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Changes in *In Situ* Ultrasonic Properties of Rock on Strain Relaxation

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In situ *and laboratory measurements of ultrasonic velocity have been compared to test for the effect of strain relaxation on rock properties. For granites, the larger changes in compressional-wave velocity* (V_p) *correlate with higher* in situ *stresses, the maximum* V_p *being parallel to the directory of maximum compressive stress. For sedimentary rocks, the relation between changes in* V_p *and* in-situ *stress is dependent on lithology. In sandstone, the direction associated with the maximum decrease in* V_p *accompanying strain relaxation is parallel to the maximum compressive stress. Limestone is virtually isotropic with little decrease in* V_p *on strain relaxation.*

INTRODUCTION

More than half a century ago, Adams and Williamson [1] recognized that hydrostatic compression affected the elastic properties of rock and that the change in properties was associated with the behaviour of microcracks under load. Birch [2] systematically studied the change in compressional wave velocity on reloading rocks in hydrostatic compression. Tocher [3] and Nur and Simmons [4] recognized that uniaxial stresses induce velocity anisotropies with the largest velocity change taking place in the direction of the applied stress. All of these studies concern reloading a rock that has been removed from an outcrop. The purpose of this paper is to consider the effect of initial unloading on ultrasonic velocities and velocity anisotropies within rock. Observations presented here indicate that the effect on the elastic properties of rock on unloading (strain relaxation) varies with lithology and environmental conditions in a manner that cannot be predicted from the classic reloading experiments mentioned above.

Much of the previous work on the effect of strain relaxation on the ultrasonic properties of rock is by Swolfs and co-workers [5–8]. Their experiments on sandstones consist of stress relieving blocks greater than a metre on a side where the ultrasonic velocities within the block decrease upon relaxation. In contrast, the ultrasonic properties of cores less than 15 cm dia are not consistent with the changes that took place *in situ*. In some cases, the velocities within cores were higher than found within the blocks prior to strain relaxation. The behaviour of the cores is attributed to differences in moisture content of the cores compared to the *in situ* conditions. For Barre granite, Swolfs [7] reports that cores have a lower ultrasonic velocity than found *in situ*, but a saturated core of Barre granite may have about the same velocity as found *in situ* [Swolfs, 1982, personal communication].

A non-destructive test to measure earth stress may involve the use of ultrasonic techniques providing that a thorough knowledge of the relation between ultrasonic properties and *in situ* stress is developed. An ultrasonic *in situ* stress tool is being developed by Lawrence Livermore National Laboratory [9]. The tool uses a pulsed phase locked loop technique which relies on relative measurements of tangential and radial shear wave components at several locations around the borehole. Another approach is to take advantage of changes in ultrasonic properties on strain relaxation. Here, the idea is to compare the ultrasonic properties of relieved core with *in situ* properties. In this paper we examine the feasibility of using the changes in compressional wave velocities (V_p) and V_p anisotropy to gain information on *in situ* stress.

TECHNIQUES

This paper describes a correlation between surface (depth < 2 m) *in situ* stress and ultrasonic properties for several rock types in the northeastern United States (Fig. 1). The lithologies include sandstone, limestone, diabase, metasediment, hornblende gneiss and granite. The sandstone and limestone sites are on the Appalachian plateau [10], the gneiss and metasediment sites are located within the Precambrian Adirondack Mountains [11], the diabase site is part of the Triassic–Jurassic Newark Basin, and the granite sites are within Pennsylvanian and Jurassic aged plutons in new England [12].

In situ stress was measured using a modified 'doorstopper' technique where strain gauge rosettes are bonded to the end of boreholes and subsequently overcored [13]. On overcoring, a strain relaxation of the core

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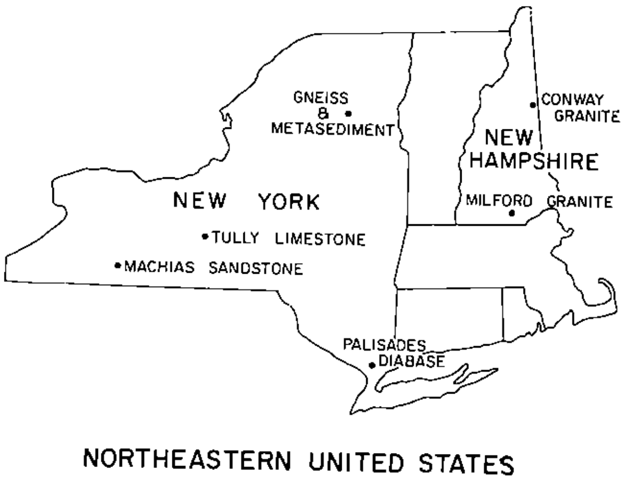


Fig. 1. The location of six sites where *in situ* stress and ultrasonic properties were measured.

was measured; stress was calculated using moduli determined by reloading the cores in laboratory tests. At each site, the stress was measured in the near surface (< 2 m) in several (3–7) boreholes separated by 1–3 m. The outcrops used for these measurements were selected so that few, if any, joints intersected a line between the test holes. Because *in situ* ultrasonic velocity was measured along different paths between the 7.6 cm dia boreholes, joints between the boreholes would interfere with the ultrasonic travel time.

The ultrasonic technique used in the field was an adaptation of the method developed by Cannaday and Leo [14] and Swolfs [7]. *In situ* compressional-wave velocities (V_p) were measured using transducers in cylindrical anvils which where shaped to fit snugly inside 7.6 cm dia boreholes (Fig. 2). The anvils were loaded against the wall of the boreholes with the aid of hydraulic pistons. The transmitter used a 300 kHz, 2.54 cm dia barium titinate disk driven at 20 Hz with a 500 V, 1.5 μsec rise time pulse. The receiver was a matched barium titinate disk whose output was amplified and displayed on a Tektronix 335 portable oscilloscope. All electronics were powered with a 12-V automobile battery; this allows *in situ* velocity measurements at remote locations.

To measure the travel time between boreholes, a delay box was used where the outgoing pulse could be matched with the return signal to within 1 μsec. The high voltage pulse triggers the oscilloscope sweep as well as a pulse which is delayed and displayed on the oscilloscope superimposed on the return signal. This method gave a greater accuracy in identifying the travel time than did the method using the delay-time mode of the oscilloscope. The field experiment was calibrated before and after use by measuring travel time in an aluminium rod.

In the laboratory, ultrasonic P-wave travel times were measured along core diameters at 15° or 30° intervals to detect horizontal anisotropy [15, 16]. The travel time through cores was measured using anvils shaped to the outside diameter of the core. In these tests, the delay-time mode of a 585A Tektronix oscilloscope was used for measuring time of flight. Measurements were calibrated using an aluminium cylinder of the size of the cores to be tested. Velocity was then computed from the travel time of ultrasonic pulses transmitted and received by piezoelectric crystals mounted in the anvils at opposite ends of a core diameter. Travel times were measured to a precision of 10 nsec using an oscilloscope.

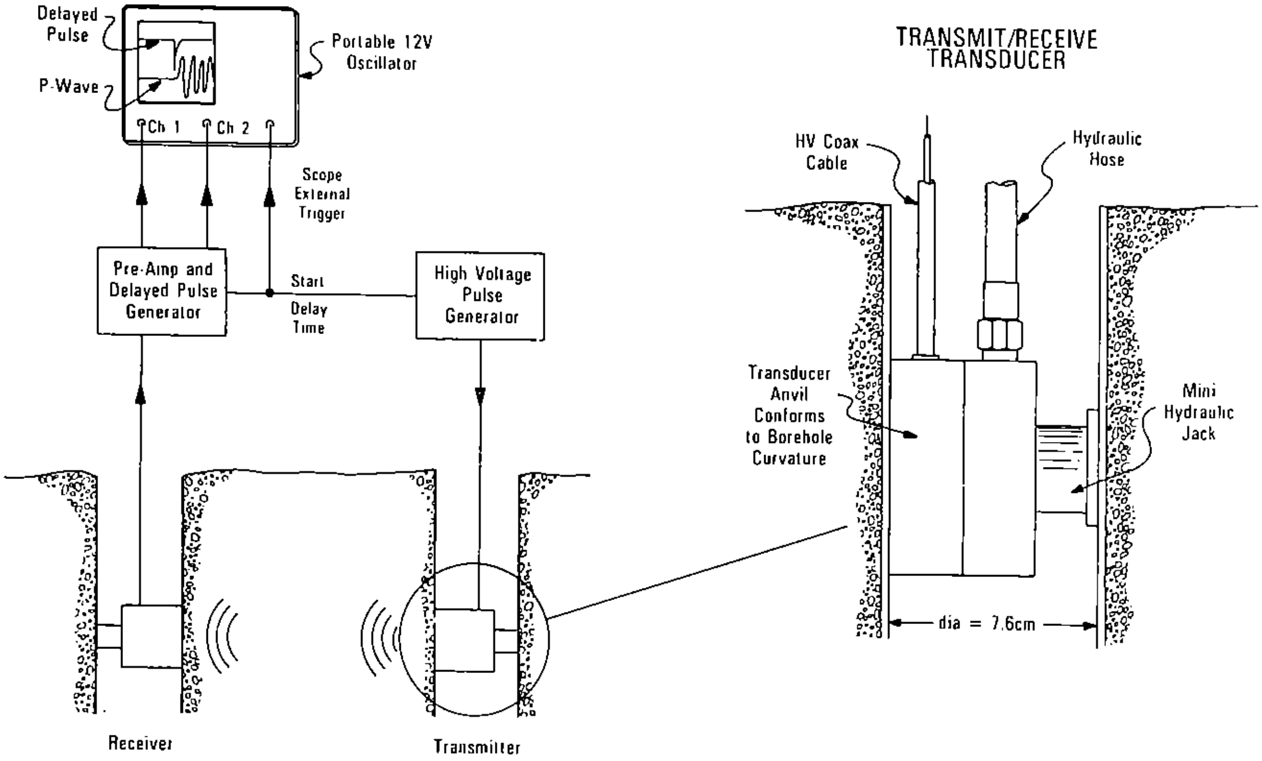


Fig. 2. A schematic of the apparatus for *in situ* ultrasonic tests.

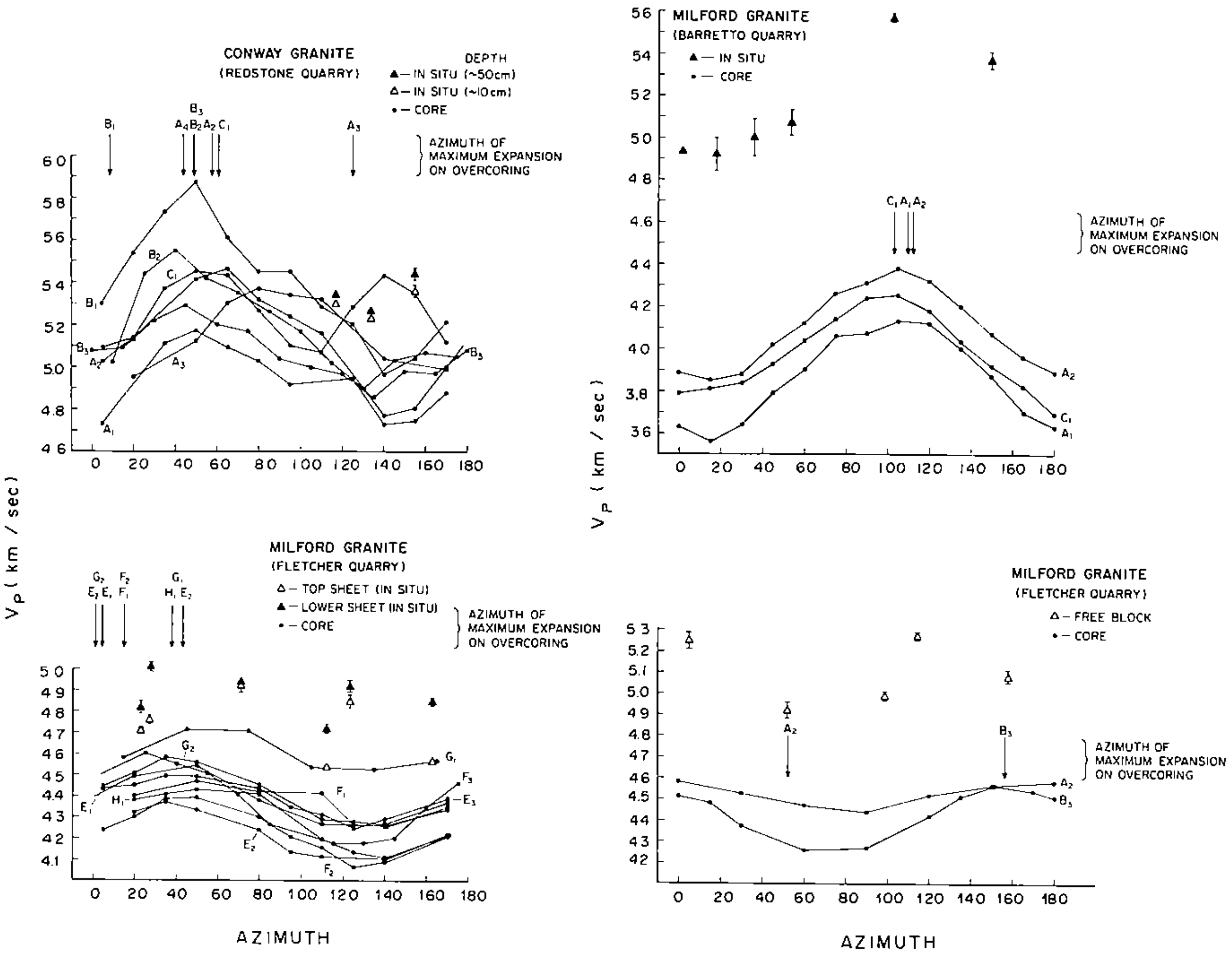


Fig. 3. Plot of compressional wave velocity (V_p) vs azimuth for the Milford and Conway granites. Both *in situ* and core velocities are shown as well as azimuth of maximum expansion on overcoring. The depth of the *in situ* velocity measurement is also noted in some cases. The Milford granite was measured at two quarries 20 km apart. At the Fletcher quarry, a free block of granite was tested. The core and overcoring labels correspond to data on strain relaxation which appears in Plumb *et al.* [12].

Velocity magnitudes relative to different cores were accurate to 3% and velocity anisotropy observed in a particular core is accurate to 1/2%.

Both *in situ* and laboratory apparatus were calibrated using 2024 aluminium which has a longitudinal wave velocity of 6.22 ± 0.05 km/sec. A 10 cm dia by 75 cm long rod was used for the *in situ* apparatus with the travel time measured along the length of the rod. A 7 cm dia by 10 cm long cylinder was used for the laboratory apparatus with the flight time measured across the diameter. Velocities measured in both pieces of aluminium were less than 1% from 6.22 km/sec.

In situ velocity data were collected between September 15 and November 15 when the ambient air temperature was between 0° and 20°C. At all sites, the rocks were above the local water table and, hence, not saturated. Room-dried cores at about 20°C were used for laboratory measurements. The exact moisture content within either the *in situ* rocks or cores was unknown.

IN SITU VELOCITY VS *IN SITU* STRESS

Our data are displayed on plots of compressional wave velocity versus azimuth (Figs 3, 4 and 5). *In situ* velocity data include measurements at different depths at some sites and, where no depth is indicated, the measurement was taken at about 30 cm below the surface. Core data include velocities at several aximuths from each of several cores taken at each site (data points from individual cores are linked). Arrows indicate the azimuth of maximum expansion on overcoring for several tests and this azimuth is the approximate direction of maximum compressive stress within the outcrop. Common labels designate velocity data from cores for which the azimuth of maximum expansion is plotted.

On strain relaxation, the common behaviour was a decrease in velocity (ΔV_p) which varied from 1% in the Tully limestone to 20% in the Milford granite. For granite, this ΔV_p upon strain relaxation correlates with the *in situ* stress, i.e. the magnitude of stress decrease on

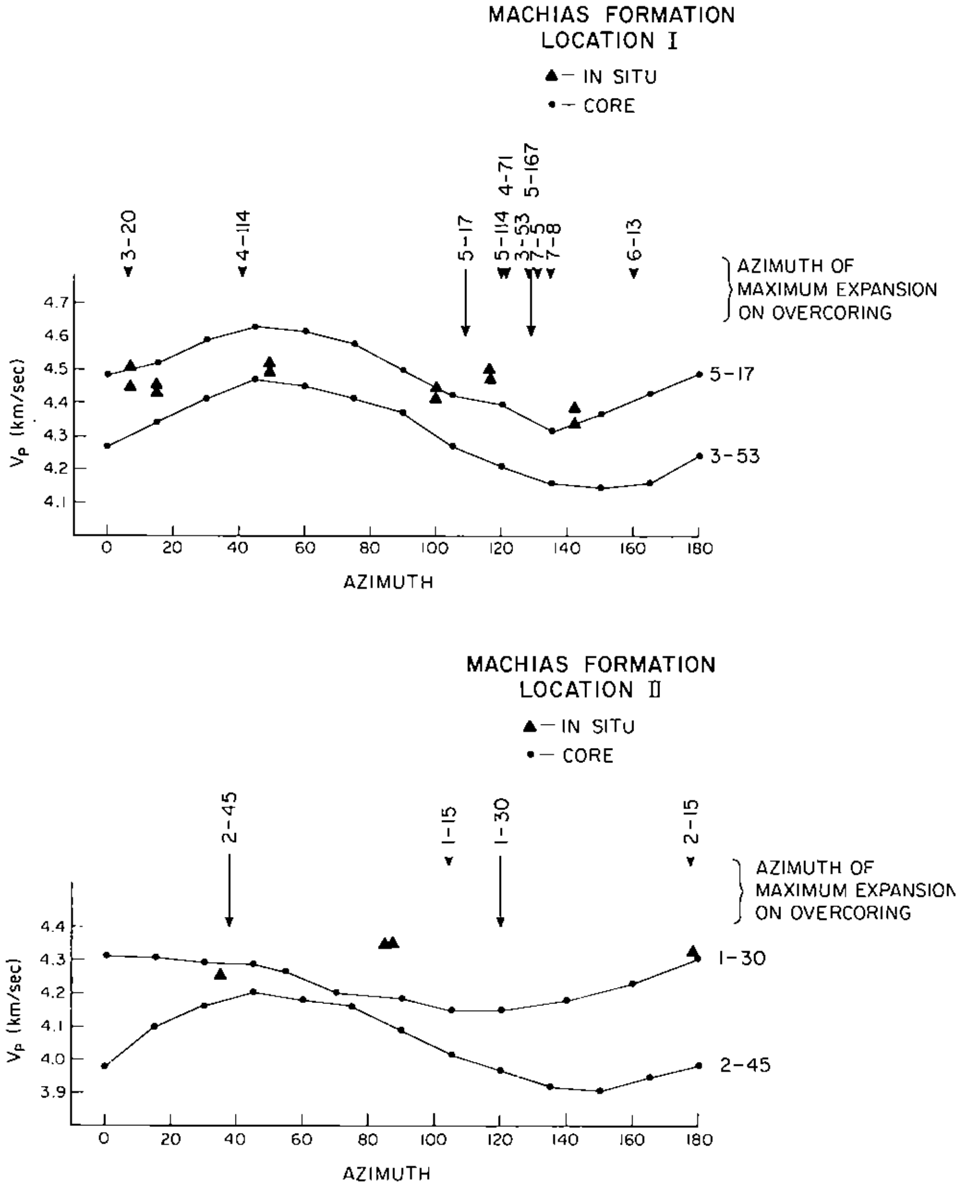


Fig. 4. Plot of compressional wave velocity (V_p) vs azimuth for the Machias sandstone. Both *in situ* and core velocities are shown as well as azimuth of maximum expansion on overcoring. The core and overcoring labels correspond to data on strain relaxation which appears in Engelder and Geiser [10].

overcoring ($\Delta\sigma$); this behaviour is compatible with the reloading experiments of Birch [2]. The stress dependent decrease in V_p is best illustrated by comparing the ΔV_p between the Barretto and Fletcher quarries in the Milford granite (Fig. 3). Our data at the Barretto quarry were taken from the quarry floor 50 m below the surface of surrounding land, whereas data at the Fletcher quarry were taken from less than 5 m below surface level in a zone of sheet fractures. The natural processes of sheet-fracturing near the land surface would be expected to relieve some of the stress within the Milford granite. This is indicated by the magnitude of the *in situ* stress [see 12] where more highly stressed granite at Barretto shows a larger decrease in V_p on strain relaxation than does the granite at Fletcher.

No two lithologies *in situ* exhibit the same variation of velocity with azimuth; three general types of variation are evident. The Tully limestone shows little or no variation in V_p with aximuth (Fig. 5). Another type of variation gives the well defined anisotropy found in the Milford granite at Barretto quarry (Fig. 3). Rocks such as the Palisades diabase and the hornblende gneiss of the Adirondacks show neither a constant velocity with azimuth nor a well defined anisotropy. The outcrops of Palisades diabase and hornblende gneiss are cut by joints that seem to have affected the time of flight so it does not vary systematically with orientation. The non-systematic variation of velocity with azimuth in the hornblende gneisses is also caused by inhomogeneities in stress and microcrack density [11].

The velocity and anisotropy of cores also varies with lithology. The Tully limestone, which shows no anisotropy, also displays the least variability among cores with velocities clustering within 0.2 km/sec (Fig. 5). The

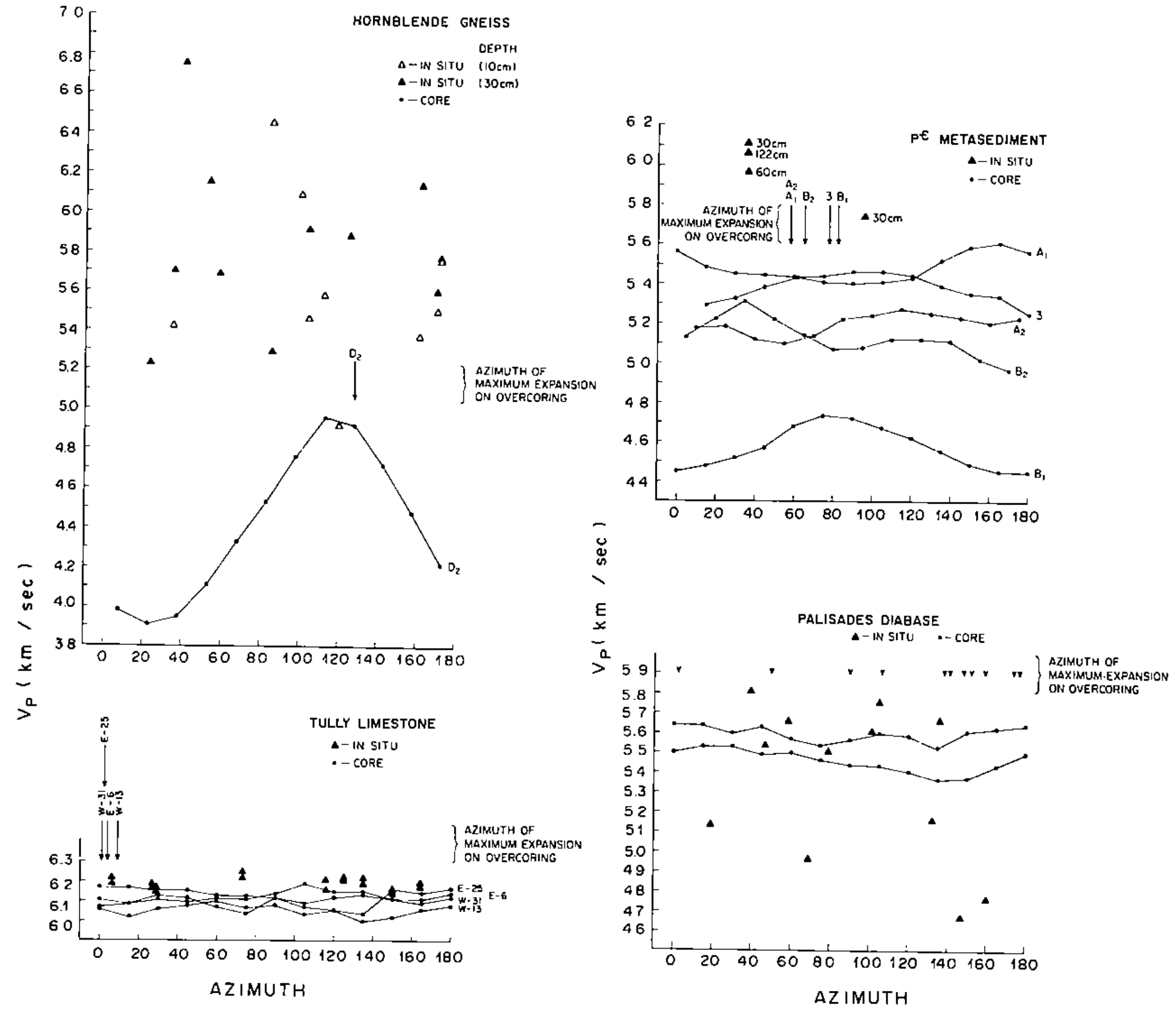


Fig. 5. Plot of compressional wave velocity (V_p) vs azimuth for the Tully limestone, the Palisades diabase, a hornblende gneiss and a Precambrian metasediment (Sagamore). Both *in situ* and core velocities are shown as well as the azimuth of maximum compression on overcoring. The *in situ* velocity measurement is also noted in some cases. The core and overcoring labels correspond to data on strain relaxation which appears in Plumb *et al.* [11].

Palisades diabase shows a hint of anisotropy, whereas many cores from the remaining sites are strongly anisotropic.

Some cores of the Precambrian metasediment show an anisotropy in V_p but the pattern is not consistent from core to core. Within a suite of cores from one outcrop, the velocity at one azimuth may vary as much as the anisotropy within one core. For velocity measured in one direction, some cores such as the Conway granite vary by more than 0.5 km/sec over a suite of seven cores (Fig. 3).

Regarding the relation between maximum expansion on overcoring and V_p anisotropy, the rocks divide into the three possible categories:

(1) those with maximum expansion parallel to the maximum V_p;

(2) those with maximum expansion parallel to the minimum V_p; and

(3) those with no relation because the rock lacks a homogeneous anisotropy.

Maximum expansion parallel to maximum V_p, *in situ*, is seen in the Milford granite at the Barretto and Fletcher quarries and the Conway granite at the Redstone quarry (Fig. 3). In all these examples, the correlation between maximum V_p and maximum expansion is not perfect, largely because repeated stress measurements show a variation in magnitude and orientation of *in situ* stress even when experimental techniques are consistent from one measurement to the next [12]. The hornblende gneiss and the Precambrian metasediment (cores B and 3) may also fit this category.

The maximum expansion correlates with the minimum V_p in the cores of the Machias sandstone and possibly the Palisades diabase (Fig. 4 and 5). In the Machias sandstone, two *in situ* samples of V_p were taken with the *in situ* V_p at location I about 0.2 km/sec faster. The two *in situ* samples were taken within the same bed, a siltstone about 1 m thick. The samples were taken about 4 m apart with joints separating the two sample sites (Fig. 7 in [10]). Here the dominant joint set is parallel to the direction of maximum expansion. The

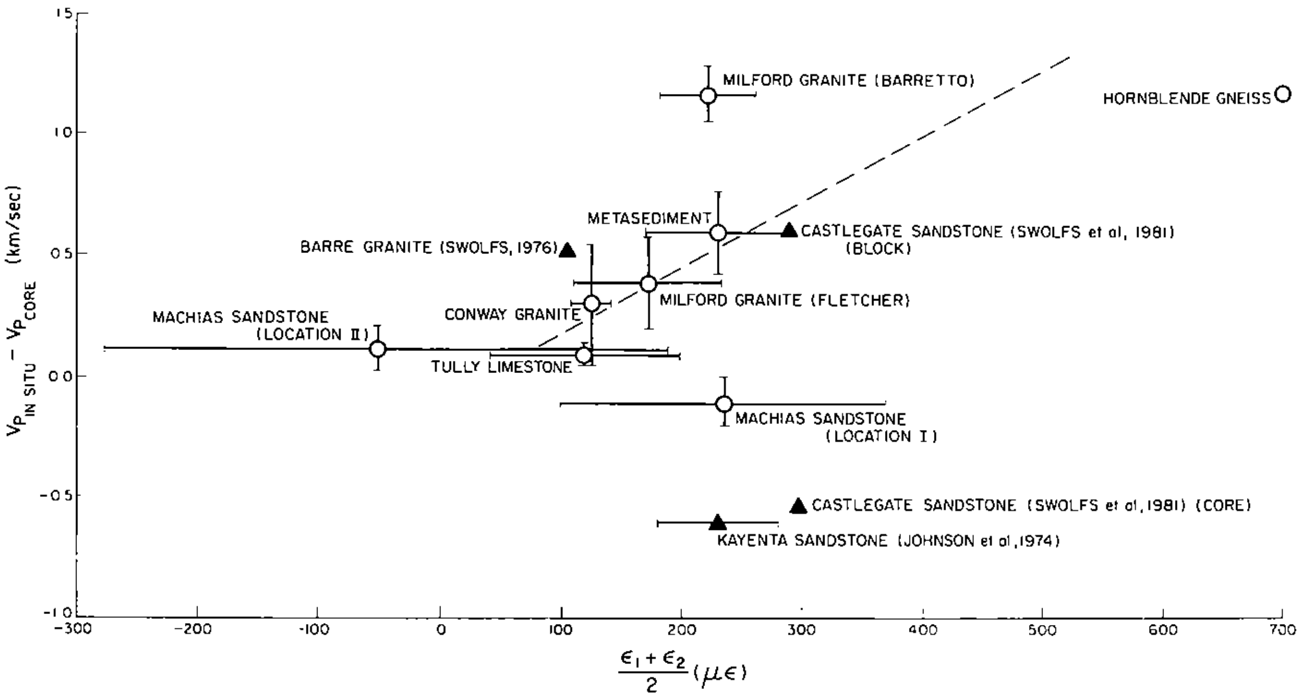


Fig. 6. Change in velocity between *in situ* conditions and relieved cores vs mean strain. The average velocity is determined by adding all available azimuthal data (e.g. 12 V_p measurements per core) and dividing by the number of measurements.

cores at location I were correspondingly faster. The difference in velocity also correlates with the *in situ* stress which was larger at location I.

The Tully limestone shows a well clustered orientation for maximum expansion upon overcoring, but the lack of any consistent anisotropy pre-empts any correlation with V_p (Fig. 5). Stress and V_p were also measured on a free block of Milford granite (3 × 2 × 2 m). The residual stress within the block was very low and had no consistent orientation. Here the relieved block showed no tendency to store a residual strain related to a velocity anisotropy (Fig. 3).

With the exception of the Machias sandstone there is no correlation between velocity anistropy and joints.

DISCUSSION

Our data, together with that generated by Swolfs and co-workers, show that ultrasonic properties of rock change upon strain relaxation [8]. The interesting question that both data sets suggest is whether there is a correlation between the magnitude and orientation of the *in situ* stress and the change in ultrasonic properties. The correlation upon overcoring between mean strain and the change in V_p shows a trend toward the large ΔV_p with larger mean strain (Fig. 6). The larger uncertainties in the data may be attributed to inhomogeneities in most rocks causing both the variation of mean strain which is typical for overcoring measurements and the variation in velocities among cores in a single outcrop. Environmental factors such as moisture content and temperature also contribute to the uncertainties. As pointed out earlier in the paper, the major shortcoming of the comparison of laboratory velocities on cores with *in situ* velocities is the lack of control of the environmental changes that take place between the field and the laboratory. Despite the uncertainty in reproducing the field environment in the laboratory, there is a trend which is also seen for a plot of differential stress vs ΔV_p; the higher the stress, the larger the velocity change (Fig. 7).

Sandstones do not conform well with the correlation between strain relaxation and velocity decrease following strain relaxation (Fig. 6). The Castlegate sandstone [8] and the Machias sandstone (location I) are two examples of cores that had higher velocities than the rock *in situ*. Likewise, the Kayenta sandstone showed cores with a higher velocity than was observed *in situ* [5]. Although changes in the environment may have contributed to the discrepancy, it is not clear how sample drying would contribute to a velocity increase.

Assuming that environmental effects are minimum, we hypothesize that stress induced opening or propagation of microcracks affects the ΔV_p as shown in Fig. 7. Despite extensive thin section observations, the identification of those microcracks that actually participate in the strain relaxation is difficult. The difficulty is best illustrated for the granites where the *in situ* and core anisotropy are the same magnitude. On relaxation, there appears a consistent shift in the velocity curves (the velocity decrease is independent of azimuth) (Fig. 3). The anisotropy both *in situ* and in the cores correlates with a set of transgranular cracks that are readily apparent in thin section [12]. The consistent shift in the velocity curves imples that microcracks opened on relaxation but no particular orientation of microcrack was favoured (Fig. 8). The well-developed set of microcracks seemed not to participate in the relaxation. If other microcracks are responsible for the relaxation, they are

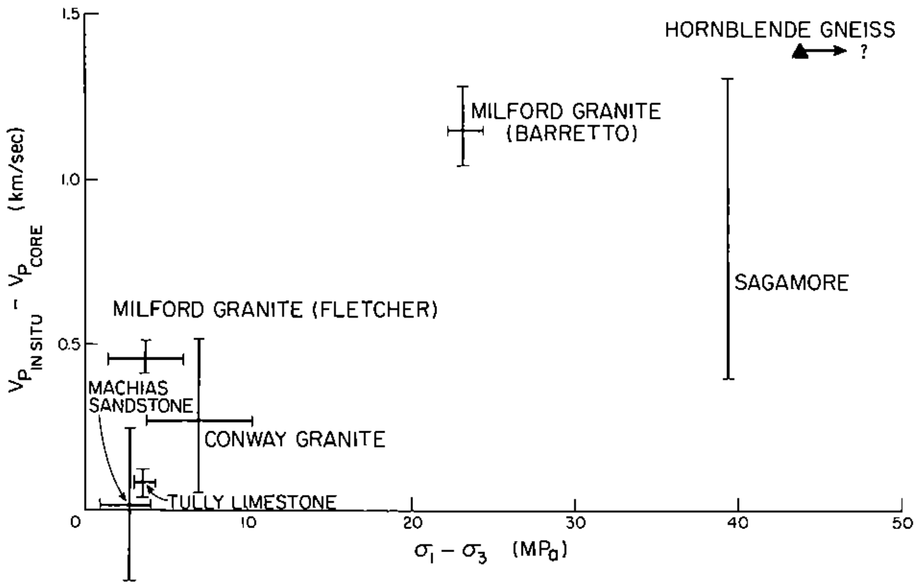
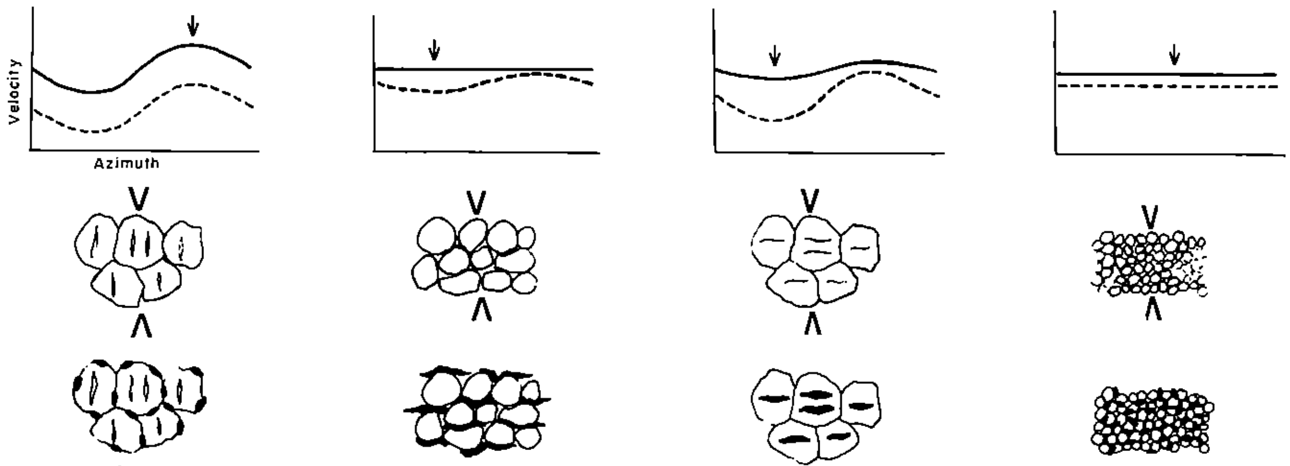


Fig. 7. Change in velocity between *in situ* conditions and relieved cores vs deviatoric stress.

not readily apparent when the granite is viewed in thin section.

The ΔV_p on strain relaxation of granite did not conform to Nur and Simmons [4] experiments which predict that a maximum ΔV_p should occur in the direction of the maximum stress change. Although a detailed explanation for this behaviour of granites *in situ* vs Nur and Simmons' experiment is not forthcoming, it is relevant to point out that unloading a rock for the first time involves the release of time-dependent stresses as well as residual strain [17]. Thus, it is reasonable to suppose that unloading of granite *in situ* will not have the same effect as removing boundary loads imposed for a short period in the laboratory.

Our measurements of ΔV_p in the Machias sandstone conformed to Nur and Simmons' [4] prediction that the maximum ΔV_p would occur in the direction of maximum stress change (Fig. 1). Yet, even here, ΔV_p behaviour in the Machias differed from the laboratory behaviour documented by Nur and Simmons [4] where the largest anisotropy occurred under load. The largest anisotropy appeared upon removal of the load, whereas, *in situ* and under load, the Machias sandstone showed little tendency to be anisotropic (Fig. 4). Our interpretation is that relaxation was accompanied by the propagation of a set of microcracks which have a preferred orientation with poles to microcrack planes parallel to the maximum compressive stress. This is consistent with the behaviour



Milford granite

Machias sandstone

Barre granite

Tully limestone

Fig. 8. A schematic diagram showing four different types of behaviour for the change in ultrasonic velocity with respect to *in situ* stress. The top row consists of plots of velocity vs azimuth where the solid line is the *in situ* velocity and the dashed line is the velocity measured on a core in the laboratory. The orientation of the maximum compressive stress is shown by the arrow above each set of velocity vs azimuth curves. The middle row shows four rocks under load where the maximum compressive stress is indicated by arrows. Pre-existing microcrack fabrics are shown where appropriate. The third row shows the growth or opening of microcracks (indicated in black) upon removal of the *in situ* stress by overcoring. Each column illustrates a rock described within the text.

predicted by Strickland and Ren [18] for the stress release of sandstone. In contrast, the laboratory samples of Nur and Simmons [4] contained microcracks which closed under pressure and opened without propagation on release of pressure.

The Tully limestone appears to have behaved much like the granite in that a consistent shift in velocity accompanied strain relaxation. As in the granite, microcracks without a preferred orientation participated in the strain relaxation. In contrast to the granite, no anisotropy was apparent prior to relaxation (Fig. 8).

The inhomogeneity of rock is illustrated by the variation in *in situ* velocity of the Machias sandstone between locations I and II (Fig. 4). It is further illustrated by the variation of properties in cores from the Conway granite (Fig. 3) or the Precambrain metasediment (Fig. 5). This inhomogeneity is also evident by the variation in magnitude and orientation of the *in situ* strain relaxation data. Another type of inhomogeneity appears in the comparison of *in situ* velocities at different depths. Often, the deeper measurements show a higher velocity, as is the case for two sheets of Milford granite at the Fletcher quarry. One odd comparison is that the velocities in the free block of Milford granite at the Fletcher quarry are higher than the *in situ* velocities. It was expected that the free block which was stress relieved should have shown lower velocities. Here again, inhomogeneities in the Milford granite pluton may be the source for the errant behaviour of the free block relative to the *in situ* velocities at the Fletcher quarry. *In situ* velocities at the Barretto quarry within the Milford granite pluton are even higher than the free block at Fletcher. So the possibility that the free block at Fletcher came from a location of high *in situ* velocity (i.e. high stress) within the Fletcher quarry is very real.

CONCLUSIONS

(1) Ultrasonic velocities decrease upon *in situ* stress relief.

(2) There is some correlation between the magnitude of change in ultrasonic velocities and the magnitude of the strain relaxation.

(3) Three trends are observed between orientation of maximum compression and core anisotropy, depending on lithology. The trends are: parallel; perpendicular; and everything inbetween. Anisotropy may be used to infer the direction of *in situ* stresses axes; but the direction of maximum stress can only be predicted if the mechanism causing anisotropy is known.

(4) Anisotropy in the Tully limestone is small compared with the Machias sandstones and granites; if these sites are representative of the use of ultrasonic logs to infer state of stress, the method is likely to be more successful in sandstones and granites than in limestones.

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