Re-Evaluation of Fault Slip, Geodetic Strain, and Seismic Hazard in the Light of Active Subsidence, Compaction, and 3D Fault Geometry

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Investigations undertaken

1. Collect and analyze available porosity-versus-depth data to determine compaction histories. Model the contribution that such aseismic and anelastic processes, like compaction and gravity-sliding, may make to measured horizontal and vertical motions or to fault geometry.
2. Continue to integrate available subsurface well data with other subsurface information, such as seismicity, gravity, and topography. Extend the integrated 3D database to include results from similar studies conducted offshore in the eastern Santa Barbara Channel.
3. Continue to construct 3D structure contour maps of various reference stratigraphic surfaces, such as Near-Top Pico, Top Lower Pico, Top Monterey and Base Vaqueros formations, to help define long-term deformation fields. Compare 3D reference surfaces to evaluate the evolution of strain with time and to document the spatial pattern of uplift and subsidence.

Results

The highest rates of measured geodetic shortening in southern California occur across the Los Angeles and Ventura basins. This surface deformation is inferred to represent a significant seismic hazard, and is presumed to be largely accommodated by active hanging-wall faulting, folding, and tectonic uplift. In southern California, however, these deep, subsiding basins are often bounded by oblique reverse faults (**Fig.1**) that thrust early-Cenozoic and older rocks over young unconsolidated sediments. **Figure 1** also shows the rotated and non-planar geometry of the Oak Ridge and San Cayetano faults, suggesting that footwall deformation, subsidence, and compaction may play an important role in contributing to the apparent high rates of observed crustal strain [*Nicholson et al.*, 2000; 2001]. Although often neglected, effects like compaction can be significant (**Fig.2**). Even in the absence of active crustal shortening, sediment compaction alone can produce surficial motions that mimic deep fault slip or elastic strain accumulation. Differential subsidence, pressure solution, and 3D compaction of footwall sediments relative to hanging-wall basement rocks can lead to increased vertical separation and fault rotation about horizontal axes (**Fig.3**). Such effects would contribute to net horizontal and vertical motions in both geologic and geodetic data, and—if not properly accounted for—would result in incorrect estimates of the inferred seismic hazard.

More importantly, subsidence and compaction can increase the potential for gravity-sliding towards the basin and the development of significant non-planar 3D fault geometry. A prime example occurs along the San Cayetano fault that bounds the eastern Ventura basin (**Fig.1**). Detailed structure contour maps and cross sections of the fault surface derived from industry subsurface well data reveal a fault geometry reminiscent of thrust nappes in the western Alps. At shallow levels, a thin-skinned thrust sheet (the Modelo Lobe) with low dip extends out in front of the deep, steeply-dipping fault segment by over 4 km, is nearly 2 km thick, and occupies over 60 cubic km. This geometry is strongly indicative of gravity-driven (sackungen-type) failure resulting from hanging-wall uplift and basinward tilt enhanced by footwall subsidence and compaction (**Fig.4**). Failure of this mega-slide off the hanging-wall block most likely occurred within the Rincon Formation, a ~400-m thick ductile shale sequence that often accommodates bedding-plane or detachment slip. Further reactivation of the slide may have been accommodated by additional shale layers within the Modelo Formation, and augmented by the presence of overpressured fluids trapped below the base of the slide as a result of continued sediment compaction and overburden loading.

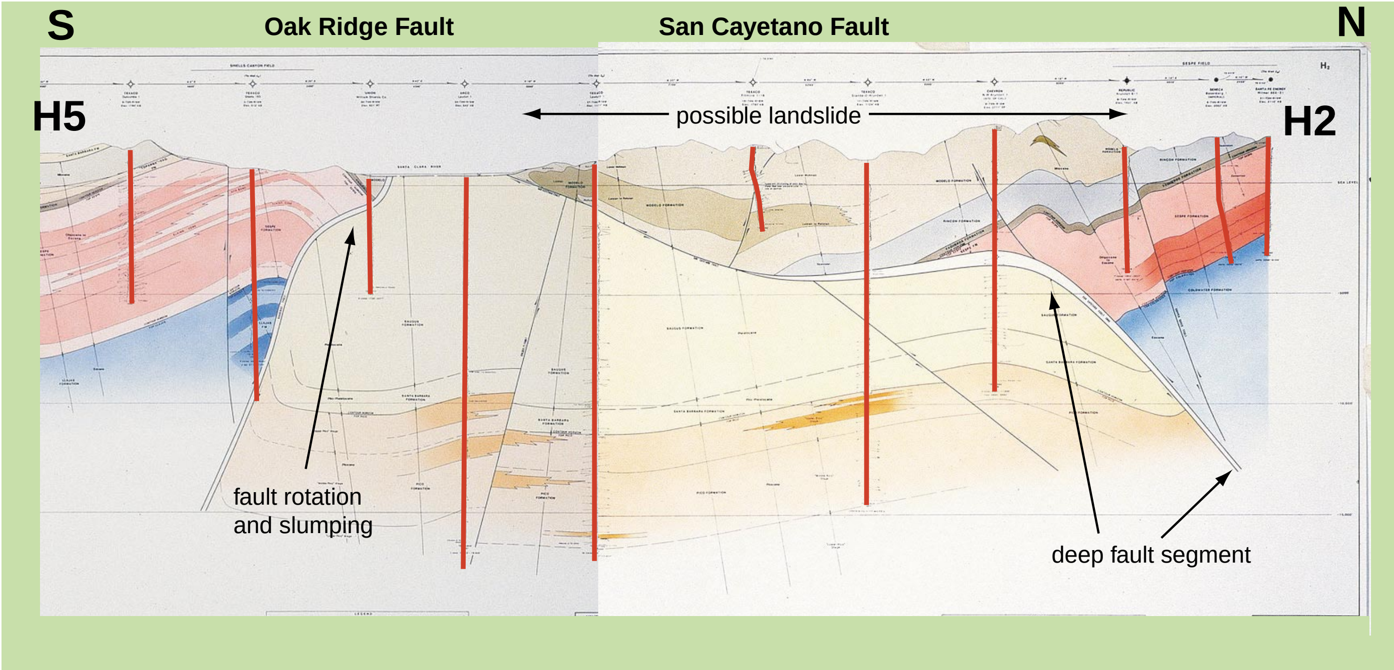

Figure 1. Vertical cross section (H2-H5) across Ventura basin, and Oak Ridge and San Cayetano faults (Hopps et al., 1992). Red lines show well control. This shows how oblique-reverse faults overthrust early-Cenozoic and older rocks over mostly Plio-Pleistocene and younger sediments. Note the rotated and non-planar geometry of both faults. Also note the folding, differential compaction and other aspects of footwall deformation within the basin. Possible landslide responsible for the thrust-nappe 3D geometry of San Cayetano fault is shown. Red - Sespe Formation (~30 Ma); Yellow - Saugus Formation (~0.5 Ma); Gray - Rincon shale (possible slide surface).

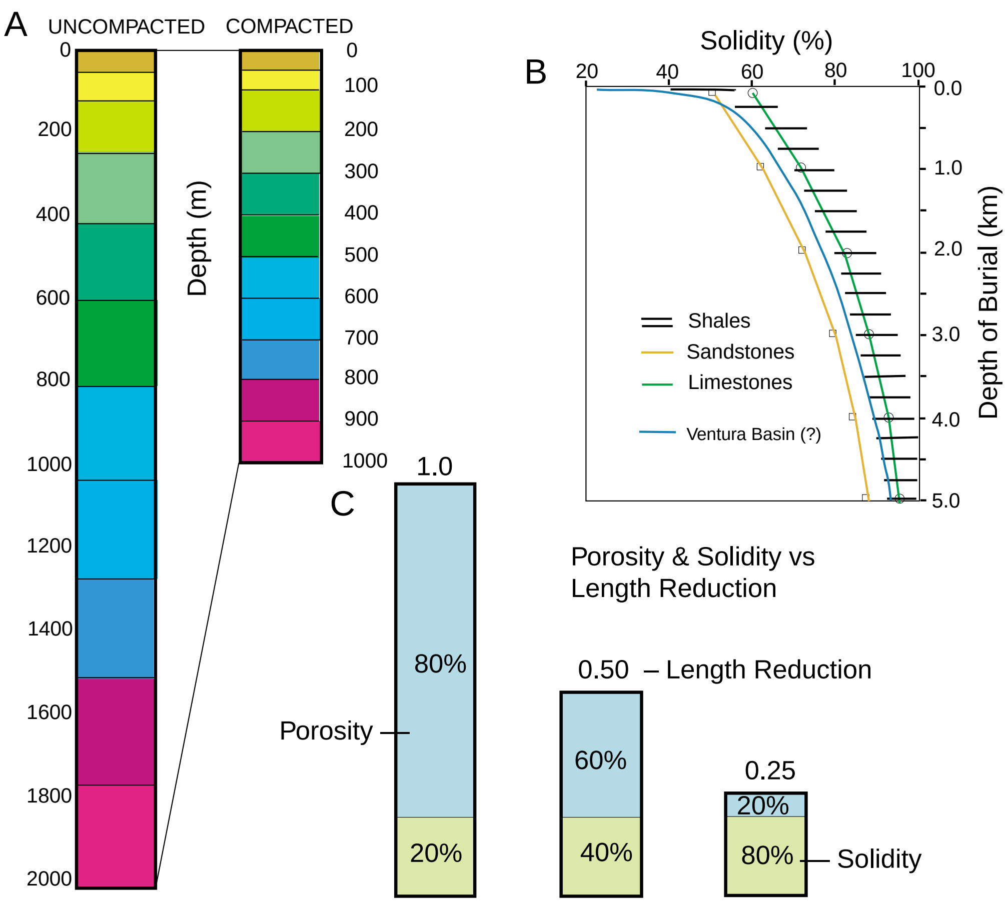

Figure 2. Possible extent of the problem: Sediment compaction and its effects on vertical line lengths. **A)** Typical amount of uncompacted terrigenous sediments needed to produce a compacted 1-km section (Hamilton, 1976). **B)** Compaction curves (solidity versus depth) for sandstones, limestones, an shales (from Baldwin and Bulter, 1985). Blue line is a preliminary compaction curve for the Ventura Basin based on porosity well-logs. **C)** Relation between percent solidity (green shaded) versus percent porosity (blue shaded) during compaction. Top ratios are 1D length reductions produced by the vertical compaction. Such vertical length reductions may induce net horizontal motions in both geologic and geodetic (GPS) data, while differential compaction across steeply dipping faults may appear as net vertical separation or fault offset.

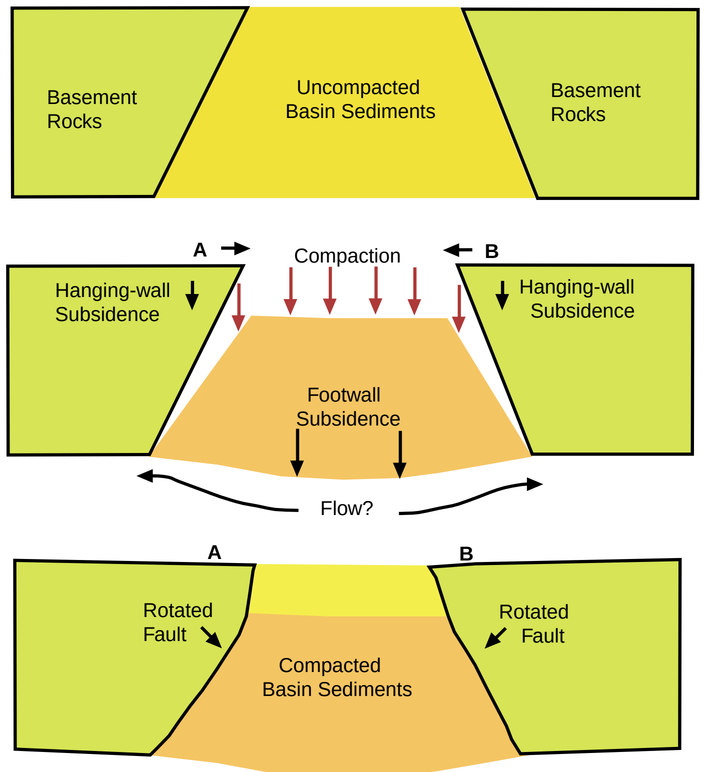

Figure 3. Simple schematic model suggesting how differential basin compaction and isostatic subsidence can produce: (1) apparent vertical separation across faults; (2) surficial displacements (points A & B moving towards each other) that mimic tectonic shortening; (3) tilting and subsidence of hanging-wall blocks towards the basin; and (4) rotation and deformation of faults into non-planar geometry. All this in the absence of any real fault offset or net tectonic shortening.

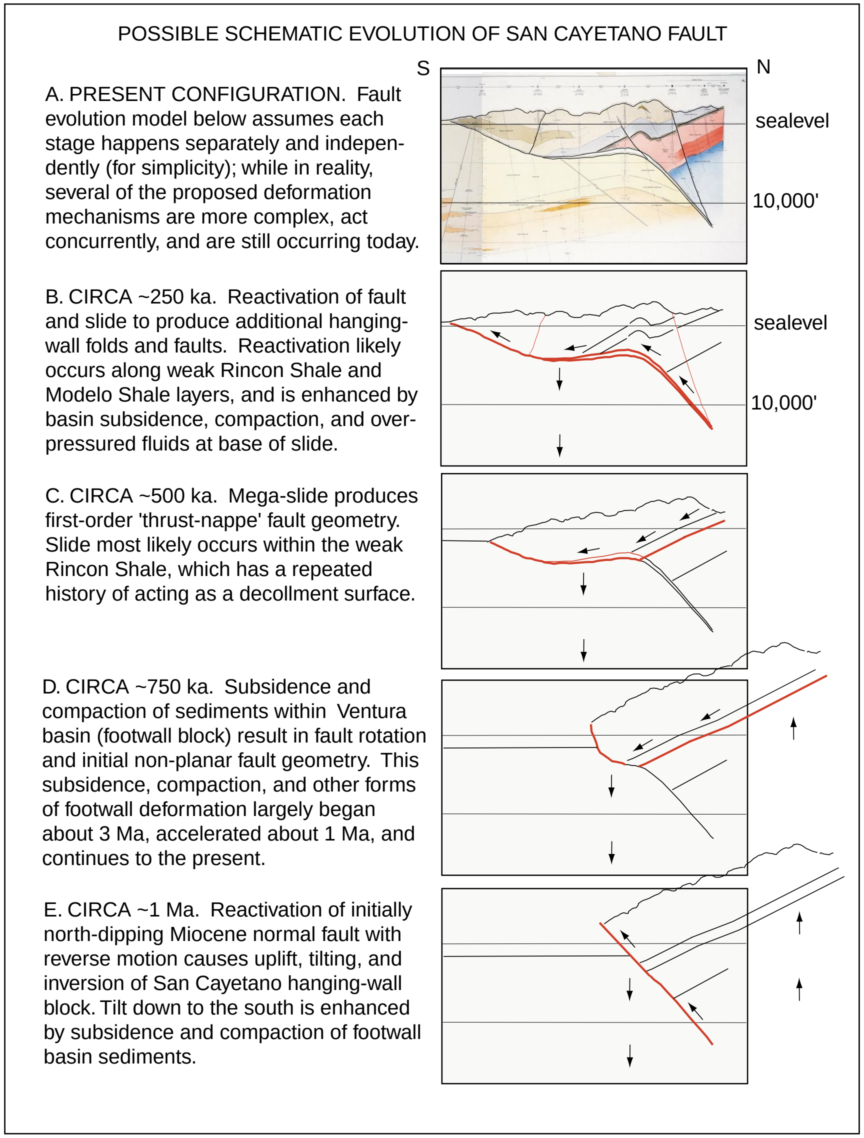

Figure 4. Possible schematic evolution of the 3D San Cayetano fault geometry. Initial fault uplift and basin subsidence causes fault to rotate (E). Subsidence and compaction induces slumping and bending of fault surface (D). Mega-slide creates initial thrust-nappe geometry (C). Continued basin subsidence and compaction, along with uplift and folding of the hanging-wall block creates present 3D geometry. Slide reactivation is enhanced by the weak shale layers in the Rincon and Modelo Formations, over-pressured sediments due to compaction, and by continued uplift and dynamic slip of the fault.

The thrust-nappe geometry of the San Cayetano fault has significant implications for how the fault might behave during dynamic rupture. Dynamic slip may be inhibited at shallow levels by the presence of the slide and the change in fault dip with depth. However, if the shallow thrust sheet does fail, the shallow slip may or may not be related to tectonic slip on the deep fault segment. If the thrust-nappe geometry is the result of an ancient gravity slide, the slide can be reactivated independent of slip at depth and/or aseismically. Large ruptures may reactivate the slide, either by dynamic triggering of the weak slide surface or by statically pushing the thrust wedge from behind. In either case, observations of near-surface slip or large slip events at the toe of the slide may not be indicative of tectonic slip or large earthquakes at depth on the fault. The hazard associated with such deep-seated slides is increased by their possible occurrence in oversteepened terrain, their large potential slip (unrelated to accumulated elastic strain), and by the high accelerations that may be produced if dynamic rupture is abruptly terminated at shallow depth when it encounters the slide.

Non-technical Summary

High rates of geodetic shortening occur across the Los Angeles and Ventura basins. These deep basins are often bounded by faults that thrust older rocks over young unconsolidated sediments. This suggests that footwall deformation, subsidence and compaction may play an important role in producing the apparent high strain rates. Even in the absence of active shortening, sediment compaction alone can produce surficial motions that mimic deep fault slip. Subsidence and compaction can also increase the potential for gravity-sliding and the development of significant non-planar 3D fault geometry. Such 3D geometry has significant implications for how the fault may accommodate slip, or behave during dynamic earthquake ruptures.

Reports published

Nicholson, C., M.J. Kamerling, and J.N. Brune (2001), Thrust nappes and mega-slides: Implications for active fault geometry, dynamic rupture, and seismic hazard in southern California, *Seismol. Res. Lett.*, **v. 72**, n.2, p. 291.

Nicholson, C., M.J. Kamerling, C.Sorlien, and J.N. Brune (2001), Subsidence, compaction and gravity-sliding: Implications for active 3D fault geometry, dynamic rupture and seismic hazard in southern California, *2001 SCEC Annual Meeting Proceedings and Abstracts*, p.101.

Nicholson, C., M.J. Kamerling, C.Sorlien, and J.N. Brune (2001), Subsidence, compaction and gravity-sliding: understanding geodetic strain data across basin-bounding faults in southern California, *Eos (Trans. AGU)*, **v.82**, n.47, p. F268.

Data Availability

Structure maps and cross sections produced by the Ventura Basin Study Group (VBSG) are available from our website (http://www.crustal.ucsb.edu/projects/hopps). Printed blue-line copies are available for research purposes by contacting Criag Nicholson (craig@crustal.ucsb.edu). Additional structure contour maps of specific reference horizons (Near-Top Pico, Top Lower Pico, etc.) are available from http://www.crustal.ucsb.edu/projects/vbmrp .