Three-Dimensional Compressional Attenuation Model ($Q_p$) for the Salton Trough, Southern California

by Guoqing Lin

Abstract  I present a frequency-independent 3D seismic attenuation model (indicated by $Q_p^{-1}$) for the crust of the Salton trough and the adjacent regions in southeastern southern California. The simul2000 tomographic algorithm was used to invert the frequency-independent attenuation operator $t^*$ values measured from amplitude spectra of 23,378 $P$-wave arrivals of 1203 events through a recently developed 3D velocity model. The $Q_p$ model has a uniform horizontal grid spacing of 5 km, and the vertical-node intervals range between 2 and 5 km down to 27 km depth. In general, the $Q_p$ values increase with depth and agree with the surface geology in the shallow depth layers. Low $Q_p$ values are observed in the Imperial Valley, California, which are consistent with the sedimentary deposits and may also reflect the presence of pore fluid in the active fault zones, whereas greatly elevated $Q_p$ values are shown in the surrounding crystalline ranges. The new $Q_p$ model provides an important complement to the existing velocity models for interpreting structural heterogeneity and fluid saturation of rocks in the study area.

Online Material: Figures of checkerboard resolution tests, $Q_p$ versus $V_p$, and $Q_p$ versus heat flow.

Introduction

Seismic attenuation can provide important independent constraints on rock composition, fluid content, and temperature that are distinct from those provided by compressional ($P$-) and shear ($S$-)wave velocities (Jackson and Anderson, 1970). However, attenuation studies have generally fallen behind velocity inversions because of the much greater scatter exhibited by observed amplitudes. Tomography has been applied to determine the 3D seismic attenuation structure in a manner similar to velocity inversion. The simul2000 program (Eberhart-Phillips, 1990; Thurber, 1993; Thurber and Eberhart-Phillips, 1999) is one of the most widely used algorithms for attenuation tomography. During the inversion, the high-frequency decay rate of direct-wave amplitude spectra is used to determine the whole path attenuation, quantified by the frequency-independent attenuation operator $t^*$ values. The $t^*$ values for each source–receiver pair are then inverted for the 3D attenuation structure, indicated by the inverse of quality factor $Q$, by tracing the ray paths through a given velocity model.

The Salton trough is located along the southernmost section of the San Andreas fault (SAF) and is surrounded by crystalline ranges (Sharp, 1982). It sits over several other major fault systems in southern California, including the Imperial fault and the San Jacinto fault zone (SJFZ) (Fig. 1a). In this paper, I present a frequency-independent 3D compressional-wave attenuation model ($Q_p$) of the crustal structure near the Salton trough and the adjacent fault zones by tracing rays through a newly developed 3D velocity model by Lin (2013). The $Q_p$ model provides an important complement to the existing velocity structure for understanding the structural heterogeneity and evaluating the seismic hazards in the study area.

Data and Processing

The seismic data used in this study are the same as those for the velocity tomography inversion and earthquake relocation studies in Lin (2013), obtained from the Southern California Earthquake Data Center and recorded by the stations (triangles in Fig. 1b) of regional seismic networks, including the Southern California Seismic Network and the ANZA Seismic Network. I apply the simul2000 algorithm (Eberhart-Phillips, 1990; Thurber, 1993; Thurber and Eberhart-Phillips, 1999) for the inversion of the $Q_p$ model by inverting the frequency-independent attenuation operator $t^*$ values. Their relation can be expressed by the
Assuming an f\textsuperscript{2} source model (Brune, 1970), the velocity amplitude spectrum \( A_{ij}(f) \) of event \( i \) at station \( j \) can be described by

\[
A_{ij}(f) = 2\pi f |\Omega_{ij}|^2
\frac{f_{ci}}{|f_{ci} + f|^2} \exp[-\pi f t_{ij}^*],
\]

in which \( |\Omega_{ij}| \) is the long-period amplitude, \( f_{ci} \) is the source corner frequency of event \( i \), and \( t_{ij}^* \) is the frequency-independent attenuation operator (Scherbaum, 1990). Using computed spectra from multitaper, the source corner frequency for each event and the frequency-independent attenuation operator \( t^* \) for each source-receiver pair are determined in an iterative spectra-fitting procedure. In this study, I only use measurements with the signal-to-noise ratio above 2.0 in a continuous 10-Hz-wide frequency band from 2 to 30 Hz. The source corner frequency is grid searched between 2 and 20 Hz. Similar parameters are used to develop a recent \( Q_p \) model for the crust and uppermost mantle of northern and central California (Lin, 2014). I selected 1203 events (black dots in Fig. 1b) consisting of 23,378 \( t^*_p \) values for the tomographic inversion. Figure 2 shows examples of amplitude spectra and \( t^* \) for an event.

### Model Setup

The inversion grid for the \( Q_p \) model is the same as that for the velocity tomography in Lin (2013). The horizontal grid spacing for the model is 5 km (squares in Fig. 1b) and the vertical-node intervals range between 2 and 5 km from the surface to 27 km depth (relative to mean sea level). The inversion grids are rotated 45\textdegree \ counterclockwise, with the \( x \) axis pointing to the southwest and \( y \) axis to the northwest. The inversion grid nodes (orange squares) are rotated 45\textdegree \ counterclockwise with respect to latitude and longitude, with the \( x \) axis pointing to the southwest and \( y \) axis to the northwest. The origin is located at 33.1\textdegree, -116.0\textdegree \ (shown by the red star). Blue straight lines indicate profiles for the cross sections in Figures 5 and 6.

![Figure 1](image)

**Figure 1.** (a) Major geological features in the study area, enclosed by the red box. The black lines denote major faults, and the pink lines denote the United States–Mexico border. White letters show the locations of several major geothermal fields in this area (B, Brawley; E, East Mesa; H, Heber; M, Mesquite; and S, Salton Sea). Other abbreviations include BFZ, Brawley fault zone; BRF, Buck Ridge fault; CCF, Coyote Creek fault; CF, Clark fault; EFZ, Extra fault zone; ERF, Elmore Ranch fault; EVF, Earthquake valley fault; IF, Imperial fault; LSF, Laguna Mesa; H, Heber; M, Mesquite; and S, Salton Sea). Other abbreviations include BFZ, Brawley fault zone; BRF, Buck Ridge fault; CCF, Coyote Creek fault; CF, Clark fault; EFZ, Extra fault zone; ERF, Elmore Ranch fault; EVF, Earthquake valley fault; IF, Imperial fault; LSF, Laguna Mesa; H, Heber; M, Mesquite; and S, Salton Sea). (b) Seismic stations (solid triangles) and events (open circles) used in the 3D tomographic inversions. The inversion grid nodes (orange squares) are rotated 45\textdegree \ counterclockwise with respect to latitude and longitude, with the \( x \) axis pointing to the southwest and \( y \) axis to the northwest. The origin is located at 33.1\textdegree, -116.0\textdegree \ (shown by the red star). Blue straight lines indicate profiles for the cross sections in Figures 5 and 6.
I ran a series of single-iteration inversions and chose the one giving the minimum data misfit as the best constant $Q_P$ value for the study area. As shown in Figure 3a, a $Q_P$ value of 450 gives the minimum root mean square (rms) of data misfit. For the range of $Q_P$ between 100 and 1000 shown in the figure, the rms varies from 0.103 to 0.0128 s. Next I use 450 as the starting $Q_P$ value to run another set of single-iteration series and use the layer-average values of the resulting model as the starting model for the next iteration. This process is repeated a few times until the layer-average attenuation values of the
inverted model are not significantly different from the input model and they fit the data equally well. This final 1D model is used as the starting model for the final 3D attenuation inversion shown in this paper. The rms of the $t^*_{p}$ residuals is reduced from 0.0128 to 0.0125 s during this process. Figure 3b shows examples of the above-described 1D models.

The optimal damping of 0.012 for $Q_p$ is selected to stabilize the inversion process by running a series of inversions with a large range of damping values and plotting the data variance versus model variance trade-off curves, similar to the approach applied to the velocity model inversion (Lin, 2013).

Final Attenuation Model Results

The tomographic inversion converges after five iterations. The rms of the $t^*_{p}$ residuals is reduced from 0.0125 to 0.0081 s after the inversion.

Model Resolution Test

To assess the model quality, I performed a checkerboard resolution test similar to those for the velocity model inversions (e.g., Lin et al., 2010; Lin, 2013). I computed synthetic $t^*$ values through the starting 1D model with ±20% $Q_p$ perturbations across two grid nodes and alternating at different depths. Event hypocenters, station locations, and synthetic $t^*$ values have the same distribution as the real data. I also applied the same inversion parameters, such as the damping parameter, as in the real data inversion. Figure S1 (available in the electronic supplement to this article) shows comparisons between the true and inverted $Q_p$ models. The $Q_p$ model is best resolved at 7 and 10 km depths as a result of the abundant seismicity in this depth range.

Map Views

Figure 4 shows the map view slices of the $Q_p$ model at different depths from 4 to 14 km below sea level. Because of the lack of shallow earthquake data in the uppermost part of the $Q_p$ model, the near-surface attenuation structure is not resolved well. At 4 km depth, the well-resolved regions in the southeast portion of the model are dominated by low $Q_p$ values (~100), which may be attributed to the sedimentary deposits in the trough, which have thickness ranges between 3.3 and 5.0 km (Fuis et al., 1982). However, these low values also seem to be correlated with the active fault zones, such as the Superstition Mountain fault, the Superstition Hills fault, the Brawley fault zone, and a buried fault in the southeast corner. Similar $Q_p$ values are observed in the SJFZ and the SAF in the northern portion of the study area. The lowest $Q_p$ values (~65–80) occur in the Salton Sea geothermal field on the southeast shore of the Salton Sea. Unfortunately, the $Q_p$ model at this layer depth is poorly resolved in other geothermal areas shown in Fuis et al. (1982), such as the Brawley, East Mesa, Heber, and Mesquite geothermal fields. A similar $Q_p$ pattern is observed at 7 km depth with greatly improved model resolution and weaker $Q_p$ contrast. The low $Q_p$ values correspond to the north-east-trending zones labeled as geothermal resource areas by Fuis et al. (1982). At 10 km depth, the most significant features are the greatly elevated $Q_p$ values in the northern portion of the study area, mainly between the Elsinore fault (EF) and the SJFZ and between the SJFZ and the SAF.
model is best resolved at this layer due to the abundant seismicity around this depth range. The $Q_p$ values within the mean sea level contour are generally lower than other areas with an exception under the center of the Salton Sea, where a high $Q_p$ body is resolved. At 14 km depth, the well-resolved $Q_p$ values within the mean sea level contour are still lower than the surrounding mountain ranges. Low $Q_p$ values are also observed near the buried Sand Hills fault and the Algodones fault in the southeast corner of the study area. The highest $Q_p$ values are observed in the area halfway between the EF and the SJFZ.

Cross Sections

The $Q_p$ variations with depth can be seen more clearly in cross sections through the model. In these cross sections, the fault zones are generally characterized by low $Q_p$ values at shallower depths. These low $Q_p$ values may reflect the presence of pore fluid, which is a more dominating attenuation mechanism in the upper crust (Winkler and Nur, 1979). In Figure 5, I show the $Q_p$ model along the profiles in the southwest–northeast direction, moving from the northwest to southeast. In the first cross section (1–1'), the lowest $Q_p$ values (~130) occur beneath the SJFZ and mostly overlie the seismicity. The second profile (2–2') cuts through the three faults in the SJFZ, including the Coyote Creek fault (CCF), the Clark fault (CF), and the Buck Ridge fault, along which the majority of the seismicity lies. The $Q_p$ contrast across the SAF is visible along this profile, with lower values on the northeast side and higher values on the other side above 5 km depth. Studies of the velocity structure in this area all show higher $V_p$ values on the northeast side of the SAF; these are attributed to the Orocopia schist compared to that of the Peninsular Ranges granitic rocks on the southwest side (e.g., Hauksson, 2000; Süss and Shaw, 2003; Lin et al., 2007, 2010; Tape et al., 2009; Allam and Ben-Zion, 2012; Fuis et al., 2012; Lin, 2013). The contrasting behavior of the velocity and attenuation across the fault clearly reflects different factors that dominate their variations. Velocity is more dependent on composition, whereas attenuation is more influenced by pore fluids (Winkler and Nur, 1979). The low $Q_p$ values on the northeast side of the SAF may be an indication of pore fluid in the hidden faults. Along profile 3–3', the seismicity is focused beneath and northeast of the EF and in the SJFZ, mainly near the CF. The high $Q_p$ body below the seismicity is clearly seen. The $Q_p$ model is poorly resolved near the SAF. In the next cross section further to the southeast (4–4'), the model is relatively uniform, and the seismicity is mainly focused within a low $Q_p$ body near the Salton Sea geothermal field. In the last two cross sections, the seismicity concentrates near the Laguna Salada fault at the United States–Mexico border. The fault zones are again dominated by low $Q_p$ values above 5 km depth, including the Superstition Mountain fault, the Superstition Hills fault, and the Imperial fault, indicating the existence of pore fluid.

Figure 5. Cross sections through the $Q_p$ model along the southwest–northeast profiles, including the relocated seismicity (black dots) from Lin (2013) within ±3 km distance of the profile line. The white contours enclose the regions with resolution above 0.1. Zero depth corresponds to mean sea level. The black curve at the top of each cross section shows the local topography, and small triangles mark the surface traces of the faults (black), the Salton Sea boundary (pink), and the United States–Mexico border (blue). Abbreviations are EF, Elsinore fault; SJFZ, San Jacinto fault zone; SAF, San Andreas fault; CCF, Coyote Creek fault; CF, Clark fault; BRF, Buck Ridge fault; Border, United States–Mexico Border; SMF, Superstition Mountain fault; SHF, Superstition Hills fault; and IF, Imperial fault.

Figure 6 shows cross sections of the $Q_p$ model along six profiles in the northwest–southeast direction parallel to the SAF, sliding from the southwest to the northeast side. Profile A–A' is subparallel to the EF. The $Q_p$ structure in this section does not show as strong variations as in other sections. Profile B–B' is between the EF and the SJFZ. The majority of the seismicity is near the United States–Mexico border. The highest $Q_p$ in the study area is observed at 10 km depth along this section. The $Q_p$ model shows complex structure in cross section C–C' along the SJFZ. The seismic activity mainly coincides with the high $Q_p$ values at 10 km depth. The $Q_p$ structure along D–D' is relatively uniform except for the very low values at shallow depths. Along profile E–E' through the center of the Salton Sea, the most significant features are the high $Q_p$ body at 10 km depth beneath the Salton Sea and the low $Q_p$ values above 5 km depth near the Salton...
Sea geothermal field. Because of the stratigraphic monotony in the Salton trough, it is believed that the geologic framework beneath the Salton Sea is similar to that beneath its southeastern onshore near the Salton Sea geothermal field (Hulen et al., 2002). Fuis et al. (1982) and Fuis and Kohler (1984) used data from an extensive seismic refraction survey to show that sedimentary rocks in the Salton trough can be as thick as 12 km with metamorphosed material below 5 km depth, which exhibits similar properties to crystalline basement. The high $Q_P$ along 10 km depth beneath the Salton Sea may represent these metamorphosed material. The near-surface $Q_P$ values are very low in the southeast resolved parts of the last cross section (F–F') that is near the SAF.

Discussion and Conclusions

Generally, the $Q_P$ values in this study increase with depth, and the range of variations is similar to the regional-scale studies (e.g., Hauksson and Shearer, 2006). Ho-Liu et al. (1988) used S-to-P-wave amplitude ratios to invert for seismic attenuation variations in the Imperial Valley, California, but a $Q_P$ model was not available. Previous regional studies only observed weak attenuation variations in the Salton trough due to the large grid spacing used in their inversions (Schlotterbeck and Abers, 2001; Hauksson and Shearer, 2006). In this study, predominantly low $Q_P$ values are observed in the vicinity of the Imperial Valley, which may be attributed to the sedimentary deposits but also correlated with the active fault zones. The mountain ranges in the northwest portion of the study area show greatly elevated $Q_P$ values. The model also shows great variations even where the velocity structure is relatively uniform, especially at 10 km depth, which may be due to fluid content and can be more clearly seen in the model cross sections. In the active fault zones, low $Q_P$ values are generally observed at shallow depths, which may be caused by the presence of pore fluids near the surface. In the middle crust near the CCF, high $Q_P$ values are coincident with seismic activity, suggesting highly competent rocks that are able to sustain great stress before earthquake rupture, similar to the attenuation study in the aftershock region of the 1989 Loma Prieta earthquake (Lees and Lindley, 1994).

Figure 6. Cross sections through the $Q_P$ model along the northwest–southeast profiles, including the relocated seismicity (black dots) from Lin (2013) within ±3 km distance of the profile line. The white contours enclose the regions with resolution above 0.1. Abbreviations are the same as in Figure 5.
In Figure S2, I show the \( Q_P \) values inverted in this study versus the \( P \)-wave velocities of Lin (2013) at the well-resolved \( Q_P \) inversion nodes. A general increase of \( Q_P \) with \( V_P \) is observed. At shallow depths (i.e., between 0 and 4 km depths), \( Q_P \) slowly increases from 20 to 500 with \( V_P \) ranging between 3 and 6 km/s. However, in the next two layers (7 and 10 km depths), the \( Q_P \) values show great variation, ranging from 200 to 1400, whereas \( V_P \) remains near 6.2 km/s. Values in the deeper layers (\( \geq 14 \) km depth) do not show \( Q_P \) values greater than 800, probably due to the limited resolution at these depths. A linear relationship between \( Q \) and velocity is usually expected for the near surface (Olsen et al., 2003; Brocher, 2005). However, our model is not resolved well within the depth range of interest in these previous studies.

Seismic attenuation not only depends on lithology and fluid content, but also on the temperature of rocks, which is roughly proportional to the heat flow. Hence, a spatial correlation between heat flow and attenuation is usually expected. In Figure S3, I compare the well-resolved \( Q_P \) model at 0 km depth with the heat-flow data at borehole locations in the study area (obtained from the U.S. Geological Survey, see Data and Resources). Although the \( Q_P \) values at shallow depth do not show point-by-point correlation with the heat-flow data, a general increase of well-resolved \( Q_P \) with reduced heat flow is observed. The best correlation occurs near the Salton Sea geothermal field, where high heat flow is prominent with the corresponding low \( Q_P \) values.

In summary, a frequency-independent 3D \( Q_P \) model is developed for the Salton trough and the adjacent San Jacinto fault zone. The new \( Q_P \) model in this study provides a first-order measurement of the attenuation in the study area and serves as an important complement to the 3D velocity model about rock properties and structure heterogeneity. It can also be used as a starting point for future frequency-dependent attenuation studies.

Data and Resources

Catalog picks and waveform data were obtained from the Southern California Earthquake Data Center and originate principally from the Southern California Seismic Network. The heat-flow data at borehole locations in the study area are obtained from the U.S. Geological Survey. The previous velocity model, location catalog, and multitaper library used in this study were collected from published studies listed in the references. Figures were made using Generic Mapping Tool software (Wessel and Smith, 1991) and MATLAB (www.mathworks.com/products/matlab).

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Department of Marine Geosciences
Rosenstiel School of Marine and Atmospheric Science
University of Miami
Miami, Florida 33149

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