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A Summary of Attenuation Measurements from Borehole Recordings of Earthquakes: The 10 Hz Transition Problem

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Abstract—Earthquake seismograms recorded by instruments in deep boreholes have low levels of background noise and wide signal bandwidth. They have been used to extend our knowledge of crustal attenuation both in the near-surface and at seismogenic depths. Site effects are of major importance to seismic hazard estimation, and the comparison of surface, shallow and deep recordings allows direct determination of the attenuation in the near-surface. All studies to date have found that Q is very low in the near-surface (~ 10 in the upper 100 m), and increases rapidly with depth. Unlike site amplification, attenuation at shallow depths exhibits little dependence on rock-type. These observations are consistent with the opening of fractures under decreasing lithostatic pressure being the principal cause of the severe near-surface attenuation. Seismograms recorded in deep boreholes are relatively unaffected by near-surface effects, and thus can be used to measure crustal attenuation to higher frequencies (≥ 100 Hz) than surface recordings. Studies using both direct and coda waves recorded at over 2 km depth find Q to be high (~ 1000) at seismogenic depths in California, increasing only weakly with frequency between 10 and 100 Hz. Intrinsic attenuation appears to be the dominant mechanism. These observations contrast with those of the rapidly increasing Q with frequency determined from surface studies in the frequency range 1 to 10 Hz. Further work is necessary to constrain the factors responsible for this apparent change in the frequency dependence of Q, but it is clearly unwise to extrapolate Q estimates made below about 10 Hz to higher frequencies.

Key words: Crustal attenuation, site-effects, high frequency, earthquakes, borehole seismology.

Introduction

Seismic waves which propagate through the earth are attenuated both by scattering and anelastic processes. Seismometers therefore record only a depleted amount of the high frequency energy radiated from earthquakes and other seismic sources. Seismograms recorded at the earth's surface are also contaminated by seismic noise, both environmental and man-made. The combined effects of seismic

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noise and attenuation limit the frequency range of the observed signal to below a few tens of Hz at most surface sites. Consequently, the frequency range over which attenuation can be measured is also limited. This makes it difficult to link observations of attenuation in the earth with the much smaller scale (and hence higher frequency) laboratory studies of attenuation mechanisms. Additionally, investigation of the behaviour of Q with frequency requires measurements over a wide frequency range. Measurements of Q above a few tens of Hz would extend the bandwidth of data and hence provide further insight of the principal mechanisms responsible for attenuation within the crust. In addition, wider bandwidth seismograms are essential to resolve fundamental questions regarding the nature of earthquake sources. Over the last decade there has been considerable controversy concerning the scaling of earthquake source parameters, resulting from the inherent ambiguity in extracting source and attenuation parameters from surface seismograms. For example, ARCHULETA *et al.* (1982) proposed that earthquake self-similarity breaks down below about $M_L 3$, at a scale length of a few hundred metres. ANDERSON (1986), however, argued that this could be entirely an artifact of crustal attenuation, and it was difficult to see how such fundamental questions concerning the nature of earthquake sources could be answered with surface data.

The large distances at which seismic energy above 1 Hz is recorded are evidence that attenuation within the seismogenic and deeper crust is too low to be responsible for the effects observed by ARCHULETA *et al.* (1982) and many subsequent earthquake source studies. Deployments of closely spaced seismometers, however, have shown extensive variation in recorded amplitude, frequency content and coda duration over short distances, suggesting that the near-surface, near-receiver, rock has a strong effect on earthquake recordings. The site effect, as it has become known, includes amplification in the relatively low velocity, low density near-surface rocks, scattering and resonance within the shallow layers, and attenuation of higher frequency energy. Site effects are important, not just in investigating the nature of earthquakes sources, but also because they play a major role in the distribution of damage in large earthquakes (BORCHERDT *et al.*, 1970; CELEBI *et al.*, 1987). Strong site effects have been shown to amplify and prolong the ground shaking significantly, and consequently now form a major component of seismic hazard analyses.

Installing seismometers in even shallow boreholes decreases the level of background noise considerably, hence improving the quality of the recorded signal. The indications that significant attenuation and distortion of seismic waves are occurring at relatively shallow depths have led to the deployment of seismometers in deeper holes. The principal goals of such deployments have been to learn more about the propagation of seismic waves through the near-surface, and to record seismograms, uncontaminated by site-effects, for high resolution study of earthquake sources and the properties of the seismogenic crust. Throughout the last decade, many instruments have been deployed at depths of a few metres to a few tens of metres. Instruments at depths of a few hundred metres are also becoming more common, for example, the High Resolution Seismic Network (HRSN) at Parkfield, California (MALIN *et al.*, 1989). The deepest instruments to date have been at depths of a few kilometres, and include the Varian well, Parkfield (operational to 1 km, e.g., JONGMANS and MALIN, 1995), Cajon Pass (to 2.9 km, ABERCROMBIE and LEARY, 1993), Long Valley (2 km, P. V. KASSEMEYER, personal communication, 1995) and the Kanto District, Japan (to 3.5 km, KINOSHITA, 1994). A high frequency sensor at 4 km recorded drilling induced events in the KTB hole, Germany (ZOBACK and HARJES, 1997), and more long-term installations are planned there. Deploying and operating borehole seismometers becomes more difficult with increasing depth, partly because the instrument is simply far-removed, and drilling and installation costs increase. More importantly, temperature increases with depth, restricting the sensor types which can be used, and the duration of recording; high temperatures are probably the principal limiting factor on the depth of installation. At 2.9 km at Cajon Pass the temperature is 120°C, similar to that at 4 km depth at KTB where the heat flow is lower. MANOV *et al.* (1996) provide a good overview of the logistics and constraints of deep borehole recording.

In this paper I review representative studies which use borehole recordings of earthquakes, and show how they have contributed to our knowledge of attenuation. First I consider attenuation in the near-surface, as determined by comparison between seismograms recorded at borehole and surface sensors. Secondly I describe recent measurements of crustal Q and its frequency dependence in the approximate frequency range 10–100 Hz.

Attenuation in the Near-surface

The effect on seismic waves of propagating through the near-surface rocks can be obtained by simply comparing earthquake recordings made at a surface seismometer with those from a borehole seismometer directly beneath it. In such studies the thickness of the "near-surface" is defined as the depth of the deepest seismometer. It has become relatively common practice to calculate spectral ratios between recordings at different depths and to use these ratios to estimate Q and amplification effects in the near-surface. This approach uses the same techniques and assumptions as surface studies of site effects, which compare various sites of interest to a hard rock reference site. Borehole recording is advantageous in that the reference site is a better approximation of the waveform entering the near-surface rocks at the site of interest than is a neighboring hard rock site. When using borehole recordings in spectral ratios, however, you have to take into account the fact that they include reflections from the surface and shallow layers. These surface reflections are usually very small in amplitude, especially at deep sensors (e.g., Abercrombie, 1997), indicating high attenuation near the surface. These reflections can either be avoided by the careful choice of window lengths (e.g., Abercrombie, 1997) or corrected for using simple reflectivity codes (e.g., Steidl, 1996).

Typical values of both *P* wave and *S* wave total Q (Q_P and Q_S, respectively) in the upper 100 m are very low, around 10 in the frequency range of a few Hz to a few tens of Hz. They also appear to be almost independent of rock type. Abercrombie (1997) compares the results of a study at Cajon Pass, southern California, with a number of other Californian studies (Abercrombie, 1997, Table 4) including those of Hauksson *et al.* (1987) in the Los Angeles Basin, Malin *et al.* (1988) at Oroville, Aster and Shearer (1991) at Anza, Blakeslee and Malin (1991) and Jongmans and Malin (1995) at Parkfield, Archuleta *et al.* (1992) at Garner Valley, and Gibbs *et al.* (1994) in the Santa Clara Valley. These experiments encompass a wide range of rock types, but find relatively small differences in Q values in the upper few hundred metres. In the upper 500 m typical Q values are $Q_P \leq 50$ and $Q_S \leq 30$.

At depths of less than 500 m differences in rock type produce considerably more variation in site amplification than in Q. For example, Abercrombie (1997) compares local earthquake recordings made at 2.9 km depth in the Cajon Pass borehole, at the wellhead, and at a surface granite site only 1 km away. The principal difference between the two surface sites is that the upper 500 m at the wellhead site are Miocene sandstone and at the granite site, granitic rocks. Abercrombie finds $Q_P \sim 50$ and $Q_S \sim 23$ in the upper 2.9 km at the granite site which are essentially within the errors of the values obtained at the wellhead (see Fig. 1). The site amplification, however, is approximately three times higher at the wellhead than at the granite site.

Studies involving recordings made at a range of depths show that Q increases rapidly with depth, although some low Q zones are observed, for example, in the Oroville fault zone (Malin *et al.*, 1988). A comparison of the attenuation profile at the Cajon Pass drillhole (Abercrombie, 1997) and the Varian Well (Jongmans and Malin, 1996; Abercrombie, unpublished data) is shown in Figure 1. Both studies show low Q near the surface, increasing with depth. Despite the difference in rock types between the two sites, the Q profiles are essentially the same, within errors, to about 1 km. At greater depths, the thicker sediments and lower velocity Franciscan rocks to the NE of the San Andreas fault at Parkfield appear to have lower Q than the Mesozoic granite at similar depths at Cajon Pass.

All the studies considered to date in this review assume that near-surface Q is frequency independent. If this is the case, then the spectral ratios between different recordings depths will have linear slopes on a log-linear plot. Figure 2 displays some average spectral ratios between the wellhead and 2.5 km depth at Cajon Pass (Abercrombie, 1997). They are well modelled by a straight line, indicating that near-surface Q is either frequency independent, or at least only very weakly dependent on frequency, in the frequency range of ~ 2 to 100 Hz. This result is in good agreement with that of many other studies which use both earthquakes (e.g., BLAKESLEE and MALIN, 1991) and artificial sources (e.g., GIBBS *et al.*, 1994). The assumption of frequency independent Q in the near-surface thus appears to be a sound one.

The reliability of a Q estimate made using the spectral ratio technique depends on the frequency range available for measuring the gradient of the spectral ratio

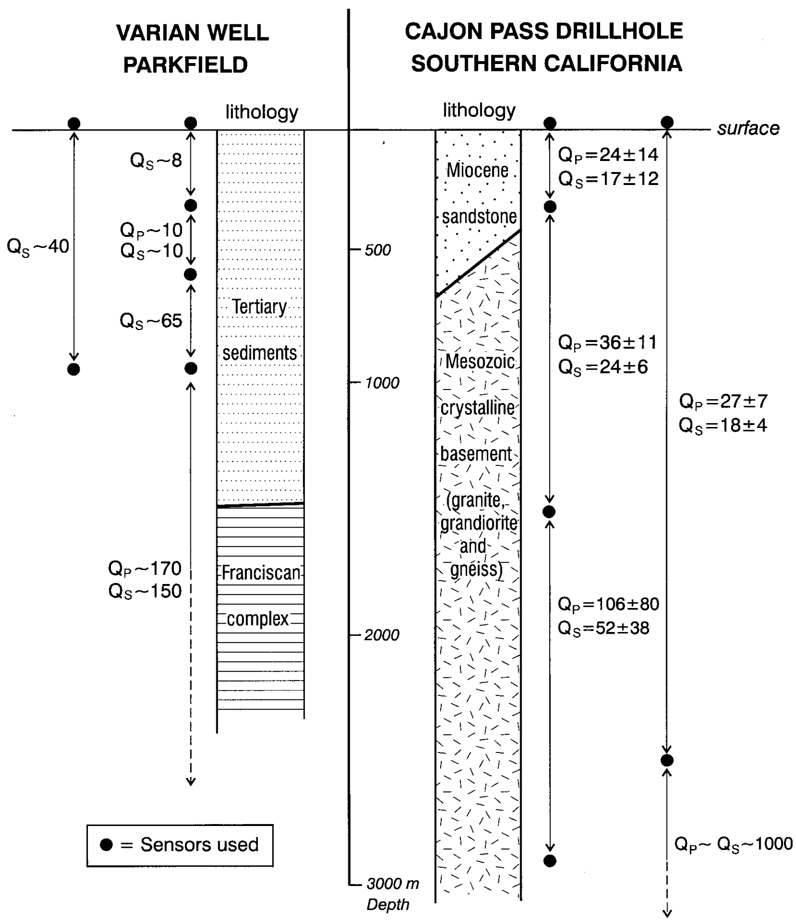

Figure 1
A comparison of the attenuation profiles with depth at the Cajon Pass scientific drillhole, southern California, and the Varian well, Parkfield, California. The Q values at Cajon Pass are estimated by ABERCROMBIE (1995, 1997) in the approximate frequency ranges 2–100 Hz (P waves) and 2–20 Hz (S waves), and errors of one standard deviation are shown (see Fig. 2). The Q values at Varian are from JONGMANS and MALIN (1996) and ABERCROMBIE (unpublished data). Both sites show very low Q near the surface, increasing with depth.

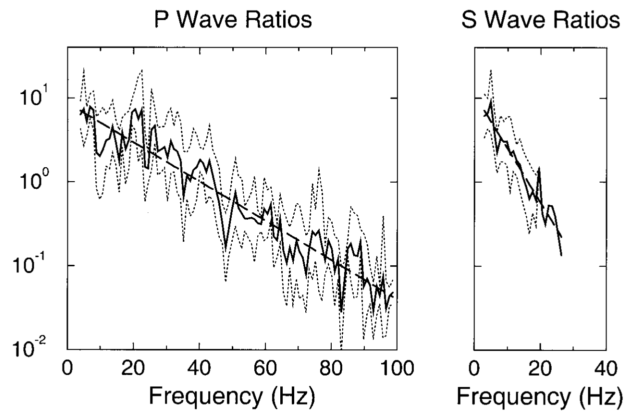

Figure 2
The mean spectral ratios (0/2.5 km) of 6 local earthquakes recorded at Cajon Pass (ABERCROMBIE, 1997). The dotted lines are 1 standard deviation and the dashed lines are the best fits, assuming Q is frequency independent ($Q_P = 27 \pm 7$, $Q_S = 18 \pm 4$). On the log-linear plots the slopes are well modelled by a straight line, implying that the assumption of frequency independent Q is reliable. Both plots are at the same scale.

(Fig. 2), and on the attenuation experienced by the waves travelling between the two sensors. Increasing the frequency range decreases the susceptibility of the gradient measurements to noise and resonance effects, and hence improves its reliability. The attenuation is directly dependent both on Q and also on the distance travelled between the two sensors. Even when the Q is very low, it is hard to constrain values over small depth ranges (say < 100 m) because the total attenuation, and hence the slope of the spectral ratio, is very small. For example, compare the errors estimated over the depth ranges 0–300 m and 0–2.5 km at Cajon Pass (Fig. 1). At frequencies less than about 10 Hz, amplification and resonance effects can be large, which makes it hard to measure Q by the spectral ratio technique. At higher frequencies and over extensive depth ranges, however, the severe near-surface attenuation becomes the dominant factor and the spectral ratio method for measuring Q works well.

The borehole studies confirm that attenuation is severe in the near-surface, distorting earthquake recordings and limiting the signal bandwidth. Comparison of surface and downhole (2.5 km) recordings at Cajon Pass by ABERCROMBIE and LEARY (1993) shows clearly the effect of near-surface attenuation on measurements of earthquake source parameters. ABERCROMBIE (1995) extends this work to over 100 earthquakes and confirms that near-surface attenuation is sufficient to account for the possible breakdown in earthquake scaling below about $M_L 3$. The undistorted, high frequency seismograms recorded at 2.5 km demonstrate that earthquake self-similarly continues to at least $M_L 0$ and source sizes of less than 10 m radius. ABERCROMBIE (1996) shows that the magnitude-frequency relationship also continues unchanged to $M_L 0$, using the small earthquakes undetected by the regional network but recorded downhole because of the low attenuation and low background noise level.

A pertinent question to earthquake source studies is "How deep must you go to remove the site effect?" As discussed in the next section, it is possible to estimate the attenuation beneath the borehole sensors, and the relevant values for the Cajon Pass and Varian Wells are included in Figure 1. ABERCROMBIE (1997) calculates that for an earthquake recorded at the Cajon Pass wellhead, with a hypocentral distance reaching 15 km, over 90% of the attenuation would occur in the upper 3 km, 80% in the upper 1.5 km, and 50% in the upper 300 m (at frequencies of a few Hz and above). The deepest instruments, over 2 km beneath the top of the granitic bedrock, are essentially beneath the site effect. However, attenuation along the relatively high Q paths to the deep instruments can still significantly affect the frequency content recorded from more distant earthquakes. Also, it cannot be ignored in very high resolution analyses which use the highest frequencies recorded, for example estimating the radiated seismic energy. At Parkfield, at least on the north-east side of the San Andreas fault, the situation is very different. Using the Q values in Figure 1, we can estimate in a similar manner, that for earthquakes at 15 km hypocentral distance from the Varian Wellhead, less than 50% of the attenuation occurs in the upper 1 km. Thus, a significant amount of attenuation occurs beneath 1 km, suggesting that at this site, the "site effect" extends to greater depth. It is interesting to compare average Q values beneath the deepest Varian sensors with those estimated beneath the stations of the HRSN, at around 200 m depth. In terms of attenuation at least, it appears that the propagation path to a sensor at 1 km depth on the northeast side of the San Andreas fault is comparable, if not lower Q, than that to a sensor at only 200 m on the SW side of the fault where the bedrock is Salinian granite (crustal attenuation and site effects at Parkfield, California, R. E. ABERCROMBIE, in preparation, 1998). It cannot, therefore, be assumed that just because a seismometer is down a borehole, all site and attenuation effects can be ignored.

To date, borehole recordings of tectonic earthquakes have been limited to frequencies below a few hundred Hz, but observations of man-made events, such as those induced by mining and drilling, have been made at higher frequencies. For example, FEUSTEL *et al.* (1996) recorded microseismicity produced during excavations at Strathcoma Mine (Canada) at 400 to 1600 Hz. The hypocentral distances were in the range 40–120 m, and both sources and sensors were at about 600 m depth in granitic bedrock. They use the multiple lapse time method (HOSHIBA, 1993) to estimate the intrinsic and scattering coefficients of S wave attenuation and their frequency dependence. They find $Q_S \sim 110$ (800 Hz) at this depth, and that intrinsic attenuation is approximately four times higher than scattering attenuation. The Q_S values are very similar to those obtained in the previously mentioned Californian studies at this depth. Both intrinsic and scattering Q exhibit a stronger dependence on frequency, increasing over the range 400–1600 Hz, than was observed in the earthquake studies. FEUSTEL *et al.* (1996) attribute this to local structural effects at a scale of a few metres. This very high frequency Q variation is therefore likely to be strongly site dependent.

The lack of a strong correlation between near-surface attenuation and rock type suggests that some other factor is principally responsible for the rapidly increasing attenuation towards the earth's surface. Laboratory studies of attenuation find that both Q_P and Q_S increase rapidly with increasing pressure up to about 1000 bars ($\sim$4 km) and then level off (JOHNSTON *et al.*, 1979). This pressure dependence of attenuation has been interpreted as resulting from the closure of cracks in the rocks with increasing confining pressure. Measurements of fracture densities in outcrops and cores, and from shear-wave splitting in the upper 500 m are about an order of magnitude larger than those made at greater depth (e.g., RENSHAW, 1997). JOHNSTON *et al.* (1979) find that at the pressures typical of the upper few kilometres, friction at cracks is the most probable dominant mechanism of intrinsic attenuation. As fractures are also major scatterers of seismic energy, scattering attenuation should also decrease with increasing depth as the fractures are closed. MORI and FRANKEL (1991) observed a significant decrease in scattering attenuation below about 5 km depth in southern California, consistent with this hypothesis. Additional support for the hypothesis that fractures are responsible for the high near-surface attenuation comes from a study of mining induced events recorded at 2 to 3 km depth in South Africa. SPOTTISWOODE (1993) found that along ray paths through solid rock Q is about 1000, similar to the values determined at similar depths at Cajon Pass. If the ray path was through a highly fractured region near the stope faces, however, then Q decreased to about 20, clearly demonstrating the importance of fractures in the attenuation of seismic waves at shallow depths. At greater depths, where fewer fractures remain open, then other attenuation mechanisms (perhaps with different frequency relationships) may be dominant.

Attenuation above 10 Hz at Seismogenic Depths

Earthquake seismograms recorded at a few hundred metres to a few kilometres beneath the earth's surface typically have a wider signal bandwidth, extending to higher frequencies than is possible with surface recorded data. Downhole seismograms thus can be used to measure crustal Q at frequencies of up to a few hundred Hz. Similar methods to those used at the surface, are used to estimate Q from downhole sensors, with the advantage that no assumptions need be made to remove strong site effects (including amplification) with poorly constrained frequency dependence. One such method is to assume that the source spectra have an ω^{-2} fall-off at high frequencies (e.g., BRUNE, 1970) and that attenuation is exponential, with Q independent of frequency (e.g., ANDERSON, 1986). ABERCROM-

BIE (1995) uses this method to analyse direct waves from over 100 earthquakes recorded at 2.5 km depth in the Cajon Pass drillhole, California, and obtains $Q_S \sim Q_P \sim 1000$ in the frequency range approximately 2 to 200 Hz. The earthquakes spanned hypocentral depths in the range 5 to 20 km, and distances of 5 to 120 km, suggesting that these Q values are averages within the seismogenic crust, at depths greater than 2.5 km. The close earthquakes (distance ≤ 20 km) have experienced negligible attenuation, however the spectra from the more distant events exhibit the exponential fall-off predicted by the frequency independent Q model used, over two decades of frequency bandwidth (ABERCROMBIE, 1995).

Studies of earthquakes also recorded at Cajon Pass, using direct and coda waves, have been performed to investigate the frequency dependence of Q_S at high frequencies in more detail. LEARY and ABERCROMBIE (1994) use seven earthquakes recorded at 2.5 km depth, and a single scattering approximation to estimate Q_S between 10 and 100 Hz. They find a weak increase in Q_S with frequency (from ~ 500 at 10 Hz to ~ 1200 at 100 Hz), and that intrinsic attenuation is the dominant mechanism; $Q_{\mathrm{Scatter}} > 10 Q_{\mathrm{intrinsic}}$ at all observed frequencies. ADAMS and ABERCROMBIE (1998) perform a more comprehensive analysis using over 100 earthquakes recorded at a range of depths in the Cajon Pass drillhole. They employ the multiple lapse time method (HOSHIBA *et al.*, 1991) to determine the intrinsic and scattering contributions to Q_S and their frequency dependence. They confirm the weak frequency dependence of Q_S at high frequency ($Q_S \sim 800$ at 10 Hz increasing to ~ 1500 at 100 Hz), indicating that the assumption of frequency-independent Q_S made by ABERCROMBIE (1995) was reasonable. The absolute values of Q_S between these three studies at Cajon Pass also show good agreement (Fig. 3). ADAMS and ABERCROMBIE (1980) also find intrinsic attenuation to be the dominant mechanism. They estimate it to be approximately twice the level of scattering attenuation at seismogenic depths.

The weak frequency dependence of Q_S observed above about 10 Hz is not a simple extrapolation of the trend observed between 1 and 10 Hz (see Fig. 3). A number of studies using coda and Lg waves (e.g., JIN *et al.*, 1994; BENZ *et al.*, 1997) find Q_S to increase rapidly from about 30 at 1 Hz to a few hundred at 10 Hz in active tectonic areas such as the western U.S.A. HOUGH *et al.* (1988) use seismograms recorded on the granite batholith at Anza (California) and estimate Q from direct P and S waves. They also find that Q is essentially frequency independent from 30–70 Hz (~ 700), but lower at 10 Hz (~ 400). KINOSHITA (1994) makes use of deep borehole earthquake recordings to measure Q_S in the southern Kanto area of Japan. His results, in the frequency range 0.5 to 16 Hz, are similar to the measurements of Q_S made in California, showing an increase to about 5 Hz, and then a levelling off at higher frequencies (Fig. 3).

It is interesting to speculate on the possible causes of this change in the frequency dependence of Q at 5–10 Hz. It could result from changes in the nature of the crust at scale lengths of a few hundred metres, or alternatively, could simply be an artifact of incorrect assumptions in the models used to estimate Q. The models assume either body or surface waves, and isotropic attenuation which does not vary laterally or with depth. These assumptions are perhaps more justified for the high frequency borehole data than for the lower frequency surface recordings. Several recent studies find the coda of surface seismograms to be dominated by energy scattered near the receiver (DODGE and BEROZA, 1997) and by slow surface waves (MEREMONTE *et al.*, 1996). It is therefore possible that the frequency behaviour of Q shown in Figure 3 is an artifact of a frequency dependence to the appropriateness of the model assumptions. Alternatively the observed variation in the frequency dependence of Q_S could be providing us with information relative to the nature of the earth's crust at different scales. AKI (1980) noted that the absolute value and frequency dependence of coda Q (0.02–25 Hz) was dependent on the level of current tectonic activity. The frequency dependence shown in Figure 3 is

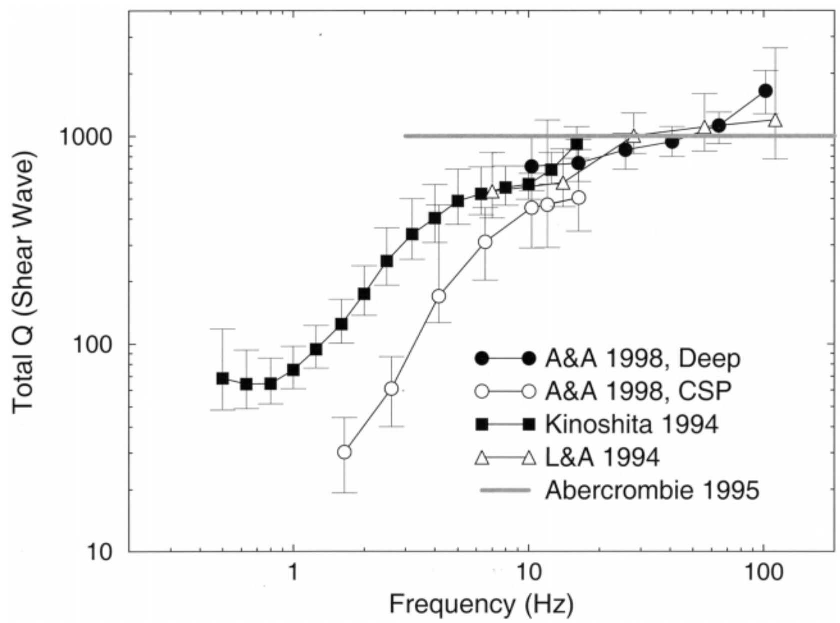

Figure 3
The frequency dependence of Q_S between 1 and 100 Hz. Various studies find Q to increase from approximately 1 to about 10 Hz. The results of KINOSHITA (1994) from the Kanto district, Japan, and ADAMS and ABERCROMBIE (1998) from a surface site in California (A & A, 1998, CSP) are plotted as examples. Above 10 Hz, however, recent borehole studies at Cajon Pass by ADAMS and ABERCROMBIE (1998) and LEARY and ABERCROMBIE (1994), labelled A & A, 1998 deep and L & A, 1994, respectively, have found only a small increase in Q with frequency. The estimate of Q, assuming frequency independence obtained from spectral fitting of direct waves travelling to the 2.5 km sensor at Cajon Pass by ABERCROMBIE (1995) is included for comparison.

also only observed in active tectonic regimes. In more stable, cratonic areas, FRANKEL and CLAYTON (1986) and BENZ *et al.* (1997) find Q_S to be higher and to show only a slight increase with frequency between 1 and 10 Hz. I am, unfortunately, not aware of any borehole studies of Q_S at seismogenic depths in the frequency range 10 to 100 Hz in stable cratonic areas. SPOTTISWOODE (1993), however, reports $Q \sim 1000$ in solid rock at a few kilometres depth around South African gold mines. The cause of the change in frequency behaviour of Q_S at 5–10 Hz must therefore be restricted to active crust. A thinner, warmer crust, and the presence of large crustal faults, characterized by low velocity zones (e.g., EBERHART-PHILLIPS *et al.*, 1995; LI *et al.*, 1994), are possible candidates.

Summary

This review demonstrates how deep borehole recordings of earthquakes have extended our knowledge of crustal attenuation both in the near-surface, and at seismogenic depths.

Q is very low in the near-surface (~ 10 in the upper 100 m), and increases rapidly with depth to a few kilometres. Unlike site amplification, near-surface attenuation appears to be almost independent of rock type. These two observations combine to suggest that the primary cause of severe near-surface attenuation is the opening of fractures with decreasing lithostatic pressure. The observed levels of near-surface attenuation are easily adequate to provide for the proposed breakdown in earthquake scaling at small magnitudes. The low correlation of this attenuation with rock type implies that it cannot be considered negligible in source studies even at hard rock sites.

Measurements of Q_S at seismogenic depths using direct and coda waves are high (~ 1000) and show only a weak increase with frequency between 10 and 100 Hz. Intrinsic attenuation appears to be the dominant mechanism; estimates of scattering Q are at least twice the value of intrinsic Q. Combining these results with those from surface studies at lower frequencies reveals a significant change in the frequency dependence of Q_S at about 10 Hz in active tectonic regions. Further work is required to determine the factors responsible for this apparent change in Q_S behaviour, but it is clearly unwise to extrapolate Q estimates made below 10 Hz to higher frequency data.

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