THE ROLE OF WATER IN SEISMIC VELOCITY RATIOS AS EARTHQUAKE PRECURSORS

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ABSTRACT

Changes in the ratio of compressional to shear seismic wave velocities prior to an earthquake have been suggested as possible precursors to earthquake occurrence. Two models have been suggested to explain the mechanism by which the compressional wave velocity is allowed to vary relative to dilatancy; one model requires the influx of water and the other does not. Dry and saturated rock specimens were fractured or allowed to experience stick-slip in an effort to determine the affect of pore water on the compressional velocity. It was found that water had no effect on the arrival time of compressional waves in dilatant rock. Moreover, the value of V_p falls off consistently just before the throughgoing fracture (indicated by stress drop) which indicates a severe weakening of the rock, possibly some cataclasis or grain boundary slip occurring prior to the throughgoing fracture.

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INTRODUCTION

That the crust of the earth is a dynamic system is evidenced by worldwide examples of surface deformations. These deformations may be as large in scale as the Rocky Mountains or as small as microscopic fractures in a sand grain. The deformations take one of two forms or a combination of both. If the deformation occurs continuously and at a very slow rate, it produces folding, flow, or creep in the rock. More rapid changes tend to produce short, discreet intervals of faulting.

The most common example of fault deformation is the occurrence of an earthquake. The processes in an earthquake were described by Harry Fielding Reid in his "Fault Theory of Earthquakes" shortly after the catastrophic 1906 San Francisco earthquake. Reid stated that tectonic forces below the surface result in an accumulation of elastic strain energy in a body of rock. At some point, this strain overcomes the frictional forces that hold the rock grains together and the rock fractures. The strained rocks suddenly yield, releasing their stored elastic strain energy. This energy is in the form of seismic waves that vibrate through the earth.

Reid's theory is quite simple; there is still much unknown about <u>how</u> the strain energy is accumulated and released. Even less is certain about how the factors of boundary conditions and varying rock properties affect the mechanism of an earthquake. We study earthquakes because of their potential for damage and destruction of public and private property, and their resultant danger to human life. The estimated damage to public property in this century is nearly $400 million*. More seriously involved than money, the number of lives claimed by just fifteen of the greatest earthquakes well exceeds two million people.

The study of earthquakes by researchers in seismology and geophysics has intensified over the past twelve to fifteen years as earthquake prediction becomes an increasingly realizable goal. Prediction is the specification of the time, location, and magnitude of an individual event. Some seismologists are studying rates of earthquake reoccurence in particular regions. The country being studied can be broken up into different areas depending on frequency of occurence and magnitudes. Another way of defining "high risk areas" is to look at "seismicity gaps" along known fault lines. The theory in this case is that a section of land along a fault which has not slipped recently has stored more elastic strain energy and is therefore closer to failing.

The vast majority of earthquake research money is invested in studying characteristic phenomena that precede earthquakes. The goal is to initially discover localized anomalous behavior of one or more observable

* For example, the 1933 Long Beach, Ca. earthquake alone was responsible for damages estimated, at that time, at over $50 million (Richter, 1958).

quantities which occur repeatedly before - and only before - an earthquake. Researchers then attempt to scale the size and/or duration of the anomaly to the magnitude and time of occurrence of a future earthquake (Kisslinger, 1974). These earthquake precursors include: anomalous variations in the ratio of compressional seismic wave velocity to shear seismic wave velocity, tilt of the surface, regional and local crustal movements, changes in electrical resistivity, changes in the frequency of microearthquake occurences, underground fluid migration, and rotation of stress axes within the volume of affected rock (focal region). Different approaches have been taken to relate these precursors to an earthquake.

THEORY

The unifying concept of this, and much other earthquake precursor research, is really a key phenomenon observed in laboratory studies of rock fractures. The concept is dilatancy which is defined as the inelastic, volume expansion of a body of rock. This expansion is caused by the formation and propagation of microcracks oriented parallel to the axis of maximum compression. The microcracks open in the direction of least compression (Scholz, 1973). The phenomenon can be described in three stages preparatory to rock failure (whether by laboratory controlled fracture or full scale field fracture):

I. Real rocks have a random distribution of microcrack defects, the number and size of which increase as the rock is exposed to tectonic strain. As long as the occurence and distribution of the microcracks remain uniform however, no precursive phenomena are observed.

II. The transition to Stage II occurs when a critical average density of microcracks (depending on the particular rock) is achieved. The microcracks begin to interact and open up, resulting in an increased pore volume. Additional changes in associated physical characteristics can be noted. Figure 1 clearly shows the onset of several of these precursive anomalies at the beginning of Stage II.

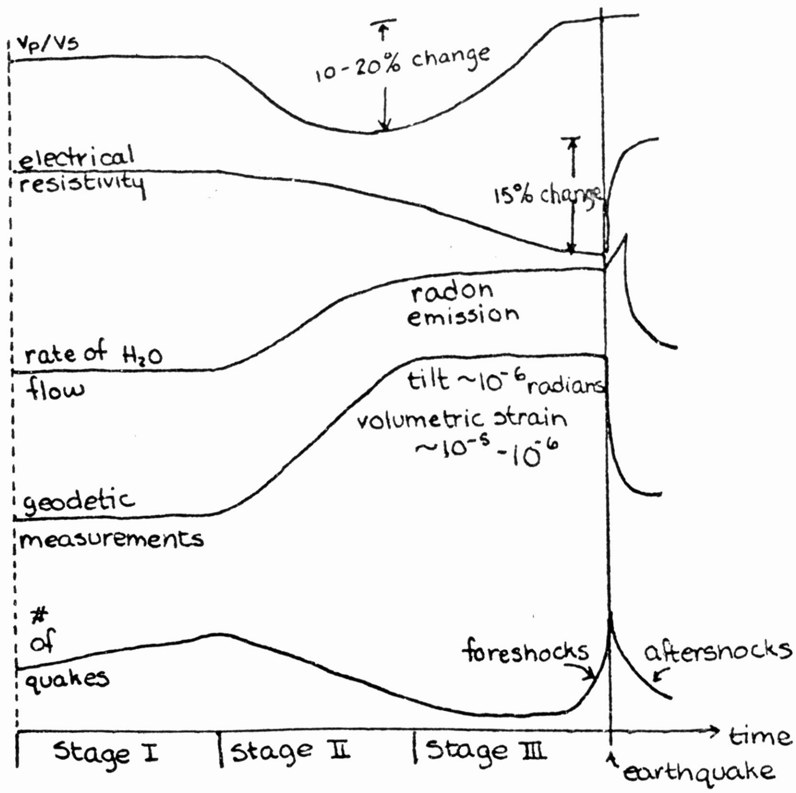


Fig. 1) Predicted changes in various physical parameters as a function of time during the earthquake cycle for the dilatancy model (Scholz, 1973).

III. By the onset of the third stage of the dilatancy phenomenon, the affects of the microcrack interaction are at their maximum. During this stage many of the physical changes tend to decelerate or reverse due to fluid redistribution within the rock.

This investigation is concerned with the first of the precursors listed, i.e., the behavior of the compressional, to shear, seismic wave velocity ratio (Vp/Vs) as related to dilatancy. A controversy exists as to what happens inside the interacting microcracks of Stage II and why the velocity ratio returns to normal before the earthquake in Stage III. Current explanations tend to polarize toward what have become known as either the Dry or Wet models.

The Dry model (Brady, 1975) states that local physical changes, at the onset of the precursors of Stage II, create a heterogeniety in the medium. While microcracking due to increasing stress does occur (as indicated by decreasing Vp), this heterogeneity increasingly confines the unstable deformations to a relatively narrow zone. This zone can be represented by elastic inclusions whose moduli are lower than those of the surrounding material. Outside the inclusion zone, the medium acts more like a stable block. In Stage III intergranular stresses decrease, cracks stop developing, and many of the original rock characteristics return to those of the outer block region, including the initial Vp. In fact, closing the outer cracks creates even more of a contrast between the block and inclusion parts of the material. Within the narrow, unstable inclusion zone there is an increased concentration of small faults parallel to the future main fault. The throughgoing fault then forms when the cracks are so numerous that they coalesce, the material between them collapses, and the earthquake occurs.

This model for earthquake source preparation was designed to consider only the mechanics of fracturing. However, it has been well accepted because several of the precursor phenomena can be illustrated within its framework. It is possible that the observed behavior of the seismic velocities ratio results from just such a process.

The Wet model (Nur, 1972) suggests that the behavior of seismic wave velocities prior to an earthquake can be explained on the basis of dilatancy in low porosity rocks, initially saturated with water under the increasing differential stress of tectonic loading. Figure 2 illustrates the dependence of Vp and Vs on effective pressure (confining pressure -pore pressure) for saturated and dry rocks.

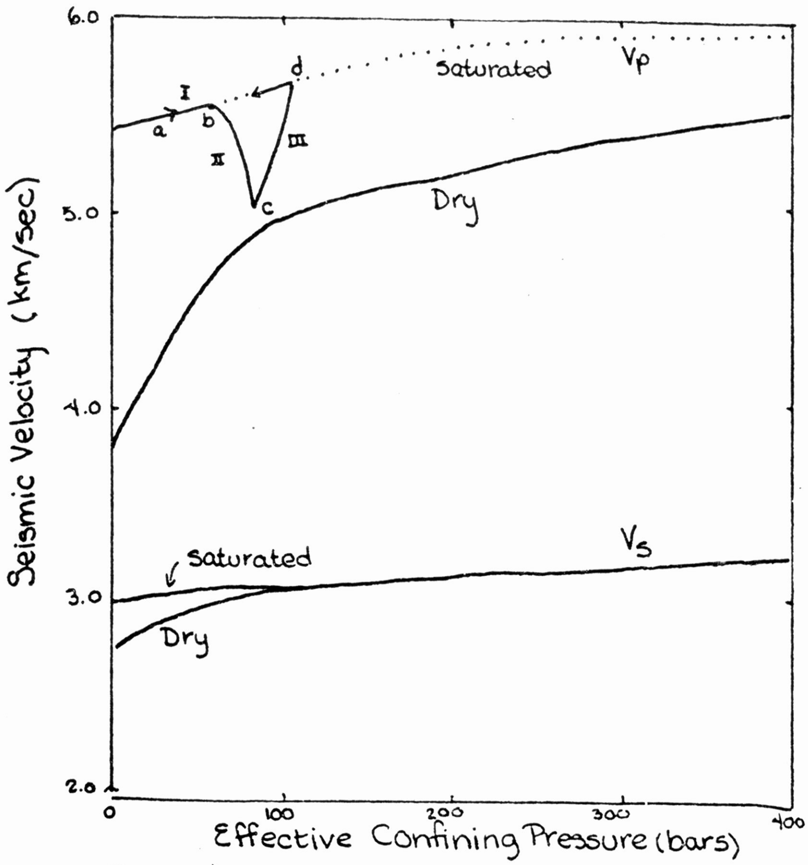


Fig. 2) Velocity data from Nur & Simmons (1969) for saturated and dry Westerly granite, as a function of effective confining pressure (Whitcomb, 1973).

Along $\overline{bc}$ of Stage II, fluid in the dilatant zone is being redistributed. The pressure forcing the grains apart (pore pressure) decreases, consequently the grains are held together more tightly. This effectively strengthens the rock and inhibits further microcracking. At c the rate of fluid flow has dominated the propagation of microcracks so the rock becomes increasingly saturated. During the period of $\overline{cd}$ of Stage III the compressional velocity increases with more pore water and confining pressure to point d. The Wet model states that it is this resaturation that weakens the rock, causing failure. A most important conclusion of Nur's hypothesis is that the increase in the pore volume of the rock should result in a decreasing velocity ratio in dry rocks or an increasing velocity ratio in wet rocks. Also, the primary factor in regaining a high velocity ratio is an increased amount of pore fluid, not the closing of microcracks.

By duplicating the dilatant behavior observed by Nur, this study will examine the seismic wave velocity ratio (actually the compressional wave velocity, for shear wave velocity changes relatively little) to determine the need for fluid migration into the microcracks, in an attempt to verify either the Dry or Wet model.

PREVIOUS STUDIES

Very little experimental work has been done to acquire the velocities that all this conjecture surrounds. Laboratory measurements of the compressional and shear seismic wave velocities have been made by Bonner, Gupta, Hadley, and Matsushima.

Gupta (1973) measured Vp and Vs along three mutually perpendicular directions as a function of the axial load. His specimens were dry, unjacketed, and unconfined rectangular prisms of limestone. It was found that the ratio of Vp to Vs remained nearly constant along the long axis of the prism, decreased somewhat (~2%) along the short axis parallel to the induced fault, and dropped considerably (~12%) along the other short axis (traversing the induced shear fracture) in response to increased axial load.

Bonner examined compressional and shear velocities along the direction of maximum compression. Kerosene was used as the pore fluid in granodiorite specimens whose velocities were measured by transducers mounted in the piston. A single pulse excited both the transverse shear and compressional wave energy. One receiving transducer was used to record these arrivals with an estimated accuracy of 4%. Under a slow strain rate (5×10^{-6}/sec) Vp/Vs increased monotonically with shear stress until failure. Interestingly, the ratio seemed to be controlled by Vs rather than Vp as most authors have suggested. Bonner attributes the increasing velocity ratio to either increased porosity coupled with decreased aspect ratio (maximum crack dimension/minimum crack dimension) or to a high rate of fluid flow of the same order as the dilatant volume increase.

Matsushima (1960 a) examined the difference in the elastic wave velocities in deforming rocks at low versus high confining pressure. He found that at confining pressures below 1 kbar, the velocities exhibit little of the directional anisotropy noted by Gupta.

Hadley (1975) measured Vp and Vs perpendicular to the long axis of copper jacketed granite specimens relative to volumetric strain. The primary wave velocity was measured as the rock was unloaded between stress cycles. Specimens were never taken to fracture stress, but exhibited a consistent decrease in Vp with increased "dilatant stress". While this was one of the first experiments to consider pore fluids in the dilatancy model, the fluid used in the experiment was CO_2 gas which provides only a poor approximation of in situ conditions. When velocity ratio increases were exhibited they were usually on the order of 1 - 3% of the average value of the ratio. Hadley attributes velocity ratio drops to 1) large dilatant strain when pore fluid volume was held constant or, 2) change from liquid to vapor states in pores at high confining pressure. However, she does not elaborate on any increase in the ratio to create the effect of the velocity return possibly seen in some of the field data.

PROCEDURE

Flat surfaces (approximately 3/4"^{2}) were filed out of the sides of two right circular dogbone cylinders of Berea sandstone, and two right circular sawcut cylinders of Coconino over Tennessee sandstones. The approximate dimensions of the cylinders were: Berea: 1.5" interior diameter, 5" length, Combination: 2" diameter, 4" length. Circular lead zirconate, 1 MHz., compressional transducers were affixed to the flat surfaces with Bipax tra-duct conducting epoxy. The transducers were placed 1.5" from the ends of the dogbone and 1.0" from the ends of the sawcut, and on opposite sides of the cylinders. The ground lead was brought from under the transducer and the conducting lead was epoxyed to the outer surface of each transducer. The transducers were insulated with rubberized caulking material. The whole sample was then jacketed with a polyolefin shrink tubing through which the transducer leads were brought after tinning with solder. The jacket area surrounding the lead holes was roughened and then sealed with Elmer's clear epoxy. The transducer leads were then soldered to a pre-wired piston, whose leads were brought out of the pressure vessel (Figure 3) and connected as in the wiring diagram (Figure 4).

The Berea specimens were confined at 50 bars effective pressure and the Coconino/Tennessee specimens were confined at 500 bars effective pressure. In all experiments, the strain rate was 10^{-5}/sec. One transducer was driven for each loading experiment and the output of the opposing transducer was amplified, filtered, and displayed on the oscilloscope. Photographs of the arriving wave were taken at discreet

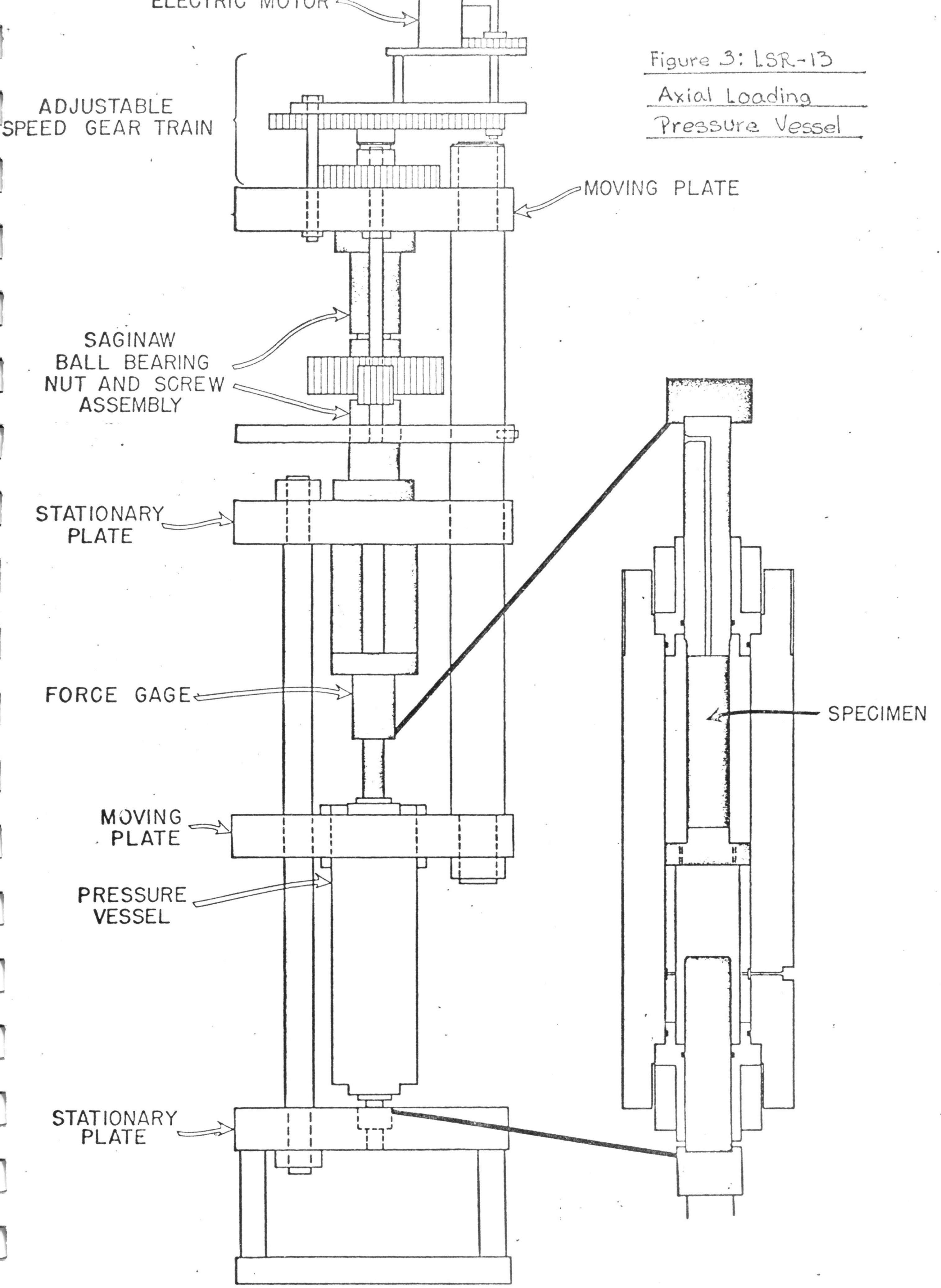


Figure 3: LSR-13
Axial Loading
Pressure Vessel

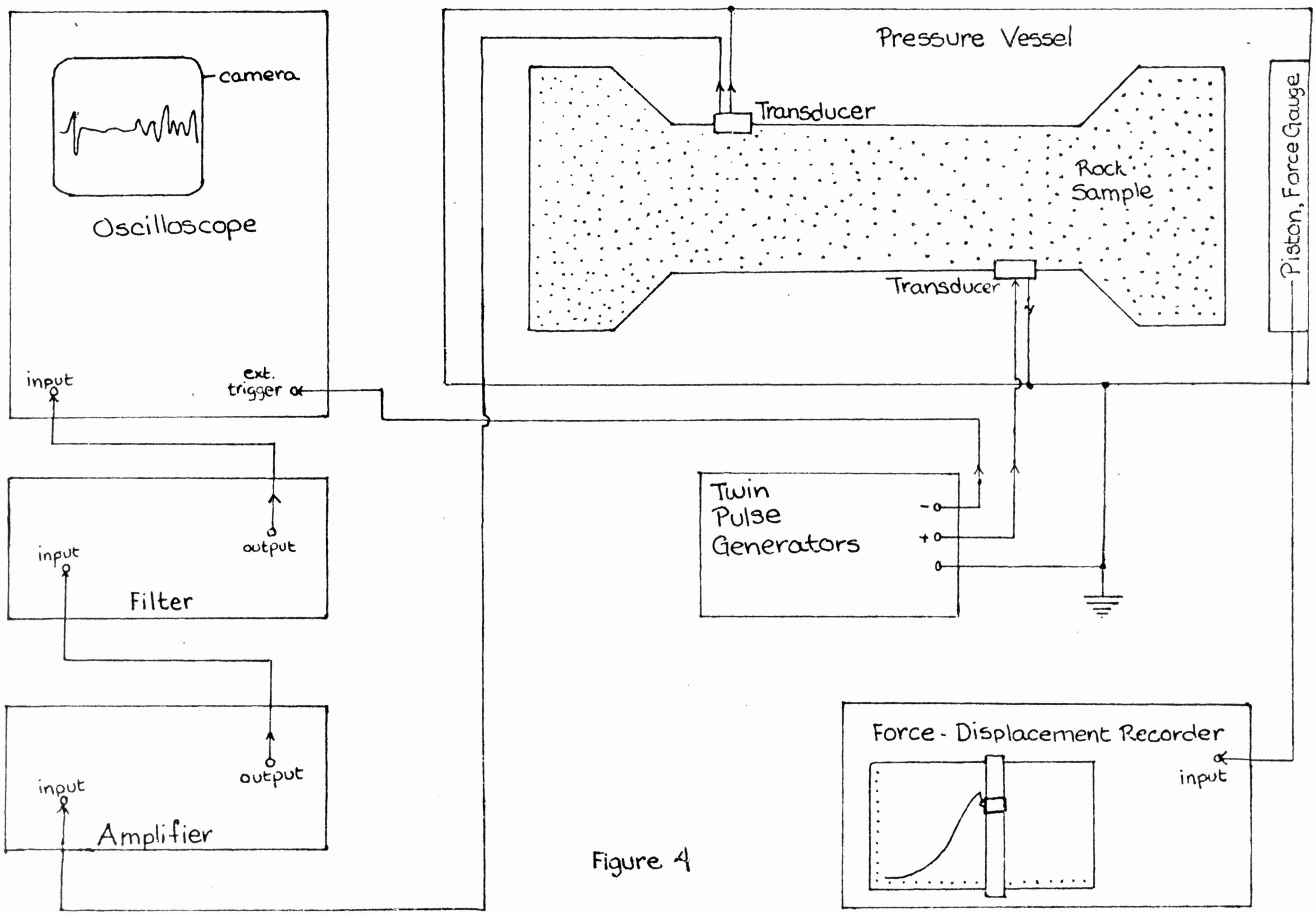

camera
Oscilloscope
input
ext.
trigger
Pressure Vessel
Transducer
Rock
Sample
Transducer
Piston, Force Gauge
Twin
Pulse
Generators
-
+
input
output
Filter
input
output
Amplifier
Force - Displacement Recorder
input

Figure 4

points of the force/displacement curve (an example of such a photograph is shown in Appendix 1). Loading was temporarily discontinued at the time of each photograph to insure clarity of the picture. The arrival time of the direct primary wave corresponds to the first break of the arriving wave train. The resolution of the p-wave train was not great enough to separate it from the shear wave but qualitative observations were made.

RESULTS

Four loading experiments were completed, two examining the pre-fracture dilatancy of Berea sandstone and two examining stick-slip dilatancy between Coconino and Tennessee sandstones.

Berea sandstone is known to exhibit dilatancy beginning at about one half of the fracture stress (Figure 5) (Jamison, personal communication). From the plots of the velocity data for the dry and saturated specimens, relative to the displacement (Figure 6), the velocity of the compressional seismic wave is seen to decrease from 2.92 km/sec dry and 2.90 km/sec saturated with the onset of dilatancy. The decrease continues to 2.88 km/sec dry and 2.86 km/sec saturated with increased piston displacement (proportional to increased load). A major drop, averaging .255 km/sec, in Vp occurs consistently at 4.06×10^{-3} inches of displacement prior to the recorded fracture (indicated by the stress drop). The only notable difference between the behavior of the p-wave velocity for dry and saturated Berea specimens is the initial velocity difference of 1.86 km/sec dry versus 2.82 km/sec saturated when the rock is under confining pressure but no axial load. In the dry case the confining pressure was 50 bars, while in the saturated specimen the confining pressure was 150 bars. (The saturated specimen contained fluid at a pore pressure of 100 bars so that effective pressure was then 50 bars in either case.)

Notable also are the amplitude changes in the wave train back of the first arrival. The amplitudes tended to increase with piston displacement and then fall off at the same time the p-wave velocity decreased.

Figure 5. Number of pore pressure pump handle turns necessary to maintain constant pore pressure in saturated Berea sandstone under increasing axial load. Influx of pore fluid indicates increasing pore volume or dilatation. Note that two pump handle turns are equivalent to a change in the specimen's volume by .210 cc (Jamison, personal investigation).

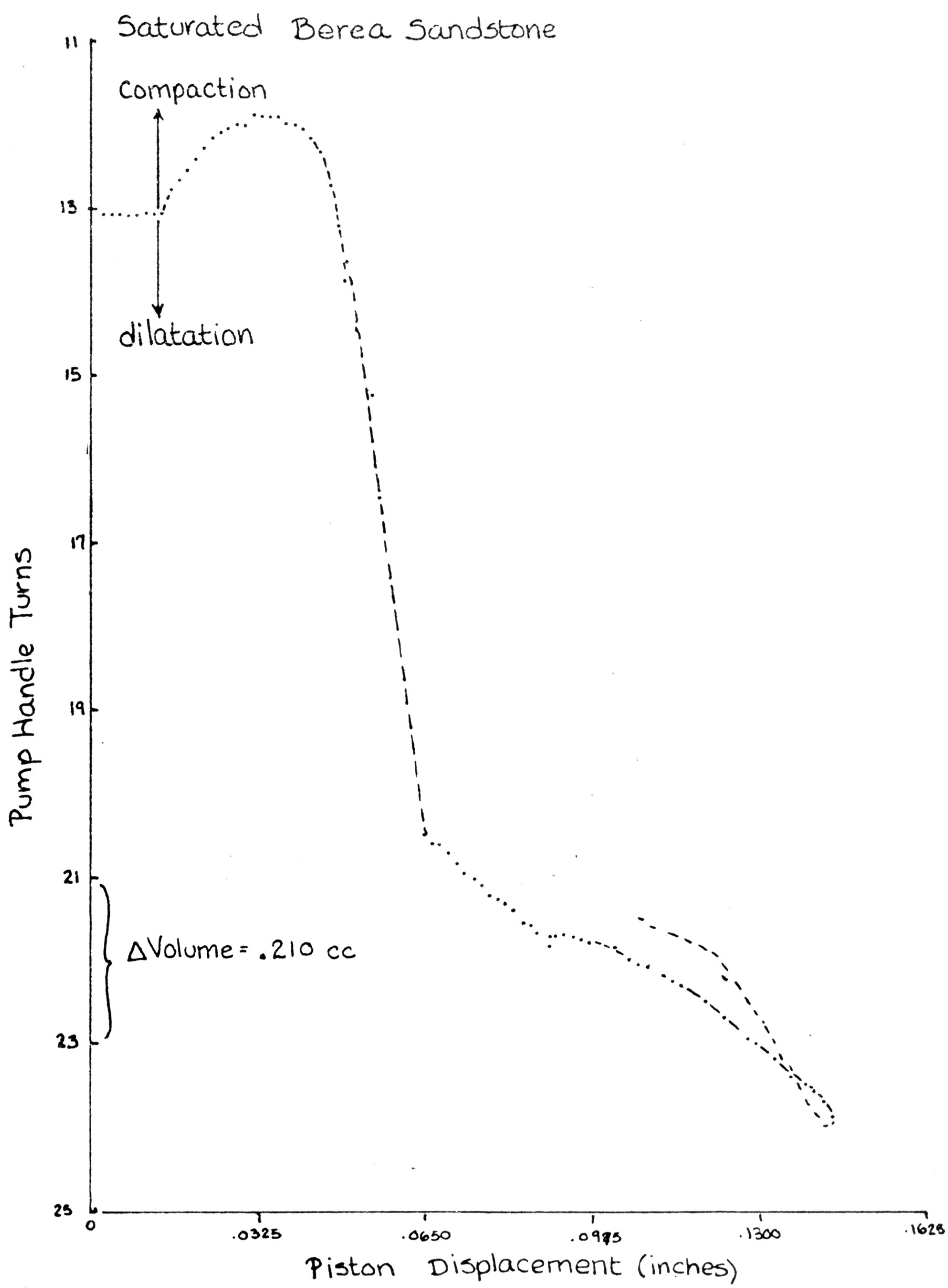

Saturated Berea Sandstone
Compaction
dilatation
ΔVolume = .210 cc
Pump Handle Turns
11
13
15
17
19
21
23
25
0
.0325
.0650
.0975
.1300
.1625
Piston Displacement (inches)

Figure 5

<u>Figure 6</u>. Changes in p-wave velocity (dotted line) with axial loading (i.e., piston displacement) relative to position on the force-displacement curve (solid line) for solid Berea sandstone under dry and saturated conditions.

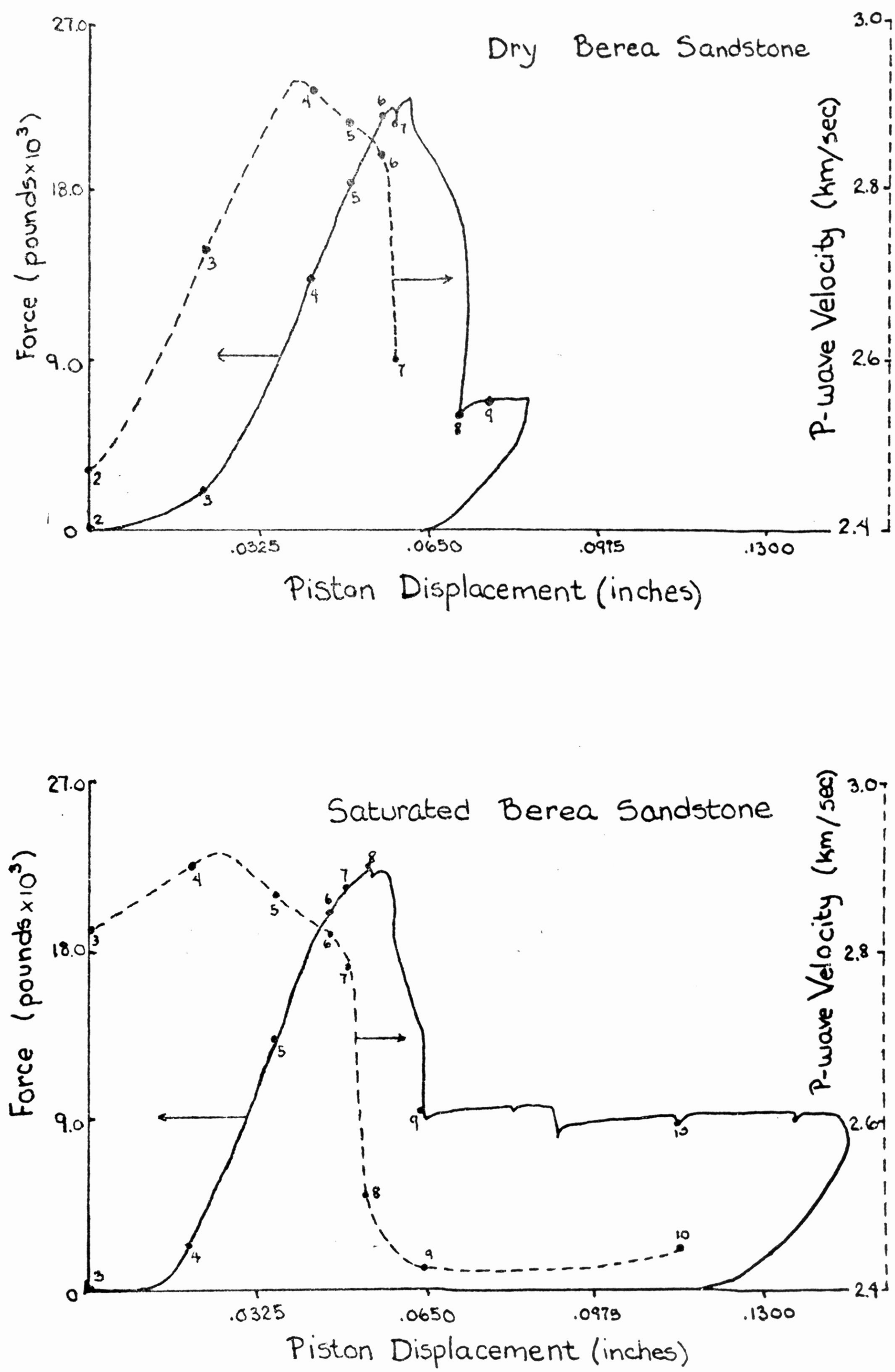

Dry Berea Sandstone
Force (pounds×10³)
P-wave Velocity (km/sec)
Piston Displacement (inches)
27.0
18.0
9.0
0
3.0
2.8
2.6
2.4
.0325
.0650
.0975
.1300
Saturated Berea Sandstone
Force (pounds×10³)
P-wave Velocity (km/sec)
Piston Displacement (inches)

Figure 6

Lastly, cursory thin section examination of the fracture surface shows very little microfracturing along the surface (Jamison, personal communication).

The Coconino sandstone was combined with Tennessee sandstone in an effort to measure velocity behavior due to stick-slip dilatancy. Consistent stick-slip was achieved for both dry and saturated configurations and pore pressure changes indicate dilatancy did occur (Figure 7). The compressional velocity, however, did not exhibit any changes after the axial load was applied, regardless of the position on the individual stress cycle (Figure 8).

Figure 7. Changes in pore pressure with increased axial load on saturated Coconino over Tennessee sandstones. Increased pore pressure indicates dilatant behavior (Teufel, personal investigation).

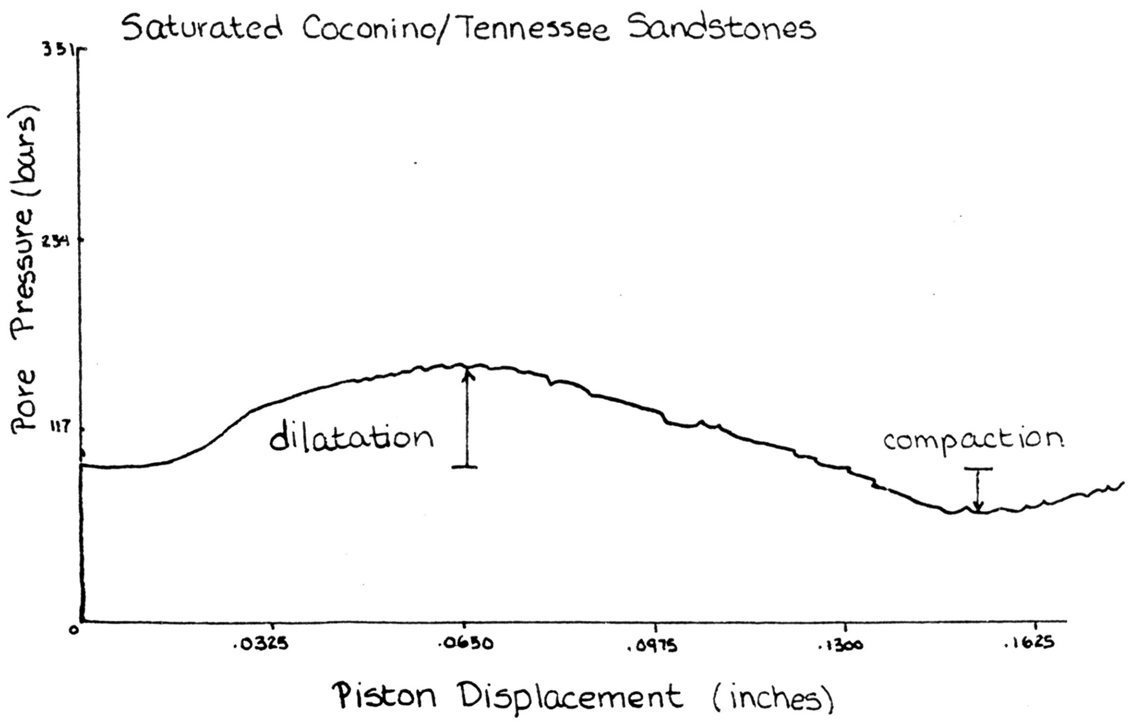
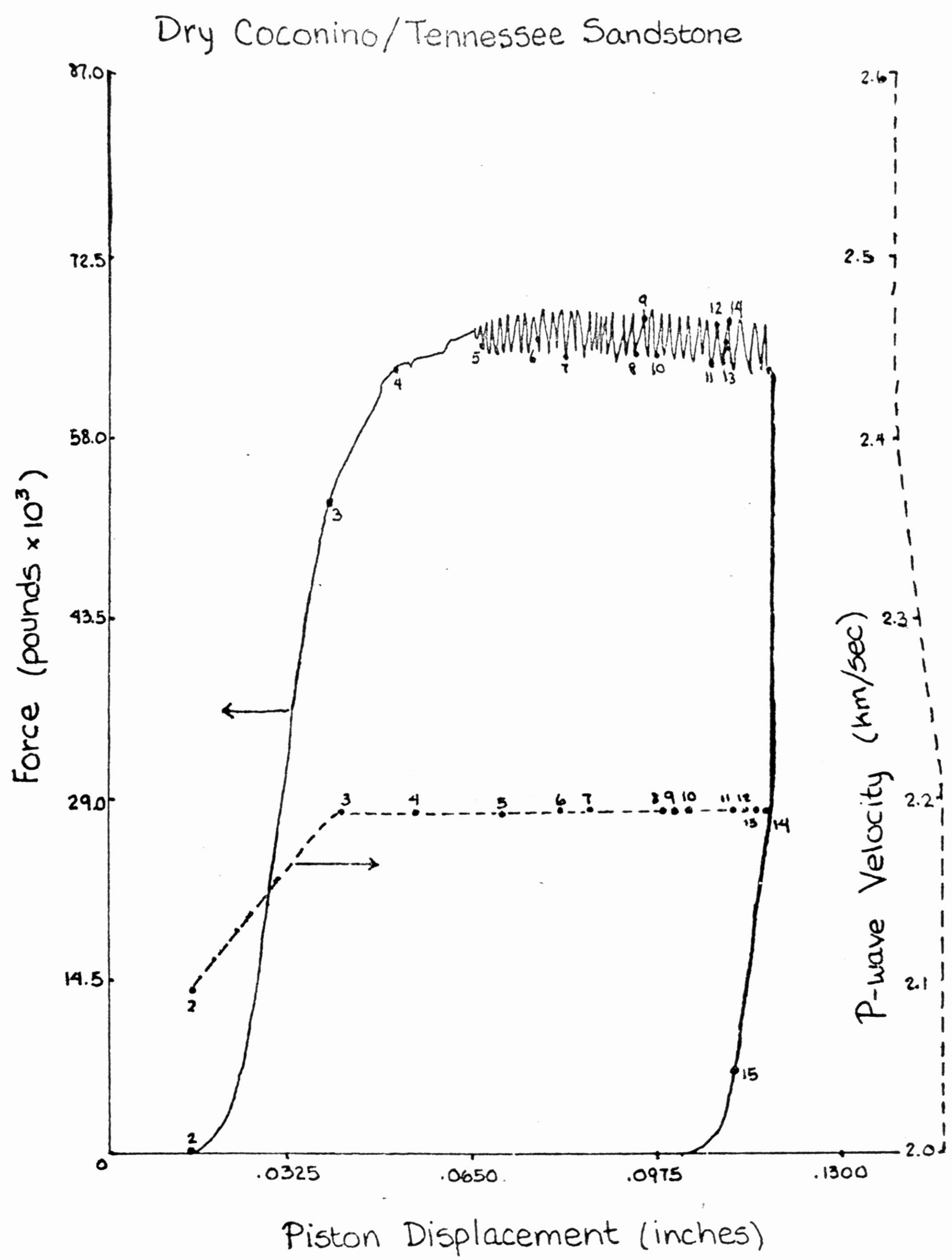

Saturated Coconino/Tennessee Sandstones
351
234
117
0
Pore Pressure (bars)
dilatation
compaction
.0325
.0650
.0975
.1300
.1625
Piston Displacement (inches)

Figure 7

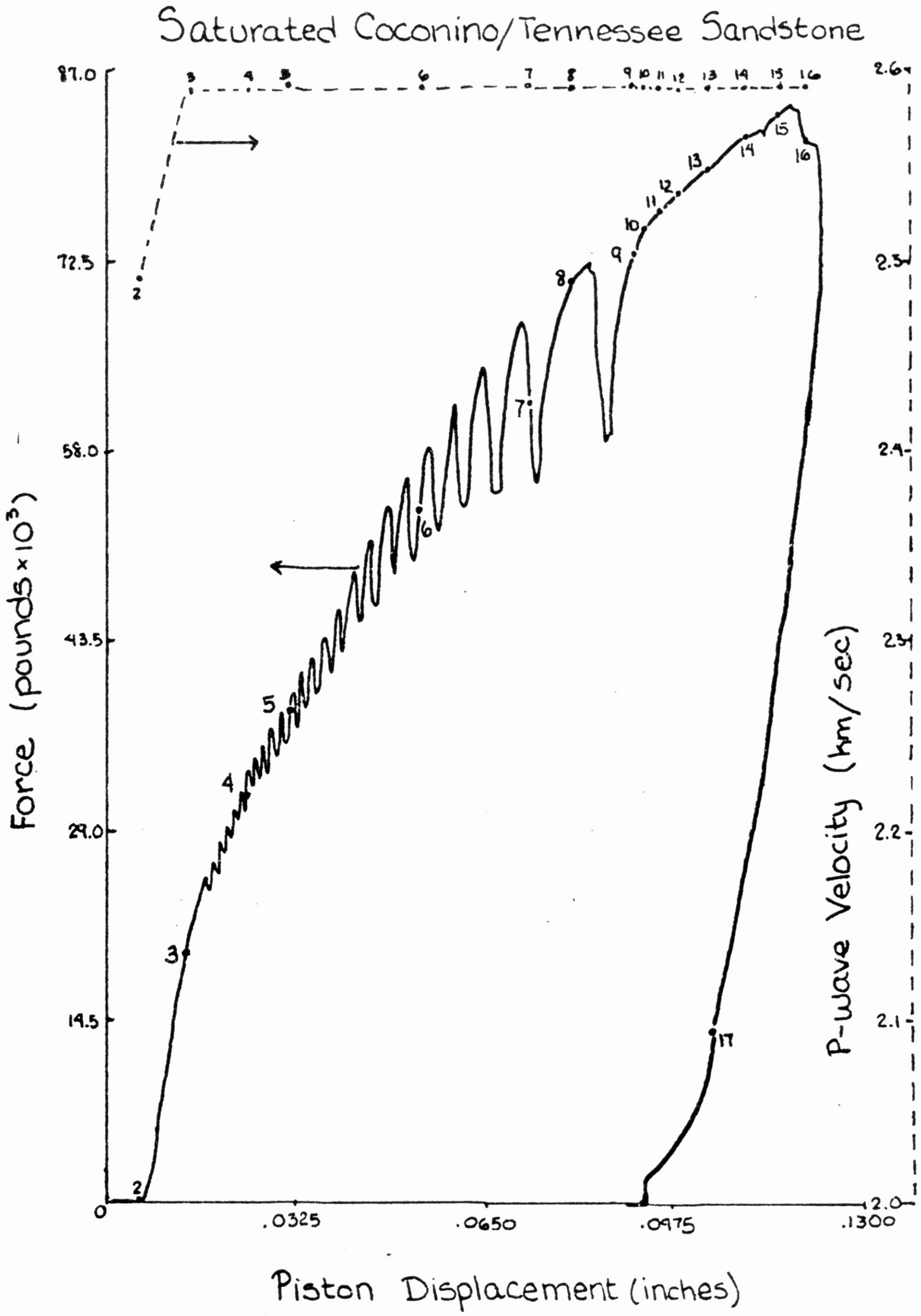
Figure 8a. Changes in p-wave velocity (dotted line) with axial loading (i.e., piston displacement) relative to position on the force-displacement curve (solid line) for sawcut Coconino over Tennessee sandstones under dry conditions.



Dry Coconino/Tennessee Sandstone
87.0
72.5
58.0
43.5
29.0
14.5
0
Force (pounds x 10^3)
2.6
2.5
2.4
2.3
2.2
2.1
2.0
P-wave Velocity (km/sec)
.0325
.0650
.0975
.1300
Piston Displacement (inches)

Figure 8a.

Figure 8b. Changes in p-wave velocity (dotted line) with axial loading (i.e., piston displacement) relative to position on the force-displacement curve (solid line) for sawcut Coconino over Tennessee sandstones under saturated conditions.



Saturated Coconino/Tennessee Sandstone
Force (pounds × 10³)
P-wave Velocity (km/sec)
Piston Displacement (inches)
87.0
72.5
58.0
43.5
29.0
14.5
0
.0325
.0650
.0975
.1300
2.6
2.5
2.4
2.3
2.2
2.1
2.0

Figure 8b.

DISCUSSION

It appears, from this study, that there are no distinct differences between the behavior of compressional seismic velocities in dry and saturated rocks that are deformed under otherwise identical conditions. While shear wave velocities were not measured per se, changes in amplitudes of the wave train at later arrival times may indicate a superposition of the primary wave train over a time shifting shear wave train. This would produce a change in the ratio Vp/Vs with trends possibly differing from the Vp behavior plotted alone. While the data is not compelling, a few of the photographs indicate a shear wave whose velocity decreases more rapidly with load than does the compressional wave velocity. The ratio may, in fact, fall more steeply than does the Vp alone.

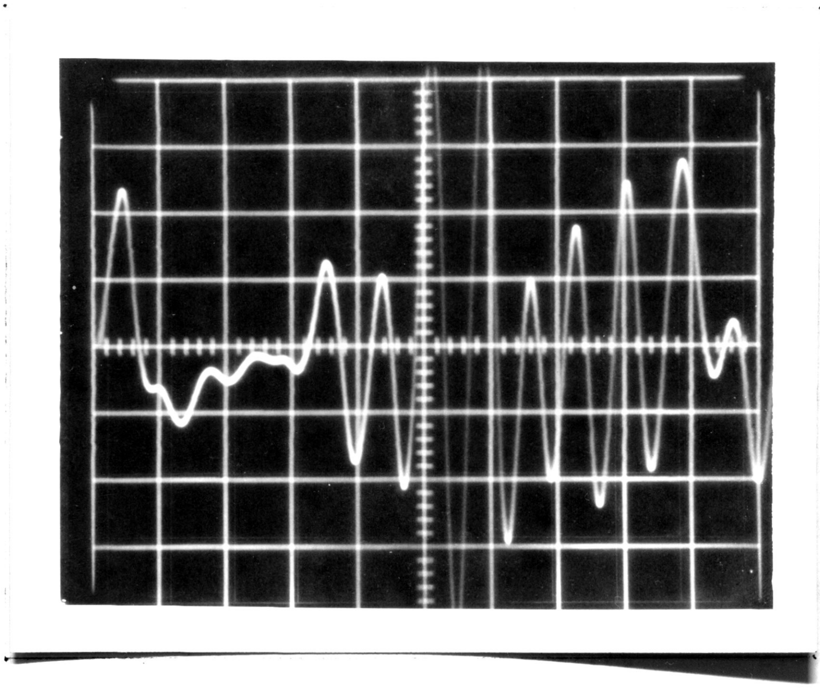
The lack of any dilatant velocity anomaly in the sawcut specimens indicates the zone of deformation is quite narrow relative to the transducer separation. Again, the consistency between the Vp plots indicates no dependency on pore fluids. The migration of pore fluids within a dilatant rock does not seem to enhance the velocity anomaly.

Considering the experiments of "Previous Studies" and the results of this study, it is evident that velocity behavior varies widely depending upon experimental objectives and techniques. None of these studies present a strong argument for a return of the velocity ratio prior to an earthquake. Moreover, there is growing doubt among some researchers that such a return is actually seen in the field data. It would appear that revision of the velocity ratio precursor model is necessary to bring it into accord with all the data available.

Perhaps equally as important as the above conclusion is the information attained from these experiments on the mechanics of rock failure. Until this time it was assumed that the rapid stress drop corresponded to the throughgoing fracture of the rock. The velocities and pore pressure measurements (Jamison, Master's research; Teufel, Doctoral research) indicate a marked drop in both quantities immediately before the stress drop. This may be due to the coalescence of enough microcracks to allow grain boundary slip and cataclasis along the plane of the fracture before the actual failure. It is possible that this behavior was not noted in previous experiments because of the type of specimen used. Crystalline rocks such as granites and granodiorites are not likely to suffer cataclasis prior to fracture.

SUMMARY

The compressional wave velocity is found to decrease with an increase in pore volume of a rock under dilatant strain. The decrease in Vp is independent of the presence or absence of pore fluids in the rock, therefore water is not a necessary constituent in the velocity anomaly earthquake precursor model. The rate of decrease in Vp increases sharply just before the stress drop in both the dry and saturated specimens, reflecting possible cataclasis and grain boundary slip characteristic of creep prior to fracture in soft sedimentary rocks.



Typical compressional wave arrival in dry Coconino/Tennessee sandstones under 500 bars confining pressure.

Point on Force-Displacement Curve	First Signal Peak (μ sec)	First Arrival Peak (μ sec)	t_p (μ sec)	V_p km/sec (1)
1. Dry Solid Berea	dt = 5.16 cm.			
1	2.75	31.00	28.25	1.86
2	2.75	24.00	21.25	2.47
3	↓	22.00	19.25	2.73
4		20.75	18.00	2.92
5		21.00	18.25	2.88
6		21.25	18.50	2.84
7		23.00	20.25	2.60
8 } 9 }	2.75	no clear first arrivals - transducers were separated from rock by fracture		
2. Saturated Solid Berea		dt = 5.16 cm.		
1	3.00	amplitude too low to observe accurately		
2	↓	20.25	17.25	2.99 *
3		21.00	18.00	2.82
4		20.50	17.50	2.90
5		20.75	17.75	2.86
6		21.00	18.00	2.82
7		21.25	18.25	2.78
8		23.25	20.25	2.51
9		24.00	21.00	2.42
10	3.00	23.75	20.75	2.45
11	marked decrease in amplitude invalidates this pt's data			

* Pc but no Pp applied

Point on Force-Displacement Curve	First Signal Peak (μ sec)	First Arrival Peak (μ sec)	t_p (μ sec)	V_p km/sec (1)
3. Dry Sawcut Coconino/Tennessee		dt = 6.73 cm.		
1	2.25	amplitude too low to distinguish first arrival		
2	↓	18.25	16.00	2.10
3	↓	17.50	15.25	2.59
↓	↓	↓	↓	↓
14	2.25	17.50	15.25	2.59
4. Saturated Sawcut Coconino/Tennessee		dt = 6.73 cm.		
1	2.25	amplitude too low to distinguish first arrival		
2	2.25	15.75	13.50	2.49
3 **	1.50	15.25	13.75	2.59
↓	↓	↓	↓	↓
16	1.50	15.25	13.75	2.59

(1) $V_p = \frac{d_t}{t_p}$ where: d_t = transducer separation
t_p = travel time of first arriving wave (direct p-wave)

(Transducer separations used in calculation varied between specimens)

** oscilloscope adjusted at this point

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