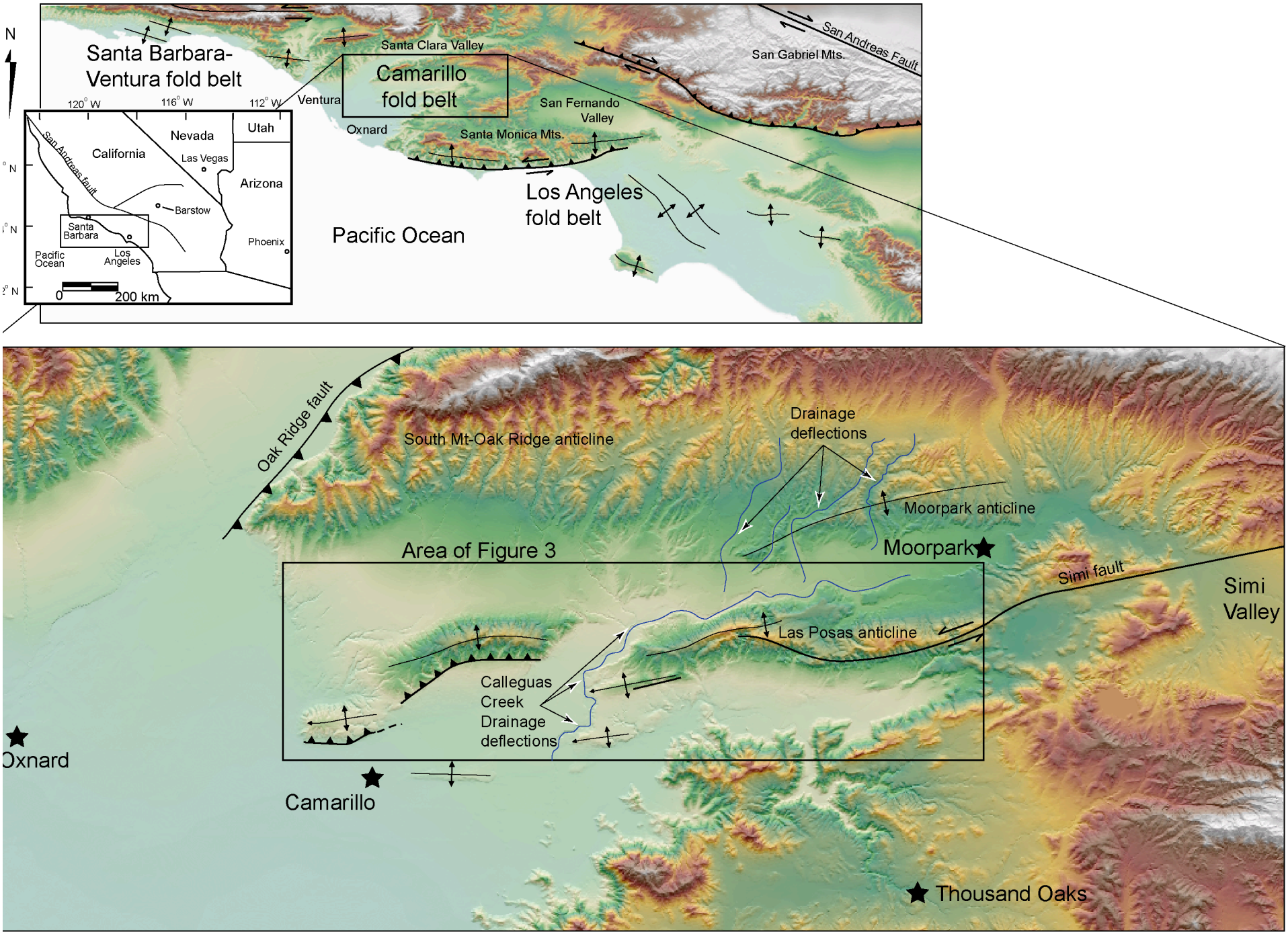
The Camarillo fold belt (CFB) is composed of several active south-verging folds and reverse faults, including the left-slip Simi fault, that pose an unknown seismic hazard to nearly one million people living in the cities of Ventura, Camarillo, Oxnard, and Thousand Oaks. Faults and folds within the study area lie immediately south and along the same trend as the more significant Oak Ridge fault (Fig. 1), but since the total amount of shortening is less to the south the CFB the topographic expression is less impressive. Yet, because the rates of slip and slip history of these faults is poorly known, it is not clear whether the folding in the CFB is the result of 1) southward migration of the deformation front and youthful tectonics at high strain rates, 2) contemporaneous back-thrusting off of the Oak Ridge fault and relatively low slip rates, or 3) related to left-lateral strike-slip faulting on the Simi fault. Additionally it is not known if discrete faults traces in the CFB are linked across segment boundaries and rupture coseismically or whether faults are independent seismic sources. Although, numerous consulting reports exist, no thorough tectonic synthesis of the region has been completed and scant attention has been paid to the interactions among multiple, synchronously active structures.

In order to identify propitious sites for future paleoseismic studies we have focused our research on: 1) detailed mapping of known faults and deformed geomorphic surfaces, 2) use DEM-analysis and indices of active tectonics to illuminate the relative timing of deformation on discrete structures, 3) establishing the Quaternary chronology of the region, and 4) compiling the extensive wealth of geotechnical data into a single GIS-database.

Field Mapping

Quaternary Stratigraphy

Although, numerous published and unpublished geologic maps of the area exist our new mapping highlights the need for better correlation of Quaternary strata across the region and a detailed geochronologic investigation. Previous researchers correlate much of the deformed Quaternary strata of the area with the Saugus Fm. mapped in the Santa Clara River valley (e.g., Kew, 1924; Jakes, 1979; Dibblee, 1992; Tan et al., 2004). The Saugus Fm. was deposited as a prograding conglomeratic fluvial wedge by the ancestral Santa Clara river that flowed from the San Gabriel Mts. Deposition began in the early Pleistocene and ending approximately 0.2-0.4 Ma, based on an amino acid racemization near Ventura (Yerkes et al., 1987). Therefore, much of the Saugus Fm should have been deposited across the CFB before uplift of South Mt., which now isolates the Camarillo and Moorpark area from the modern sediments of the Santa Clara River, which are still being deposited on the Oxnard delta. However, our mapping suggests strata, previously mapped as Saugus Fm. in the CFB, are characterized by two distinct local sources; South Mt. to the north and the Santa Monica Mts. to the south (Fig. 1). This would suggest that the base of the Quaternary strata, at least where exposed along the Simi fault (Fig. 1) is a million years younger than previously thought and post-dates uplift of South Mt. (~500 ka).



igure 1. False color DEM showing the geographic and tectonic setting of the Camarillo fold belt (CFB) with respect to other well tudied fold belts in southern California. Notice the decrease in relief and disection of folds in the CFB from east to west and westward eflection of streams suggesting westward progagation of folds.

Along the southern flank of South Mountain, north of Moorpark, a southwest-dipping erosion surface is beveled on Sespe and Saugus Fms. This surface is interpreted to correlate down-dip with scattered aggradational deposits along Calleguas Creek, and may correlate along-strike with backfilled drainages on the south flank of South Mt. that dip downward beneath Las Posas Valley (Fig. 2). Determining the precise age, both along- and across-strike, of this geomorphic marker is crucial to understanding the timing and magnitude of regional uplift and tilting of South Mt. and may be important in understanding deformation to the south (*see Geochronology, below*).

Structural Domains

We have divided the CFB into three discrete structural domains based on differences in the relative timing and style of deformation; the Simi fault zone, Santa Rosa fault zone, and the Springville fault zone (Fig. 3). The easternmost zone of faulting contains the well-studied Simi fault, which is exposed in the core of a west-trending anticlinal ridge defined by a thin veneer (<50m) of oppositely dipping Saugus Fm. The Simi fault zone is composed of pair of steeply north-dipping (75-85°), right-stepping en echelon faults, herein referred to as the Presilla and Worth Rd. segments (Fig. 3). North of the fault the Saugus everywhere rests unconformable on north-dipping Oligocene Sespe Fm. (Tsp), while south of the fault the Saugus rests on Miocene strata of the Topanga Fm. or Conejo volcanic rocks. This is interpreted to reflect early Middle Miocene down to the south normal faulting on the Simi fault. Although, Hitchcock et al. (2001) showed Holocene slip on the Simi fault to the east in Simi Valley, our mapping along the Simi fault in the CFB shows Quaternary deformation is limited to folding in Quaternary strata. Folds are best expressed along the western tip of each fault segment where Quaternary slip is likely at a minimum.

Separating the Simi fault zone from the Santa Rosa fault zone is a previously unmapped NNW-striking cross fault, herein referred to as the Camarosa fault (Fig. 3). Similar to the Simi fault, the Camarosa fault appears to have an older and younger deformational history and may have served as a Miocene fault segment boundary. The fault is manifested by 1) the termination of the Simi fault at the surface and in the sub-surface, 2) distinct changes in the relative timing, complexity, and geomorphic expression of faulting and folding (*see GIS-based analysis, below*), 3) sedimentological and thickness change in the Saugus and Topanga Fms., and 4) juxtaposition of the Sespe Fm to the east against Saugus Fm, to the west. East of the Camarosa fault, the Sespe Fm is exposed at the surface however, structural contour maps of the top of the Sespe Fm. (Jakes, 1979) show the Sespe Fm. at greater than 300m depth west of the fault. Similarly, contour and isopach maps of the Saugus and Topanga Fm. show thickening west of the Camarosa fault. In addition, the Saugus Fm. east of the Camarosa fault is characterized by terrestrial alluvial fan deposition while west of the fault Saugus strata are dominantly shallow to intermediate depth marine rocks. All these relations suggest the Camarosa fault was likely active during post-middle Miocene time, coeval with the Simi fault, and continued to slip with a down to the west sense during deposition of the Saugus Fm. There is no surface expression of this fault however it appears to continue to serve as a structural domain boundary to active deformation in the area (*see GIS-based analysis, below*).

Across Calleguas Creek, the Springville fault zone, north of the town of Camarillo, are composed of two discrete anticlines, the Camarillo hills anticline and Springville anticline (Fig. 3). Most of the faulting occurs along the south side of the hills and is concealed beneath younger alluvium. However, extensive geotechnical trenches have been opened and the precise location

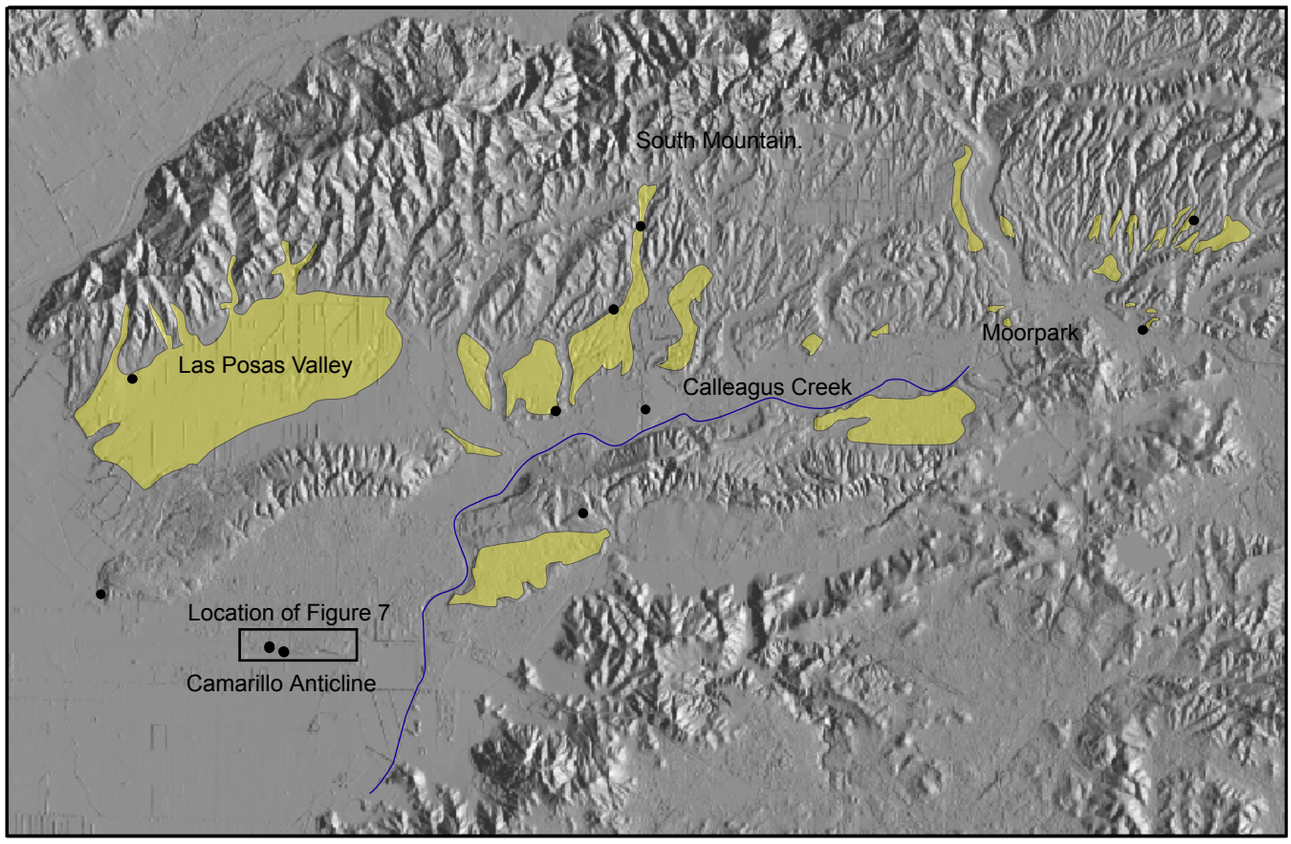


Figure 2. Hillshade of the CFB showing the distribution of regional erosion surface north of Moorparkand associated fill deposits along Calleguas Creek and to the west (shown in Yellow). Black dots denote the location of OSL sample sites.

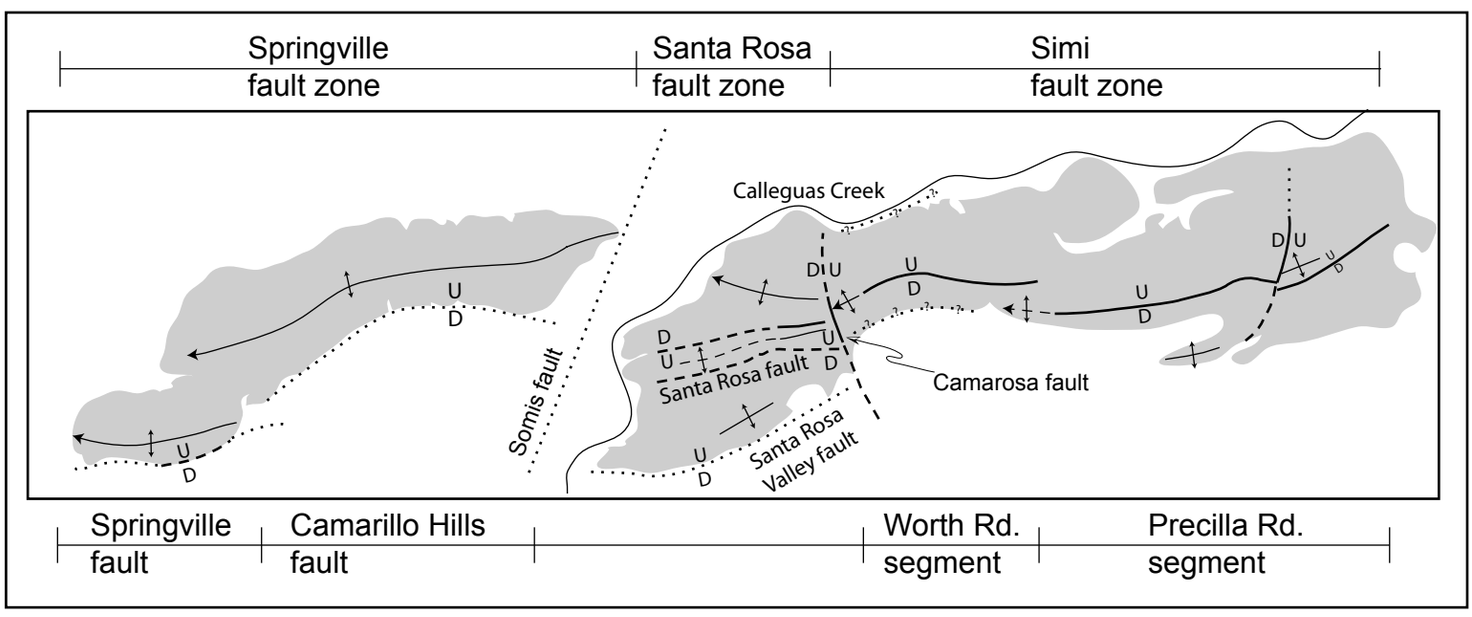


Figure 3. Generalized structure map of the CFB. Fault zone names are shown across the top and individual fault names are across the bottom. See Figure 1 for location and scale.

of the fault is known in many places. Locally, marine Saugus Fm. strata are overturned on the south limb of the Camarillo hills fold. Significantly less uplift and tilting has occurred on the Springville anticline. Fault maps either depict a left-stepping en echelon pair of faults, the Camarillo hills and Springville faults (Fig. 3) or a single curvilinear fault extending along the entire length of both anticlines. Based on distinct contrasts in the relative ages of the two folds, from our GIS-Analysis, we prefer the former.

GIS-based analysis

Bedrock exposures are rare in the CFB and much of the fold belt is either urbanized or being used for agricultural purposes, so we applied high-resolution DEM analysis to evaluate the relative tectonics of individual structures. The CFB is an ideal location for such a topographic analysis given the small regional extent and small magnitude of relief we can assume that individual faults and folds have likely experienced similar climatic and base level effects since their inception. In addition, the Saugus Fm. is the primary recorded of deformation in the CFB so lithologic and cementation variations are at a minimum and thus changes in the degree of erosion, stream gradient, and drainage elaboration should reflect the relative timing of topographic generation.

For this study we focused on the *Mean Erosion*, *Hypsometric Integral,* and *SL-index* of individual watersheds and stream profiles developed across the CFB. Both the mean erosion and hypsometric integral are a quantitative measure of the degree of dissection of a given drainage basin. For the hypsometric integral higher values indicate a higher mean elevation relative to the total relief and are interpreted to reflect young topography that has not been deeply incised. In contrast, high values of mean erosion suggest older topography and deep incision. While, the previous methods are valuable for quantifying the magnitude of erosion, the SL-index is a measure the slope along a given stream reach normalized by the distance from the source. Since stream power increases down slope with increased drainage area, the slope should decrease down-section. Perturbations in this trend are interpreted to be the result of either tectonics or changes in rock competency. Since a single rock unit composes most of the area we assume that increased values of the SL-index reflect tectonic perturbations.

Simi and Santa Rosa fault zones

Since the Simi and Santa Rosa fault zones comprise a continuous topographic feature we felt it was useful to compare these two zones to better understand the relative timing of deformation of this composite system of folds and faults. Based on our structure mapping we divided the two fault zones into three groups, two of which are characterized by segments of the Simi fault and the third characterized by watersheds west of the Camarosa fault (Fig. 3). Both the Worth Rd and Presilla segments of the Simi fault are virtually identical in terms of mean erosion and the hypsometry (Fig. 4). We interpret these data to suggest that both segments of the Simi fault are coeval and likely grew as an en echelon pair of faults, perhaps during the Miocene and continued to slip into the Quaternary. However a sharp contrast exists across the Camarosa fault, where the mean erosion of watersheds in the Santa Rosa fault zone decreases by a factor of three (Fig. 4). In addition, the hypsometric integral for the Santa Rosa fault zone shows distinct increase relative to the Simi fault zone. We interpret these data to suggest that the Santa Rosa fault zone is characterized by more youthful topography than that of the Simi fault zone.

The SL-index shows a dense concentration of steepened topography along the southern margin of the Santa Rosa fault zone suggesting youthful tectonics along the Santa Rosa Valley

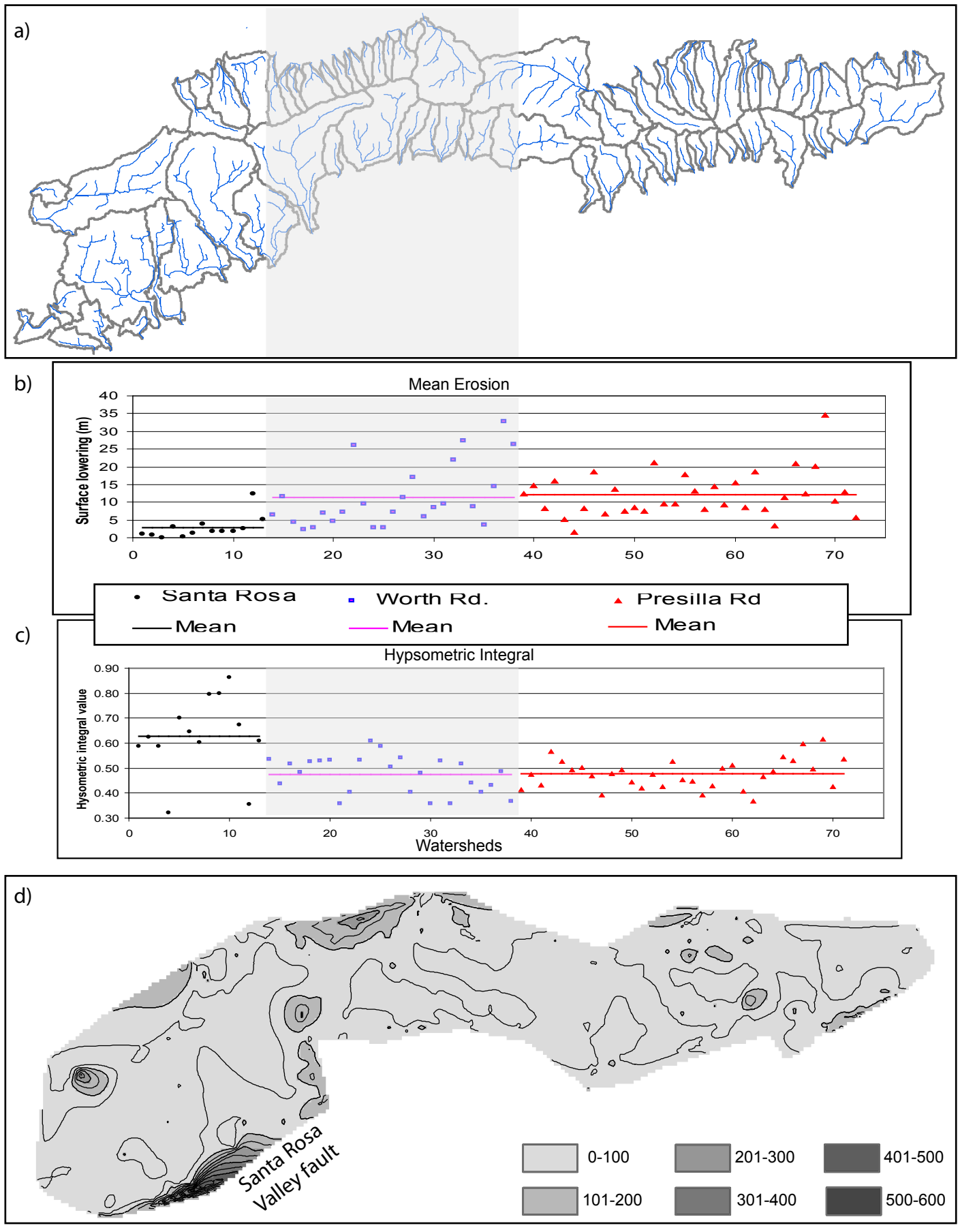


Figure 4. a) Watershed map of the Simi fault zone. Seventy-two distinct watersheds are recognized. b) Mean Erosion plot showing 3-fold decrease in mean erosion from east to west. c) Hysometric Integral plot showing progressivly higher values toward the west indicating more youthful to the west. d) SL-indexe showing elevated values along the southern margin of the Santa Rosa fault zone suggesting active faulting.

fault (Fig. 4). This uplift north of the Santa Rosa fault abruptly ends at the Camarosa fault. Thus the tectonic geomorphology and the structural analysis (*see Structural Domains, above*) of this region indicates the Camarosa fault not only acted as a structural barrier to Miocene faulting but continues to serve as a boundary between the Simi and Santa Rosa fault zones.

Springville fault zone

Based on our DEM analysis and structure mapping we divided the Springville fault zone into three regions 1) Camarillo hills anticline, 2) the Springville anticline, and 3) the accommodation zone between them. While the data from the Springville fault zone is less compelling than the Simi-Santa Rosa zones, obvious trends are present in the data. Mean erosion from east to west show a progressive decrease with mean erosion on the Springville anticline being 20% that of the Camarillo hills anticline, with the accommodation zone falling in between (Fig. 5). Although, the hypsometric integral shows a statistical trend towards increased values to the west, no statistical difference can be shown for discrete means. However, taken together in conjunction with the decreased structural relief observed in the field we feel confident that the Springville fault segment represents a younger fault segment. This conclusion is supported by across-strike topographic profiles (Fig. 6), which show an increase in the topographic expression of the Springville fault from east to west and a better-preserved expression of the underlying asymmetric fold structure indicative of youth topography and lack of embayment.

Regional Analysis

Our regional analysis of drainage patterns, and geomorphic and topographic aspects of growing folds, suggest folds are growing above left-stepping en-echelon faults that are migrating southwest with time. This is evident within the Springville fault zone, as well as within the composite system of the Simi-Santa Rosa fault zones. Although, we have not yet characterized all the streams in the area there is an obvious pattern of stream deflection to the west by individual fault segments. This is most obvious along Calleguas Creek where faults of the Santa Rosa fault zone have progressive deflected the stream to the west as faults stepped southwestward (Fig. 1). Similarly, westward deflection of streams that traverse the Moorpark anticline (Fig. 1) support the interpretation that lateral fold propagation is an important mechanism of deformation in the area.

Geochronology

One of the biggest challenges of this research will be to establish the Quaternary chronology of the area. Since little is known about the true or approximate age (<500 ka(?)) of deformed strata in the CFB, choosing the appropriate Quaternary geochronometer will be challenging. At this time we have started a pilot study of the Quaternary chronology using Optically Stimulated Luminescence (OSL). Sampling was conducted during January of 2007 and targeted on Quaternary units that we were sure would be within the range of OSL (<150 ka). Our primary emphasis with OSL is to constrain the age of younger alluvial deposits associated with the regional erosion surface beveled on the south flank of South Mt and younger terrace deposits along Calleguas Creek (Fig. 2). Additionally, we sampled what we interpreted to be the youngest parts of the Saugus Fm. One site was at the westernmost tip of the Springville anticline and a second site along the Santa Rosa fault. Six additional samples were collected from two fault trenches across the Camarillo fault (Fig. 7). Both trench sites exposed steeply south tilted

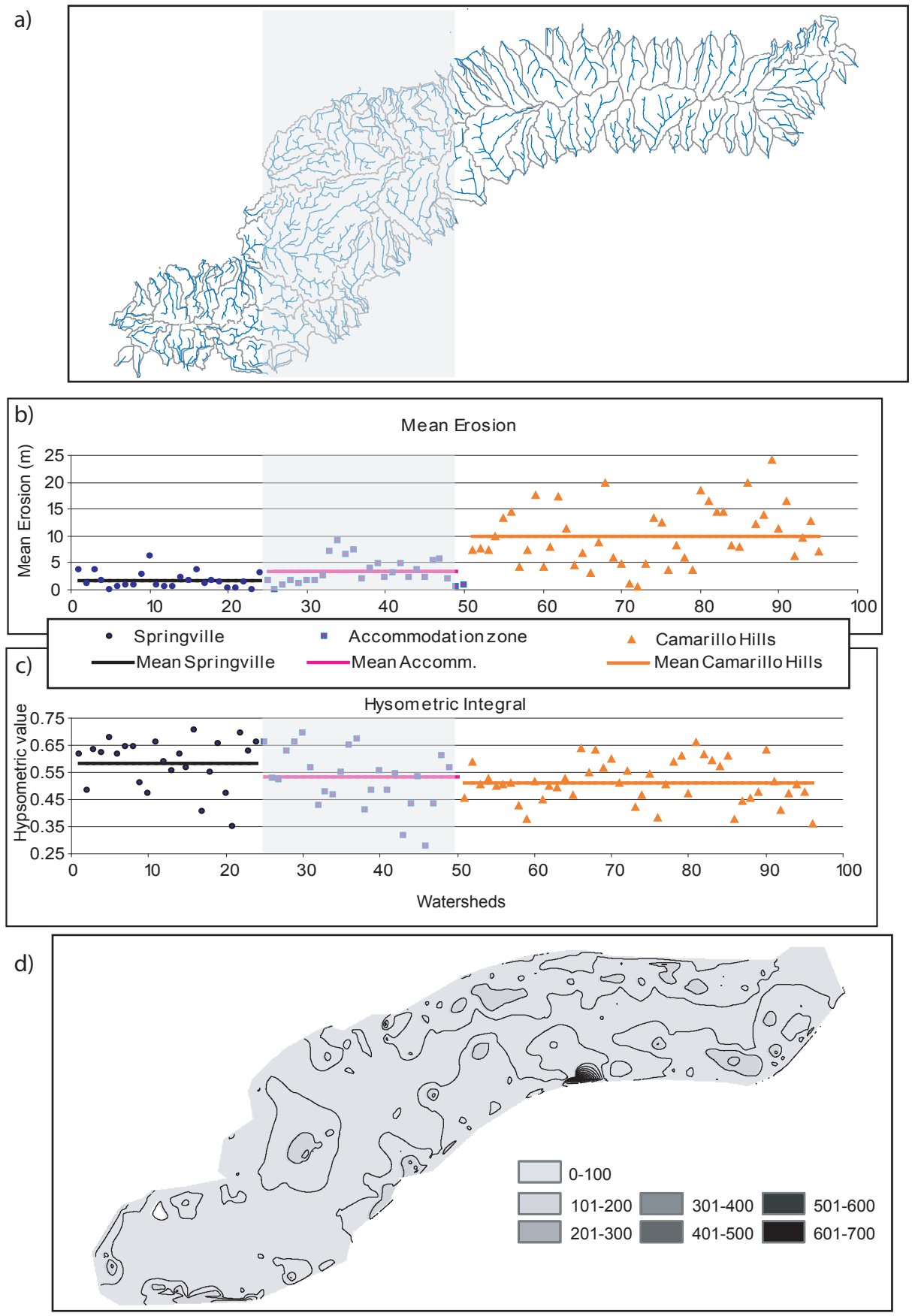


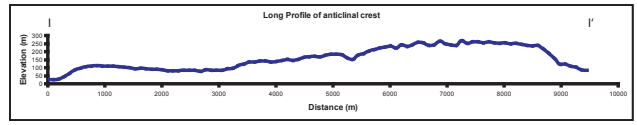
Figure 5. a) Watershed map of the Springville fault zone. Ninety-six distinct watersheds are recognized. b) Mean Erosion plot showing 2-fold decrease in erosion from east to west. c) Hypsometric Integral plot showing progressively higher values toward the west indicating a more youthful. d) SL-index showing elevated values along the south side of the topgraphy suggesting actice faulting.

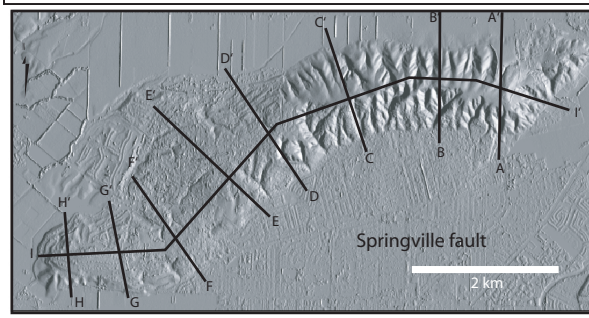
Figure 6.
Eight across strike profiles from east to west (A-H, respectively) and one along strike profile (I-I') are shown to illustrate the along strike topographic variability of the Camarillo Hills and Springville folds.

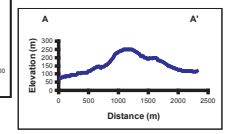
1) Note that cross sections on the Camarillo fold (A, B, and C) are broadly symmetrical across the anticline and show deep incision on the steeply dipping southern forelimb. Also note the lack of an escarpment on the southern boundary where the cross-section traverses the Springville fault.

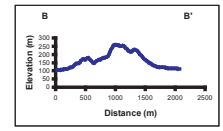
2) Note that cross-sections across the transition zone and Springville anticline all have a steep escarpment where the traverse the Springville fault and a well-expressed asymmetrical form with a steep forelimb to the south and more gentle backlimb to the north.

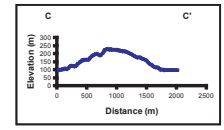
3) Note the overall decrease in disection and topographic relief from east to west on cross-section I.

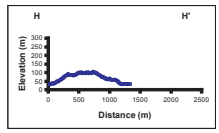


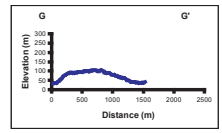


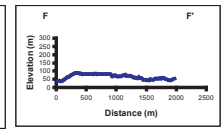


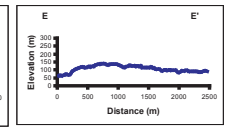


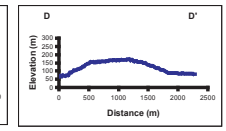












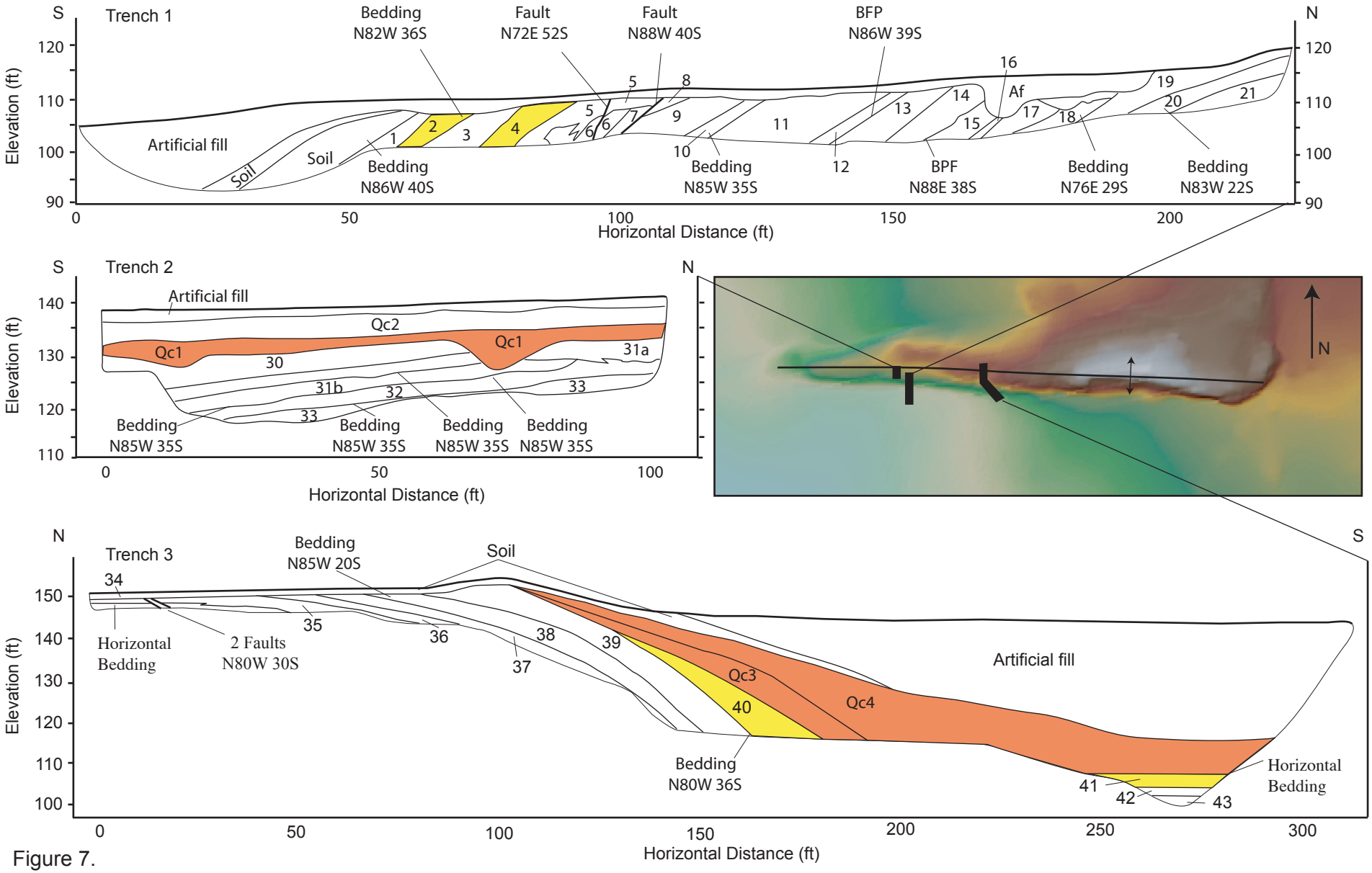


Figure 7.
Schematic line drawings of trench logs across the Camarillo fault/fold zone (see Figure 2 for location). Numbered units (1-43) are an interbedded sequence of well-sorted fluvial conglomerate, sandstone, and sitstone beds characterized as Saugus Formation in consultant logs. Yellow numbered fluvial strata were sampled for OSL dating. Qc units (1-4), lie in angular discordance with the underlying fluvial strata and are interpreted to record post-tectonic deposition on a growing fold. Shaded orange units reflect Quaternary colluvial packages sampled for OSL dating. Trenches 1 and 3 expose several south-dipping faults interpreted as backthrusts or bending moment normal faults. The Camarillo fault was not encountered in any of the trenches. Deformation along the Camarillo fault zone is best characterized by blind faulting. Note Trench 3 is not the same scale as Trenches 1 and 2.

fluvial sediments and colluvial wedge deposits we interpret as tectonic in origin. We anticipate analysis of OSL samples to be completed during the summer of 2007.

Geotechnical Database

Our collaboration with Jerry Treiman at the California Geological Survey (CGS) and Thomas Blake, who is the geological reviewer for the City of Camarillo, both of whom have worked extensively in the Camarillo area, has provided us with a strong foundation for compiling the wealth of pertinent geotechnical data available. The locations of trench localities, bore hole sites, previously mapped fault traces and lineaments documented by numerous professionals and researchers is currently being compiled into a single GIS database. This database will be made available via the web as an interactive site and will contain precise UTM coordinates and significant earthquake hazard data from each site, including: relative and absolute ages of quaternary units, magnitude of offset, recency of faulting and slip rates at trench sites.

Summary and Conclusion

Over the past year we have focused on detailed mapping of latest Quaternary units and working with high-resolution topographic data to recognize the active process deforming the region to improve our understanding of the long-term (>100 ka) deformational history of the area. The most profound conclusion from this years research is that both the Simi and Springville fault zones appear to be growing southwestward independent of one another with time. This suggest that the Springville fault is not kinematically linked to the Simi fault as previous researchers had suggested (e.g., Jakes, 1980), which is important to understanding how strain is partitioned across the area and assessing the maximum earthquake magnitude these faults might generate in the future. If segment boundaries, such as the Camarosa fault, represent significant impedance to the growth of fault systems as our data suggests then cross faults may serve to minimize the maximum magnitude of a given rupture. In the coming months our work on developing the Quaternary chronology and absolute dating in the area will aid in our understanding of the timing of regional deformation and the fault slip history on the Camarillo fault. We are also working on a collaborative NEHRP proposals to conduct U-series dating on pedogenic carbonates, which are common in the Saugus Fm. throughout the CFB. We expect that this technique will enable us to completely characterize the timing and rate of deformation on individual structures.

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