Lunar Rock Q in 3000-5000 Range Achieved in Laboratory

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Lunar rock Q in 3000–5000 range achieved in laboratory

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Q measurements carried out by the vibrating bar technique on lunar sample 70215,85 have yielded Q values as high as 4800 at room temperature. The strong outgassing procedures necessary to raise the Q to these high values from $Q \approx 60$ (when received) and studies of the effect on Q by a variety of different gases shows that the removal of thin layers of adsorbed H_2O are responsible for the dramatic increase in Q. Experiments carried out with a low frequency apparatus on a terrestrial analogue at 50 Hz suggest similar increases in Q with outgassing, thus providing evidence that dramatic effects on Q can be expected to occur down to seismic frequencies. These results, in part, explain the contrast between seismic data in the lunar and terrestrial crust in terms of the absence and presence respectively of adsorbed H_2O.

Introduction

We have recently reported the discovery that trace amounts of absorbed volatiles can have a profound effect on the Q of rocks and other porous media (Tittmann *et al.* 1974). We have obtained Q values in excess of 2000 in a strongly outgassed analog of a lunar basalt (whose Q was about 75 in ordinary laboratory atmosphere).

This result would appear to have direct bearing on the interpretation of lunar seismic data. Since Latham *et al.* (1970) had indicated that the *in situ* seismic Q of near surface lunar rocks is in the range of 3000–5000, many people, for example Pandit & Tozer (1970), have suggested that the Q of rocks really free of volatiles measured in the laboratory should be similar. Our recent observations of dramatic increases in Q with outgassing in terrestrial analogs of lunar basalt (Tittmann *et al.* 1974) support these suppositions.

Several important questions must be answered before the full significance of these results can be realized. Can these effects be reproduced in lunar rocks? Does the Q continue to rise, as the gas pressure is lowered into the ultra-high vacuum range? Does the dramatic increase in Q with outgassing observed at kHz frequencies also take place at seismic frequencies? What is the effect of Q on exposing a thoroughly outgassed rock to a variety of geologically important gases? How is the Q affected by a confining pressure both before and after outgassing? What is the effect on the Q of going to high temperatures? More generally, how and why do volatiles affect the mechanical Q and what mechanisms are operative to give rise to the dramatic attenuation?

One motivation for these studies is the strong possibility that once the absorption mechanism is understood and described by a physical model, the high Q values for lunar crustal material determined from the seismic data can be used to place strong constraints on the exposure of subsurface lunar rocks to volatiles such as H_2O. Such studies should also be invaluable in future examinations of other planets whenever seismic experiments are planned as part of the exploration.

Q MEASUREMENTS IN LUNAR ROCK 70215,85 WITH ULTRA-HIGH VACUUM APPARATUS

In order to extend the work on the terrestrial analogue and to provide an even better and cleaner vacuum for the lunar rock, a special ultra-high vacuum apparatus has been constructed. Instead of a glass bell jar, diffusion pump, and mechanical force pump, this system is all stainless steel and employs a Vac-Ion pump and molecular sieve sorption pump so that any back streaming of oil vapour is eliminated. The system allows for the attachment of a residual gas analyser to obtain quantitative information on the gases in the sample chamber. With this system, pressures have been achieved as low as 5×10^{-10} Torr (7×10^{-8} Pa) at room temperature and 10^{-11} Torr (1.3×10^{-9} Pa) with immersion of the system into liquid N_2. The Q measurement technique carried out with this system is patterned after Wegel & Walther (1935).

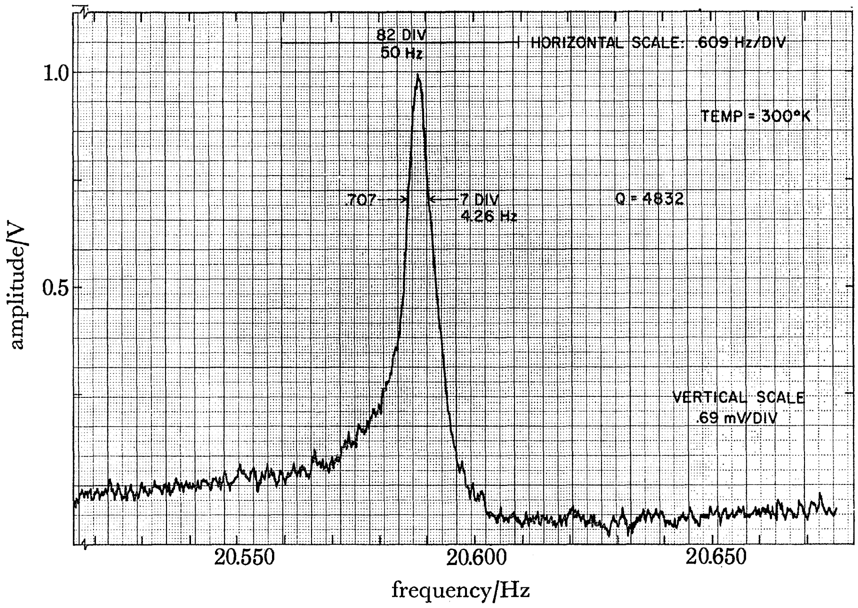

FIGURE 1. Sample data sheet on strongly outgassed lunar sample 70215,85. Chart recording of bar resonance in compressional mode.

Lunar sample 70215,85 ($0.4 \times 0.6 \times 8.5$ cm^3), a fine-grained subvariolitic basalt with microphenocrysts of ilmenite, olivine, and clinopyroxene, when received, gave a $Q \approx 60$ at about 20 kHz in laboratory air. Following of the outgassing procedures developed previously with the terrestrial analogues of lunar basalt gave successively higher and higher Q values. Thus lunar rock Q values above 3000 were achieved readily (Tittmann *et al.* 1975) and a high value has now been recorded (figure 1) at $Q = 4832$. These values of Q are substantially greater than those achieved in thoroughly outgassed terrestrial analogues and fall in the range of lunar seismic Q values previously reported (Latham *et al.* 1970). Why the hard-vacuum-Q of the lunar sample is so much higher has not yet been established. However, the probable presence of combined water (hydroxyl group) within the structure and of liquid and gas inclusions in microscopic closed cavities must be held accountable for some of the loss in Q in the terrestrial rock. These sources of H_2O, completely absent on the lunar rock, are not removed by the heat treatments (~ 300 °C) given the rocks in the present experiments.

A noteworthy feature observed was the increase of several percent in the room temperature resonant frequency ν_{res} when the pressure was lowered into the high vacuum range. Increases in ν_{res} have also been observed when a terrestrial analogue (*in vacuo*) was subjected to a field of intense microwave radiation which removed H_2O with little or no heating of the rock itself. The fact that these increases in ν_{res} are nearly reversible suggests that they are in part due to a 'healing' of the fracture tips when the H_2O is removed in a way similar to that observed in corrosion studies on fractured materials when the samples are subjected to changes in moisture. These increases in ν_{res} with outgassing are in contrast to the decreases in room temperature ν_{res} as a result of very rapid cool-downs from high bake-out temperatures. It is surmised that in those cases the increase in ν_{res} is offset by decreases in ν_{res} due to a permanent change in texture such as a substantial change in microfracture density.

Nature of volatiles

In order to find out which volatiles are playing a role in the damping mechanism, carefully controlled experiments were undertaken with the few gases most likely to have been present in the lunar environment. The effect of CO_2, O_2, CO, H_2, and H on Q was measured for an analogue of a lunar basalt. The sample was first outgassed at 300 K and 10^{-8} Torr to $Q \approx 500$, then suddenly exposed to 1 atm (10^5 Pa) of the gas, with the decrease in Q monitored with time. An inert gas, He, was used as reference gas for calibration purposes. The He gas was seen to have little or no effect, while CO_2, O_2, H_2, H, and CO_2 reduced the Q by 8, 15, 25, 40, and 45 % respectively. The experiment with H was carried out by heating the sample to 170 °C to cause dissociation of the molecular hydrogen. By comparison with the effect of H_2O (changes by factors of 10^2), the decrease in Q is small for these gases. This experiment was more sensitive than our previous test of the influence of various volatiles (Tittmann *et al.* 1973), largely because the sample was much more thoroughly outgassed initially. Residual gas analysis carried out at 10^{-8} Torr (10^{-6} Pa) after bake-out revealed the presence of equal amounts by volume of H_2O and CO in the test chamber. This result shows that H_2O is still probably the most serious factor preventing the achievement of higher Q values.

Low frequency Q measurements

For measurements of Q values in the laboratory at near-seismic frequencies the vibrating bar technique was modified by end-loading the sample (Tittmann *et al.* 1975). Figure 2 shows some representative results on a terrestrial analogue of a lunar basalt of size 87 mm × 6 mm × 4 mm. Figure 2*a* shows a photograph of the signal decay with a time scale of 0.2 s/cm and a resonant frequency of 56 Hz for the rock as received. The $Q = 51$ at room temperature in laboratory air. (When the rock was tested in somewhat reduced air pressure to remove any air drag on the end loads the Q increased only slightly to $Q = 62$.) Then the bar was cleaned ultrasonically in acetone and alcohol and then baked in air at 280 °C for 3 h. After a 15 min cooling period, the sample was mounted on the fixture and placed in the vacuum chamber. After about 1 h in 10^{-3} Torr (10^{-1} Pa) the Q was measured from the decay curve and found to be 310 at 300 K. Consequently, the entire apparatus was inserted into the bell jar and exposed to 10^{-6} Torr (10^{-4} Pa). While *in vacuo* the sample was heated to 200 °C for 48 h and then allowed to cool. A Q value of about 1100 was obtained as shown in figure 2*b*. Considering the limited outgassing this procedure afforded, this increase by a factor of 20 is quite substantial. By comparison with previous similar studies at kHz frequencies (Tittmann & Housley 1973) this result leads to the conclusion that similar or even greater increases in Q may be expected at low frequencies when strong outgassing procedures are carried out.

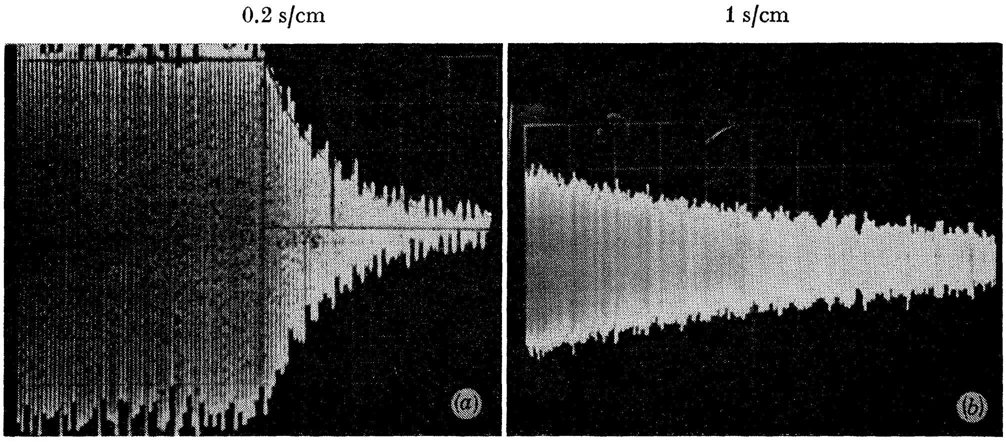

FIGURE 2. Signal decays of terrestrial analogue of lunar basalt. (*a*) As received $Q \approx 51$; (*b*) after some outgassing $Q \approx 1100$. Note increase by factor of 5 in horizontal (time) scale.

CONCLUSION

The attainment of Q values in the lunar seismic range, i.e. $Q = 3000$–5000 by strong outgassing of a lunar basalt and the observation of increases in Q with outgassing at frequencies near 50 Hz (the upper end of the seismic frequency range) represents convincing evidence for the thesis that it is the absence of large amounts of volatiles in the lunar crust which permit the anomolously long signal decays in the lunar seismograms. Our studies of the effect on Q by exposure to various geologically important gases shows the adsorption of H_2O in thin layers gives, by far, the most pronounced effect, reducing the Q by as much as two orders of magnitude. However, CO, H, H_2, O_2, and CO_2 also affect the Q, each by a different amount, while He, N_2, and Ar have a negligible effect on Q. Once the absorption mechanism for each type of volatile is understood, these results open the door to a possible characterization of gas exposure from seismic data and become a useful technique in the exploration of the crust of other planetary bodies.

Note added in proof (August 1976)

We have recently developed the technique of measuring Q under confining (gas) pressure. $Q > 10^4$ on reference samples (polycryst. Al) establishes a low loss measurement base to several kbar. In addition to being able to study rocks under terrestrial conditions, we can also approach simulated lunar conditions. This is difficult because the rocks are porous and have to be encapsulated under vacuum in a thin wall Cu sheath while in a fully outgassed state. We have accomplished this by sealing the sections of the capsule in 10^{-5} Torr by electron beam welding. Once the rocks are thoroughly outgassed, substantially higher Q values ($\times 5$) are realized at 0.5 kbar.

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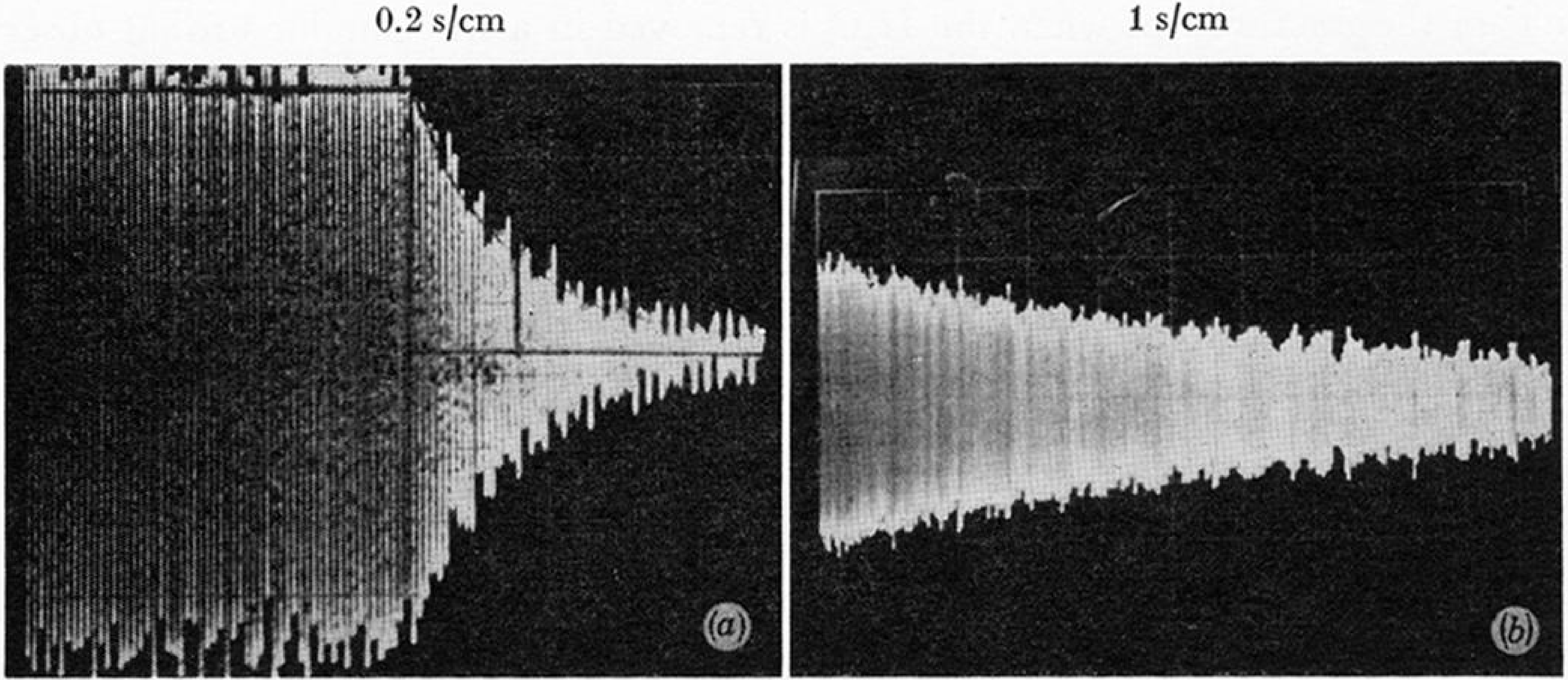
0.2 s/cm

1 s/cm

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