many of the 1981 eruptions at Mount St. Helens, no unusual change in the seismic pattern was evident until after ground deformation near the dome had been reported (*6*). This absence of seismic events implies that strain rates were not high enough at that time to cause earthquakes; under those conditions the rock around the rising magma could deform plastically. As the magma neared the surface, either the strain rate increased, causing the rock to fracture, or the near-surface rock was cool enough so that even at the same strain rate it could not deform without brittle failure. We speculate that the change from type-m to type-l events represents a transition of the maximum deformation front from one rock type to another. The type-m events are, on the average, slightly deeper (1 to 3 km below the dome) than the type-l (0 to 2 km) events. Alternatively, the difference in waveforms may reflect different source mechanisms, such as shear versus tensile failure or gas explosions within the magma. The direction of first motion for most events is not clear, and so reliable focal mechanisms cannot be determined. The change from low-frequency shallow earthquakes (types m and l) to surface events (types s and a) apparently coincides with the beginning of the extrusion. Once the magma reaches the surface, the strain rate drops and no new rock is fractured.

This pattern, with minor variations, has been common to all ten eruptions. In particular, the eruption of 19 March 1982 was preceded by an anomalously long period of precursory seismicity that included both the typical shallow (types m and l) events as well as a swarm of very small, deep, type-h events (*7*). The eruption on 4 April 1982 was preceded by only a very brief, small increase in both type-l and type-s events. There appears to be a relation between the duration of the time period of precursory events to an eruption and the time interval since the previous eruption. The longer the interval between eruptions, the longer and stronger the precursory seismicity pattern. At one extreme is the 4½-month quiescence before the eruption of 19 March 1982, whose precursory seismic events lasted almost a month. At the other extreme is the inter-eruption period of 2 weeks preceding the eruption of 4 April 1982, all of whose precursory seismic events took place in less than a day. Between these two extremes lie most of the eruptions of 1981 and 1982, which occurred about every 2 months and which had seismic precursors lasting about a week.

If the eruptive process remains fundamentally unchanged, we believe that it will be possible to predict the timing of future eruptions of Mount St. Helens using techniques outlined here. The eruption of 19 March 1982 had a small explosive component that was not specifically anticipated. Consequently, we are not as confident of our ability to predict whether future eruptions will be explosive, with high-hazard potential, or nonexplosive, with relatively low hazards.

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Deformation Monitoring at Mount St. Helens in 1981 and 1982

Abstract. *For several weeks before each eruption of Mount St. Helens in 1981 and 1982, viscous magma rising in the feeder conduit inflated the lava dome and shoved the crater floor laterally against the immobile crater walls, producing ground cracks and thrust faults. The rates of deformation accelerated before eruptions, and thus it was possible to predict eruptions 3 to 19 days in advance. Lack of deformation outside the crater showed that intrusion of magma during 1981 and 1982 was not voluminous.*

Ground deformation has been used to forecast volcanic eruptions at some volcanoes (*1*). Magma ascending beneath a volcano forcefully displaces the surrounding rock, and the resulting deformation can be measured at the surface. Such monitoring quantifies precursory patterns of deformation upon which eruption predictions can be based (*2*) and provides data on eruption processes. Deformation monitoring at Mount St. Helens has been used with unprecedented success in predicting the nine dome-building eruptions that occurred between December 1980 and the end of 1982 (*2*, *3*).

Five methods are used to measure deformation at Mount St. Helens: (i) trilateration and triangulation around the volcano to monitor the changes in the shape of the volcanic edifice; (ii) long-ranging distance measurements to points in the crater made from Harry's Ridge, 8.5 km north of the lava dome; (iii) measurements of short horizontal and vertical distances across active cracks and thrust faults on the crater floor; (iv) slope-distance and vertical-angle measurements from sites on the crater floor to targets on the floor and dome; and (v) measurements of ground tilts on the crater floor by means of electronic tiltmeters and precise leveling. The tilt studies are discussed by Dzurisin *et al.* (*4*); the other four methods are discussed below.

Before the eruption of 18 May 1980, a geodetic network on the outer flanks of Mount St. Helens was used to monitor the intrusion of magma that resulted in the growth of the famous "bulge" on the north flank (*5*). After 18 May 1980, the network was reestablished and expanded. Measurements during the summer and fall of 1980 suggested that the edifice expanded before eruptions and contracted afterward (*6*). However, since late 1980, measurements approximately once a month have shown no changes beyond expected survey error.

In the summer of 1980, we initiated slope-distance and vertical-angle measurements from Harry's Ridge to points inside the crater. Distances to points north of the vent shortened before eruptions (*6*). These measurements provided the first convincing evidence for ground deformation preceding eruptions after 18 May 1980.

The inner crater is filled with deposits of the explosive eruptions of 1980 that are unconsolidated at the surface and welded below about 3 m. In September 1980, ground cracks were first observed on the crater floor; these cracks extended radially outward from the dome. Some cracks widened at rates that increased before eruptions (*6*). In addition, new cracks formed, existing cracks propagated away from the lava dome, and some cracks showed strike-slip components of movement. The cracks ranged from hairline fractures to fissures 3.5 m wide and 10 m deep.

During the December 1980 eruption, thrust faults formed on the crater floor. By the summer of 1981, a complex system of thrust blocks had disrupted much of the southwestern part of the floor (Fig. 1). The thrust-fault blocks are lobate and are bounded by radial cracks that act as tear faults [figure 2 in (*2*)]. The thrusts form as small buckles less than a centimeter high and may grow to have frontal scarps 5 m high facing away from the dome. Fault planes dip between 15° and 35°, calculated from the ratio of the horizontal to vertical displacement of the upper plate relative to the lower plate (Fig. 2).

The thrust blocks move up and radially away from the dome (Figs. 2 and 3). One can monitor the lateral movement of the thrusts by measuring with a steel tape the distances between a point on the upper plate and two points on the lower plate. To monitor vertical displacements, a network of survey points is leveled. Thrust movements accelerate systematically before eruptions; these movements have provided the most consistent and reliable long-term predictive tool at Mount St. Helens. A given thrust moves progressively less over succeeding eruptions, but, as some thrusts die out, new ones form [*7*; figure 6 in (*2*)].

Beginning in early 1981, points on the rampart north of the vent were periodically trilaterated from a base line 1 km north of the dome in order to determine horizontal displacement vectors. These measurements showed nearly radial movements (Fig. 3).

Starting in October 1981, we began to make frequent measurements of the distances and vertical angles between instrument sites on the crater floor and targets on the lava dome to monitor preeruption expansion of the dome. The results are striking. Before the August 1982 extrusion, horizontal displacements as large as 32 m were measured on the west side of the dome (but were an order of magnitude smaller on the other sides). The rate of dome expansion consistently accelerated before eruptions. Generally, points highest on the dome moved most. Thick snow during the winter buried most thrusts and cracks, so that measurement of the hot, relatively snow-free dome became the dominant means for monitoring preeruption deformation.

In May 1982, we placed several targets between the dome and the crater walls to determine how the floor as a whole deformed. Before subsequent eruptions, the distances between targets along radials decreased and the distances along tangential arrays increased. All targets moved radially outward; those closest to the dome moved most. In one area lacking thrusts or cracks, strains were distributed across the entire floor. Thrusts and cracks accounted for most of the observed strain elsewhere.

Measurements of deformation in the crater provide the most sensitive indicators of impending eruptive activity at Mount St. Helens. Detectable movement of the dome and crater floor begins 3 to 4 weeks before an eruption. Acceleration of this movement becomes well defined as much as 3 weeks before the eruption [figure 6 in (*2*)]. In 1981–1982, the intervals between eruptions ranged from 39 to 140 days. After each eruption the rates of deformation slowed abruptly, but during the shorter intervals the rates did not reach background levels before starting to increase again [figure 6 in (*2*)]. During the longer intervals, eruptions were followed by 1 to 3 months of constant, slow deformation.

The rates of deformation ranged widely at different points before one eruption as well as at a single point over a period of several eruptions. Movements were largest on the west and southwest sides of both the dome and the crater floor. This difference probably reflects nonhomogeneous subsurface structure, possibly influenced by the location of the 22 July 1980 explosion crater, which was elongate to the southwest (*8*). Nevertheless, most rates accelerated by about four to five orders of magnitude (from millimeters per day to meters per hour) before eruptions. The temporal change of rates, not their magnitude, is the key to predictions; when cumulative displacement is plotted versus time, the resulting curve is nearly asymptotic to the eruption date [figures 3, 4, and 5 in (*2*)].

Can deformation monitoring be used to distinguish between forthcoming explosive and nonexplosive eruptions? During the summer of 1980, the volcano may have expanded before some explosive eruptions (*6*). However, no such expansion preceded the explosive onset of the much smaller 19 March 1982 eruption, nor did crater measurements detect unusual behavior, although seismicity was somewhat different (*9*). The available data are thus insufficient to answer this question.

Vertical displacements are partly reversible. Broad uplift of the crater floor before an eruption generally gives way to

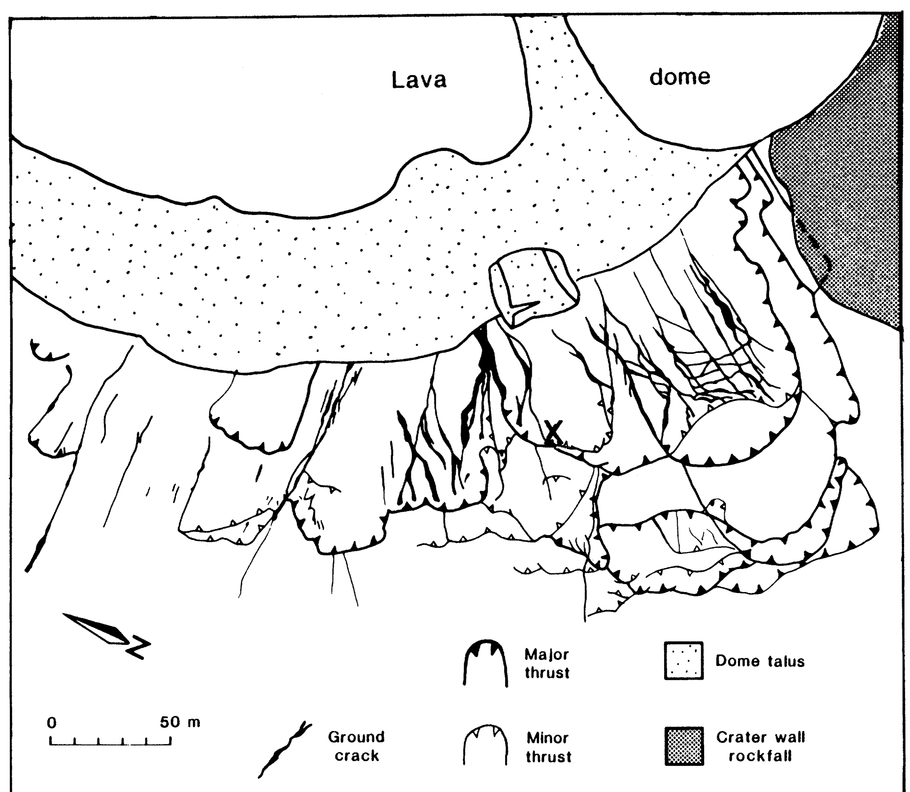

Fig. 1. Geologic map of the crater floor southwest of the dome, showing major and minor thrust-fault scarps (teeth on upper plate) and ground cracks [figure 2 in (*2*) is a photograph of same area]. This map was made on 11 November 1981. Point X is discussed in the captions to Figs. 2 and 3.

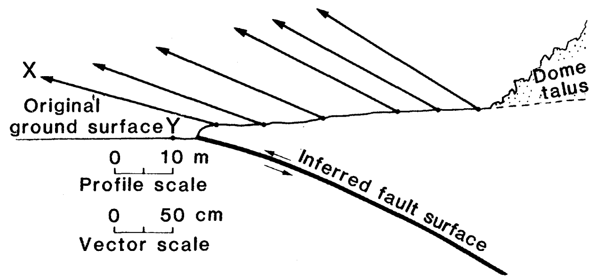

Fig. 2. Cross section radial to the dome of a thrust fault in the southwest crater floor, showing displacement vectors relative to point Y between 15 September and 31 October 1981. Eruptions occurred on 6 September and 30 October 1981. The fault surface is assumed to lie parallel to the plunge of vectors, steepening toward the dome. Steepening probably reflects superimposed broad uplift centered on the dome. Vector X shows the movement of station X in Fig. 1.

lesser subsidence after the eruption. Targets on the dome are uplifted slightly and then start to move downward a few days before the eruption as the dome starts to fail. In contrast, horizontal displacements of both the dome and the crater floor are irreversible and cumulative. Horizontal deformation is commonly 1½ to 10 times faster than vertical. Horizontal displacement vectors on the floor and dome consistently project back to the presumed feeder conduit near the center of the dome, evidence that the conduit has not migrated during 1981 and 1982 (Fig. 3). Displacement vectors in a vertical plane project to shallow depths just beneath the dome (Fig. 2) and become shallower before eruptions, documenting the ascent of magma.

We interpret the driving mechanism for deformation of the crater floor and dome to be the intrusion of magma from a depth of less than 1 to 2 km into the conduit and dome. Intrusion begins weeks before eruption and expands the conduit, which in turn spreads the dome and shoves the crater floor against the relatively stable crater walls. The dome locally overrides the adjacent floor as it expands. Outward movement of the crater floor causes radial compression, which results in thrusts, and tangential extension, which opens radial cracks. The floor begins to move no earlier than the dome; this timing suggests that the conduit remains filled with viscous lava between eruptions. The shallow part of the conduit expands as it is reintruded by each successive pulse of magma. The partial reversibility of vertical deformation probably results from the relaxation of magmatic pressure after eruption, loading of the crater floor during eruption, and contraction of the dome because of cooling and degassing.

Preeruption swelling of the dome shows that substantial internal growth occurs before lava appears at the surface. The volume of a new extrusion is therefore only a part (generally 80 to 90 percent) of the total volume of new material added to the dome during a given eruptive cycle. The larger the dome becomes, the more internal growth it can accommodate. Deformation of the crater floor nearly stops within the 24 hours before extrusion begins. Deformation of the dome, however, continues for several hours after extrusion begins, possibly until the rate of extrusion equals that of intrusion. The near absence of explosive activity since 1980 suggests that magma entering the dome during preeruption growth is relatively degassed and is forced upward as gas pressure builds slightly within a deeper magma body. The lack of edifice-wide deformation between late 1980 and the end of 1982 suggests that no large magma bodies have been emplaced within a few kilometers of the surface. Rather, the data indicate repetitive intrusion and eruption from a relatively closed, shallow magmatic system.

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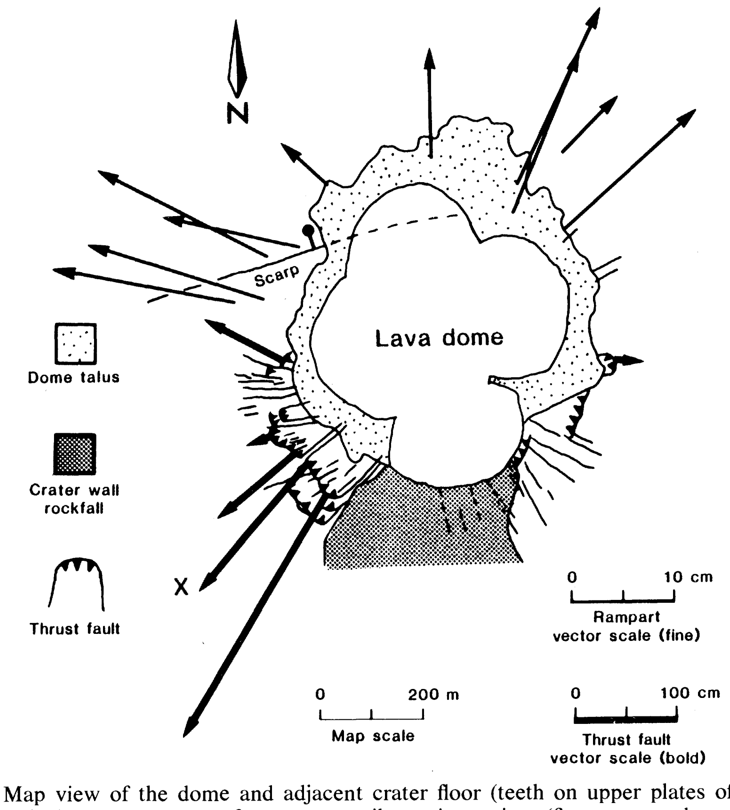

Fig. 3. Map view of the dome and adjacent crater floor (teeth on upper plates of thrusts), showing displacement vectors for rampart trilateration points (fine vectors, based on data between 18 September and 21 October 1981) and thrust faults (bold vectors, based on data between 6 September and 31 October 1981) (note the different vector scales). Eruptions occurred on 6 September and 30 October 1981. "Scarp" is a normal fault bounding the north edge of the inner crater (ball on downthrown side, dashed where covered). Crater-floor ruptures do not extend north of this fault. The direction of the east-side thrust vector is based on data from an earlier eruption. The vector labeled X shows the movement of station X in Fig. 1.

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