low-temperature continental weathering (from rivers).

This leads to the intriguing possibility that the ratio of germanium to silicon buried in siliceous oozes on the sea floor provides a continuous geologic record of variations in the relative rates of chemical weathering of the continents and hydrothermal weathering of the sea floor, processes which control the fluxes of the major cations and anions through the oceans (*11*). Since virtually all silicon and presumably all germanium brought to the oceans are removed with siliceous tests, changes in the Ge/Si ratio buried in opal would reflect contemporaneous changes in the fluxes of elements through the oceans. An understanding of such variations would help us to understand the geological history of seawater and the controls on its geochemical composition (*12*).

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# Lateral P-Velocity Gradients near Major Strike-Slip Faults in California

*Abstract*. *The P-wave velocity in shallow crystalline rock decreases systematically from a normal value of about 5.5 kilometers per second 20 kilometers or more from the Garlock and San Andreas faults to less than 3 kilometers per second at distances of less than 2 kilometers from these faults. This lateral velocity gradient closely resembles the shear stress profile. It is proposed that the velocity gradient results from increased fracturing nearer these major strike-slip faults and that this fracturing dominates the response of the shallow crust to tectonic stress.*

Granitic rocks in situ often exhibit compressional wave velocities ($V_p$) significantly different from velocities in laboratory specimens of otherwise identical rocks. Values of $V_p$ in situ are often lower because of joints or fractures too large or pervasive (not appropriately modeled by a single saw-cut) to deal with in standard laboratory measurements (*1*, *2*). Interpretation of crustal $V_p$ in terms of stress, fluid saturation, or other rock properties related to earthquake prediction research is hampered by the low resolution of most surface refraction methods. Some authors (*3*) have recognized the difficulty in explaining the difference between their layered crustal models and the velocity structure predicted by laboratory measurements. Even when a vertical gradient similar to $V_p$ dependence on pressure observed in the laboratory is used to fit surface refraction data, $V_p$ rises (at least in the Gabilan Range of central California) more gradually with depth than is predicted by microcrack closure (*4*). Shear wave velocities ($V_s$), which could provide information regarding the mechanism (undersaturation or fracturing?) responsible for the low $V_p$ in situ, are not routinely measured during most crustal velocity studies.

We measured travel times between a surface source and a three-component Geophone package lowered into boreholes in granitic rock of the Mojave Desert of southeastern California (Fig. 1). Boreholes allow good depth interrogation from modest source energy as well as relatively low ambiguity in resolving velocity as a function of depth. Also, $V_s$ is more easily measured in boreholes than by refraction spreads. The nine boreholes, ranging in depth from 80 to 140 m, had been drilled as part of a U.S. Geological Survey (USGS) heat flow study (*5*).

We set up a weight-drop source for P waves 3 m from the borehole. The recording truck was parked on a railroad tie, also 3 m from the borehole. Hammer blows on opposite ends of this timber provided reversed polarity shear waves (*6*). Our Geophone package was lowered in 5- or 10-m increments to detect waves generated by two to four weight drops and two or three hammer blows of each polarity. Reference Geophones placed near the center of the railroad tie and near the weight-drop impact point provided time breaks. Records were made at a paper speed of 40 cm/sec, with 10-msec timing lines. Our amplifier and camera were designed for exploration refraction studies, so high-frequency components were not recorded. Since the timing errors (±1 to 2 msec) were too large for us to compute $V_p$ from travel-time difference at such short (5 or 10 m) depth intervals, the travel time–depth data were fit with smooth functions and the time derivative taken to obtain a velocity-depth curve.

A variety of functions were tested for their ability both to fit our data and to predict reasonable velocities when extrapolated to greater depths. Linear regression (intervals of constant velocity) fit the travel time–depth data as well as functions involving a vertical velocity gradient (linear term with a decaying exponential), except for borehole GAR, where a gradient fit is better. Borehole GAR is the deepest but exhibits the lowest $V_p$ of the nine holes studied. Longer travel times resulting from low $V_p$ and greater depth lessen the relative influence of the timing errors. Future studies with better recorders and deeper boreholes should resolve the $V_p$ gradient in shallow crystalline rocks.

Although we were unable to show statistically which of the functions tested provided a superior fit to our travel time–depth data (*7*), such details are not important for this report. The scatter in bottom-of-hole (BOH) $V_p$ from well to well retains the general pattern shown in Table 1 for all functions tested, with a difference in $V_p$ between the slowest and the fastest wells of at least 2.5 km/sec.

The $V_p$ values ranged from about 5.5 km/sec, comparable to velocities reported for laboratory specimens of granitic rock, to 3.0 km/sec, with a scatter of intermediate values (Table 1). We ascribe $V_p$ values lower than that typical of laboratory measurements to fracturing


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Table 1. Data on nine boreholes studied by Zappe (7). Values are given for $V_p$ at bottom of hole (BOH) and at a depth of 70 m. The distance from the nearest trace of the Garlock fault is Δ. The $V_p/V_s$ shown is the lower bound on allowable $V_p/V_s$ values; $V_p/V_s$ is listed only for wells where clear reversed polarity events permitted unambiguous timing of the S-wave arrival. Lack of a downhole clamping device and orientation control seriously hampered our ability to consistently record shear waves.

| Well | Depth (m) | $V_p$ (km/sec) | | Δ (km) | $V_p/V_s$ |
|---|---|---|---|---|---|
| | | BOH | 70 m | | |
| | | *Garlock fault* | | | |
| GAR | 152 | 2.96 | 2.57 | 1.8 | 2.0 |
| LMT | 106 | 4.88 | 4.88 | 7.9 | 1.77 |
| SPH | 101 | 4.40 | 3.48 | 9.1 | |
| CBL | 76 | 5.52 | 5.37 | 24.0 | |
| FPK | 102 | 5.49 | 5.49 | 24.4 | |
| | | *Eastern Mojave* | | | |
| HHL | 138 | 4.27 | 3.21 | N.A.* | |
| SMS | 107 | 5.23 | 5.21 | N.A. | 2.16 |
| TPK | 102 | 3.74 | 3.69 | N.A. | 1.85 |
| YGR | 102 | 5.16 | 5.10 | N.A. | |

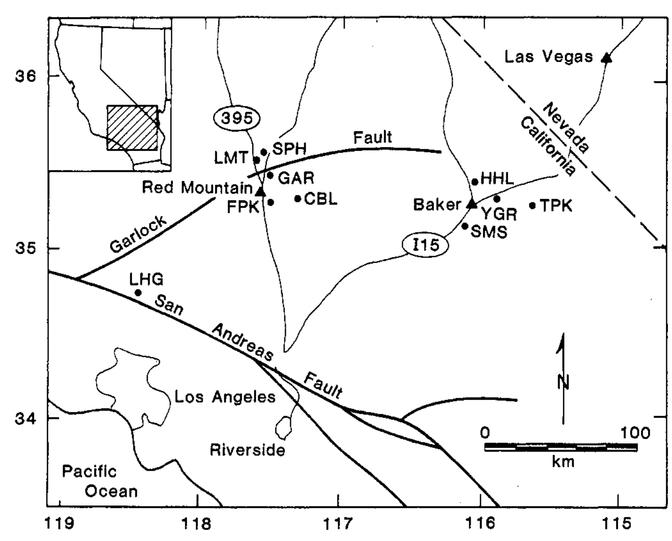
*Not applicable.

rather than undersaturation or weathering for several reasons. Wells for which we obtained good S-wave arrivals exhibited $V_p/V_s$ of 1.77 or higher (Table 1). Undersaturated rocks should yield lower $V_p/V_s$ values. Although we failed to obtain high-quality shear waves in most wells, other observations suggest that the rocks near low-$V_p$ wells contained water. Phreatophytes noted near low-$V_p$ wells (GAR, TPK) were more successful than those near high-$V_p$ wells (FPK, CBL, SMS). Although these plants may lower the water table somewhat, lack of oxygen probably attenuates root development below 10 to 20 m in all but the most porous soils. Springs near TPK offer additional evidence of saturation at fairly shallow depths. Thin sections of chips from drilling debris near the boreholes, as well as rocks in outcrops or adits near the wells, show that little alteration of minerals has occurred.

Low P-wave velocities have been correlated with fractures in boreholes by Stierman and Kovach (8) and Zoback *et al.* (9). Sjøgren *et al.* (10) quantitatively related fracture density with $V_p$ over a range of 3.0 km/sec (19 cracks per meter) to 5.5 km/sec (3.5 cracks per meter). Evidence is mounting that discrepancies between the low $V_p$ measured in situ and the $V_p$ measured in the laboratory are due to the fractures present in situ but absent in laboratory specimens.

The five boreholes studied in the northwest Mojave (Fig. 1) show an apparently systematic decrease in $V_p$ approaching the Garlock fault (Fig. 2). The $V_p$ values remain well below 5 to 5.5 km/sec, the low range for $V_p$ in "normal" granites, out to 12 to 20 km. Beyond 20 km, $V_p$ in very shallow rocks approaches 5.5 km/sec, the P-wave velocity Kanamori and Hadley (11) assign to the upper 4 km of the crust of the Mojave Desert. We do not think that this lateral gradient is fortuitous. Values of $V_p$ measured in four boreholes drilled into granitic rock and along one refraction line interrogating shallow granite, plotted as a function of distance from the San Andreas fault, exhibit a similar pattern (Fig. 2). In general, the shallower boreholes (GBS) fall below our curve, while deeper wells (STC, LHG) exhibit slightly higher $V_p$'s. This is consistent with a vertical velocity gradient (9) and is not surprising.

Velocities measured in four eastern Mojave Desert locations vary from 3.7 to 5.2 km/sec at bottom of hole. Low velocities at HHL might be considered evidence for eastward extension of the Gar-



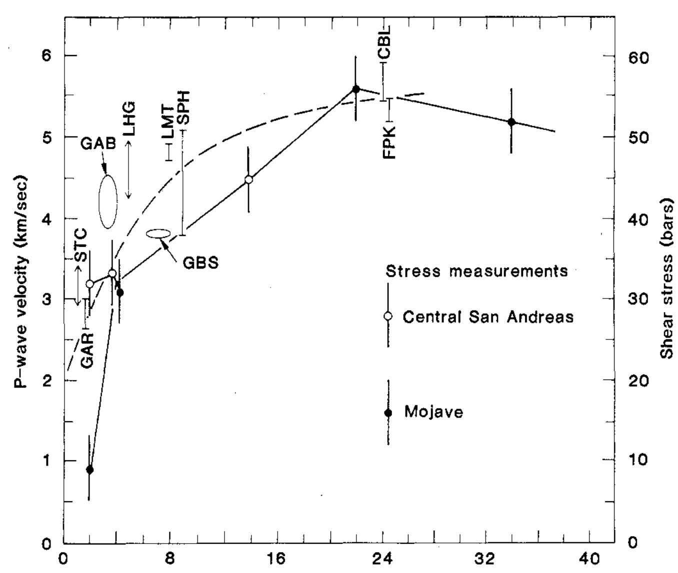




Fig. 1 (left). Index map showing location of wells. Fig. 2 (right). P-wave velocity as a function of distance from the Garlock fault (GAR, LMT, FPK, CBL, SPH) and the San Andreas fault [STC (8), GBS (15), LHG (Lake Hughes), GAB (4)]. Bars show the range of $V_p$ at bottom of hole for different velocity-depth functions tested (7) for Garlock fault wells. GBS represents two 30-m-deep boreholes at Frenchman's Creek and El Granada (15). STC and LHG show the range of $V_p$ measured by sonic logging tools in boreholes from depths of 50 to 600 m. GAB shows shallow $V_p$ (within 200 m of the surface) defined by a refraction line in the Gabilan Range, central California (4). The dashed curve is a fit of $V(\Delta) = V_f - Ve^{-a\Delta}$ to the composite data (entire range of reasonable $V_p$ at bottom of hole) from the five Garlock wells; $V_f$ and $a$ are constants, and $V$ is the difference between $V_f$ (the distant velocity) and the measured velocity $V(\Delta)$. The values $V_f$ = 5.65 km/sec, $V$ = 3.63 km/sec, and $a$ = 0.151 km$^{-1}$ fit with a correlation coefficient of .93. This curve is nearly identical to the fit to $V_p$ at 70-m depth ($V_f$ = 5.57, $V$ = 3.43, $a$ = 0.155, correlation coefficient = .98). Shear stress is plotted as a function of distance from the San Andreas fault as reported by Zoback *et al.* (16) for central California and the Mojave Desert.

lock fault, but no such explanation can be invoked for TPK. Scatter in these control data indicates that the lateral P-velocity gradient may extend only a few (~ 2) kilometers rather than the 20-km upper limit suggested by the data from locations near major faults. If boreholes GAR and STC are discarded from Fig. 2 on the assumption that they are possibly within the fault zone proper, the significance of the low velocities at LMT, SPH, LHG, GAB, and GBS with respect to the high velocities at FPK and CBL is not compelling evidence that a lateral velocity gradient exists over the 20-km range from the faults. Even if this zone of fractured rock extends only 2 km (rather than 20 km) beyond the mapped active trace and gouge zones of the San Andreas and Garlock faults, it is a significant, and seldom reckoned with, component of our major faults.

A major structure such as the fault-controlled band of fractured rock that we postulate from our $V_p$ studies, extending 2 to 20 km from major faults, has profound implications for earthquake prediction research and other crustal studies conducted in this zone. The lateral fracture gradient that we infer from our $V_p$ gradient may control the decrease in shear stress reported by Zoback and Roller (*12*) approaching the San Andreas fault near Palmdale (Fig. 2). The similarity between the $V_p$ and stress curves (Fig. 2) suggests some relation between $V_p$ and stress. The increase in maximum horizontal stress ($\sigma_1$) with distance from the fault may increase $V_p$ by holding closed more cracks and fractures (*13*). On the other hand, increased fracturing nearer the fault may allow this zone to adjust more easily to stress changes, placing a limit on the amount of strain near-surface rocks may accumulate before the fractures accommodate the stress. Chan *et al.* (*14*) attribute large discrepancies between observed and predicted strains (and the inferred stresses) during heating experiments in hard granite to expansion of the rock into preexisting fractures. Similar adjustments probably occur in fractured rock as tectonic stress gradually increases.

Many experiments conducted in search of earthquake precursors are located within 10 km of major faults, possibly within this zone of fractured rock. Strain and tilt, changes in ground-water levels or radon emission rates, anomalies in electrical measurements or seismic wave propagation, and perhaps other phenomena reported as possible earthquake precursors should be sensitive to changes in these fractures as the crust responds to a changing strain field. Lateral rigidity gradients and anisotropy in these fractured rocks contribute additional complexity. If dilatancy occurs prior to earthquakes, it is probably confined to fractures adjacent to the fault rather than distributed through the more competent crustal rocks at greater distances. We must, at the very least, unravel the seismic velocity structure of fault zones if we are to properly monitor and interpret velocity variations prior to earthquakes. On a broader scale, geophysical measurements near major faults should probably be interpreted in terms of the physical properties of fractured rocks rather than the properties of laboratory samples.

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## Generation of Stabilized Microbubbles in Seawater

Abstract. *Bubbles of less than 1 micrometer and as large as 13.5 micrometers in diameter, stabilized by an apparent compression of substances sorbed onto their surfaces, were examined to determine their physical and temporal stability. Their ease of formation is related to the qualities of the water in which they are formed. Their presence in the water column must now be considered when interpreting acoustic data gathered to determine marine bubble populations.*

Marine bubble populations inferred from acoustic measurements are sometimes very large, strikingly anomalous, and impossible to interpret in terms of conventional mechanisms explaining bubble formation and loss (*1, 2*). We believe that these large and relatively persistent populations are due to the presence of stable microbubbles, which are a common feature of the near surface region of the oceans and of many aqueous systems.

There is previous evidence for the existence of stable microbubbles. Degens (*3*) found 1-μm hollow spheres as suspended particles in Lake Kivu, East Africa, and suggested that such spheres might be precursors of primordial cells. He concluded that the spheres result when bubbles, forming deep in the remarkable Lake Kivu waters, become coated with resinous materials that are subsequently stabilized by metal ion complexing.

Minute bubbles stabilized by encapsulation in an organic film have long been invoked to explain low thresholds for ultrasonic cavitation in liquids (*4*). The possibility that stable microbubbles are present in the bloodstream and act as nuclei for the formation of larger bubbles has been suggested to explain decompression sickness in scuba and deep-sea divers (*5*). While small bubbles are certainly favored in energetic terms as nuclei for the formation of larger bubbles, many investigators of the physics of nucleation have assumed that gas nuclei exist only in the crevices of hydrophobic surfaces (*6, 7*). We now present a photographic record of the formation of stable spherical microbubbles and report their temporal and mechanical stability in samples of natural seawater.

In preparation for each experiment, 2 liters of seawater from the Dalhousie University Aquatron seawater inlet were filtered through preoxidized glass fiber filters (Gelman Sciences, model GFD) and then partially degassed under vacuum. The water was then stirred for 10 hours in a shallow bath maintained at

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