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An empirical study of the distribution of earthquakes with respect to rock type and depth

Yuval Tal¹ and Bradford H. Hager¹

¹Earth Resources Laboratory, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Abstract:

Whether fault slip occurs seismically or aseismically depends on the frictional properties of the fault, which might be expected to depend on rock type and depth, as well as other factors. To examine the effect of rock type and depth on the distribution of earthquakes, we compare geologic models of the San Francisco Bay and the southern California regions to the distribution of seismicity. We normalize the number of earthquakes within each rock type and depth interval by the corresponding volume to determine the earthquake density. Earthquake density is determined primarily by depth, while whether the rock is sedimentary or basement has only a secondary, depth-dependent effect on the earthquake density. At very shallow depths there is no difference in earthquake density between sedimentary and basement rocks. The earthquake density of basement rocks increases with depth more rapidly than that of sedimentary rocks to a similar but shallower maximum.
**Introduction:**

A common view is that earthquakes occur via a frictional instability [e.g. Scholz, 1998]. Rate-and state-dependent friction constitutive laws [Dieterich, 1979; Ruina, 1983] have emerged as powerful tools for investigating the mechanics of earthquakes and faulting [Marone, 1998]. These constitutive laws suggest that the response of frictional resistance to a change in sliding velocity includes an instantaneous response followed by an evolution with slip distance. This behavior is characterized by two material property constants, \( a \) and \( b \), respectively. The steady-state velocity dependence of the friction coefficient is characterized by \((a - b)\). When \((a - b) \geq 0\), the material is velocity strengthening and slip is stable; when \((a - b) < 0\), the material is velocity weakening, and an earthquake can nucleate if the system is not too stiff. Laboratory experiments have shown that the \((a - b)\) parameter depends on normal stress [Marone and Scholz 1988; Scholz, 1998], temperature [Scholz, 1998], slip velocity [Tsutsumi and Shimamoto, 1997; Blanpied et al., 1998] or stressing rate [Dieterich, 1994], and in the case of fault gouge, gouge layer thickness [Marone et al., 1990] and shear strain [Marone, 1998; Mair and Marone, 1999; Ikari et al., 2011]. However, available laboratory data do not yet conclusively define the effect of rock type on whether stable or unstable behavior is expected. Studies by Carpenter et al. [2009], Ikari et al. [2011], and Kohli and Zoback [2013], and the data summarized by Paterson and Wong [2005], addressed this problem and found that materials with low frictional strength of \( \mu < 0.5 \), such as clay dominated fault gouges, are generally velocity strengthening. Their data show that materials with
coefficients of friction $\mu \geq 0.5$ can exhibit either velocity strengthening or velocity weakening. The most studied rock type, granite, shows mostly velocity weakening behavior, especially for large slip, at temperatures $\leq 350$ °C. For higher temperatures, granite is velocity strengthening.

We adopt an empirical approach to examine the dependence of seismic vs. aseismic slip on rock type and depth. We combine three-dimensional geologic models of the San Francisco Bay region (available at http://earthquake.usgs.gov/data/3dgeologic/, Jachens et al. [2006]) and southern California [Süss and Shaw, 2003; Plesch et al., 2011] with the three-dimensional distribution of seismicity in these regions [NCEDC, 2013; Hauksson et al., 2012] in order to correlate seismic behavior and rock type and depth. The effects of the average geothermal gradient and overburden pressure are lumped together in the variation with depth. We do not address the effects of lateral variations of other parameters that might affect seismic vs aseismic slip such as temperature, stress, stressing rate, or pore fluid pressure. Lateral variations in temperature occur at spatial scales large compared to the distances over which rock type varies so are not expected to affect one rock type preferentially. Variations in stress, stressing rate, and pore pressure are likely to occur at spatial scales comparable to the distances over which rock types vary, but are not well constrained.

Data and Methods

2.1 Geologic models
Figure 1 shows the coverage of the geologic models. The geologic model of the San Francisco Bay region [Jachens et al., 2006] is composed of 25 major faults that break the map volume into 26 fault blocks, which in turn are populated with geologic units defined by boundary surfaces that represent their tops. Both faults and boundary surfaces in the 3-D geologic models are discretized using triangles. The model is based on a century of geologic mapping, 50 years of gravity and magnetic surveying, double-difference relocated seismicity, seismic soundings, P-wave tomography, and well logs [Jachens et al., 2006]. The fault blocks are populated with geologic units in the following groups: water, Plio-Quaternary deposits, Tertiary (or undifferentiated Cenozoic) sedimentary and volcanic deposits, Mesozoic sedimentary or plutonic rocks, mafic lower crust, and mantle rocks [Jachens et al., 2006]. We divide the rock units in the model into seven groups: Mantle, lower crust, gabbro, Franciscan (KJf), granodiorite, sedimentary rocks, and volcanic deposits. The 3-D geologic model of southern California includes only two rock units, sedimentary and basement rock, with bounding surfaces discretized using triangles. These surfaces include offsets associated with major faults in the region, including thrust faults that locally duplicate the stratigraphy. The topography/bathymetry of this region is represented by another triangulated surface. At large depths, the sedimentary units include also low-grade metasedimentary rocks. The distinction between these rocks and crystalline basement rocks is based mostly on different acoustic properties and involves larger uncertainty where the sedimentary rocks experienced larger compaction [J. H. Shaw, personal communication, 2013].
2.2 Seismicity

The seismic catalog of the San Francisco Bay region we use includes 24,531 earthquakes with magnitude $M \geq 2$, from 01/01/1975 to 31/05/2013 [NCEDC, 2013]. The hypocenters in this catalog were obtained using Hypoinverse2000 [Klein, 2002], which allows some complexity by using multiple 1-D velocity models. In each model, velocity varies only with depth. 9099 earthquakes are located in the Geysers geothermal field. These earthquakes are associated with water injection and steam extraction at the Geysers [Majer and McEvilly, 1979; Eberhart-Phillips and Oppenheimer, 1984; Smith et al., 2000; Majer et al., 2007]. The scope of this research is to examine tectonic of seismicity, rather than the induced seismicity at the Geysers. Therefore, all of the earthquakes with hypocenters that are both located inside the boundaries of the Geysers geothermal field, which covers an area of 78 km$^2$, and are shallower than 5 km, are excluded in this study. The average absolute vertical and horizontal errors of the hypocenter locations of the remaining 15,432 earthquakes are 0.78 km and 0.32 km, respectively. The seismic catalog of southern California that we use [Hauksson et al., 2012] includes 86,826 earthquakes with $M \geq 2$ from 1981 to 2011. In this catalog, the average absolute vertical and horizontal errors of the hypocenter locations are 1.18 km and 0.64 km, respectively. Almost all hypocenters in this catalog were obtained with a 3-D velocity model [Lin et al., 2007; Hauksson et al., 2012]. Examination of earthquake depth distribution histograms of the two seismic catalogs (Figure S1) does not show hypocenter depths preferentially at any velocity model boundaries, except for a relatively large number of
earthquakes at very shallow depths in the San Francisco Bay region. However, those shallower earthquakes have relatively large depth errors, which are incorporated in the analysis, as described in the following section.

2.3. Correlation between earthquakes and rock units

The model of the San Francisco Bay region divides the volume into fault blocks that are further subdivided by boundary surfaces into geologic units. Therefore, for each hypocenter it was necessary to determine the fault block first, then the rock unit. The fault blocks were determined with a ray-casting point-in-polyhedron test, which is a simple extension of a well-known point-in-polygon ray-casting algorithm. In this test, a ray is cast vertically from the hypocenter to the surface. Next, the number of intersections between the ray and a fault block is determined. If this is an odd number, the hypocenter lies inside this fault block, otherwise it is outside. In order to count the number of intersections, the intersection between the ray and the triangulated surface of the fault block was tested with the algorithm of Möller and Trumbore [1997]. In order to make this procedure faster, data were preprocessed to ensure that the minimal number of triangles is tested with the algorithm above. The determination of the rock units in which the hypocenters are located was also attempted with the ray-casting point-in-polyhedron test. However, because there are unconformities in the geologic model, in some cases the rock unit could not be identified with this test. In these cases, the rock units were identified with specific logical conditions for each fault block. In the case of southern California,
the determination whether the hypocenters are located above or below the top of the basement rocks was also done with the algorithm of Möller and Trumbore [1997].

The depth errors of the hypocenters were included in the correlation process in both regions. In both catalogs the vertical error given is one standard deviation. In the San Francisco Bay region, each hypocenter was represented by five points with equal probability in a normal distribution, i.e. located at cumulative normal distribution values of 0.1, 0.3, 0.5, 0.7, and 0.9. In southern California, because there are two continuous surfaces, the top of the basement rocks and the topography/bathymetry, the vertical errors were inserted analytically, using a continuous normal distribution. In both regions, some of the error bounds extend above the topography/bathymetry surface. In these cases, the weighted points/areas that are below this surface were normalized to one.

3. Results

3.1 Number of earthquakes

Figure 2 shows the depth distribution of earthquakes in sedimentary and basement rock in southern California and the San Francisco Bay region. In the latter, all rock units that are non sedimentary are considered as basement rocks. The bars show the data, while the curves are a running average of the data over a window of 3 km. The curves for earthquakes with \( M \geq 3 \) were magnified by a factor of 10 to plot on the same scale. The errors are quantified with 5000 bootstrap resamplings [Efron and Tibshirani, 1993]. In both regions, the number of earthquakes in basement rocks increases with depth to a maximum value at depths of 5 – 7 km, and then decays with depth, with a broader peak in
southern California. In both regions, the number of earthquakes in sedimentary rocks at depths shallower than 1 km is about equal to that in basement rocks, but it remains approximately constant with increasing depth in the sedimentary rocks, thus the number of earthquakes in sedimentary rocks is significantly lower than in basement rocks. In the San Francisco Bay region, the ratio between the number of earthquakes in sedimentary rocks and basement rocks is lower than 0.1 at depths of 2 - 7 km and then increases slightly. In southern California, this ratio is lower than 0.1 at all depths greater than 3 km. Similar trends are also obtained for earthquakes restricted to $M \geq 3$.

### 3.2 Earthquake density

To address whether the difference in the number of earthquakes at depth depends on material properties or can be accounted for simply by the relative volumes of the respective rock types, we examine the density of earthquakes. We define the earthquake density, $\rho_{eq}$, as the average number of earthquakes per year in a given rock unit at a given depth, normalized by the volume of this rock unit. In order to calculate the distribution of rocks in the San Francisco Bay region, the geologic model was discretized into cells of 1 km$^3$, and the depth and rock unit were determined for each cell. In the case of southern California, the area of the geologic model was discretized into squares of 0.25 km$^2$, and the volume of the sedimentary and basement rocks under each square was calculated. The 2-D seismic distributions (see Figure 1) show that there are regions with no seismicity that we believe should not be included in the analysis. Therefore, only earthquakes that have a neighbor earthquake at a horizontal distance less than 8 km were included and
only grid cells that are at a horizontal distance less than 5 km from the nearest earthquake were included.

Figure 3 shows the depth distribution of earthquake density in sedimentary and basement rocks in southern California and the San Francisco Bay region. The bars show the data, while the curves are running averages of the data over a depth window of 3 km. Again, the curves for earthquakes with $M \geq 3$ were magnified by a factor of 10 and the errors are quantified with 5000 bootstrap resamplings. In both regions, the average earthquake density of sedimentary rocks is somewhat smaller than that of basement rocks. In southern California, the ratio between the average earthquake density in sedimentary rocks and basement rocks at depths shallower than 15 km is 0.79 for earthquakes with $M \geq 2$ and 0.85 for earthquakes with $M \geq 3$. In the San Francisco Bay region, those ratios are 0.66 and 0.69. The depth of 15 km was chosen because there are no sedimentary rocks at greater depths in Southern California.

In both regions, and for both rock types, earthquake densities for earthquakes with $M \geq 2$ and depth shallower than 2 km are about $0.25 \times 10^{-3} / (\text{km}^3 \cdot \text{year})$. Earthquake density increases with depth by up to about a factor of 10, then decreases. For basement rocks, the maximum earthquake density peaks at a shallower depth (5 – 7 km) than for sedimentary rocks (7 – 9 km in Southern California and 9 – 11 km in the San Francisco Bay region). In southern California, the maximum value of earthquake density for sedimentary rocks is slightly larger than that for basement rocks, while in the San Francisco Bay region it is slightly lower. Similar trends are obtained also for earthquakes
restricted to $M \geq 3$, with larger differences between the maximum values of earthquake density.

### 3.3 Gutenberg–Richter relation

Motivated by the difference of earthquake density between earthquakes with $M \geq 2$ and $M \geq 3$ (see Figure 3), we examine the Gutenberg–Richter relation [Gutenberg and Richter, 1944] with respect to rock type and depth. The Gutenberg–Richter relation states that the number of earthquakes, $N(M)$, which have a magnitude greater than or equal to $M$ is given by the relation $\log N(M) = a - bM$, where $a$ and $b$ are constants. In the San Francisco Bay region, the difference observed in Figure 3 between earthquakes with $M \geq 2$ and $M \geq 3$ (scale by factor of 10) results from the catalog is not being complete to magnitude 2 (Figure S2). In southern California, the catalog is complete to magnitude 2 (Figure S2), and the $b$-value clearly depends on both rock type and depth. While sedimentary rocks have $b$-values smaller than 1 at depths shallower than 10 km, the basement rocks have $b$-values equal or larger than 1 at depths of 2 – 11 km (Figure 3). We verify the observed trends in southern California with a more detailed analysis based on the maximum likelihood estimate of Aki [1965] and Utsu [1965] and the formula of Shi and Bolt [1982] for standard errors (text S2 and Figure S3). This analysis also shows that for basement rocks in southern California, the $b$-value increases with depth to a maximum value of $b = 1.05 \pm 0.01$, then decreases gradually to $b = 0.9 \pm 0.01$ at a depth of 15 km. In the San Francisco Bay region, the $b$-value of basement rocks decreases with depth, with $b$-value larger than 1 at depths shallower than 8 km. For sedimentary rocks,
the errors are quite large, but the $b$-value is equal or larger than 1 at depths shallower than 12 km (Figure S3).

3.4 Detailed distribution of earthquakes with respect to rock unit

The three dimensional geologic model of the San Francisco Bay region enables a more detailed distribution of earthquakes with respect to rock unit and depth to be determined (Figure 4). Because there are no mantle rocks and a small volume of lower crust rocks at depths where most of the earthquakes occur, and volcanic rocks occupy a very small volume in this region, only sedimentary, granodioritic, Franciscan, and gabbroic rocks are shown. At depths of 0 – 8 km, the earthquake density in granodioritic rocks is approximately half of the earthquake density in sedimentary rocks, 1/4 of the earthquake density in Franciscan rocks, and 1/25 of the earthquake density in gabbroic rocks. At depths of 8 – 12 km, sedimentary rocks tend to experience more earthquakes than the other rock units. At depths of 12 – 14 km, granodioritic rocks tend to experience most of earthquakes, but the total number of earthquakes is very small. Similar trends are obtained also for earthquakes restricted to $M \geq 3$ (Figure S5).

4. Discussion

The existence of 3 – D geologic models enables the definition of a new quantity, earthquake density, which describes the tendency of different rock units at different depths to experience earthquakes, based on field data. The extent of the geologic models and the voluminous seismic data, which includes 102,258 earthquakes outside the Geysers with $M \geq 2$, should provide sufficient statistics to overcome local errors in the
geologic models and the hypocenter locations. Moreover, the vertical errors of the hypocenters, which are approximately two times larger than the horizontal errors, are included in the analysis.

The difference in earthquake density between basement and sedimentary rocks is smaller in southern California, where 85% of the earthquakes in this study occurred. It is important to note that although basement rocks in both regions may include different rock units, the earthquake density of basement rocks is similar in both regions, while that of sedimentary rocks is smaller in the San Francisco Bay region. In the latter, we defined all non-sedimentary rocks as basement rocks, including Franciscan rocks, due to their association with the large shear deformation of the subduction zone and because they partly include high-grade metamorphic rocks. Examination of the depth distribution of earthquake density in sedimentary and basement rocks without including the Franciscan rocks (Figure S6) shows similar trends to those obtained including the Franciscan rocks.

In the case of the San Francisco Bay region, a more detailed analysis with regard to rock type is performed, and a significant dependence of earthquake density on rock type is observed, especially at depths of 2–8 km. The difference between rock type, and especially the large earthquake density of gabbro, might be attributed to the different proximity of rock units to the main active faults in this region. However, we try to account for this effect by our filtering process, in which we eliminate isolated earthquakes and rock volumes that are not in proximity to earthquakes. This part of the research should be treated with more caution because it includes only 15,432 earthquakes.
and only the San Francisco Bay region model, while the research on sedimentary versus basement rocks includes 102,258 earthquakes and a second geologic model, which covers a significantly larger area.

An implicit assumption in this study is that to some extent the fault rocks inside the fault zone represent the wall rock types, thus we attribute also earthquakes that occurred within fault zones to their wall rock types. This assumption might be questionable for earthquakes that occurred within faults that have accumulated large displacements. We cannot quantify directly how much the gouge in those fault zones represent the current wall rock, but we examine the robustness of our results by calculating earthquake density also with the removal of earthquakes and rock volumes that are at distance of less than 0.5 km from seven strike slip faults in the San Francisco Bay region and six strike slip faults in southern California with offset larger than 10 km (Text S1). The 3 – D geometries of those faults were obtained from the three-dimensional geologic model of the San Francisco Bay region (available at http://earthquake.usgs.gov/data/3dgeologic/, Jachens et al. [2006]) and from the SCEC Community Fault Model (CFM, available at http://structure.harvard.edu/cfm, Plesch and Shaw [2003] and Plesch et al. [2007]).

In southern California, only 7.5 % of the earthquakes (6470) are associated with large offset strike slip faults. Therefore, the removal of those earthquakes has a minor effect on earthquake density (Figure S7). In the San Francisco Bay region, 42 % of the earthquakes (6205) are associated with large offset strike slip faults. If these are omitted,
the earthquake density values of both basement and sedimentary rocks decrease significantly (Figure S7), but the trends are similar to these described in section 3.2. When the more detailed distribution with respect to rock type is analyzed (Figure S8), the most striking effect is the decrease of earthquake density of gabbroic rocks. At depths of 2 – 6 km, it is still the largest, but with significantly smaller differences from other rock types, and at depths of 6 – 8 km, it is smaller than that of Franciscan rocks and similar to that of sedimentary rocks.

The depth distribution of $b$-value for basement rocks in the San Francisco Bay region agrees with Mori and Abercrombie’s [1997] observation that the $b$-value decreases with depth. However, similar to Spada et al. [2013], in southern California we observed this trend only for basement rocks at depths larger than 5 – 6 km.

Due to the limitation of the geologic models that cover such an extensive area, this research focuses on how seismogenic sedimentary rocks behave as a whole, with no distinction between different sedimentary rock types. Further studies, using a detailed geologic model, would be necessary to examine the seismogenic behavior of different types of sedimentary rocks.

5. Conclusions

Depth is the primary parameter that determines earthquake density, with more than one order of magnitude variation in earthquake density with depth, while whether a rock unit is sedimentary or basement has a secondary effect on the earthquake density. This secondary effect is depth dependent. At very shallow depths there is no resolvable
difference between sedimentary and basement rocks; the earthquake density of basement rocks increases more rapidly with depth to a shallower peak. On average, the earthquake density of sedimentary rocks is 0.77 times that of basement rocks.

Based on the San Francisco Bay region data, we conclude that gabbro has significantly higher tendency to experience earthquakes than other rock types at depths of 0 – 8 km, in which most of the earthquakes occur in this region, and that granodioritic rocks tend to experience fewer earthquakes than sedimentary and Franciscan rocks.

The $b$-value depends on both rock type and depth. The southern California data, which include 85 % of the earthquakes in this study, shows that in most of the seismogenic depth range, basement rocks have larger $b$-values than sedimentary rocks.

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the alternate catalogs of the Southern California Earthquake Data Center (http://scedc.caltech.edu/research-tools/altcatalogs.html). We thank Ake Fagereng, Chris Marone, and an anonymous reviewer for their thorough reviews and constructive comments. This research was supported by DOE grant DE-FE0009738.
References


Figures

Figure 1. The areas investigated, with near-surface map views of the 3-D geologic models of San Francisco Bay and southern California regions, along with maps of the epicenters included in the study.

Figure 2. A histogram of earthquake number vs. depth in sedimentary and basement rocks in the southern California region and the San Francisco Bay region for earthquakes with \( M \geq 2 \) and 3. The curves are running averages of the data with a window of 3 km. The curves (dashed) for earthquakes with \( M \geq 3 \) were magnified by a factor of 10, so that they would plot on approximately the same scale. The error bars were derived from 5000 bootstraps and represent one standard error.

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Figure 4. Earthquake density as a function of rock unit and depth in the San Francisco Bay region. The four main rock units at depths of 0-14 km are included. The error bars were derived from 5000 bootstraps and represent one standard error.
Sedimentary rocks at depth of 300 m

San Francisco Bay region

Southern California