FRICTIONAL CHARACTERISTICS OF SERPENTINITE FROM THE MOTAGUA FAULT ZONE IN GUATEMALA

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INTRODUCTION

The Motagua fault is similar to other major earthquake producing strike-slip faults in that they all contain geologically significant amounts of serpentinite. For the Motagua fault Dengo (1973) has reviewed the tectonic implications of the serpentinite, indicating that it is located within the fault zone, which is an active plate boundary.

Allen (1968) has implied that the great abundance of Fransiscan serpentinite within the San Andreas fault, between Hollister and Parkfield, may be responsible for controlling movement along that segment of the fault. Scholz (1977), among others, has brought attention to the widespread occurrence of serpentinous rock along the Alpine fault of New Zealand. He suggests that the correlation between serpentinite and seismically active areas requires that a more in depth study of the frictional characteristics of this rock be done. Furthermore, oceanic fracture zones, which exhibit seismic activity, also contain large amounts of serpentinite (Scholz, 1977; and Bonatti and Honnorez, 1976).

Thus the presence of serpentinite along active faults makes it desirable to investigate how its frictional behavior may affect movement along a fault. Unfortunately little is known about the frictional characteristics of serpentinite. Such knowledge is required if a program of earthquake prediction and control is to be effective in areas as those mentioned.

The mechanical behavior of serpentinite has been studied by Raleigh and Paterson (1965). They found that at intermediate pressures and temperatures serpentinite undergoes a transition from a strong ductile rock to a weak brittle rock. The transition is induced by the dehydration of serpentine to less hydrous phases plus water vapor. The released water vapor increases the pore fluid pressure and thus reduces the effective normal stress. Their conclusion that brittle failure takes place at shear stresses which are low compared with the total pressure in dehydrating serpentinite led them to suggest that dehydration mechanisms could be an important seismic focal mechanism in areas with abundant serpentinite. Such conclusion is in agreement with that of Griggs and Handin (1960) in which they suggest that dehydration reactions could allow for brittle fracture at depths where otherwise it would be inhibited.

In a study to characterize the sliding modes of different rock types Brace and Byerlee (1968) found that a dunite containing 3% serpentine resulted only in stable sliding. They concluded that serpentinite cannot exhibit stick-slip sliding, even at room temperature. Nevertheless, in a later study, by Summers and Byerlee (1977), it was found that a simulated gouge layer of crushed serpentinite (0.064 cm thick) placed between Westerly granite, did exhibit stick-slip sliding, at confining pressures greater than 150-300 MPa. A period of stable premonitory slip was observed prior to the stress drops.

It was in view of this uncertainty in the behavior of serpentinite and, in recognition of the significance of the problem, that this study was initiated. The sliding behavior of five blocks of serpentinite, taken from different locations along the Motagua fault zone (Figure 1), has been investigated as a function of confining pressure and composition. The effect of other environmental parameters on the sliding mode of serpentinite was not investigated. Therefore, this study is intended as a first step towards providing needed laboratory documentation that the frictional behavior of serpentinite is important when this rock type is found along earthquake generating faults. The study has yielded results which could have meaningful implications to our understanding of the Motagua and other similar faults.

EXPERIMENTAL PROCEDURE

Triaxial experiments were conducted on air-dried right circular cylinders with a 35° precut to the cylinder and load axis, at confining pressures up to 200 MPa, room temperature, and a nominal displacement rate of 2.5×10^{-4} cm/sec. The apparatus used is fully described by Handin and others (1972). Force measurements are recorded in the upper piston with an accuracy of $\pm 5 \times 10^7$ dynes. The displacement measurements are made with a DCDT, mounted parallel to the load direction and, which monitors the movement of the pressure vessel (the moving member of the apparatus) relative to the fixed piston, with an accuracy of $\pm$ 0.02 cm. The specimens with the precut are approximately 3.3 cm in diameter and 7.1 cm in length, whereas those used for fracture strength tests are 2.4 cm in diameter and 5.6 cm in length. The angle of the precut to the load axis is accurate within 0.5° for each half of the specimen. The ends of the assembled specimen are within 0.03 cm of parallelism. The sliding surface and the ends of the specimen are surface ground with an 80 grit wheel. Each experiment is repeated a minimum of two times and reproducability of results, as indicated by the value of peak stress obtained, is within 2-4%. Five polyolefin jackets are used to isolate the specimen from the confining fluid. A thin layer of molykote (MoS_2) is applied to the specimen-piston interfaces

LITHOLOGIC CHARACTERISTICS

Specimens were cored from five different blocks of serpentinite. The compositions and textures of the blocks are given in Table 1, along with the approximate locality where each block was collected. Compositions were determined by petrographic and X-ray diffraction methods.

Based on lithology, the five blocks can be divided into two groups. The first group (blocks 1, 3, and 4) is a mesh-textured serpentinite, which is characterized by isotropic cores of lizardite surrounded by a finer grain size mat of antigorite (Figure 2). The ratio of lizardite to antigorite is approximately 2:1. Minor chrysotile is present as vein infilling. Enstatite phenocrysts (with a maximum measured diameter of about 5 mm) are present in varying degrees of alteration to the pseudomorph bastite. The figures given in Table 1 for the percentage of enstatite represent the mineral in its least altered state, that is when original crystal properties (i.e., cleavage and Schiller structure) can be clearly identified. The oxides are magnetite, hematite and minor chromite, all of which are products of late stage oxidation. Olivine and carbonate (undifferentiated) are present in minor amounts. The enstatite and antigorite show undulatory extinction and kink banding.

The second group (blocks 2 and 5) are flare-textured serpentinites, that is they are characterized by radiating aggregates of antigorite (which is the dominant serpentine phase identified, Figure 3). Enstatite is present in amounts less than 5% and is fine grained. The percent of oxide minerals and the phases identified are similar to those reported for the mesh-textured serpentinites. They also are a product of late stage oxidation. Minor amounts of magnesite, olivine, and talc have been identified. Undulatory extinction of pyroxenes is observed. The main differences between the two groups are that the mesh-textured serpentinites (blocks 1, 3, and 4) contain lizardite as the dominant serpentine phase and significant amounts of enstatite phenocrysts, whereas the flare-textured serpentinites (blocks 2 and 5) contain almost exclusively antigorite as the serpentine phase and almost no enstatite at all.

The petrographic analyses give an estimate of the overall compositions of the rocks. There is difficulty in the optical determination of the phases identified as minor, mainly because of the fine grained nature of these. The amount of these phases present may be revised by future work, nevertheless such variations will not affect the conclusions presented in this paper concerning the effect that lithology has on the sliding mode. The three dominant phases identified (serpentine, enstatite, and oxides) have been identified with an accuracy of $\pm$ 4% for serpentine, and $\pm$ 2% for the other two.

EXPERIMENTAL RESULTS

Introduction

Stick-slip sliding was proposed by Brace and Byerlee (1966) as a model for earthquakes, an idea set forth earlier by Bridgman (1936). As used in the laboratory studies stick-slip sliding is an instability in the sliding mode and will occur whenever the applied force decreases with displacement at a rate greater than the loading system is capable of following. The force-displacement curve (Figure 8) will be characterized by a 'stick' portion, where elastic strain energy accumulates to a critical point and, by a 'slip' portion where a given amount of the force is suddenly released.

Stable sliding has been correlated with fault creep (Byerlee and Brace, 1968; and Scholz and others, 1969). As applied in the laboratory experiments stable sliding describes the continuous nature of the displacement (Figure 6) and is also characterized by the absence or low level of seismic events (Logan, 1977). Logan (1977) also states that the distinction between sliding modes is a function of the sensitivity of the displacement and force transducers and that future investigations into the mechanics of frictional sliding may show such a distinction to be arbitrary.

Effects of confining pressure. With an increase in confining pressure the sliding mode for most rocks will go through a transition, where stable sliding will give way to stick-slip (Brace and Byerlee, 1968; and Logan, 1977). Scholz and others (1972) have pointed out that such transition is not always abrupt, but may be gradational. Logan (1977) has discussed the gradation as a function of experimental technique, rock type, and variation of the external parameters. Nevertheless, its importance lies not in the absolute values, but in the implication that a mechanical change along the sliding surface takes place, leading to the instability.

The transition from stable sliding to stick-slip was only obtained for blocks 2 and 5. Figure 4 shows such a transition for block 2, where the transition takes place at about 25 MPa confining pressure. At 50 MPa confining pressure block 2 is well within the stick-slip regime. The experiments were not conducted at confining pressures above 75 MPa due to the large magnitude of the stress drops (about 190 MPa, Figure 4). An increase in the magnitude of the stress drops with increasing confining pressure (or increasing normal stress) has been observed for other rock types (Griggs and others, 1960; Scholz and others, 1972; Humston, 1972; and others). Block 5 has the transition into the stick-slip regime at about 10 MPa confining pressure, and at 50 MPa confining pressure is also well within the stick-slip region. Figure 5 shows the comparison of both blocks (2 and 5) at 50 MPa confining pressure. The differences in the values of peak stress between both curves most likely reflects minor compositional variations between the two blocks.

The transition to stick-slip was not obtained for the remaining three blocks (1, 3, and 4). Up to confining pressures of 200 MPa all blocks were stable. Figure 6 shows the force-displacement curves for blocks 1, 3, and 4 at confining pressures of 50 MPa and 100 MPa. A comparison of the curves indicates that there is a consistent trend in the value of peak stress reached, where block 3 is higher than block 1 which is higher than block 4.

Unstable stick-slip sliding has only been observed for the flare-textured serpentinites (blocks 2 and 5). The mesh-textured serpentinites (blocks 1, 3, and 4) resulted only in stable sliding.

Coefficients of friction. The coefficient of friction (μ_s) is a measure of the rocks' resistance to frictional sliding and is defined as the ratio of the shear stress (τ) to the normal stress (σ_n) (Jaeger and Cook, 1969). The coefficient of friction is usually determined either at peak stress or at the onset of sliding and is dependent on the normal stress (Byerlee, 1977) or effective pressure (Stesky, 1977). For this study it was calculated at maximum differential stress (peak stress) during sliding and the values are reported in Table 2. Although there is some variability in μ_s at a given condition, the importance of the value of μ_s is to compare the different blocks, so it is the relative and not absolute values which are of interest.

There is a significant difference in the values of μ_s between the stick-slip and the stable sliding blocks. For example, at 50 MPa confining pressure, block 2 has a coefficient from .80 - .82, whereas block 4 has values from .53 - .56. Figure 7 is a plot of shear stress vs normal stress for the values reported in Table 2. The relative differences between both groups can be seen by comparing the slopes of the best fit lines. The shear stress required to cause sliding for the stick-slip blocks is given approximately by the equation $\tau = 0.77\ \sigma_n$, and for the stable sliding blocks by $\tau = 0.56\ \sigma_n$. This difference may imply that the

Fracture Strength. Fracture strength experiments were conducted on specimens from all five blocks at a confining pressure of 50 MPa (Figure 9). The fracture strength for blocks 2 and 5 plot closely together as do the values for blocks 1 and 4. The difference between these two groups is about 125 MPa. Block 3 has intermediate strength, but still plots lower than the stick-slip blocks. The results agree with those of the sliding experiments in that the flare-textured serpentinites (blocks 2 and 5) support a higher load than do the mesh-textured serpentinites (blocks 1, 3, and 4).

Premonitory Slip. Premonitory slip is referred to stable sliding prior to stick-slip (Logan, 1977) and has been widely recognized in experiments with precuts (Byerlee and Summers, 1975; Engelder and others, 1975; Teufel and Logan, 1978; and others). A typical experiment showing premonitory slip is shown in Figure 8. The force-displacement curve is characterized by an initial linear slope indicating an accumulation of elastic strain energy. Within 10% of the value of peak stress the curve becomes non-linear, indicating the onset of premonitory slip. Then there is a period of stable sliding which is followed by an acceleration as the major event is approached.

Premonitory slip is poorly understood and no consistent trend relating premonitory slip to the magnitude of the stress drops, or to the total displacement along the precut has been observed. Brace (1977) shows that, in a gabbro, displacement during premonitory slip is much larger than the displacement during the stress drop. Scholz and others (1972), using Westerly granite, report that premonitory slip is only a fraction of the displacement during the stress drop. Teufel and Logan (1978) have shown that for Tennessee sandstone the amount of premonitory slip increases with total displacement along the precut.

No quantitative statement about premonitory slip associated with serpentinite can be made at the present time, nevertheless there are some trends which merit attention. These are: (1) large amounts of premonitory slip occur prior to the large stress drops, as opposed to occurring prior to the smaller events (Figures 5 and 8); (2) the amount of premonitory slip is consistently several orders of magnitude greater than the amount of slip during the stress drops, and (3) a smooth transition to stick-slip is commonly observed.

DISCUSSION

Lithologic effects on the sliding mode. The results indicate that serpentinite not only slides in a stable manner as postulated by Brace and Byerlee (1968), but that it can undergo the transition to stick-slip at confining pressures as low as 10 MPa. The correlation of stable sliding with the mesh-textured serpentinite and stick-slip with the flare-textured serpentinite indicates that there must be a lithological control on the sliding behavior. By lithological control it is meant that textures imply compositions and vice-versa. These and other major differences in the physical properties of the two groups are discussed below.

Textural differences are a direct result of compositional variations which may result from differences in the petrogenesis of the rocks, or in the deformation history of these. Petrographic observations demonstrate that in several of the flare-serpentinites the antigorite crystals exhibit a weak preferred orientation, probably induced by shearing of the rock during its emplacement or during subsequent faulting. The mesh-serpentinites show no anisotropy at all.

Antigorite (the only serpentine phase identified in the stick-slip rocks) has different crystal properties than does lizardite. Wicks and Whittaker (1975) among others, have shown that antigorite has a corrugated crystal structure of anomalous thickness, whereas lizardite has a flat layer crystal structure. Evans and others (1976) have shown that there exists compositional variations between the two phases, such that they cannot be considered true polymorphs. Antigorite has a higher SiO_2 and lower MgO and H_2O content than does lizardite. Such differences may account for antigorite having a higher density (2.6 g/cm^3) and hardness number (up to 3.5, Mohs' scale) than does lizardite, whose density is 2.4 g/cm^3 and hardness is up to 2.5 (Deer and others, 1965).

Marked grain size differences exist between both groups of rocks. The average grain size for the serpentine matrix of the mesh-serpentinites (excluding block 3) is about .25 - .30 mm and that of the flare-serpentinites is about .08 - .12 mm, resulting in a difference between the two of about .17 - .18 mm. A correlation between grain size and fracture strength has been noticed for other rock types by Paterson (1958), Brace (1963), and Friedman (1975). They show that rocks with a smaller grain size have a higher fracture strength. Our results agree with such observations. The higher fracture strength for block 3, relative to the other two stable sliding blocks, is interpreted as a result of a smaller serpentine grain size (.14 - .18 mm), even though this rock is still mesh-textured. The grain size differences have been given only for the serpentine matrices because the serpentine minerals make up such a large percentage of the rocks (Table 1). If the pyroxene grain size is included with that of the mesh-serpentinites the difference between these and the flare-serpentinites would become more pronounced. The grain size of the oxide minerals has not been considered because similar sizes, as well as variations, have been observed in both rock types.

Our results also confirm those of Raleigh and Paterson (1965), where they found a significant strength difference between an antigorite (Cabramurra, New South Wales) serpentinite and a mesh serpentinite (Fidalgo Island, Wash.). They do not report data for both rocks at 50 MPa confining pressure, but at 350 MPa confining pressure and room temperature the difference is about 240 MPa, the antigorite serpentinite having the higher fracture strength.

Differences in the hardness between both groups of serpentinite, are manifested in the deformation characteristics (that is gouge generated) observed along the sliding surfaces, after displacement has occurred. For the mesh-serpentinites the deformation is concentrated along carrot shaped wear grooves which increase in width and depth in the downslip direction (Figure 10). These wear grooves are not evenly distributed across the sliding surface. For the flare-serpentinites the gouge is of approximately uniform grain size and is distributed evenly over the entire sliding surface (Figure 11). In thin section (Figures 12 and 13) it can be observed that the depth of penetration of the deformation is greater for the mesh than the flare-serpentinites. Furthermore, the relative softness of the mesh-serpentinites is evidenced by the rate of gouge generation; the gouge being rapidly generated within the first 5 mm of displacement,whereas the flare-serpentinite, at the same amount of displacement have much of the original surface still preserved.

The fact that lithology is one of the controlling parameters in allowing for stick-slip to occur is confirmed with the experiments conducted on blocks 4 and 5. For these, the compositions and textures were determined first and, based on the results, the sliding mode, at 50 MPa confining pressure, was successfully predicted. Nevertheless, the problem still remains as to what mechanical implication lithology has in allowing one rock to slide in a stick-slip fashion while the other remains stable. Two hypothesis can be postulated, both of which are a function of the rocks' relative hardness.

Johnson and Scholz (1976) observed that a well defined rupture propagates along the sliding surface before the onset of stick-slip at a speed close to shear wave velocity. Based on this observation Shimamoto (1977) states that the onset of sudden slip does not occur simultaneously over the entire sliding surface, but that the localized breakage of locked portions propagates over the sliding surface. Shimamoto's work was concerned with hardness differences in a rock-gouge-rock system but it has implications which may be valid for a rock on rock system that has significant hardness differences, as do the serpentinites. The basis for the hypothesis is that the rock's will have differences in their shock-absorbing properties such that the following could happen. In the softer mesh serpentinite a small shock, caused by breakage of a locked portion, is absorbed in the system so that the localized perturbation will never spread over the entire sliding surface to cause stick-slip. In the harder flare-serpentinites the shock will not be so easily attenuated and could spread across the sliding surface more rapidly. Shimamoto (1977) based his argument on the fact that the softer material is the one with a higher porosity. Porosity measurements have not been made, but optical examination indicates that the tight packing of the fine grained antigorite needles in the flare-serpentinite should result in a lower porosity than the less well packed arrangement found in the mesh-serpentinites.

An alternative possibility is that due to the mesh-serpentinites' inability to sustain high loads, fracturing (cataclasis) of interlocking asperities will happen early in the displacement history. As the gouge is rapidly generated the sliding mode is stabilized (Shimamoto, 1977).

Regardless of which is the exact mechanism, or if they do interact, it is beyond doubt that the relative hardness of the serpentinites, which is a function of composition, plays a significant role in controlling the instability. Observations of the sliding mode of other rock types agree with those reported here. Byerlee (1967), Byerlee and Brace (1968) and Logan and others (1972) showed that for rock on rock friction brittle and more stronger rocks (i.e., granites and quartzosandstones) exhibit much more unstable sliding behavior than do softer and more ductile rocks.

(i.e., porous limestones and sandstone).

Implications of the frictional sliding of serpentinite to the earthquake problem. Laboratory data have no significance unless they can be applied towards increasing our understanding of the natural feature being studied, in this case the Motagua Fault. The results obtained are promising in that they show that with knowledge of the lithology of the serpentinite some inferences can be made about its sliding behavior, thus increasing our capacity for prediction. It would seem appropriate therefore to investigate what the spatial distribution of Lithological types is along the fault and more so, if the distinction between the two groups can be made for more samples than the five studied here.

Table 3 gives the modal analyses of different samples collected along the fault zone. Although there is some variation, the petrographic determinations indicate that the overall division of the serpentinite into mesh and flare-textured still holds. The trends agree with those reported in Table 1, where the flare-textured serpentinites are finer grained and usually contain a higher percentage of serpentine than the mesh-textured serpentinites. More work is required before any definite statement can be made about the outcrop distribution and many more samples should be analyzed to increase the statistical validity of the existance of the two groups.

The observation that premonitory slip is always associated with stick-slip may be important to our understanding of earthquake mechanisms. Although there is no consistent relationship between the amount of premonitory slip and the event it preceeds, the displacement path which premonitory slip follows before the event is always the same (Teufel and Logan, 1978). They report that for frictional sliding of Tennessee sandstone premonitory slip begins slowly and accelerates as the major event is approached. Our results confirm these observations (Figures 5 and 8). Accelerated fault creep has been reported by Nason (1973) and Scholz (1972) for several large earthquakes along the San Andreas fault. The anology that this observed fault creep may indeed represent premonitory slip prior to a major earthquake has been made by Scholz and others (1972).

Premonitory slip, as discussed by Teufel and Logan (1978) could play an essential part of the earthquake process, in particular for a rock like serpentinite which has a strong potential for dehydration. Raleigh (1977) proposed that premonitory slip is necessary to generate the instability that results in the earthquake. He states that dehydration or other thermally active processes provide the mechanism for the instability. If premonitory slip acts to condition the surface before the major event at least two possible sequence of events could happen, both of which involve increasing the pore fluid pressure (which reduces the effective normal stress) by a thermally activated process. The two cases to be considered assume: (1) a "wet" state; where pore fluids (probably water) are present along the fault surface, and (2) a "dry" state; where no significant amounts of pore fluids are present.

It has to be emphasized at this point that there is a difference in the amount of temperature that can be generated during frictional sliding. There are average surface temperatures and temperatures generated only at the asperity contacts (the true contact areas of the fault plane).

Teufel and Logan (1978) have shown that for stable sliding of Tennessee sandstone, at 50 MPa confining pressure and a displacement rate of 2.6 x 10^{-2} cm/sec, the average surface temperature increases by frictional heating to 75°C. Yet, under equal conditions, the temperature at the asperity contacts can exceed 1000°C.

For the wet case, if slip is confined to a plane, the pore fluids will prevent a large increase in temperature (Sibson, 1973), so it would be appropriate to consider only the effect of the lowest possible temperatures which can be achieved during frictional heating (i.e., 75°C). Furthermore, if the pore fluids are present along a fault plane which is confined by an impermeable material, be it rock or gouge, the system can be assumed to be a closed one and the pore fluids therefore kept at a constant volume. Sibson (1975) and Bradley (1975) report that when water is kept at a constant volume, at conditions equal to a depth of about 5 km, the pressure increase due to the thermal expansion of water will be about 1.5 MPa for every degree centigrade. A rise of only 75°C would produce such a high pore pressure that the lithostatic overburden would be overcome. Sudden slip may then occur. This is of course a crude first approximation, but it serves to indicate that thermally activated high pore pressures alone could be an earthquake mechanism, if the temperatures are raised before the main event happens, as may be done by premonitory slip.

On the other hand, if pore fluids are absent, then localized high temperatures may start to be generated during premonitory slip, and the dehydration of the serpentine minerals initiated. Temperatures of about 500°C are required to dehydrate serpentine, although this value can range from 400 - 600°C depending on pressure and composition (Raleigh and Paterson, 1965). At a hypocenter depth of 5 km the ambient temperature (assuming a normal geothermal gradient of 30°C/km) would be about 150°C, so an increment of 350°C would be required for dehydration to be feasible. The data discussed previously, from Teufel and Logan (1978), indicates that temperatures far above those required for dehydration could be generated at the asperity contacts. Furthermore, Friedman and others (1974) and Hundley and Moody (1977) have observed glass on surfaces of sandstones, generated as a result of frictional heating. McKenzie and Brune (1972) and Richards (1976) have proposed that frictional heating during an earthquake might lead to melting on the fault surface. Raleigh (1977) proposed that if seismogenic fault zones contain hydrated minerals, dehydration should preceed melting during the frictional heating process.

The dehydration of the serpentine minerals will produce a two-fold effect. First, the released water vapor will cause an abnormal pore pressure effect which will reduce the effective normal stress. Secondly, the dehydration process will lead to the formation of other phases, one of which could be talc (Raleigh and Paterson, 1965). Talc has a lower static coefficient of friction than does serpentine. For dry samples the coefficients are for talc $\mu_s = 0.36$, for serpentine $\mu_s = 0.62$; and for wet samples the coefficients are: for talc $\mu_s = 0.16$, and for serpentine $\mu_s = 0.29$ (Horn and Deere, 1962). Talc would therefore act as a lubricant along the sliding surface and its generation would enhance slip along the fault. In the present study the formation of talc was not detected. Analytical difficulties were encountered because the material is too finely granulated for optical determinations and, too contaminated with other phases for X-ray diffractometry. Its generation should therefore not be precluded. It should be noted that the time required for half of the available water in serpentine to dehydrate off is 0.54 sec, at 700°C (Raleigh, 1977). Raleigh (1977) also concludes that dehydration of serpentines and clays should run quickly at 600 - 700°C.

In the previous discussion we have presented two possible mechanisms for the generation of earthquakes. Both conform: to the experimental data obtained in this study, particularly the implications of premonitory slip; the current knowledge of rock friction and frictional heating; and to the dehydration characteristics of serpentinite. Two extreme cases (the wet and the dry) were presented so as to cover the full range of possible behaviors. A more meaningful discussion, which would probably involve the interaction of both mechanisms, cannot yet be developed simply because knowledge of the exact conditions, at depth, along a fault plane are non-existant.

The abundance of serpentinite along the Motagua and other faults and the marked difference in coefficients of friction reported for both rock groups have other implications to the earthquake problem. Unfortunately fault creep data of the Motagua fault and general knowledge of the subsurface geology is badly lacking. The outcrop distribution of serpentinite follows a trend parallel to the Motagua fault and, Eggler and others (1973) have found serpentinite along the Cayman Trough, which is the continuation into the Caribbean of the Motagua (Dengo, 1967; Malfait and Dinkelman, 1972; and others). This would imply that serpentinite may be more widespread along the fault zone than what is otherwise indicated by surface outcrops and, that perhaps it forms an almost continuous belt at depth, similar to the model proposed by Bonatti and Honnorez (1976) for oceanic fracture zones. Because the vertical and lateral distribution of serpentinite is not well documented (except for where it crops out) in the following discussion the assumption that serpentinite exists at hypocenter depths, is made based on analogy to similar tectonic features such as the San Andreas fault, where Allen (1968) proposed a magnetic model which accounts for serpentinite existing to depths of several kilometers if not more.

Dengo (1969b, 1973), Molnar and Sykes (1969), and others have proposed that the Motagua fault is the plate boundary between the North American and Caribbean plates. Plate tectonic theory indicates that the thickness of these lithospheric plates are in the order of 100 km, yet data from the main event as well as aftershocks from the 4 February 1976 earthquake indicate that the earthquake activity is concentrated within the upper 15-20 km of the crust (Person and others, 1976; Langer and others, 1976; and Matumoto and Latham, 1976).

A similar problem was addressed by Savage and Burford (1973) for the San Andreas fault, where depths of earthquakes are limited to 15 km or less. They have suggested that the relative displacement of the lithospheric plates takes place by some aseismic creep process. In view of this Wesson and others (1973) proposed a model for "patches of difficult slip." The basis for the model is that the displacement of the lithospheric plates at depth will generate, either continually or episodically, dislocations which travel to the near surface. The dislocations may appear at the surface as fault creep or may get pinned, by patches of difficult slip. The patches of difficult slip will locally retard or impede creep along the fault such that elastic strain is stored in the adjacent rocks.

Assuming that the two types of serpentinite vary in their spatial distribution at a significant geographic scale (although local variations are probable) there will be areas along the fault plane with contrasting coefficients of friction (where μ_s is assumed to be scale independent). Therefore the model to be considered is one in which concentrations of flare type serpentinite (with a high resistance to frictional sliding) will create patches along the fault where slip is difficult to accomplish, relative to areas that have the mesh-serpentinite (or perhaps even another rock type with a low μ_s) which will be patches of easy slip.

Sudden failure, as observed in an earthquake, will not take place over substantial portions of the patch unless failure conditions are met for the entire patch. Conceivably, before this condition is met, small earthquakes could be produced at very localized points where failure conditions are favorable. Slip on portions of the fault which are not pinned need not only slide by aseismic creep. Such areas, adjacent to patches of difficult slip could move along with the patch during the earthquake. Furthermore, if adjacent patches of difficult slip were loaded to near failure, the failure of one such patch could rapidly load the adjacent patch and the intervening region of easy slip, causing a sequence of multiple events.

SUMMARY

Two types of serpentinite have been identified. One is a mesh-textured serpentinite that results in only stable sliding up to confining pressures of 200 MPa. The other is a flare-textured serpentinite which undergoes the transition from stable sliding to stick-slip at confining pressures as low as 10 MPa. Relative hardness differences between the two groups may be one of the factors allowing for unstable stick-slip sliding to take place. The mesh-serpentinites are the softer of the two, as indicated by differences in mineral properties, fracture strengths, coefficients of friction, and deformation characteristics produced during frictional sliding.

Premonitory slip has been observed in all stick-slip experiments. It has been noted that: premonitory slip occurs at stress levels within 10% of the value where stick-slip takes place; large amounts of premonitory slip occur prior to the largest of the stress drops; and the amount of premonitory slip is several orders of magnitude greater than the amount of slip during the stress drop.

The contrast in the value of the coefficients of friction between the mesh and flare-textured serpentinites provides a basis for formulating a model in which the frictional behavior of serpentinite is responsible for the earthquake generating process. The model complies with current knowledge of fault creep, rock friction, and the geology of the Motagua Fault zone. Stresses generated at depth by the relative motions of the lithospheric plates (Caribbean and North American) are transmitted to the near surface, by a dislocation mechanism, where they concentrate along areas with a high resistance to frictional sliding. The earthquake will not occur until failure conditions are met over the entire "stuck patch." Microseismic activity or fault creep may occur by localized failure along points of the patch. Such fault creep may be equated with premonitory slip.

Premonitory slip prior to the main event will raise the ambient temperature along the sliding surface by frictional heating. If pore fluids are present the thermal expansion of these will create abnormally high pore pressures which may be sufficient to reduce the effective normal stress to near zero and produce the earthquake. A temperature increment of less than 100°C would be required for this process.

If on the other hand, pore fluids are not present in substantial amounts to be meaningful, frictional heating may cause high temperatures (maybe in excess of 1000°C). The serpentine minerals will dehydrate causing an abnormal pore pressure effect. Dehydration may also yield talc, which will serve as a lubricant and enhance slip along the fault plane.

The results obtained in this study may have meaningful implications to our understanding of the Motagua and other similar faults, where serpentinite is present in geologically significant amounts. If further work shows conclusively that the two types of serpentinite (mesh and flare) are distributed on a broad geographical scale, the results presented here will provide a stronger base for earthquake prediction and control. It is obvious nevertheless that an understanding of the mechanics of the Motagua fault will never be satisfactorily achieved until data such as fault creep, in situ stress at surface and at depth, pore fluid compositions and pressures (if present) and, material properties at depth are obtained. Such a data bank can only be developed through a comprehensive and costly drilling program.

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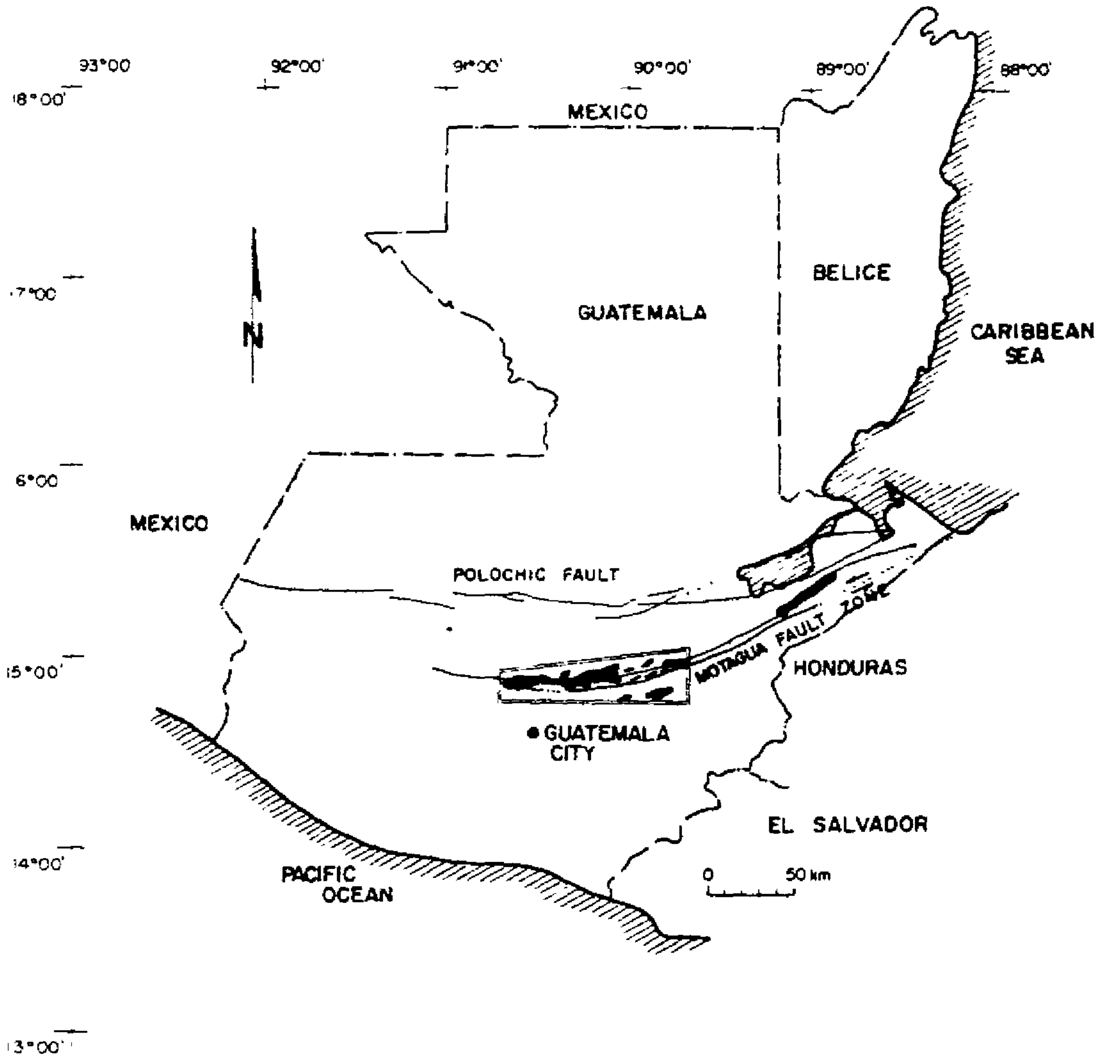

Figure 1. Location map showing the serpentinite outcrops in black and the area of study in the enclosed block. Locations where samples were collected are given in Tables 1 and 3.