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Southern California Earthquake Center Geologic Vertical Motion Database

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[1] The Southern California Earthquake Center Geologic Vertical Motion Database (VMDB) integrates disparate sources of geologic uplift and subsidence data at 10^4- to 10^6-year time scales into a single resource for investigations of crustal deformation in southern California. Over 1800 vertical deformation rate data points in southern California and northern Baja California populate the database. Four mature data sets are now represented: marine terraces, incised river terraces, thermochronologic ages, and stratigraphic surfaces. An innovative architecture and interface of the VMDB exposes distinct data sets and reference frames, permitting user exploration of this complex data set and allowing user control over the assumptions applied to convert geologic and geochronologic information into absolute uplift rates. Online exploration and download tools are available through all common web browsers, allowing the distribution of vertical motion results as HTML tables, tab-delimited GIS-compatible text files, or via a map interface through the Google Maps™ web service. The VMDB represents a mature product for research of fault activity and elastic deformation of southern California.

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1. Introduction

[2] Understanding the vertical component of crustal motion is particularly important in regions of complex faulting and distributed deformation such as occurs across the active Pacific–North America plate boundary in southern California [e.g., *Plesch et al.*, 2007]. Vertical motions are a direct result of reverse displacement common to both exposed and blind faults that threaten the urban region [e.g., *Dolan et al.*, 1997; *Oskin et al.*, 2000; *Grant et al.*, 1999; *Huftile and Yeats*, 1996; *Yeats and Rockwell*, 1991; *Sorlien et al.*, 2000; *Pinter et al.*, 2001, 2003]. Recoverable vertical motions, if differentiated from permanent deformation, can also test alternative models of strain accumulation on faults [e.g., *Argus et al.*, 1999] and discriminate postseismic relaxation processes [*Peltzer et al.*, 1998; *Pollitz et al.*, 2001].

[3] Continuously operating GPS stations of the Southern California Integrated GPS Network (SCIGN) and the Plate Boundary Observatory (PBO) establish ever-longer time series from which vertical motions may be resolved [*Nikolaidis*, 2002; *Herring et al.*, 2006], while new methods that combine sparse continuous GPS observations with permanent scatterer–Interferometric Synthetic Aperture Radar (InSAR) provide spatially continuous, regional measurements of vertical tectonic motions [e.g., *Bürgmann et al.*, 2006]. The challenge in analysis of new vertical geodetic data is to discriminate tectonic loading signals from nontectonic effects, and to interpret tectonic loading in terms of elastic versus permanent strain accumulation. As *Bawden et al.* [2001] and *King et al.* [2006, 2007] demonstrate in the Los Angeles area, ground surface displacement results from fluid infiltration and extraction, which significantly affects vertical and horizontal geodetic velocities. Other nontectonic motions of the Earth's surface, such as landslides, can also be detected, purposefully or not, using common geodetic techniques [e.g., *Hilley et al.*, 2004; *Saroli et al.*, 2004]. In order to distinguish geodetic sites affected by such nontectonic motions, information on the long-term geologic rates of vertical deformation in southern California is required.

[4] To that end, we have developed the Southern California Earthquake Center Geologic Vertical Motion Database (VMDB). This database contains ~1800 geologic vertical motion rates (10^4- to 10^6-year timescale) for southern California and northern Baja California (Figure 1). Vertical motion rates are derived from four principal geologic data sources for which past elevations can be determined: marine terraces, river terraces, shallow marine stratigraphic horizons, and exhumation rates from low-temperature thermochronometers. The database uses an innovative architecture to separately store observations (e.g., modern elevations of uplifted marine terraces and terrace ages) from alternative reference frame models (e.g., paleo-sea-level curves) such that multiple reference frame models may be applied to the interpretation of vertical motion rates, and the compatibility and veracity of various data models can be assessed. The database is available online (http://www.scec.org/resources/data/vmdb/). Data localities may be filtered by geographic coordinates, or by a search radius around existing seismic and GPS stations in southern California (Figure 2a). A web-based interface allows the user to select among a variety of data models that can be applied to derive vertical motion rates (Figure 2b), and the results are returned as an HTML table, a tab-delimited, GIS-compatible text file, or an interactive Google Maps™ interface.

2. Geologic Vertical Motion Data

[5] A single geologic vertical motion rate datum requires four distinct data types: the present-day elevation of a marker, the paleoelevation of that marker, the age of the marker, and a paleoelevation datum for determining absolute vertical motion (typically relative sea level). These data types are either stored in the database as fixed values (e.g., the present-day elevation of a marine terrace), or generated on-the-fly on the basis of user-selected criteria (e.g., paleoelevation of a marine terrace, which is a function of terrace age and a user-selected sea-level curve). Relative uplift of a marker is determined from an elevation and paleoelevation. Relative uplift is converted into a rock uplift reference frame (uplift with respect to sea level) via a paleoelevation datum. Uplift rates are calculated by dividing absolute uplift by age. Uplift data and datum are unique to a specific class of markers (e.g., marine terraces, fluvial terraces, stratigraphic horizons), while age data types are independent. The ages of most markers are determined via correlation to other markers of known age. For example, dozens of marine terraces may be assigned an age based on geologic, geomorphic, or topographic similarities to a single terrace with absolute age control via biostratigraphic or isotopic methods. These correlations are tracked in the database and mapped each time vertical uplift rates are calculated, such that the addition of new absolute age controls, or recorrelations of terrace sequences, automatically propagate through the da-

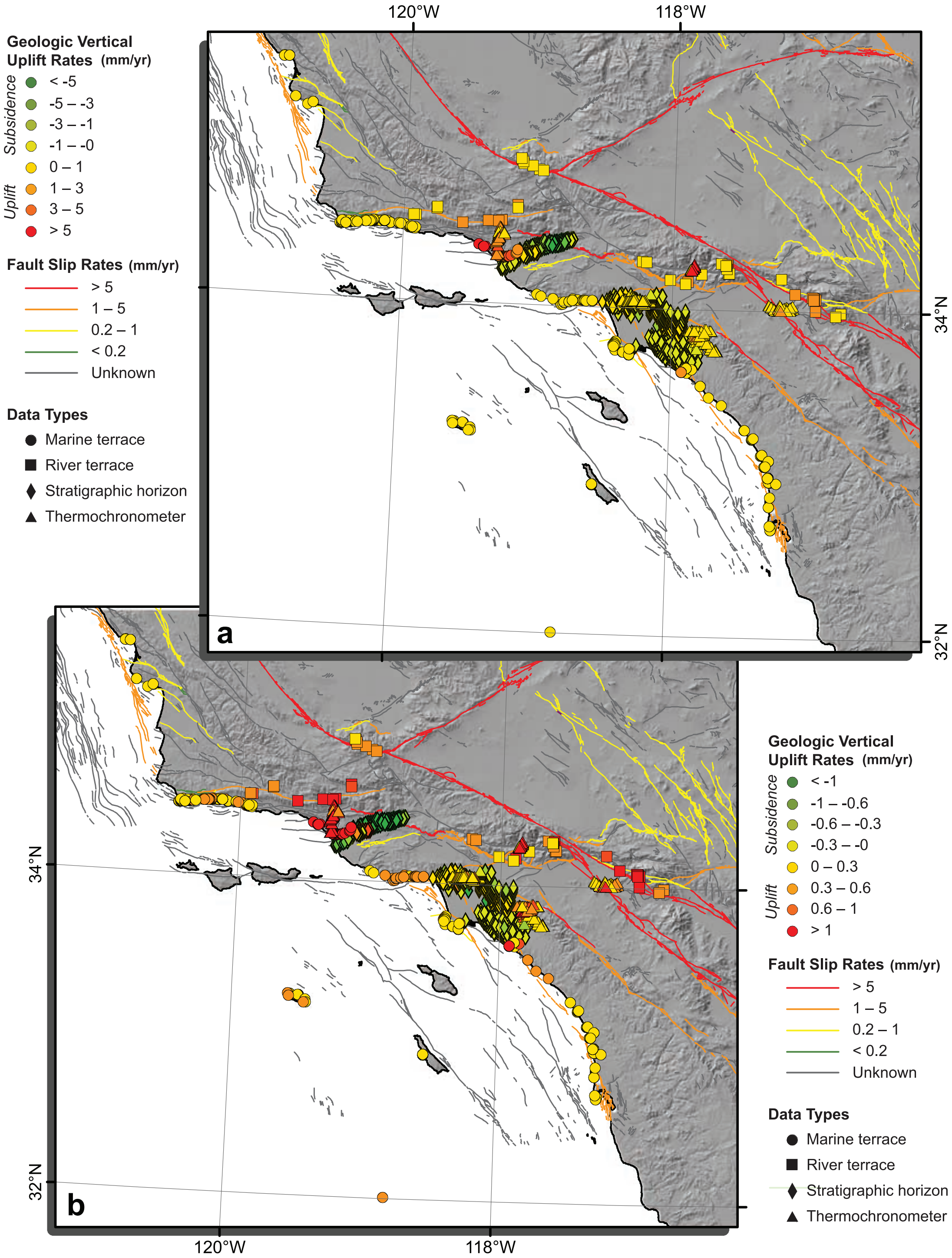
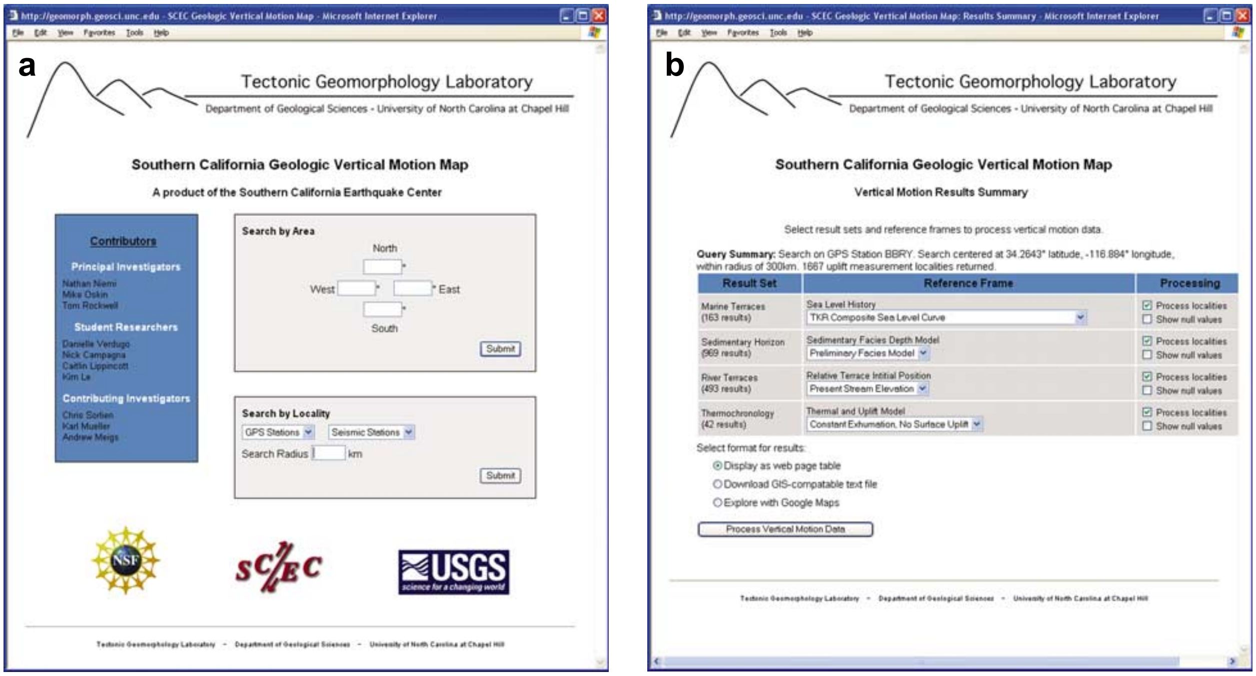


Figure 1. Map of vertical uplift data points included in the SCEC Geologic Vertical Motion Database, colored by calculated uplift rate. Uplift rate data points are primarily located along coastlines and major rivers, where terraces provide retrodeformable markers. Stratigraphic horizons observed in boreholes or seismic reflection lines are recorded for interior basins, and several thermochronologic ages are reported from the Transverse Ranges. Major active faults of southern California are shown relative to uplift rate data, colored by approximate fault slip rate (W. A. Bryant, Digital database of Quaternary and younger faults from the fault activity map of California, version 2.0, accessed 28 April 2008 from the California Geological Survey Web Page: http://www.conservation.ca.gov/cgs/information/publications/Pages/QuaternaryFaults_ver2.aspx). (a) Expanded uplift rate scale, emphasizing variability of geologic vertical uplift rates. (b) Condensed uplift rate scale, highlighting distribution of rates in the -1 to 1 mm/a rate, where the majority of the geologic uplift rates lie.



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Southern California Geologic Vertical Motion Map

A product of the Southern California Earthquake Center

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Search by Area
North °
West ° ° East
South °

Search by Locality
GPS Stations
Seismic Stations
Search Radius km

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Southern California Geologic Vertical Motion Map

Vertical Motion Results Summary

Select result sets and reference frames to process vertical motion data.

Query Summary: Search on GPS Station BBRY. Search centered at 34.2643° latitude, -116.884° longitude, within radius of 300km. 1667 uplift measurement localities returned.

Result Set	Reference Frame	Processing
Marine Terraces (163 results)	Sea Level History TKR Composite Sea Level Curve	☑ Process localities ☐ Show null values
Sedimentary Horizon (969 results)	Sedimentary Facies Depth Model Preliminary Facies Model	☑ Process localities ☐ Show null values
River Terraces (493 results)	Relative Terrace Initial Position Present Stream Elevation	☑ Process localities ☐ Show null values
Thermochronology (42 results)	Thermal and Uplift Model Constant Exhumation, No Surface Uplift	☑ Process localities ☐ Show null values

Select format for results:
● Display as web page table
○ Download GIS-compatable text file
○ Explore with Google Maps

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Figure 2. Web interface to the SCEC Geologic Vertical Motion Database. (a) Vertical motion data can be searched by geographic coordinates of a bounding rectangle, or by defining a search radius around existing GPS stations or seismic monuments in southern California. (b) Results summary page shows the number of each type of data record found in the search region, and offers the user a variety of choices for handling the data, including option for dealing with incomplete data, models for reference datums (such as sea level curves), and output formats, including web page tables, GIS-compatible text files, and a Google Maps™ display.

tabase, and are reflected in the uplift rates derived from the data set. Below we describe each of the four major data types incorporated into the SCEC VMDB, along with typical chronologic data for each type, and methodologies implemented for deriving geologic uplift rates from these data. A discussion of simplifying assumptions, limitations, and potential uses of these data is presented in a later section.

2.1. Marine Terraces

[6] Marine terraces begin as eroded bedrock platforms formed from wave erosion during time periods of stable sea level. A terrace develops when sea level falls and uplift isolates a platform from inundation. Marine terraces define high precision markers of absolute vertical motion [e.g., *Bloom et al.*, 1974; *Bloom and Yonekura*, 1985]. The VMDB contains over 300 marine terrace data points along the Pacific coastline from San Simeon to central Baja California, including nearly all offshore islands (Figure 1) [e.g., *Rockwell et al.*, 1992; *Muhs*, 1983; *Muhs et al.*, 1992, 1994, 2002]. Relative uplift is calculated from the present terrace elevation near its inland back-edge, known as the "shoreline angle," with respect to the modern shoreline angle (Figure 3a). Absolute uplift is calculated via correlation of a marine terrace to a particular sea level stage and its highstand elevation, which serves as a datum. Sea level curves currently available in the VMDB include a composite Quaternary sea-level curve [*Rockwell et al.*, 1989; *Muhs et al.*, 2002], and ^{18}O-based curves for marine isotopic stages 3 and 5 [*Muhs et al.*, 1994; *Chappell and Shackleton*, 1986]. Because sea level is a global reference frame, assignments of these datums are essentially temporal correlations, and thus depend on often incomplete knowledge of terrace ages and spatial correlation of terraces to others of known age.

[7] Several age dating methods have been used to assign ages to marine terraces and tie these to a particular sea level highstand. Each of these age dating methods is represented separately in the database in order to preserve appropriate metadata. In rare instances, absolute chronometry is available from U-series disequilibrium on solitary fossil coral [e.g., *Ku*, 1976], or for the very youngest terraces, ^{14}C of organic material. Other ages are determined relatively from faunal assemblages or amino acid racemization (randomization of shell protein structure over time) [e.g., *Miller and Brigham-Grette*, 1989] tied to absolutely dated sites. Finally, some

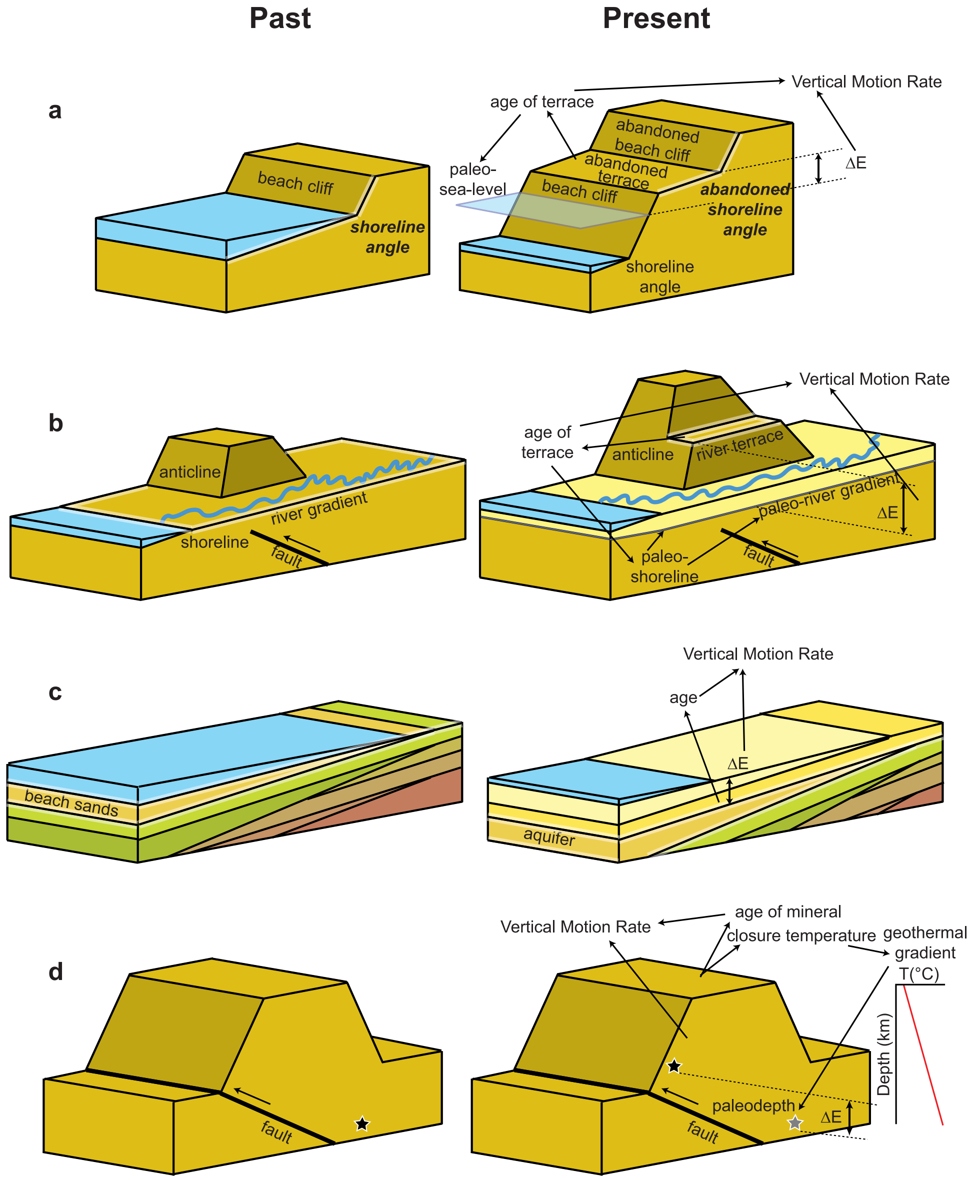

Figure 3. Schematic diagrams of the geologic development of the four uplift markers currently represented in the Vertical Motion Database, illustrated with the geologic observations necessary to derive uplift rate information from each of the four marker types. (a) Marine terrace. (b) Fluvial terrace. (c) Subsurface stratigraphic horizon. (d) Thermochronologic age constraint.

ages are assigned on the basis of cross-cutting relationships between terrace risers and the order and relative elevations of sea level highstands. These correlations become less reliable with increasing marine terrace age.

2.2. River Terraces

[8] Nearly 500 river terrace data points have been incorporated into the VMDB from the Ventura River, Los Angeles River, San Gabriel River, and Santa Ana River. These rivers drain through the major coastal basins of southern California. As with marine terraces, river terraces are formed when a portion of the river bed is isolated from inundation (Figure 3b). Typical river terrace markers in the VMDB were formed during an episode of valley infilling with sediment, followed by river incision that isolated the terrace [*Rockwell et al.*, 1984; *Bull*, 1991].

[9] Defining an appropriate datum is problematic for river terraces. Changes in sediment grain size and the balance between sediment flux and river discharge are most likely to affect river gradient over the time frame of terrace generation at the length scale of large coastal river basins [*Paola et*

al., 1992]. Sea level change is unlikely to be a major effect except during eustatic lowstands where the river mouth may drop below the shelf-slope break, instigating the formation of incised valleys upstream, or by exposing a gentle lowstand shelf that promotes aggradation of the river system upstream. Most of the terraces in the VMDB were formed well inland of the shoreline by braided rivers during times when sea level was not low enough to cause incised valley formation. Some of these terraces are fill deposits (e.g., >20-m-thick fills along the Los Angeles River [*Oskin et al.*, 2000]). Other terraces are straths cut on bedrock, but these also are likely to be formed during periods of enhanced sediment flux [e.g., *Hancock and Anderson*, 2002]. Thus we interpret that most terraces in the VMDB were probably formed as thin sheets of gravel prograded across the coastal sedimentary basins in response to changes in sediment flux and river discharge. The Ventura River is a likely exception, as this terrace sequence is preserved proximal to the coastline and has preserved terraces that were isolated during sea-level lowstands [*Rockwell et al.*, 1984, 1988].

[10] We make the simplifying assumptions that (1) the depositional slope of a gravel sheet (and thus the balance of discharge and sediment flux during gravel sheet formation) is invariant on a given reach of a river system, and (2) the surface elevations of subsiding basins upstream and downstream of a flight of terraces does not change appreciably over the short timescale of terrace records. Because all of the uplifts over which river terraces have been preserved are underlain by easily eroded marine rocks or unconsolidated fluvial deposits, we do not expect these uplifts to form resistant barriers and therefore a constant gradient was maintained across an uplift during each terrace-forming event. Thus, any relative changes in gradient of a terrace with respect to the present river elevation across these uplifts is interpreted as the result of tectonic uplift. Uplift rates calculated from the difference in terrace surface elevation to the present river elevation will be more reliable for older and more highly deformed terraces where the amount of uplift well exceeds short-term changes in surface elevation along the river system. The VMDB is built to accommodate alternative reference frames, though no alternative to the present river elevation is provided currently.

[11] Ages of river terraces, like ages of marine terraces, are determined using a variety of techniques and correlations. For the youngest terraces, ^{14}C ages are available. Many river terraces are dated via soil development, a relative dating technique that quantifies soil structure, content, and thickness, and yields an age calibrated to other soils of known age [e.g., *Walker*, 1962; *Rockwell*, 2000]. In situ cosmogenic nuclides provide a method for dating fluvial terraces over ka to Ma timescales [e.g., *Repka et al.*, 1998], but at present no such ages have been published for any of the river terraces contained in the VMDB.

2.3. Stratigraphic Horizons

[12] Major stratigraphic horizons within the coastal basins of southern California help to define both uplift and subsidence rates. Uplift is calculated from a present elevation (often negative if penetrated below sea level in a well) differenced with a broadly defined paleoelevation datum based on depositional setting (Figure 3c). The VMDB contains almost 1000 stratigraphic horizon data points from the Ventura and Los Angeles basins, ranging in age from Late Quaternary to early Pliocene. The uplift (or subsidence) of these stratigraphic horizons is determined in the VMDB as the difference between the present elevation of the deposit and paleoelevation at the time of deposition.

[13] Late Quaternary stratigraphic horizons are primarily known from aquifer systems penetrated by water wells. Although generally poorly dated, the majority of these aquifer systems are developed in sands thought to be beach facies, and thus have well defined paleoelevations near sea level. Many of these horizons have subsided tens to hundreds of meters since deposition [*Yeats*, 1977; K. Mueller, unpublished data, 2003]. Early Quaternary and Pliocene stratigraphic horizons [e.g., *Cooke et al.*, 2004] are well-dated from regionally defined faunal assemblages, but were typically deposited below paleo-sea level at poorly constrained paleodepths [*Blake*, 1991]. Because these horizons are older than ∼1 Ma, the amount of deformation and integrated uplift rates are significant relative to the uncertainties inherent in the depths of deposition. Absolute ages are an integral part of the identification and correlation of stratigraphic horizons, and are thus included as part of a stratigraphic horizon datum.

2.4. Thermochronology

[14] Thermochronologic ages across southern California present a rich data set for the study of vertical motions in bedrock terrain [e.g., *Blythe et al.*, 2000]. Low-temperature thermochronologic ages (apatite U-Th/He and fission-track ages are included at present) represent exhumation of rocks

through a closure temperature, (~70°C and ~110°C, respectively [e.g., *Farley*, 2000; *Wagner and Reimer*, 1972]). This closure temperature serves as a proxy for depth with the assumption of a geothermal gradient (Figure 3d). If surface uplift is assumed to be minimal, then the rate of erosional exhumation is a proxy for rock uplift rate. Using an average geothermal gradient of ~30°C/km [*Sass et al.*, 1992], more than 2 km of exhumation is required to yield a reset fission-track or (U-Th)/He age and derive a potentially meaningful exhumation rate.

[15] Given, then, this set of simplifying assumptions (fixed geothermal gradient, zero surface uplift, known closure temperature and simple thermal history), the depth to the closure temperature of a given thermochronometer (the closure isotherm) can be treated as a paleoelevation datum. The time at which a sample passed through this datum (the thermochronometric age of the sample) can then be used to derive a bedrock uplift rate. It is important to note that the assumption of zero surface uplift is only valid to first order, and that few bedrock uplands of southern California are sufficiently exhumed to provide useful low-temperature thermochronologic ages. However, where available, thermochronologic data provide vertical motion information where no other such data exist, providing a key link from coastal basins to bedrock uplands across major range-bounding faults.

3. Database Technology

[16] The VMDB is built on the open-source PostgreSQL relational database server, with access to the database provided via a web portal (http://www.scec.org/resources/data/vmdb/). The web portal is built on the PHP scripting language, which permits interaction with users via web-based query forms. Vertical motion results are output to a web browser as HTML tables, GIS-compatible text files, or as interactive maps via the Google Maps™ web service.

[17] The VMDB uses a novel approach to compiling geologic data into a useful resource for the broader earthquake research community. Rather than attempting to produce a simple, static map of vertical motion results, the database preserves original geologic data in its intact form encapsulated in tables customized to the data type. The vertical motion database uses object-relational technology pioneered by the open-source PostgreSQL relational database system. The structure of an object-relational database mirrors the structure of object-oriented programming languages in that each table acts as a class, and each row in the table is an object. The power of this approach is the ability to make a generic base class and then derive specialized subclasses. Each subclass can be treated as an individual table, or the base class can be used to address all of the data generically, an approach known as polymorphism in object oriented programming. For example, tables that describe specific subclasses of geologic vertical motion data, such as marine terraces, river terraces, thermochronology sample profiles, or stratigraphic horizons from oil wells, inherit a generic locality table. In effect, the classes of vertical motion data are considered subclasses of the generic locality class, and each subclass is customized to hold the data required to completely describe a particular data type. Generic queries, such as a search on the common attributes of location, age, and elevation of vertical motion data, are directed at the parent class to search all customized subclasses simultaneously (Figure 4). Such a structure could be mimicked in a traditional relational database through the use of foreign keys, but the result would be locality data spread across multiple tables. The object-relational approach keeps all of the relevant data for each locality intact within its own specialized table.

[18] Through use of recursive stored procedures (another innovation of PostgreSQL), the vertical motion database also models correlation between data points. A recursive procedure is one that can call itself, and is ideally suited to querying a chain of correlations through a data set. Modeling correlation through recursion is critical because geologic vertical motion data typically rely on a few key localities with adequate age and/or elevation control. The end result of this effort to apply object-relational technology and recursion is a seamless and surprisingly simple approach to geologic vertical motion data that preserves the original geologic information and relationships, is easily updateable and expandable, and that automatically propagates newly added data through the uplift model to provide the most up-to-date vertical motion rates.

4. Discussion

4.1. Assumptions and Limitations of the VMDB

[19] The reliability of any vertical motion determination is a function of the precision of the age,

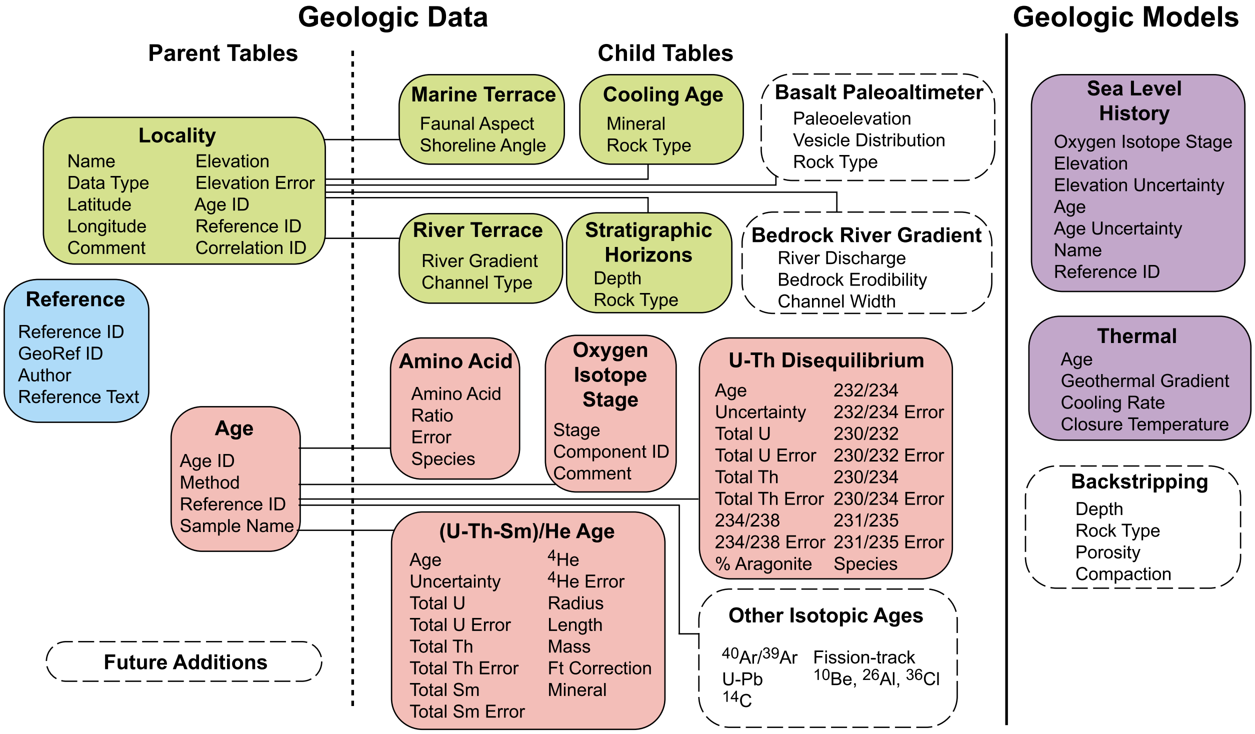

Figure 4. Database model for the VMDB. The use of parent/child table relationships simplifies handling of complex data types. Vertical motion data of any type can be searched by location through a parent table, but each data type can be processed separately, depending on the child table to which it belongs, for appropriate geologic observations and criteria. Colored tables represent data types and models currently implemented in the VMDB, including four classes of geologic observations (green), four types of geochronologic data (pink), reference information (blue), and multiple sea level history models (purple). Potential future additions to the VDMB are indicated by dashed boxes.

relative uplift value, and the datum used to transform relative uplift to absolute uplift rate in a global reference frame, such as sea level. Here we discuss some of the simplifying assumptions made in deriving geologic uplift rates in the VMDB, potential sources of error in ages and paleoelevation datums, and limitations on the use of these data.

4.1.1. Marine Terraces

[20] Not surprisingly, the VMDB is dominated by data from the coasts of southern California where marine terraces and strata are present. Vertical motion rates determined from marine terraces offer the highest-quality geologic constraints on long-term uplift rates in southern California. In most cases, the ages of marine terraces are well constrained, and the sea level datum is unambiguously tied to an absolute reference frame. Uplift rates determined from marine terraces are typically reliable to two or more significant digits. The assumption of terrace age via correlation is the greatest potential source of error in the use of geologic uplift rates derived from marine terraces, particularly for spatially isolated terraces. Limitations on marine terrace uplift rates are the narrow spatial distribution of these data along the coastline, and the preferential preservation of tectonically uplifted terraces. Marine terraces that undergo regional tectonic subsidence are simply buried under later sediment, or under present-day sea level, and are generally inaccessible for inclusion and analysis (however, see *Chaytor et al.* [2008]).

[21] The selection of an appropriate paleo-sea-level curve is also an issue in the derivation of geologic uplift rates from marine terrace data. Paleo-sea-levels for the Pacific are derived from a variety of data, including reef tracts [e.g., *Bloom et al.*, 1974], abrasion platforms [e.g., *Rockwell et al.*, 1989] and marine oxygen isotope records [e.g., *Chappell and Shackleton*, 1986]. Timing of sea-level highstand varies from method to method, with reef tracts often recording sea level at the onset (or even just before the onset) of a sea-level highstand, while abrasion platforms record sea level just prior to highstand fall. Because sea level, even during high-

stands, can fluctuate significantly [e.g., *Neumann and Hearty*, 1996], and because highstands can have durations of thousands or tens of thousands of years [*Ku et al.*, 1974; *Chen et al.*, 1991], geologic vertical uplift rates are sensitive to the choice of sea-level record, the duration of the highstand, and the difference between early and late highstand sea level elevation. Marine terraces preserved in southern California are primarily abrasion platforms, for which the most appropriate sea level curve is based on abrasion platforms recorded on Isla de Guadalupe, a stable island on a fossil spreading ridge now attached to the Pacific plate [*Muhs et al.*, 2002]. However, the selection of sea level curves is left open to the user to explore the effects of varying highstand timing and magnitude on geologic uplift rates in southern California. These effects will be modest, however, and will mainly affect portions of the coast with low (<~0.3 mm/a) uplift rates.

4.1.2. River Terraces

[22] River terraces offer an opportunity to spatially extend geologic uplift rates from the coasts toward the interior basins of southern California. As discussed above, absolute ages of river terraces in southern California are generally lacking, although some younger terraces do have ^{14}C ages, and relative age control via soil development is available in some cases. This lack of absolute age control, and assumptions discussed below regarding river paleoelevation, result in geologic vertical motion values from river terraces that are less reliable than values from marine terraces.

[23] The most significant assumption made in deriving in uplift rates from river terraces is the paleoelevation of the river system, and the type of river terrace considered. Strath terraces form during periods of relative stability, when rivers cut laterally into their banks; fill terraces, on the other hand, form when a river is unable to carry its bedload, and aggrades by deposition of this material [see *Merritts et al.*, 1994]. Incision and abandonment of a paleo-river bed, and development of river terraces, occurs when the power of a river locally exceeds that necessary to carry its bedload, and the river incises its bed. River incision and terrace development can be driven by sediment flux, discharge, tectonic or, in some cases, eustatic changes. Fluvial responses to tectonic and eustatic forcing cannot be confidently modeled to a precision necessary to extract useful paleogradient data. We therefore make the simplifying assumption that rivers in southern California have maintained a constant gradient, and absolute elevation, over the past several hundred thousand years. At long timescales, where tectonic deformation will greatly exceed variability in river elevation due to eustatic changes, geologic uplift rates derived from abandoned terraces are likely to be fairly accurate. At short timescales, when tectonic deformation of river terraces may be overwhelmed by sediment flux and discharge-driven changes in river elevation, vertical motion rates are likely to be considerably less reliable.

4.1.3. Stratigraphic Horizons

[24] Buried stratigraphic horizons offer the greatest potential for constraining subsidence (negative geologic uplift) rates in southern California basins. For many stratigraphic horizons, absolute ages are well constrained, but Late Quaternary stratigraphic horizons lack the fossil age control available to older horizons [e.g., *Cooke et al.*, 2004]. Paleodepositional depths for Early Quaternary and Pliocene deposits are less well constrained than those for Late Quaternary deposits, and this uncertainty effects subsidence rates calculated for older stratigraphic horizons that have not experiences significant burial (i.e., those that have slightly negative uplift rates). For horizons that have subsided thousands of meters (i.e., those that have significantly negative uplift rates), the uncertainty in paleo-depositional depth is trivial compared to the absolute change in elevation since deposition, and can be discounted. At present, the largest source of error in vertical uplift rates derived from stratigraphic horizons is the lack of consideration of sediment compaction and isostatic compensation. To fully consider these effects, an Airy isostatic backstripping model would need to be implemented for each stratigraphic column [*Steckler and Watts*, 1978]. Such a model would require knowledge of the depth and sediment type of all stratigraphic horizons under the horizon of interest, which is not universally available for well data in southern California, as well as estimates of initial porosity. For a tectonically active compressional regime, crustal thickening and flexural loading may also need to be considered for a complete analysis of backstripping. Such a model could be implemented in a general way in the VMDB, and this may be a future enhancement made to the database. Until that time, it should be understood that subsidence rates derived from stratigraphic horizons in the VMDB are a result of tectonic forces, sediment compaction, and isostatic adjustment.

[25] Away from the coastal basins, remnants of older marine stratigraphy, now found far inland, provide some constraints on long-term rates of uplift. Examples of the latter include Eocene marine strata found in the El Paso mountains in the northern Mojave Desert [*Cox and Diggles*, 1986; *McDougall*, 1987], Miocene marine strata in San Gorgonio Pass [*McDougall et al.*, 1999], and extraregional fluvial systems that drained across low-relief uplands of the Mojave Desert, San Bernardino Mountains and Peninsular Ranges [e.g., *Kies and Abbott*, 1983; *Howard*, 2000]. However, these data sets are presently too sparse to provide sufficient uplift constraints for comparison with present-day uplift rates.

4.1.4. Low-Temperature Thermochronology

[26] As discussed above, a number of simplifying assumptions must be made to derive a rock uplift rate from low-temperature thermochronologic data, including an assumed, and constant, geothermal gradient, a fixed closure temperature, and steady state topography (zero net surface uplift). It is, of course, likely that some, or all, of these conditions have changed over the several million years that low-temperature thermochronometers in southern California were exhumed to the surface. Even in the event that this is not the case, a number of other implicit assumptions and simplifications are made to derive uplift rates from thermochronologic data. The VMDB process does not consider the effects of mineral grain size or cooling rate on thermochronologic age [i.e., *Reiners and Farley*, 2001; *Farley*, 2002]. Additional complicating effects, driven by rapid exhumation and significant topographic relief, such as deflection of isotherms [*Stüwe et al.*, 1994; *House et al.*, 1998] and advection of isotherms [e.g., *Mancktelow and Grasemann*, 1997] are also ignored in our simple assessment of rock uplift rate. Consideration of these effects may have significant implications for geologic vertical uplift rates derived from low-temperature thermochronologic data. These effects, however, are sufficiently complex that we can conceive of no simple way to incorporate the modeling of these processes into the VMDB in a generally applicable way. As a rule of thumb, rapid uplift rates derived from low-temperature thermochronologic data are more susceptible to these effects than slow uplift rates. Nonetheless, these data offer one of the few avenues for connecting uplift rates in the interior basins across major range-bounding faults to the bedrock mountains that surround the Los Angeles basin.

4.2. Potential Database Additions

[27] The four data types included in the VMDB are not the only approaches to deriving paleoelevation histories and, thus, geologic uplift rates, although they are the most relevant to shorter geologic timescales. Additional data types that could potentially be incorporated into the VMDB include stable isotope data recorded in geologic and paleontologic samples that offer potential for assessing long-term uplift rates in the interior basins and deserts of southern California [e.g., *Poage and Chamberlain*, 2002; *Horton and Chamberlain*, 2006; *Crowley et al.*, 2008]. Such data are generally applicable to timescales of millions of years, and can be influenced by a number of factors other than changes in elevation [see *Rowley and Garzione*, 2007]. Other paleoaltimeters (e.g., basalt vesicle paleoaltimetry [*Sahagian et al.*, 2002] and clumped isotopes [*Ghosh et al.*, 2006]) also offer potential for deriving vertical uplift rates, but require continued calibration and refinement to reduce uncertainties to levels that would be useful for comparison with modern geodetic deformation rates. The inclusion of any of these data types into the VMDB is trivial, however, and the database could be easily expanded to calculate long-term, as well as short-term, uplift rates from any geologic proxy that can be tied to an absolute vertical datum.

4.3. Applications of the Database

[28] The primary impetus in developing this database was to constrain short-term ($10^4 – 10^6$ years) geologic rates of vertical motion for comparison with present-day rates of vertical motion derived from GPS geodesy across southern California. Some possible uses of such comparisons are in discriminating tectonic versus nontectonic sources of transient changes in the southern California GPS velocity field. Many, if not all, GPS monuments in southern California are susceptible to vertical motions not related to tectonic effects, particularly groundwater recharge and withdrawal [*Bawden et al.*, 2001]. A GPS anomaly in the San Gabriel Valley in 2005 was detected by several processing centers, and differentiation between a tectonic or nontectonic source was not immediately conclusive [*King et al.*, 2006], although further work clarified this anomaly as hydrologic in nature [*King et al.*, 2007]. Availability of the long-term pattern of

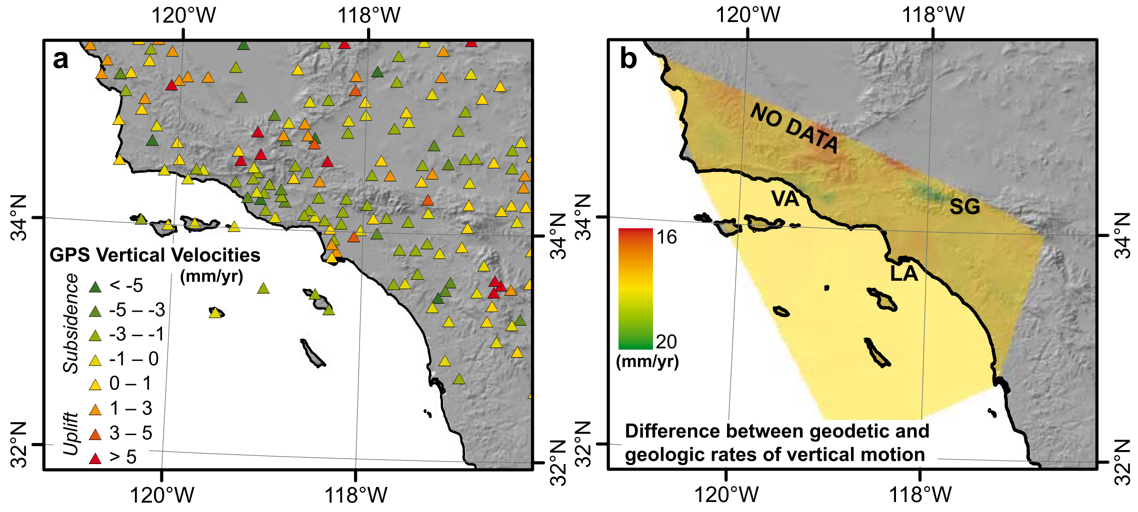

Figure 5. (a) Map of permanent Global Positioning System monuments of the Plate Boundary Observatory colored by vertical component of site velocity in a stable North America reference frame [*Herring et al.*, 2006]. (b) Difference between vertical component of GPS velocity and geologic uplift rate from the VMDB, calculated by deriving, and differencing, a triangulated irregular network (TIN) for each data set. NO DATA, lack of geologic uplift data renders difference meaningless; VA, Ventura anticline; SG, San Gabriel Mountains; LA, Los Angeles basin. See text for discussion.

vertical motion in this region would likely have been a logical discriminator between the competing hypotheses of aseismic slip and groundwater recharge for the observed rates of GPS uplift [*King et al.*, 2006].

[29] Broad-scale comparisons between geodetic and geologic rates of vertical motion can also be made (Figure 5). While some discrepancies between these two sets of vertical motion data can be ascribed to extrapolation over significant regions with no geologic vertical motion data (NO DATA in Figure 5b), other discrepancies are of potential geologic interest. Three specific examples are the Ventura Avenue anticline (VA in Figure 5b), where uplifted marine terraces indicate geologic uplift rates as high as 15 mm/a, but GPS velocities suggest minimal vertical uplift at present; the San Gabriel Mountains (SG in Figure 5b), where low-temperature thermochronologic ages suggest rock uplift rates of 1–1.5 mm/a, greatly in excess of present-day vertical GPS velocities; and the Los Angeles basin (LA in Figure 5b), where stratigraphic horizons in boreholes and wells suggest subsidence of the basin over geologic timescales at rates faster than presently observed geodetically.

[30] In the case of the Ventura anticline, the uplifted marine terraces are Late Quaternary in age, and thus the observed discrepancy is unlikely to represent a fundamental change in the tectonic regime of this fault system, although such a scenario cannot be ruled out entirely. One possibility to explain the discrepancy is that fold growth may be coseismic, and thus that vertical uplift of the Ventura anticline occurs only during seismic events. In the San Gabriel Mountains, where (U-Th)/He ages are at least several million years old [*Blythe et al.*, 2000], a change in shortening rate, and thus exhumation rate, across the mountains over this time period is a distinct possibility, and the discrepancy between geologic and geodetic vertical uplift rates may represent a long-term change in tectonic rates across this range. In the case of Los Angeles Basin, a decreased subsidence rate at present may indicate a long-term progressive change in subsidence rate, a climatic change limiting sediment supply, or simply the difference between tectonic subsidence (present-day GPS) and the combined effects of tectonic subsidence and sediment compaction (geologic rates). Or, taken as whole, the general decrease in vertical rates at present may indicate a secular changes in the regional strain field, with strike-slip kinematics dominating the southern California plate boundary at present, and suppressing vertical motions [*Dolan et al.*, 2007], while at other times, compressional kinematics would dominate the plate boundary, leading to increased rates of vertical surface motion.

[31] It is not the intent of this paper to propose solutions to all of these issues, but simply to point out that discrepancies between vertical geologic

and geodetic rates of deformation may potentially be as illuminating in understanding the tectonics of southern California as discrepancies between horizontal geologic and geodetic rates [e.g., *Donnellan et al.*, 1993; *Oskin et al.*, 2008]. Other potential applications may rely on detailed geologic uplift data on a more limited scale, such as discriminating elastic from permanent deformation during coseismic folding events [e.g., *Hudnut et al.*, 1996; *Lin and Stein*, 1989], constraining models of earthquake-by-earthquake fold growth [e.g., *Leon et al.*, 2007], or discriminating postseismic relaxation processes [*Peltzer et al.*, 1998; *Pollitz et al.*, 2001]. We are certain that there are applications for this data that have not occurred to us, but we believe that the VMDB provides an easy, intuitive interface for the geoscience community to explore and model geologic uplift rates in southern California for any purpose.

5. Conclusions

[32] The VMDB represents a mature product for research into fault activity and elastic deformation of southern California. The database structure can robustly model the fundamental vertical motion data types available, and it can incorporate new data types that may arise in future research. The VDMB is available online (http://www.scec.org/resources/data/vmdb/) to any researchers with an interest in using it, and remains open to submission of new data sets.

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