Flexural modeling of the northern Gulf of California Rift: Relating marine terrace uplift to the forebulge on a subsiding plate.

Grant Kier
Karl Mueller
Department of Geological Sciences, University of Colorado, Boulder, CO.

ABSTRACT

Well-defined marine terrace uplift rates are often used to assess local fault movements along the coast of southern California (Grant et. al., 1999 & Andreson et. al., 1994). The Pacific coast along southern California and northern Baja California, from Long Beach to Punta Baja demonstrates consistent terrace uplift rates more regionally extensive than can be accounted for with local faulting Muhs et. al, 1992 and Rockwell, personal communication). Three models for uplift are tested: A structural model whereby the terraces are uplifted on the hangingwall of a low angel thrust fault, the Oceanside fault. A flexure model in which uplift is flexural response to erosion along the Peninsular Province. And a flexure model in which uplift is a forebulge related to the active rifting in the northern Gulf of California and the Sulton Trough. By comparing the wavelength of the plate deflection to topography, uplift rates of marine terraces along the pacific coast between Long Beach and Punta Baja are shown to coincide with the plate forebulge the expected uplift at the edges of a subsiding elastic plate. Uplift rates for the flexure models range between .07 and .17 m/ka depending on the crustal model chosen for the load.

BACKGROUND

Amino acid racemization and radiocarbon dating of coral fossils allow consistent and accurate dating of marine terraces along the Pacific coast of the United States and northern Baja California, Mexico. Comparing terrace age dates to known sea level high stands in the last million years, Muhs et. al. (1992) develop accurate correlation of marine terraces to specific paleo-sea level elevations. Any uplift or subsidence that has occurred since the creation of a specific marine terrace is determined by relating known differences between historical and current sea level elevations. Using this dating method, Muhs and others show uplift rates between 0.45±0.03 and 1.08±0.03 m/ka in Oregon, 0.06±0.03 m/ka in northern California, and between 0.14±0.03 and 0.25±0.03 m/ka from southern Orange County to Punta Baja, Baja California, Mexico (Muhs et. al. 1992).

Established marine terrace uplift rates exhibit both local and regional patterns along the pacific coast. In many areas, such as the Rose Canyon fault zone near San Diego and the San Joaquin Hills in southern Orange County, marine terrace uplift rates are linked to local fault systems. Uplift rates in these areas are slightly higher than surrounding areas, limited to regions on the scale of several kilometers, and accompanied by other larger geomorphic features (such as the San Joaquin Hills). While fault slip drives local uplift rate variations, local fault systems do not provide adequate explanation for uplift rates with extensive regional consistency. Regionally consistent uplift patterns can span as many as several hundred kilometers, as they do between southern Orange County, California and Punta Baja in Baja California. The purpose of this project was to investigate this regionally consistent uplift.

METHODS

Three models for uplift are tested: a structural model for transpression, a flexural model for erosion, and a flexural model for rift formation. First, a structural model is tested whereby the terraces sit on the hangingwall of a low angel thrust fault, the

Oceanside fault. Movement of the coastal terraces along the ramp of the thrust is assumed to cause uplift in this model. If marine terraces are uplifted by a regionally active thrust fault, they provide evidence for a significant seismic hazard in southern California. Second, we investigate uplift as a flexural response to erosion along the Peninsular Province. Finally, we investigate uplift as a flexural response to the active rifting in the northern Gulf of California and the Sulton Trough. Terrace uplift due to flexure suggests less seismic hazard in southern California than active faulting.

Fault Related Uplift

Marine terrace uplift rates are based on amino acid racemization and radio carbon dating of marine corrals correlated with established interglacial marine highstands (Muhs et al, 1992). Existing depth corrected seismic profiles offshore southern California are used to establish a NNW strike and 6-9 degree dip of the Oceanside fault (Bohannon and Geist, 1998 and Shaw and Rivero, work in progress). The vertical uplift rate above the ramp of a thrust fault must equal the horizontal motion normal to the fault multiplied by the sine of the dip of the fault. Therefore, shortening must occur between 0.89 and 2.39 m/ka to achieve between 0.14±0.03 and 0.25±0.03 m/ka vertical uplift on a fault dipping 6-9 degrees. Using standard vector analysis we rotated the coordinate axes of the regional velocity field to calculate the component normal to the strike of the Oceanside fault as shown in figure 1 (SCEC Data Center, 1999). We then compare the regional surface velocity normal to the fault to the velocity required for current terrace uplift rates. This shows that the current surface shortening is within the range that would generate current uplift patterns but relies on the assumption that velocities at depth are consistent with surface velocities. The northern and southern terminations of the Oceanside fault are at approximately the San Joaquin Hills and the U.S. Mexican border respectively (John Shaw, work in progress). The northern and southern terminations of the regionally consistent terrace uplift are southern Orange County to Punta Baja, Baja California respectively (Rockwell, personal communication).

Flexural Uplift

A two-dimensional model for an elastic plate with a line load is used to establish the flexure of the crust west of the northern Gulf of California and the Salton Trough. The model is a curve based on the following equation (Turcotte and Shubert, 1982):

$$w(x) = \frac{V_0 \alpha^3}{8D} \exp\left(\frac{-x}{\alpha}\right) \left[\cos\left(\frac{x}{\alpha}\right) + \sin\left(\frac{x}{\alpha}\right)\right]$$

where **w** represents plate deflection at any given distance **x** away from the load $\mathbf{V_o}$. The variable α represents the flexural parameter and **D** represents the flexural rigidity. To determine crust density and thickness the same geophysical models of this region are used in both erosion and rift related models. A model for unloading due to erosion uses established erosion rates of the San Gabriel Mountains, .02 mm/yr in high erosion areas, as the erosion of the Peninsular Range (Spotila, 1998). This assumes that the erosion rates are similar since both are igneous rock in the same environment. Erosion estimates for the coast are based on geologic map cross sections (Spotila, 1998 & Kennedy, 1975). The erosion rate for the coast is conservative (high), demonstrating that even high erosion rates are insufficient for considerable uplift. The removed load in the erosion model is 100m of sediment with density 2400 kg/m^3 across the the 100km from the rift center to the coast. The **x = 0** location is at the apex of the Penninsular Range for the erosion model. The maximum uplift at **x = 0** is 84 m and the uplift at a distance near the coast is approximately 10 m.

For the rift related subsidence model, the load is selected based on the change in the column of crust where the rifting is shown in the geophysical cross section (figure 2). The load selection assumes that prior to rifting the continental crust maintained density 2670 kg/m^3 above 20 km and maintained density 2900 kg/m^3 between 28 and 20 km. The load is the difference in densities beween the pre and post rift column multiplied by the height km and width. The range of values tested for the height are 28km 50km, 28m chosen from cross section and 50km from the average crust thickness toward the east. The range of values selected for the width are 75km 150km based on cross sections. Since the crust thins west, an average crust thickness of 20 km was selected over the 400 kilometers represented in the graph. Since no data is available to define the behavior of the lithosphere asthenosphere boundary, this model assumes that boundary remains constant. For the rift related subsidence model, the **x = 0** location is in the eastern Salton Trough, the center of the thinning rift zone. For the subsidence model, the maximum uplift at the forebulge is 38 m for minimum load and 340 m for maximum load (figures 4 & 5). Timing of the rift formation is not well known but thinning is proposed to occur in spatial and temporal stages (Schubert et. al., 1984). Assuming that the loading of the rift has happened steadily for the past 5 million years, uplift rates of the terraces is 0.07 m/ka. Assuming that thinning has occurred over a two million year period the uplift is .17 m/ka.

DISCUSION

Fault Related Uplift

Marine terrace uplift in the San Joaquin Hills presents evidence for movement along a localized subsurface structure. Seismic reflection data and fault bend fold models suggest that these terraces are uplifted by a blind wedge-thrust structure. The base of the wedge is the Oceanside fault, dipping shallowly east, with a backthrust dipping west and joining the Oceanside fault as a wedge tip beneath the shelf-slope (Grant et., 1999). While there is a great deal of evidence for reverse faulting along the Oceanside fault, the fault does not exist far enough south to account for the consistent regional uplift pattern. Where the Oceanside fault ends at the border, the regionally consistent uplift continues well into Baja California.

Flexural Uplift

Using current erosion patterns, the adopted load in this model would be removed in 1 million years. Therefore, with an uplift rate due to erosion of 0.01 m/ka, the erosion model shows that some uplift of the Peninsular Range province is due to erosion, but erosion alone accounts for 5-7% of terrace uplift rates. Further, erosion is not likely to cease altogether south of Punta Baja where the terrace uplift ends.

The upper limit of uplift due to the forebulge provides a possible, but poorly constrained range of values within the observed terrace uplift. However, this model shows that a forebulge associated with thinning in the Salton Trough and in the northern Gulf of California is a possible source for regionally consistent uplift of marine terraces. Other relationships between topography across the Peninsular Range Province, the northern Gulf of California, and the shoreline along the pacific coast make this model more convincing. These relationships include: 1)The northern termination of the Gulf rift at the southern Transverse Range lies almost directly across from Long Beach. 2)The southern termination of regionally consistent uplifted terraces lies almost directly opposite the northern tip of the Delfin Basin, which marks a major increase in the rift depth and a stepover toward the peninsula. 3)The entire section of rift adjacent to the regionally consistent uplifted terraces demonstrates extensively low topographic relief.

Of the three models tested in this project, uplift due to forebulging on a subsiding plate provides the best fit model for the observed uplift of marine terraces. The weaknesses of this model are in the assumptions stated above. Further research in this area is necessary to develop better constraints on the model. Also, tomographic data across the Peninsular Range province would improve further modeling of this region. Future work in this area may also focus on models of lithospheric thinning and thermal bulging prior to spreading center formation (Mammerickx et. al., 1986).

References:

Anderson, R.S. and Menking, K.M. The Quaternary marine terraces of Santa Cruz, California: Evidence for coseismic uplift on two faults. Geological Society of America Bulletin, v.106,p.649-664, 1994.

Bohannon, R.G. and Geist, E. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters. V.21, no.20 p.2191-2194. 1994.

Grant, Lisa M., Mueller, Karl J., Gath, Eldon M., Cheng, Hai, Edwards, R. Lawrence. Quaternary uplift and earthquake potential of the San Joaquin Hills, southern Loas Angeles Basin, California. In press, Geology, 1999.

Kennedy, Michael P. Geology of the San Diego Metropolitan Area, California. California Div. of Mines, bulletin 200. 1975.

Plawman, T.L., Crustal structure of the Continental Borderland and adjacent portion of Baja between latitudes 30°N and 33°N: M.S. thesis, Oregon State University, Corvallis, Oregon, 95p. 1978.

Rockwell, Thomas K. San Diego State University, San Diego, CA. personal communication.

Shaw, John, Rivero, Carlos. Harvard University, Cambridge, MA. work in progress, 1999.

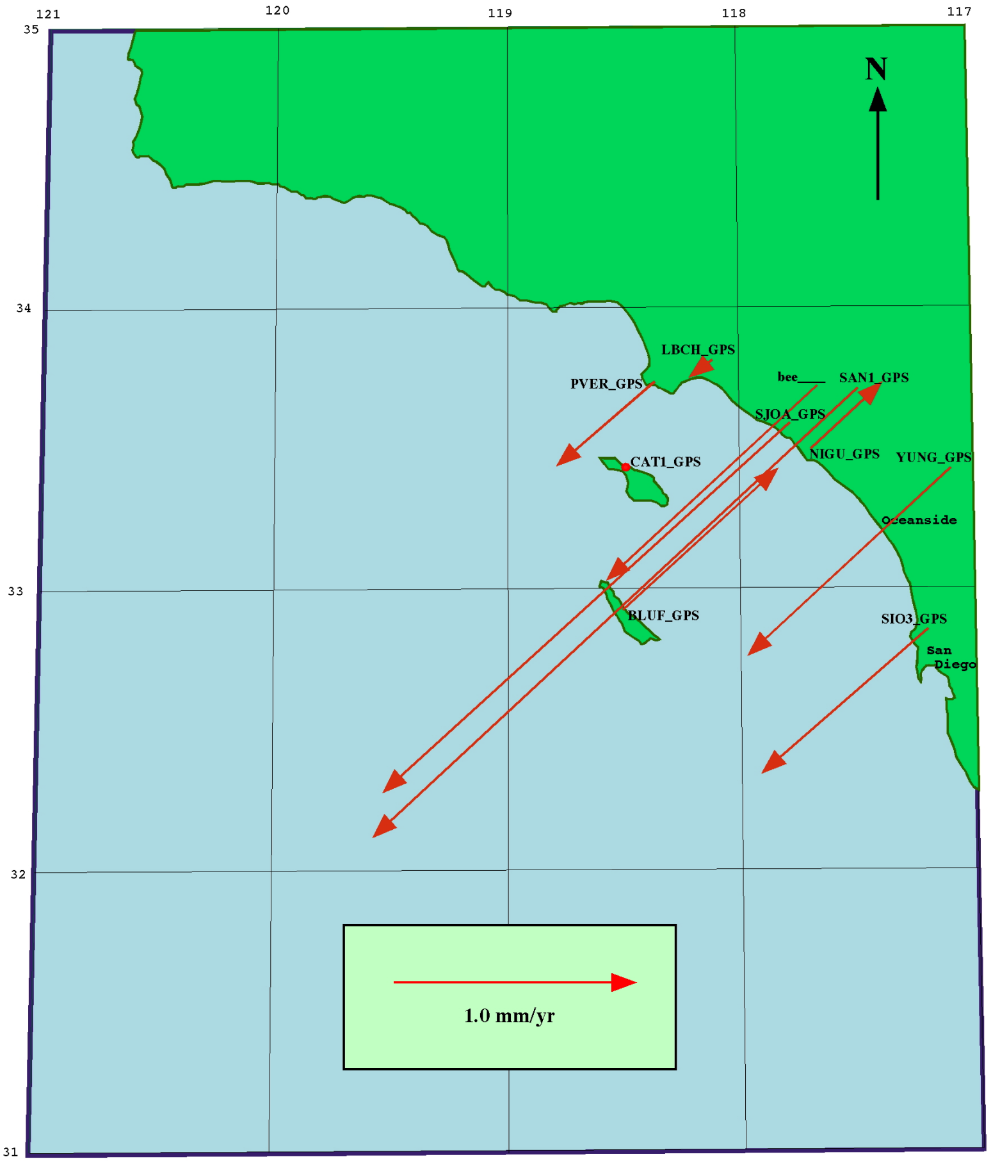
Spotila, James A. The vertical displacement field of the San Bernardino Mountains, Southern California, based on the use of a deeply weathered surface as a structural datum. Geological Society of America abstracts with programs. 30; 7. p237-38. 1998.

Turcotte, D.L., Schubert G. Geodynamics. John Wiley and Sons, New York. 1982.

Schubert, Gerald, Garfunkel, Zvi. Mantle upwelling in the Dead Sea and Salton Trough-Gulf of California leaky transforms. Annales Geophyisicae, v2, p633-648. 1984.

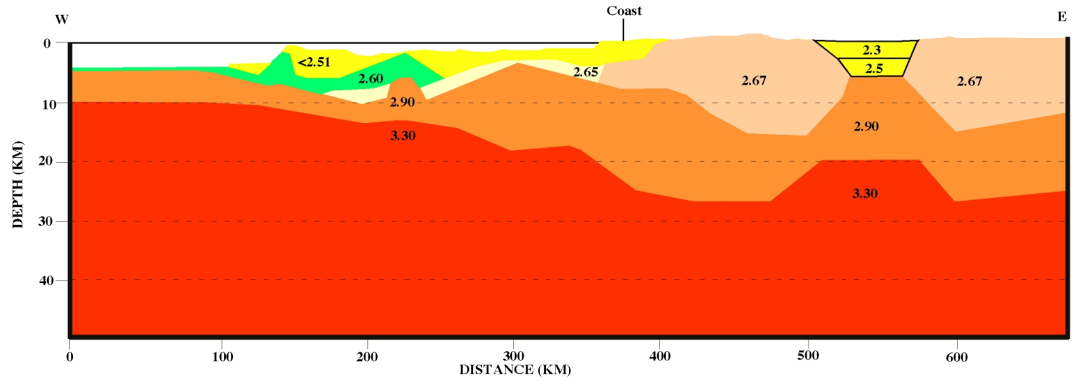
Mammerickx, J., Sandwell, D. Rifting of Old Oceanic Lithosphere. Journal of Geophysical Research, v.91, no.B2, p1975-1988. 1986.

Motion vectors for shortening normal to
the predicted strike of Oceanside detachment:
CAT1_GPS Fixed



Relative plate motion data from Southern California Earthquake Center Data Center

Figure 1



Geophysical cross section shows dense mantle replacing less dense crust beneath Salton Trough.

Figure 2

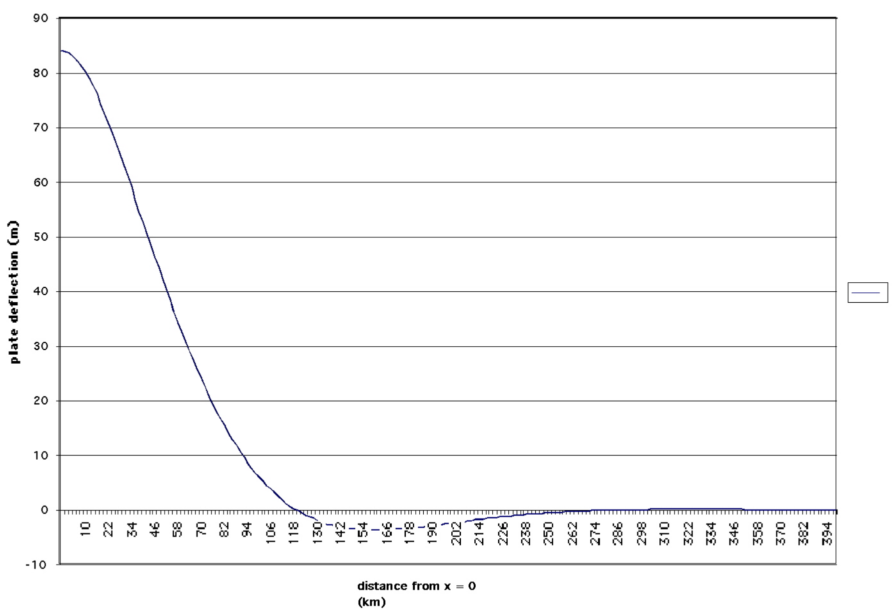


Figure 3

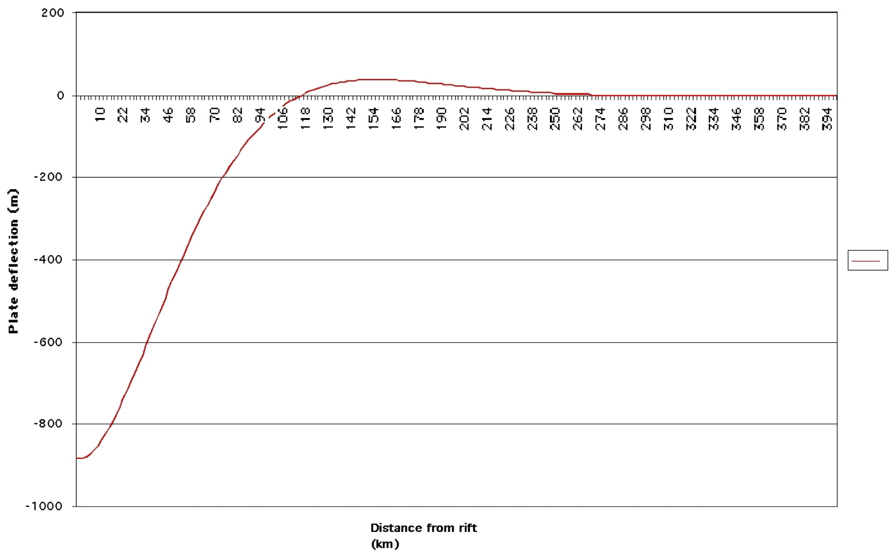


Figure 4

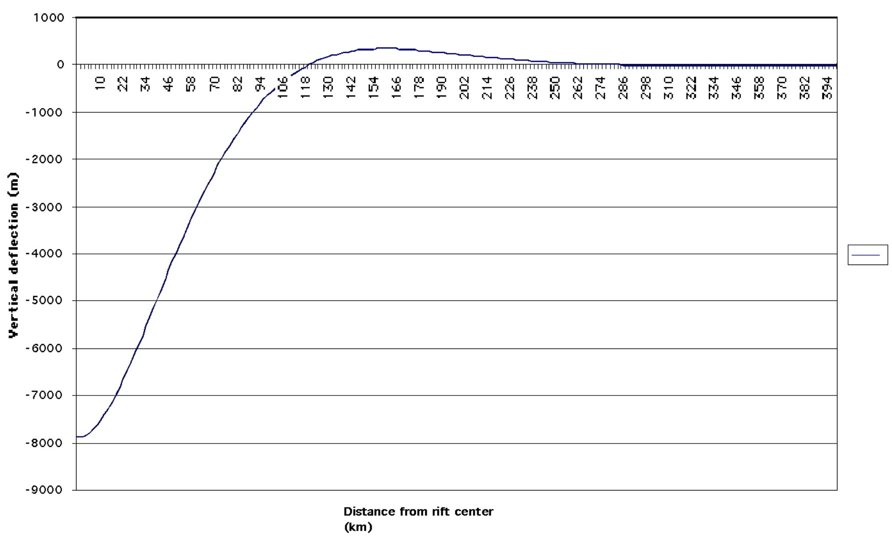


Figure 5