Table 1. Analyses of soil from prehistoric agricultural community.

Sample No.	Clay content (%)	Total soluble salts (%)	*p*H	Organic carbon (%)	K^+ (ppm)	NO_3 (ppm)	PO_4 (ppm)
1	6.4	0.1045	8.31	1.005	866	2211	56
2	1.8	.1192	8.80	1.162	920	3563	78
3	4.4	.1275	8.65	2.380	812	5237	83

that the alignments are the result of agricultural activity. Analysis of soil samples taken from depths at 5 to 10 cm in the rows between ash ridges (Fig. 1*d*) revealed five grains of maize (*Zea*) pollen in a total of 314 fossil pollen grains (*1*). A sample from the soil beneath an adjacent ash ridge in this area contained a single grain each of maize (*Zea*) and squash (*Curcurbita*) pollen in a total of 323 fossil grains. Soil samples were obtained (i) between the ash ridges in the investigated agricultural plots, (ii) under the ash ridges, and (iii) in an undisturbed control plot about 300 m south of the linear features. Of the three samples, the one from between the ash ridges (sample 1) has the highest clay content, the lowest total soluble salts, and the lowest *p*H, organic carbon, and nutrients. These data indicate an unusual degree of leaching or soil and vegetation disturbance, or both, conditions which would have been brought about by intensive cultivation (Table 1).

Sunset Crater, 22.5 km northeast of Flagstaff, Arizona, erupted in A.D. 1066 or 1067 (*2*), depositing a mantle of black ash and cinder over the area east of the San Francisco Peaks. The pyroclastic mantle, although virtually devoid of plant nutrients in an unweathered state, provided an effective soil cover that absorbed moisture while retarding evaporation. The "apparent" increased soil productivity led to an increase in population due to immigration (*2, 3*).

We found small habitation sites of four and five rooms within several hundred meters of all the linear features in the area shown in Fig. 1, and diagnostic potsherds were recovered from both the dwellings and the agricultural plots. The sherds indicate a Sinagua affiliation and an approximate date range of A.D. 1067 to 1200, that is, later than the eruption of Sunset Crater. The Sinagua, a regional cultural variant centered in the area east of Flagstaff, Arizona, is distinguished by its red or brown utility pottery constructed by the paddle and anvil technique, an extended burial position, and the incorporation of kivas into the dwelling room block.

Parallel borders of boulders outlining agricultural plots have been found at prehistoric and historic southwestern sites (*4, 5*). The Hopis use parallel lines of boulders to anchor brush so that spring winds will not remove the sand cover and damage the young plants (*5*). By analogy, low ash ridges may have provided an anchor for a brush fence, inasmuch as they are at right angles to the prevailing southwest wind; or they may have resulted from attempts to remove ash from areas where it was too deep for the young plants to penetrate the underlying soil.

The evidence from soil and pollen analysis, as well as analogies from historic and prehistoric sites, indicates the utilization of this site for agricultural activity. Thermal infrared images need to be evaluated over different climatic and edaphic zones. Data from the thermal infrared region may usefully supplement conventional aerial photographs (visible and near infrared spectra) which have been utilized in archeological research for a number of years.

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27 January 1969; 14 March 1969

High-Pressure Mechanical Instability in Rocks

Abstract. *At a confining pressure of a few kilobars, deformation of many sedimentary rocks, altered mafic rocks, porous volcanic rocks, and sand is ductile, in that instabilities leading to audible elastic shocks are absent. At pressures of 7 to 10 kilobars, however, unstable faulting and stick-slip in certain of these rocks was observed. This high pressure–low temperature instability might be responsible for earthquakes in deeply buried sedimentary or volcanic sequences.*

Mechanical instabilities are commonplace in solids (*1*) and include buckling of long columns, tensile failure of glass, and Lüders bands in mild steel under tension. For geologic materials, instabilities in compression are of special interest because, if they occur suddenly in the earth, they may be responsible for earthquakes. At a sudden instability, stress drops almost instantaneously, an elastic shock is produced, and elastic energy is radiated from the site of the instability. Although a number of such instabilities have been suggested as the cause of earthquakes, only brittle fracture (*2*) and stick-slip (*3*) have been observed in rocks in the laboratory. We now describe observations of unstable faulting and stick-slip under unexpected conditions and suggest their importance in earthquake studies.

On the basis of many laboratory studies of rock deformation (*4*), confining pressure is generally believed to increase ductility of rocks. In other words, as pressure is increased, the sudden instability associated with brittle fracture disappears and deformation occurs without sudden stress drops. This is not true for all rocks, however, for even at the highest pressures reached thus far (of the order of 11 kb), granite fails violently at room temperature at the strain rates and environmental conditions typical of laboratory experiments (*5*). Two classes of silicate rocks, namely, those that contain a large percentage of weak alteration

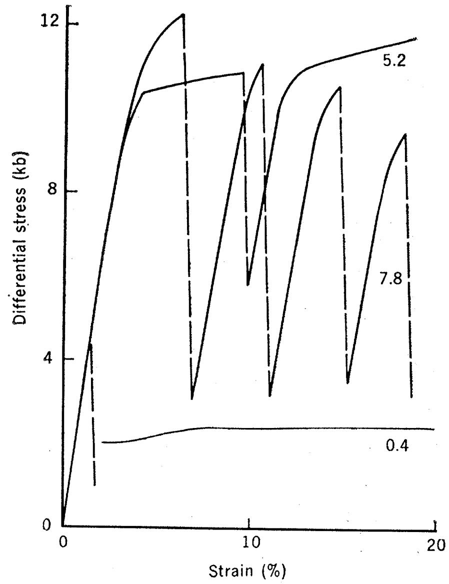

Fig. 1. Stress-strain curves for serpentinized gabbro as a function of confining pressure. The dotted portions of the curves are sudden stress drops. Pressures in kilobars are given by the small numbers at each curve. Temperature was 25°C and strain rate was 2.4×10^{-4} sec^{-1}.

minerals and those with a high porosity, do become ductile at pressures of the order of 5 kb or less (*6, 7*). It is usually assumed that, at still higher pressures, the behavior of these materials would continue to be free from instabilities. Our high-pressure experiments suggest that this assumption may not, in general, be valid.

Figure 1 shows the stress-strain curves at three confining pressures from triaxial experiments on gabbro from Nahant, Massachusetts. This rock has a low porosity and the minerals show extensive alteration to serpentine (*8*). At low pressure (0.4 kb) the material faulted unstably, as shown by the dashed line, at a differential stress of about 5 kb. At a pressure of 5.2 kb, the differential stress required to form a fault in this rock was equal to that required to cause sliding on the fault (*6*). The rock was ductile, deformation was more homogeneously distributed, and the cylindrical specimen assumed a barrel shape.

At a strain of about 10 percent, a fault formed, but after faulting the deformation became stable again. At a pressure of 7.8 kb, however, the rock became unstable, a fault formed after only a very small amount of permanent strain, and movement on the newly formed fault surface took place by stick-slip. A similar high-pressure instability was found during the deformation at a pressure of 8 kb of dunite from Spruce Pine, North Carolina (*9*). This rock also has a low porosity and the minerals have been altered to serpentine along their boundaries. At pressures between 2 and 8 kb the rock was ductile, but above 8 kb deformation was accompanied by sudden stress drops. Giardini *et al.* (*10*) reported similar behavior for Hardhat granite in which the minerals have been partly altered to chlorite and kaolinite. Stable faulting was observed for pressures from 1 to 5 kb; at higher and lower pressure, faulting was markedly unstable.

A compacted sand consisting of crushed granite also became unstable at high pressures. This is illustrated by the stress-strain curves (Fig. 2). At pressures up to about 7 kb, this material deformed stably even at strains as high as 30 percent. At pressures of about 8 kb and higher, deformation became unstable. A fault was formed and sliding on the fault surface took place by stick-slip. Another porous material, a sandstone, which had an initial porosity of about 15 percent, behaved in a similar way. Smith *et al.* (*11*) have reported sudden faulting in sandstone at high pressure.

Behavior analogous to that of our sand and porous sandstone was found for frictional sliding on fault surfaces produced in several dense unaltered silicate rocks. Figure 3 shows the stress-strain curves for Westerly granite at two confining pressures. At a pressure of 1.2 kb a fault formed with a sudden release of elastic energy, but sliding on the newly formed fault surface took place without any stress drops. At a pressure of 6.5 kb, however, sliding was by violent stick-slip. Apparently at low pressure the crushed material between the fault deformed stably. At higher pressure an instability occurred in this material in much the same way as in our sand and sandstone. Bridgman reported an effect (*12*) which may be related to the high-pressure instability reported here. A thin lens-shaped sample of a compound was sheared while being subjected to normal pressures as high as 50 kb. Some compounds sheared smoothly at all pressures; however, most of the minerals (mica, sillimanite, andalusite, graphite, and pyrite) sheared smoothly at low pressure and with a violent snapping at high pressure. Glass snapped at all pressures, whereas periclase, calcite, and limestone sheared smoothly at all

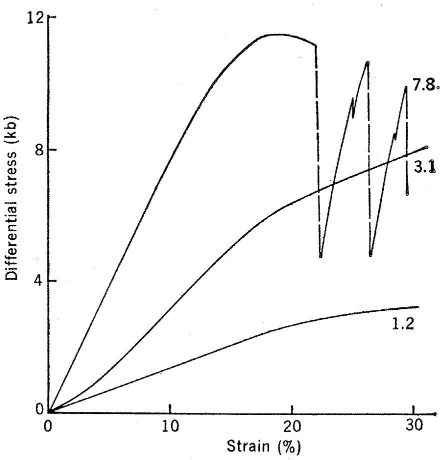

Fig. 2. Stress-strain curves for crushed granite as a function of confining pressure. Pressure in kilobars are given by small numbers at each curve. Temperature was 25°C and strain rate was 2.4×10^{-4} sec^{-1}.

pressures. Limestone showed no high-pressure instability, which is consistent with Bridgman's results and also those of Heard (*13*). Robertson (*14*) subjected another carbonate rock, dolomite, to pressures as high as 25 kb and found that this material also deforms stably at this high pressure. The snap-

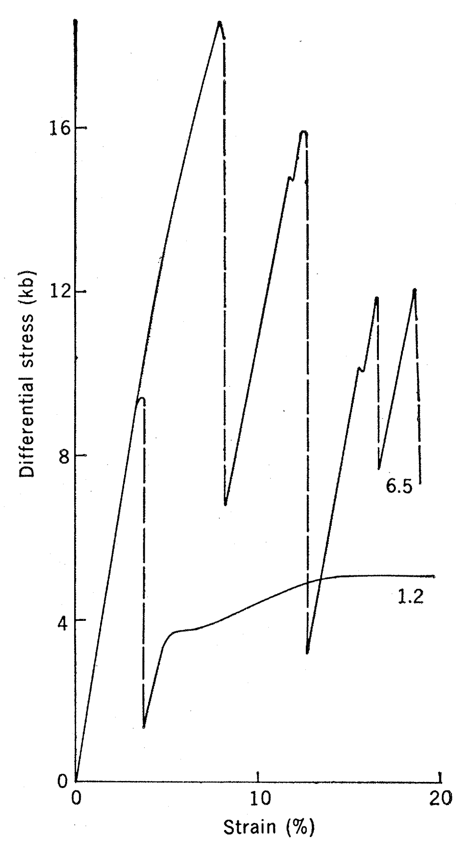

Fig. 3. Stress-strain curves for granite. Small numbers at each curve give pressure in kilobars. Temperature was 25°C and strain rate was 2.4×10^{-4} sec^{-1}.

ping observed by Bridgman in the silicates may have been a reflection of the same high-pressure instability that we have observed. Unfortunately, the two results cannot be quantitatively compared because of the difficulty in estimating the actual pressure in Bridgman's shearing experiments.

The observation that many silicates which deform stably at low pressures become unstable at high pressure raises a number of questions. It is not yet clear how faulting in this upper brittle region differs physically from that near atmospheric pressure; if the two are the same, then the intervening field of stability must be studied in even greater detail. The presence of weak alteration minerals or high porosity, or both, seems to be important but the detailed significance of these characteristics is far from clear.

The sudden instability at high pressure might, in the natural situation, produce earthquakes, although there are at least two major uncertainties in this extrapolation to the earth. The matter of scale needs further study; the samples we have studied are many orders of magnitude smaller than the natural counterpart. How should one scale stress drop, for example? Does a natural earthquake correspond to an audible stress drop in our experiments, or to one of the subaudible microfracturing events as described by Mogi (*15*), Scholz (*16*), and others? A second area of uncertainty is that of the effect on instabilities, at any scale, of the elasticity or stiffness of the surroundings. Although we found that an order of magnitude of variation in stiffness of the loading device had no effect on amplitude of stick-slip during frictional sliding (*8*), it is not known how variation in stiffness affects the stability of deformation in porous or altered silicates. And, even if we understood this variation in laboratory experiments, how may one characterize stiffness in natural rock?

If one is willing to overlook these difficulties and to apply our findings directly to the earth, then one is tempted to suggest that earthquakes of intermediate and even deep focus may be a result of high-pressure instability of silicate rocks. Before we can say whether this is true or not, we must determine the embrittlement boundary for silicates as a function of temperature as well as pressure. Griggs *et al.* (*17*) demonstrated that rocks like granite and diabase may deform stably at temperatures in excess of 500°C at 5 kb. But it is not known whether, at these temperatures, sudden instability reappears at still higher pressures as in our room-temperature experiments.

One result which may be important in earthquake studies is that the choice of geological materials in which earthquakes might be produced is broadened to include deeply buried sedimentary rocks and porous volcanic rocks and perhaps even unconsolidated granular materials as well.

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16 January 1969

Wind Measurements in Noctilucent Clouds

Abstract. *The results of eight soundings conducted from sites at high latitude during the summers of 1963 through 1965 suggest that a relation exists between the winds at the mesopause and the occurrence of noctilucent clouds. These measurements indicate that situations in which noctilucent clouds are present are associated with lower wind speeds than is the case where there are no clouds.*

For many years noctilucent clouds have been observed to occur exclusively at high latitudes during the summer, a pattern recently confirmed by Fogle and Haurwitz (*1*). Once it was established that the light from noctilucent clouds is scattered sunlight, the solar depression angles required to illuminate the clouds were determined, and it became apparent that these solar depression angles occur daily at most other latitudes and seasons (*1*, p. 286). This suggested that the extremely cold mesopause which we had observed to be unique to the high latitudes in summer might be related to the occurrence of noctilucent clouds.

In order to examine the possible relation between the temperature of the mesopause and the occurrence of noctilucent clouds, we conducted a total of eight rocket soundings during the sum-