DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

ANNOTATED BIBLIOGRAPHY, VOLCANO-DEFORMATION MONITORING

by

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Introduction

Surface deformation measurements have been used for many years to monitor volcanic activity. Deformation of a volcanic edifice sometimes precedes or accompanies an eruption. Ground deformation is manifested as vertical strain, horizontal strain, and tilt, and it can be reflected in changes in the gravitational field. Inflation and/or deflation of a volcanic edifice is usually interpreted to result from changes in pressure or volume resulting from movement of magma beneath or within the volcano. Volcanoes may inflate weeks to months before an eruption and then deflate immediately before, during, or after the eruption. Analysis of these changes can be used in conjunction with studies of other precursory activity to forecast and in some cases predict eruptions. According to Swanson and others (1985), a forecast is a comparatively imprecise statement of the time, place, and nature of the expected activity. A prediction, on the other hand, is a comparatively precise statement of the time, place, and ideally, the nature and size of impending activity. Deformation studies are well documented on basaltic shields (eg. Kilauea and Mauna Loa, Hawaii; Manam, Papua, New Guinea; and Krafla, Iceland) and to a lesser extent on composite volcanoes (eg. White Island, New Zealand; Mt. St. Helens, United States; Usu, Japan). Deformation monitoring has proven to be an effective tool for making eruption forecasts or predictions of dome-building eruptions at stratovolcanoes as has been demonstrated at Mount St. Helens, Sakura-jima, and Usu. Deformation of resurgent calderas has been studied at Iwo-Jima in Japan, Long Valley and Yellowstone in the United States, and the Phlegrean Fields in Italy, to name just a few.

In the past, visual observation was the only measure of volcanic deformation. Changes were noted only when they were dramatic: farmer's fields bulged, sea level changed, the shape of the upper slopes of the volcano changed. Quantitative observation of ground deformation as a monitoring technique on active volcanoes involving more subtle changes was first employed in the early part of this century. Today, techniques include water-tube tilt, spirit-level tilt, electronic distance- meter (EDM) measurements, precise leveling, triangulation, gravimetry, tide gauge and lake- level measurements. A wider interest in volcanology and advancing technology have led to a diversification of methods since the first half of this century, resulting in a parallel increase in the volume of volcanological deformation papers. The following annotated bibliography is a preliminary review of the current literature of deformation monitoring of volcanoes. It is the outgrowth of an attempt to synthesize baseline and precursory deformation data to build a database from case studies. Papers were chosen that present techniques, methods, and case studies.

ANNOTATED BIBLIOGRAPHY

Alaraz, A., 1960, Tilt measurements in Philippine volcanic areas: Bulletin Volcanologique, v. 23, p. 161-180.

Water-tube tilt measurements were initiated in July 1957 on Mayon Volcano and Hibok-Hibok Volcano. One year of baseline data is presented, and the method of computation is reviewed. There was no unusual activity at these volcanoes during this time.

Alvarado, G.E., Dominguez, S.A., Calderon, C.C., 1988, Interpretacion preliminar de las deformaciones associadas al Volcan Arenal (Costa Rica): Boletin del Observatorio Vulcanologico del Arenal, Ano 1, no. 2, p. 26-43.

Deformation studies have been carried out at Arenal since 1969. The data shows continuous subsidence believed to be related to the loading of lava which has been erupting since 1968.

Aramaki, S., ed., 1988, The 1986-1987 eruption of Izu-oshima Volcano: Earthquake Research Institute, 61 p.

This publication includes a complete description of the November 1986 eruption. General geology, sequence of the eruption, seismic activity, deformation, variations in the magnetic field and the electrical resistivity, petrology, geochemistry of gases and water, a model of the eruption, and the role of the civil defense in the mitigation process are described.

Leveling data was inconclusive. EDM data suggest that the caldera area was deflating before the eruption. An interpretation of the data more consistent with the observed elongation of the north flank is an inflation of the lower northwest flank of the volcano.

Banks, N.G., Koyanagi, R.Y., Sinton, J.M., and Honma, K.T., 1984, The eruption of Mount Pagan Volcano, Mariana Islands, 15 May 1981: Journal of Volcanology and Geothermal Research, v. 22, p. 225-269.

The eruption was preceded by 2 months of seismicity. It started as a magmatic eruption and quickly became hydromagmatic. Most explosive activity was restricted to 3 vent areas. The northern vent built a scoria and ash cone. Juvenile material exceeded 105 x 10^6 m^3 (75 x 10^6 m^3 of magma) on land and 70-100 x 10^6 m^3 at sea. There were no serious injuries. The paper includes eruption history (eruption dates and type of activity), petrology, deformation and seismic observations, and gas and water analyses.

Deformation monitoring was not initiated until 6 days after the eruption. The eastern lagoon water level was monitored and a drop in the level was noted. The water level drop may have resulted from uplift of the central part of the island or from drainage of the lake as a consequence of the earthquakes and eruptions. EDM reflectors were installed on the south flank of the mountain. Line length varied considerably; whether changes were due to intrusion of magma or gravitational instability is not known.

Banks, N.G., Tilling, R.I., Harlow, D.H., Ewert, J.W., 1989, Volcano monitoring and short-term forecasts, in Tilling, R.I., ed., Volcanic Hazards: American Geophysical Union, Washington, D.C., p. 51-80.

This introduction and overview of volcano monitoring techniques emphasizes seismic and deformation monitoring. Pros and cons such as cost and level of accuracy of various methods of measuring deformation are discussed.

Barberi, F., Corrado, G., Innocenti, F., and Luongo, G., 1984, Phlegrean Fields 1982-1984: Brief chronicle of a volcano emergency in a densely populated area: Bulletin Volcanologique., v. 47-2, p. 175-185.

This summary of activity describes ground deformation, seismicity, and chemical changes in fumarole gases at the Phlegrean Fields. It includes a discussion of the social problems faced by scientists involved in making short-term predictions of volcanic events.

Berrino G., Corrado, G., Luongo, G., and Toro, B., 1984, Ground deformation and gravity changes accompanying the 1982 Pozzuoli uplift: Bulletin Volcanologique, v. 47-2, p. 187-200.

Deformation data from the summer of 1982 through September 1984 are described, compared to the gravity data, and modeled. Uplift was accompanied by gravity changes. The best-fit model includes a spherical pressure source of magma several hundred meters in diameter at a depth of 3 km centered under the town of Pozzuoli.

Bonasia, V., and Pingue, F., 1981, Ground deformations on Mt. Vesuvius from 1977 to 1981: Bulletin Volcanologique, v. 44, no. 3, p. 513-520.

No significant changes occurred.

Brantley, S., and Topinka, L., 1984, Volcanic studies at the U.S. Geological Survey's David A. Johnston Cascades Volcano Observatory, Vancouver, Washington: U.S. Geological Survey Earthquake Information Bulletin, v. 16, no. 2, p. 47-121.

This bulletin summarizes the activity at Mt. St. Helens from 1980 through March 1984. It includes information on seismicity, deformation, gas emissions, thermal observations, and hydrologic monitoring. The authors have incorporated many excellent photographs and diagrams.

Caputo, M., 1979, Two Thousand Years of Geodetic and Geophysical observation in the Phlegrean fields near Naples, Italy: Geophysical Journal of the Royal Astronomical Society, v. 56, p. 319-328.

Inflation began around the year 1000 and culminated in an eruption in 1538. This paper includes a good account of that eruption. The rate of uplift increased again in 1970. Results of deformation studies from 1970 to 1977 are discussed.

Chadwick Jr., W.W., Archuleta, R.J., and Swanson, D.A., 1988, The mechanics of ground deformation precursory to dome-building extrusions at Mount St. Helens: Journal of Geophysical Research, v. 93., no. 5, p.4351-4366.

Deformation of the crater floor is modeled using the finite element method. Deformation features are best explained by a shear-stress boundary condition caused by the flow of magma up the conduit and into the dome. The magnitude of the shear stress is inversely proportional to the diameter of the conduit.

Chadwick Jr., W.W., Iwatsubo, E.Y., Swanson, D.A., Ewert, J.W., 1985, Measurements of slope distances and vertical angles at Mount Baker and Mount Rainier, Washington, Mount Hood and Crater Lake, Oregon, and Mount Shasta and Lassen Peak, California, 1980-1984: U.S. Geological Survey Open File Report 85-205, pp. 96.

The installation and baseline measurements of trilateration (EDM) networks established between 1980 and 1984 are documented at the cited volcanoes.

Chadwick Jr., W.W., Swanson, D.A., Iwatsubo, E.Y., Heliker, C.C., Leighley, T.A., 1983, Deformation monitoring at Mount St. Helens in 1981 and 1982: Science, v. 221, p. 1378-1380.

Deformation monitoring techniques used at Mt. St. Helens in 1981 and 1982 included trilateration, triangulation, EDM, crack measurement, slope-distance and vertical-angle measurements, electronic tilt, and leveling. Recurring precursory patterns of deformation were used to predict 9 dome-building eruptions. Measurable deformation typically began 3 to 4 weeks before an eruption. Deformation rates accelerated by four to five orders of magnitude before each eruptive episode.

Clark, R.H., 1971, Rates of deformation of parts of the crater floor of the White Island Volcano: in Recent Crustal Movements, Royal Society of New Zealand Bulletin, v. 9, p. 73-75.

A bulge developed in the crater prior to the January 29, 1968 eruption and disappeared following it. The rate of deformation at White Island is much higher than the highest tectonic rates in New Zealand. The vertical movements observed at White Island are oscillatory.

Clark, R.H., 1973, Surveillance of White Island Volcano, 1968-1972: Part 1 - Volcanic events and deformation of the crater floor: New Zealand Journal of Geology and Geophysics, v. 16-4, p. 949-957.

Four years prior to the 1971 eruption (1967), leveling showed that a bulge on the crater floor had developed. In addition, fumarole temperatures were elevated. After the opening of a new vent in 1968, the crater floor subsided. In December 1969, uplift resumed and continued through the eruption in 1971. The sub-crater floor is modeled as interconnected channels through which gas passes upward. These channels get periodically blocked, which causes gas pressure to increase, uplifting the surface.

Clark, R.H., 1982, Surveillance of White Island volcano 1972-77: volcanic events and deformation of the crater floor: New Zealand Journal of Geology and Geophysics, v. 25, p. 317-324.

Inflation was observed in 1972, 1973, and 1974. The magnetic field intensity decreased in 1974, prompting a forecast of an impending eruption. Localized deflation in 1975 was followed by renewed inflation in 1976. White Island erupted in December 1976. All tephra eruptions since 1967 have been preceded by uplift.

Cole, J.W., 1988, White Island (New Zealand) Surveillance Programme 1967-1988: Kagoshima International Conference on Volcanoes, Proceedings, p. 246-248.

Precise leveling networks were installed to form two loops. Measurements were made with a Zeiss self-adjusting level 2 or 3 times a year. Periods of uplift of the crater floor usually precede an eruption.

Corrado, G., Guerra, I., Lo Bascio, A., Luongo, G., Rampoli, R., 1976, Inflation and microearthquake activity of Phlegraean Fields, Italy: Bulletin Volcanologique, v. 40-3, p. 1-20.

Until 1968, the area around the town of Pozzuoli was subsiding at an average rate of 15 mm/yr. Rapid uplift occurred in early 1970. Since then, deformation has oscillated between uplift and subsidence. A recent history of deformation and seismicity is included. When the rate of uplift is low or negative, the seismic activity level is low. The uplift can be attributed to the intrusion of magma into a heterogeneous medium.

Corrado, G.; Luongo, G., 1981, Ground deformation measurements in active volcanic areas using tide gauges: Bulletin Volcanologique, v. 44-3, p. 505-511.

A method of tide gauge data analysis was tested in the Phlegraean Fields near Naples. Results were checked and agreed with leveling data. Although the tide gauge method is less accurate than leveling, it is much less expensive and provides a continuous record.

Davis, P.M., 1981, Gravity, tilt, and earth tides measured on an active volcano, Mt. Etna, Sicily: Journal of Volcanology and Geothermal Research, v. 11, p. 213-223.

Tiltmeters and tidal gravimeters were installed on Mt. Etna to determine if previously reported anomalous earthtides, which might be related to shallow bodies of magma, had an effect on the deformation of the volcano. Tidal tilts were 2.5 times less than what was theorecally predicted. Results imply that the anomalous tides might be transient phenomena associated with eruptions and could not be associated with near-surface bodies of magma.

Decker, R.W., 1968, Measurement of horizontal ground surface deformation in Iceland (abstract): Transactions, American Geophysical Union, v. 49, p. 114.

Fifty-five survey lines were established in Iceland in 1967 to detect horizontal

movements.

Decker, R.W., 1978, State of the art in volcano forecasting: in Geophysical Predictions, Geophysics Study Committee, National Research Council, National Academy Press, Washington, D.C., p. 47-57.

A good overview of the types of monitoring techniques available and their relative merit is presented. The authors also cite some interesting volcano statistics.

Decker, R.W., 1987, Dynamics of Hawaiian Volcanoes: An overview, in Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey 1350, v. 2, p. 997-1018.

The author synthesizes Hawaiian geological and geophysical research into a comprehensive model of the dynamics of Hawaiian volcanoes. A review of the literature and theories concerning magma formation, accumulation, ascent, and storage is presented. Deformation studies since 1935 have been used to identify the location of the shallow magma storage system.

Decker, R.W., Hill, D.P., Wright, T.L., 1966, Deformation measurements on Kilauea Volcano, Hawaii: Bulletin Volcanologique, v. 29, p. 721-732.

EDM measurements from October 1964 to March 1965 show horizontal expansion related to uplift and tilting of the summit prior to an eruption, and deflation during and after a flank eruption.

Decker, R.W., Kinoshita, W.T., 1972, Geodetic measurements. In: Surveillance and prediction of volcanic activity: Paris, UNESCO, p. 47-74.

A general summary of deformation techniques is provided. The authors discuss tilt, leveling, tide changes, shore-line changes, gravimetry, triangulation, EDM, alignment surveys, and crack measurements. The authors emphasize the usefulness and the shortcomings of the various techniques. A geographic summary of deformation studies that have been done on active volcanoes is included.

Decker, R.W., Koyanagi, R.Y., Dvorak, J.J., Lockwood, J.P., Okamura, A.T., Yamashita, K.M., and Tanigawa, W.R., 1983, Seismicity and surface deformation of Mauna Loa Volcano, Hawaii: EOS Transactions, American Geophysical Union, v. 64, no. 37, p. 545-547.

Surface deformation and earthquake locations are used to interpret the size and depth of shallow magma reservoirs beneath Mauna Loa. Data from 1962 to 1983 are presented. Leveling lines and EDM surveys were begun in 1964. Surface deformation, expressed by widening of the caldera, was detected one year before the 1975 eruption. Continuous inflation has occurred since 1976. The proposed model includes a common center of uplift and a shallow pressure source.

Decker, R.W., Wright, T.L., 1968, Deformation measurement on Mauna Loa Volcano, Hawaii: Bulletin Volcanologique., v. 32, no. 2, p. 401.

In 1964, a 6 km precise leveling triangle was established on Mauna Loa. EDM measurements across the caldera began in 1965.

Denlinger, R.P., Riley, F.P., Boling, J.K., Carpenter, M.C., 1985, Deformation of Long Valley, Caldera between August 1982 and August 1983: Journal Geophysical Research, v. 90, no. B-13, p. 11,199-11,209.

Deformation and seismic data were collected between July 1982 and August 1983. The pattern of deformation and the seismic swarms were attributed to a the expansion of the upper levels of a residual magma chamber beneath the caldera.

De St. Ours, P., 1987, Inflation of Rabaul caldera since its 1937 eruption as revealed by emergence of intertidal shell horizons [abstract]: Hawaii Symposium on How Volcanoes Work, Hilo, Hawaii, January 1987, p. 220.

The present cycle of uplift began soon after the 1937 eruption and continued until July 1971, when 2 earthquakes caused subsidence up to 80 cm. After the seismic activity, uplift resumed again. Net uplift amounted to a maximum of 2.5 m by 1971 and 4.5 m by 1985. Modeling of the data indicates that there 2 shallow magma reservoirs beneath the caldera.

Dibble, R.R., 1988, Eruption forecasting in New Zealand: Kagoshima International Conference on Volcanoes, Proceedings, p. 179-182.

Precursory monitoring data and the success record of forecasting eruptions (Synthetic Hit Rate or SHR developed by Nishi, 1987) for White Island and Ruapehu volcanoes are described. SHR is defined as the square of the number of successful forecasts, divided by the number of forecast judgments, and by the total number of eruptions or other forecast phenomena. Moderately successful forecasts have been made: 31% for White Island and 21% for Ruapehu.

Dietrich, J.J., Decker, R.W., 1975, Finite element modeling of surface deformation associated with volcanism.: Journal of Geophysical Research, v.80, no. 29, p. 4094-4102.

Finite-element deformation models seem to offer a better fit to observed deformation data. A model of the shallow magma reservoir of Kilauea is used as an illustration.

Duffield, W.A. and Burford, R.O.,1973, An accurate invar-wire extensometer: U.S. Geological Survey Journal Research, v. 1, no. 5, p. 569-577.

The installation and use of the Stevens Type F water-level recorders which have been used to measure crack dilation at Kilauea Volcano and displacement across the San Andreas Fault is documented.

Duffield, W.A., Jackson, D.B., and Swanson, D.A., 1976, The shallow, forceful intrusion of magma and related ground deformation at Kilauea Volcano, May 15-16, 1970 in O. Gonzales Ferran, ed., Proceedings of the Symposium on Andean and Antarctic Volcanology Problems, Santiago, Chile, September, 1974, International Association of Volcanology and Chemistry of the Earth's Interior, Special Series, p. 1-21.

Shallow seismicity and deformation centered in the south and east parts of the caldera accompanied the 1970 intrusion of magma beneath Kilauea. The intrusion was preceded by 4 months of inflation with maximum displacement reaching 19 cm vertically and 29 cm horizontally.

Dvorak, J.J., Okamura, A.T., 1987, A Hydraulic Model to explain variations in summit tilt Rate at Kilauea and Mauna Loa Volcanoes, in Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, Chap. 46, p. 1281-1296.

The center of subsidence at Hawaiian volcanoes migrates horizontally and vertically. A hydraulic model assumes that the magma flow rate is proportional to the pressure difference along the conduit. Laminar flow through a circular pipe is consistent with this model.

Dvorak, J., Okamura, A., Dietrich, J.H., 1983, Analysis of surface deformation data, Kilauea volcano, Hawaii, October 1966 to September 1970: Journal Geophysical Research, v. 88, no. B-11, p. 9295-9304.

A least squares inversion technique to analyze deformation data has been used to model shape and location of intrusions and estimate magma supply rate. Earthquake activity or episodic block movements may explain the difference between measured uplift and calculated values.

Dzurisin, D., Anderson, L.A., Eaton, G.P., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., Okamura, R.T., Puniwai, G.S., Sako, M.K., and Yamashita, K.M., 1980, Geophysical observations of Kilauea Volcano, Hawaii, Constraints on the magma supply during November 1975-September 1977: Journal of Volcanology and Geothermal Research, v. 7, p. 241-269.

Seismic, electrical self-potential, tilt, leveling, and gravity data are synthesized to form a model of the magma supply at Kilauea. The model indicates that only 12-20% of the magma delivered to Kilauea's shallow magma reservoir is erupted: the rest is permanently intruded into the rift zones. The intruded portion is partitioned between the East Rift Zone (36-57%), the summit area (23-32%), and the Southwest Rift Zone, (0-20%). The magma supply rate seemingly varies by more than a factor of two over time scales of months to years.

Dzurisin, D., Cashman, K.V., and Sylvester, A.G., 1982, Tilt measurements at Long Valley caldera, California, May-August 1982: U.S. Geological Survey Open-File Report 82-893, 34 p.

Elevated levels of seismicity and ground deformation prompted the establishment of deformation monitoring at Long Valley caldera, east-central California. Nine spirit-level tilt stations were established, and repeat surveys were conducted over the course of 4 months. Station locations and methods are described and data is presented in tabular form. Measured changes may be due to " noise", actual uplift of the dome with patterns complicated by local structures, or real uplift not centered on the dome. Additional measurements are recommended.

Dzurisin, D., Johnson, D., Murray, T., Myers, B., 1982, Tilt networks at Mount Shasta and Lassen Peak, California: U.S. Geological Survey Open-File Report 82-670, 42 p.

The establishment of deformation monitoring at Mount Shasta and Lassen Peak, California is documented. Spirit-level tilt and EDM surveys were conducted.

Dzurisin, D., Johnson, D.J., and Symonds, R.B., 1983, Dry tilt network at Mount Rainier, Washington: U.S. Geological Survey Open File Report 83-227, 44 p.

The procedures, bench mark locations, and results of the spirit level tilt array installed at Mt. Rainier in 1982 are outlined.

Dzurisin, D., and Newhall, C.G., 1984, Recent ground deformation and seismicity at Long Valley (California), Yellowstone (Wyoming), the Phlegraean Fields (Italy), and Rabaul (PNG): U.S. Geological Survey Open File Report 86-939, p. 784-829.

Geologic history and current activity are summarized for each caldera. Selected deformation and seismic histories through March 1984 are presented. Unrest at calderas is compared for similarities and differences.

Dzurisin, D., Savage, J.C., and Fournier, R.O., 1988, Recent crustal subsidence at Yellowstone caldera, Wyoming, Bulletin of Volcanology, in press.

Rapid crustal uplift at an average rate of 15±1 mm/yr was discovered by comparing leveling surveys conducted within Yellowstone Caldera between 1923 and 1984. The caldera floor stopped rising during 1984-1985, and began subsiding from 1985-1987. Two models are offered to explain the historical elevation changes, seismicity, and hydrothermal activity in the area. In the first model, uplift is caused by the injection of basalt at the base of a rhyolitic system. Rhyolite crystallizes higher in the magmatic system, releasing volatiles into the hydrothermal system. Subsidence begins when the rate of basalt supplied to the base of the system is less than the subsidence produced by the crystallization of rhyolite and fluid loss. In the second model, uplift occurs when magmatic gas and brine, released during crystallization of rhyolite, pressurizes the hydrothermal system and is then trapped beneath an impermeable self-sealed zone. Subsidence occurs episodically when this zone becomes fractured.

Dzurisin, D., Westphal, J.A., and Johnson, D.J., 1983, Eruption prediction aided by electronic tiltmeter data at Mt. St. Helens: Science, v. 221, p. 1381-1383.

Data from nine electronic tiltmeters installed at Mt. St. Helens contributed to the successful prediction of 6 dome-building episodes in 1981 and 1982. Typically, measurable tilt began several weeks before an eruptive episode. Tilt rate accelerated dramatically several days before extrusion began. This was followed by a reversal in tilt direction a few minutes to days before the onset of extrusion.

Dzurisin, D., Yamashita, K.M., 1986, Preliminary results of precise leveling and trilateration surveys in Yellowstone National Park, Wyoming, 1983-1984: U.S. Geological Survey Open-File Report 86-265-A.

The procedures, bench mark locations, and results of the spirit-level tilt and trilateration surveys conducted at Yellowstone caldera in 1983 and 1984 are presented. The level line in Yellowstone was previously surveyed in 1923 and 1976. Results indicate that uplift continues at an average rate of 22 mm/yr.

Dzurisin, D., and Yamashita, K.M., 1987, Vertical Surface Displacements at Yellowstone Caldera, Wyoming, 1976-1986: Journal of Geophysical Research, v. 92, no. B13, p. 13,753-13,766.

During the 10 year study period, the floor of Yellowstone Caldera rose at a maximum rate of 15.4 ± 1.4 to 17.0 ± 2.0 mm/yr, a trend that is consistent with data obtained for the 1923 and 1976 surveys. However, the western caldera has been rising at a rate 30% faster than during the 1923-1976 period. Yearly surveys beginning in 1983 have provided details indicating that long-term uplift may occur episodically. Uplift stopped during 1984-85 and subsidence began during 1985-86. Possible mechanisms that are driving the system are discussed, taking the geologic history of the area and trends observed at other silicic calderas into consideration. The authors have included an appendix detailing their field procedures, corrections, and error analysis.

Dzurisin, D., Yamashita, K.M., and Johnson, D.J., 1986, Preliminary results of precise leveling and trilateration surveys in Yellowstone National Park, Wyoming, 1985: U.S. Geological Survey Open-File Report 86-265-B.

The results of the spirit-level tilt and trilateration surveys conducted at Yellowstone caldera in 1985 showed no significant changes from the 1984 survey. It may be that "uplift has been steady over time scales of decades but episodic over time scales of years." The authors have included an interesting discussion of the Yellowstone magmatic-hydrothermal system. They address the question "Is Yellowstone cooling down or heating up?."

Eaton, J.P., 1959, A Portable Water-Tube Tiltmeter: Bulletin of the Seismological Society of America v. 49, no. 4, p. 301-316.

Eaton describes the principles and use of the water-tube tiltmeter for deformation monitoring. He also discusses its accuracy and limitations.

Eaton, J.P., 1962, Crustal structure and volcanism in Hawaii: Geophysical Monograph No. 6, Crust of the Pacific Basin, p. 13-29.

Earthquakes and surface deformation are related to an eruptive model for Kilauea. Magma accumulates in a reservoir beneath the caldera. Deep earthquakes may outline the source of the magma. Swarms of small shallow earthquakes that occur with the opening of fissures in the cone are precursors to impending eruptions.

Eaton, J.P., and Murata, K.J., 1960, How volcanoes grow: Science, v. 132, no. 3432, p. 925-938.

The authors discuss the geology of Hawaii and volcano monitoring of Kilauea. They offer their interpretation of the eruptive mechanisms operating at Kilauea.

Eaton, J.P., Richter, D.H., Krivoy, H.L., 1987, Cycling of magma between the summit reservoir and Kilauea Iki lava lake during the 1959 eruption of Kilauea Volcano, in Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey 1350, v. 2, p. 1307-1335.

Tiltmeters and Press-Ewing seismographs recorded deformation. This data is correlated with the record of other measurements and observations carried out before and during the 1959 eruption. A model explaining the mechanical features of the eruption is presented. Tilt associated with eruption of lava into and withdrawal of lava from the lava lake during backflow episodes offers a means of determining fluctuating volume estimates. A lava conduit connecting the supply of lava in the reservoir with the lake provided the means for the recycling of magma. Vesiculation of lava in the conduit drove lava from the reservoir up to the lake. The vent then became flooded with devesiculated lava which flowed back into the reservoir. Fresh gas-charged magma introduced into the conduit from the reservoir drove the process to repeat itself.

Eggers, A.A., 1983, Temporal gravity and elevation changes at Pacaya Volcano, Guatemala: Journal of Volcanology and Geothermal Research, v. 19, p. 223-237.

Gravity changes have been measured since 1975. Elevation changes at Pacaya have been documented since 1979. Maps of gravity change over 6 month intervals are included. Areas of gravity change and elevation change do not always coincide. This situation requires gravity decrease with little or no inflation. This could be produced by a shallow magma body in which the high-density degassed magma is displaced by low-density vesiculated magma during increased activity. Another alternative may be that the loss of gases by fumarolic activity produces a density increase and a reduction in volume of the magma during periods of declining activity.

Eggers, A.A., 1987, Residual gravity changes and eruption magnitudes: Journal of Volcanology and Geophysical Research, v. 33, p. 201-216.

Using precursory gravity changes and estimations of volatile content, pressure, and temperature of the magma, the author computes the kinetic energy of five eruptions. The magnitude of explosive magmatic eruptions is directly proportional to the quantity of dissolved and exsolved volatiles in the magma. He indicates that his methods may be used to forecast eruption magnitudes in the future.

Eggers, A.A., and Chavez, D., 1979, Temporal gravity variations at Pacaya Volcano, Guatemala: Journal of Volcanology and Geothermal Research, v. 6, p. 391-402.

Gravity changes between January 1977 and January 1978 indicate a conical gravity anomaly centered over a pit crater near the summit. These changes could be accounted for by a combination of elevation and density changes. Elevation control was lacking, therefore it is not possible to determine the influence of each mechanism.

Eggers, A., Krausse, J. Rush, H., and Ward, J., 1976, Gravity changes accompanying volcanic activity at Pacaya Volcano, Guatemala: Journal of Volcanology and Geothermal Research, v. 1, p. 229-236.

Gravity changes measured over 11 days in January 1975 indicate the possibility of either the movement of a very large magma body, or elevation changes of up to 3 m in one day, or a combination of these two processes. Unfortunately, elevation control was lacking.

Estrem, J.E., Lisowski, M., Savage, J.C., 1985, Deformation in the Long Valley Caldera, California, 1983-1984: Journal of Geophysical Research, v. 90, no. B-14, p. 12,683-12,690.

Leveling and trilateration measurements in and around the Long Valley Caldera from July 1983 to August 1984 indicate that deformation was occurring at a constant rate and was about the same as the previous year.

Ewert, J.W., 1989, A trigonometric method for monitoring ground-tilt changes on composite volcanoes: U.S. Geological Survey, Open File Report 89-223, 12 p.

A procedure for measuring ground tilt with a theodolite/EDM system is described. The equipment is more compact and lightweight than that required for spirit level tilt measurements. Longer baselines can be measured, increasing the precision of vertical deformation measurements. The disadvantage is the relatively high cost of the instrumentation.

Federal Geodetic Control Committee (1974) Classification, standards of accuracy, and general specifications of geodetic control surveys: National Oceanic and Atmospheric Administration, Rockville, Maryland.

Three National Geodetic Control Networks have been created by the U.S. Government to provide datums. These control networks consist of stable, identifiable points for which datum values are computed and published. This reference pamphlet provides detailed specifications and general procedural guidance for surveys. It provides the permissible tolerances of error for the indicated order and class of control. Appropriate uses for each order and class are discussed. See following 2 references.

Federal Geodetic Control Committee (1975) Specifications to support classification, standards of accuracy, and general specifications of geodetic control surveys: National Oceanic and Atmospheric Administration, Rockville, Maryland.

Specific procedural guidelines, sources of error, and equipment requirements to achieve appropriate standards are discussed. This pamphlet is related to the previously mentioned reference.

Federal Geodetic Control Committee, Rear Adm. J.D. Bossler, chairman (1984) Standards and specifications for geodetic control networks. National Oceanic and Atmospheric Administration, Rockville, Maryland.

Accuracy standards of first-order through third-order horizontal, vertical, and gravity surveys are defined. See the 2 previously mentioned references.

Ferri, M., Grimaldi, M., and Luongo, G., 1988, Vertical ground deformation on Vulcano, Aeolian Islands, southern Italy: Observations and interpretations 1976-1986: Journal of Volcanology and Geothermal Research, v. 35, p. 141-150.

The authors believe that the pattern of deformation at Vulcano can be explained without invoking the movement of magma. A magnitude 5.5 earthquake occurred on April 15, 1978, which initiated subsidence and opened fractures. High-temperature fluids rose along these conduits and increased activity at the fumaroles. The increased fluid flow at depth temporarily raised pressures and caused uplift. Subsequent leakage of fluids at the surface relieved the pressure at depth, and subsidence soon followed.

Fiske, R.S., Kinoshita, W.T., 1969, Inflation of Kilauea Volcano prior to its 1967-1968 eruption: Science, v. 165, p. 341-349.

The pattern of deformation prior to eruption is interpreted and a model is developed. Data suggests that a complex reservoir system including sills and feeder dikes lies at a depth of 2-3 km beneath the summit area.

Fiske, R.S., Koyanagi, R.Y., 1968, The December 1965 Eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 607, 21 p.

The summit inflated before the eruption and deflated during and after the eruption. The eruption marked the beginning of a week long seismic crisis interpreted to reflect dilation of the East Rift Zone.

Fiske, R.S., and Shepherd, J.B., 1982, Deformation studies on Soufriere, St. Vincent, between 1977 and 1981: Science, v. 216, p. 1125-1126.

Two dry-tilt stations were established on Soufriere in 1977. Inflation was recorded for the first year of monitoring (Feb. 1977 to Feb. 1978). During the next 7 months (Feb. through Sept. 1978) the results were ambiguous; one station showed inflation, one showed no change at

first and then slight deflation. No measurements were made between September, 1978 and the eruption in April, 1979, but the authors assumed that the inflationary and deflationary trends continued. Rapid deflation occurred with the onset of explosive activity in mid-April 1979. Deflation continued for over 1 year after eruptive activity ceased. Deflation recorded 6.5 km from the summit was almost twice that recorded 2.5 km from the summit. This can be explained by a magma chamber located at a depth of more than 10 km.

Fiske, R.S., and Shepherd, J.B., 1989, In press, Ten years of dry-tilt measurements on the Soufriere of St. Vincent, 1977-1986: Bulletin of Volcanology.

The tilt data from Soufriere indicate that the volcano gradually inflated before the 1979 eruption, deflated rapidly during the eruption and continued to deflate for a year after the eruption. The volcano has reinflated slightly since 1981. The maximum tilt from 1977 to 1986 was measured 6.5 km from the summit and totaled 20 urads. The authors have included many lessons of experience, problems encountered, corrections that have been made to their program, and interpretations of their data.

Fukuyama E., 1988, Saw-teeth-shaped tilt change observed at Izu-oshima Volcano, Japan: Kagoshima International Conference on Volcanoes, Proceedings, p. 321-315.

After the November 1986 eruption "saw-teeth-shaped" tilt changes corresponded to the occurrence of volcanic tremor. A magma contraction model is proposed whereby the magma beneath the central crater drains back toward the deeper crust after the huge eruption in November. This movement of magma decreases pressure in the magma chamber, and causes the tilt. When the deformation reaches a critical point, a "fracture" occurs, emitting volcanic tremors.

Grindley, G.W., 1974, Relation of volcanism to earth movements, Bay of Naples, Italy: Proceedings of the symposium on Andean and Antarctic Volcanology Problems, p. 598-612.

Three historic volcanic periods beginning 50,000 years ago describe the volcanism of the Phlegraean Fields. These periods of activity have been confirmed by radiocarbon dating. Uplift and subsidence rates have been between 10 and 20 mm per year.

Hashimoto, M., and Tada, T., 1988, Crustal movements associated with the 1914 eruption of Sakurajima Volcano, Kagoshima, Japan: Kagoshima International Conference on Volcanoes, Proceedings, p. 288-291.

Triangulation surveys were conducted at Sakurajima from 1895 to 1914. During this period, fissures on the summit extended in a N-S direction. In addition, control points on the Aira caldera moved toward the center of the crater. The authors suggest that contraction of the magma reservoir at a depth of 9 km beneath the Aira Caldera was responsible for the observed changes.

Henbest, S.N., Mills, A.A., and Ottey, P., 1978, Two tiltmeters and an integrating seismometer for the monitoring of volcanic activity, and the results of some trials on Mount Etna: Journal of Volcanology and Geothermal Research, v. 4, p. 133-149.

Two types of tiltmeters and a seismometer were tested on Etna between September and December 1986. Their positive and negative aspects are discussed.

Huntingdon, A.T., Guest, J.E., and Francis, E.H., eds., 1980, United Kingdom Research on Mt. Etna, 1977-1979: Royal Society's Volcanological and Seismological Committee, London, pp. 56.

A good summary is provided on the geologic history of Mt. Etna. The preliminary results of a seismic study, deformation data, and a gravity survey are presented. Recent eruptions are described. Mt. Etna displays a small amount of local inflation before an eruption but the entire edifice does not respond as is the case at Kilauea.

Ishihara, K., 1988, Prediction of summit eruption by tilt and strain data at Sakurajima Volcano, Japan: Kagoshima International Conference on Volcanoes, Proceedings, p. 207-210.

An underground tunnel was constructed in a lava dome 2.8 km NW of the summit in 1985. It houses a water-tube tiltmeter and an extensometer. Minor inflation and deflation have been observed which correlate with individual eruptions. In addition, the amount of inflation correlates with amount of ash emitted.

Jackson, D.B., Swanson, D.A., Koyanagi, R.Y., and Wright, T.L., 1975, The August and October 1969 east rift eruptions of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 890, 33 p.

A chronological narrative of the two 1968 east rift eruptions is presented. Deformation and seismic data and the petrography of erupted lavas are summarized. The results of the study of ground deformation during and between the two eruptions are emphasized. These results are more detailed than those of any previous flank eruption at Kilauea. Deformation monitoring techniques included leveling, trilateration, a continuously-recording mercury tiltmeter, and water-tube tiltmeters. Both eruptions were preceded by inflation of the summit. Both eruptions were accompanied by subsidence at the summit, which tilted inward as magma was withdrawn from a reservoir and moved into rift zone.

Johnson, D.J., 1987, Elastic and inelastic magma storage at Kilauea Volcano, in Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, Chap. 47, p. 1297-1306.

A magma-budget estimate for Kilauea requires a synthesis of gravity, leveling, and trilateration data. Magma storage within the reservoir is affected by a combination of elastic magma compression, elastic chamber expansion, and inelastic edifice widening.

Johnsen, G.V., Bjornsson, A., and Sigurdsson, S., 1980, Gravity and elevation changes caused by magma movement beneath the Krafla Caldera, northeast Iceland: Journal of Geophysics, v. 47, p. 132-140.

Gravity, leveling, and tilt measurements reveal a slow inflation of the caldera for several weeks or months followed by sudden subsidence. These movements are interpreted to be caused by the in- and outflow of magma.

Kaminuma, K., and Dibble, R.R., 1988, Geophysical studies on Mt. Erebus, Antartica: Kagoshima International Conference on Volcanoes, Proceedings, p. 242-245.

As part of a volcano monitoring network on Mt. Erebus, gravity surveys have been conducted once a year since 1982.

Kimata, F., Nakamura, M., Miyajima, R., Okuda, T., Fujii, I., and Aoki, H., 1988, Measurements of deformation at Yakedake Volcano, Central Japan: Kagoshima International Conference on Volcanoes, Proceedings, p. 370-372.

Yaketake erupted in 1915 and explosive activity continued through 1939. In 1962 a 500 m long fissure appeared at the summit. Currently, occasional earthquake swarms are the only activity. Leveling has been conducted once a year since 1977; EDM measurements have been made since 1973. Slight uplift has been detected.

Kinoshita, W.T., Swanson, D.A., Jackson, D.B., 1974, The measurement of crustal deformation related to volcanic activity at Kilauea Volcano, Hawaii. In: Civetta, L., Gasparini, P., Luongo, G, and Rapolla, A., eds., Physical Volcanology, Elsevier, Amsterdam, p. 87-115.

Current techniques (as of 1974) to measure deformation at Kilauea are described. A history of the development of instrumentation and a description of spirit-level tilt are included.

Kumagai, T., Takahashi, H., and Oyagi, N., 1988, Precursor of volcanism observed by crustal movement in Iwo-jima: Kagoshima International Conference on Volcanoes, Proceedings, p. 366-369.

The island of Iwo-jima lies within a submarine caldera and is composed of two active volcanoes. In the last 100 years, uplift has averaged 10-20 cm per year. The release of strain triggers earthquake swarms and phreatic explosions.

Lenat, J.F., 1985, Ground deformation associated with the 1983-84 and June 1985 eruptions of Piton de la Fournaise, Isle de la Reunion: EOS, Transactions, American Geophysical Union, v. 66, no. 46, p. 852.

Piton de la Fournaise is a basaltic oceanic intraplate volcano that has been monitored for deformation since June, 1982. No long-term inflation has been observed. No precursory deformation was observed before the 1983 eruption, but inflation was measured 2 weeks before the second phase of that eruption and before the June, 1985 eruption. It is believed that no new magma has been supplied to the shallow magma chamber.

Linker M.F., Langbein, J.O., and McGarr, A., 1986, Decrease in deformation rate observed by two-color laser ranging in Long Valley Caldera: Science, v. 232, p. 213-216.

The deformation rate in the south moat had decreased as of mid-1984 following the January 1983 seismic swarm.

Lipman, P.W., Moore, J.G., Swanson, D.A., 1981, Bulging of the north flank before the May 18 eruption - geodetic data, in Lipman, P.W. and Mullineaux, D.R., eds., The 1980 eruptions of Mt. St. Helens: U.S. Geological Survey Professional Paper 1250, p. 143-155.

Triangulation and EDM measurements of the north flank of the volcano between April 23 and May 18 indicated that the surface of a bulge was moving 1.5 to 2.5 m per day. The bulge covered an area approximately 1.5 x 2 km and later was the source of a huge debris avalanche and blast.

Lockwood, J.P., Banks, N.G., English, T.T., Greenland, L.P., Jackson, D.B., Johnson D.J., Koyanagi, R.Y., McGee, K.A., Okamura, A.T., and Rhodes, J.M., 1985, The 1984 eruption of Mauna Loa Volcano, Hawaii: EOS Transactions, American Geophysical Union, v. 66, no. 16, p. 169-171.

Mauna Loa began to gradually inflate 10 years before the 1984 eruption. Based on the historic pattern at Mauna Loa, an eruption forecast was made. The forecast proved correct for the type and style of eruption, but occurred six years late. Seismic, geodetic, gravity, geoelectrical, and fumarolic observations are described. A narrative of the eruption is included.

Malone, S.D., 1979, Gravity changes accompanying increased heat emission at Mount Baker, Washington: Journal of Volcanology and Geothermal Research, v. 6, p. 241-256.

There was a significant decrease in gravity measured at Mt. Baker over a period of four months. There were no measurable tilt changes. A model involving density change caused by mass being lost from the fumaroles is favored.

Martini, M., 1986, Thermal activity and ground deformation at Phlegraean Fields, Italy: Precursors of eruptions or fluctuations of quiescent volcanism? A contribution of geochemical studies: Journal of Geophysical Research, v. 91, no. B12, p. 12,255-12,260.

Volcanological history of the area, chemistry of the thermal waters, and an analysis of the fumarolic gases are examined along with deformation data for the period of unrest between

1982 and 1984. The author suggests that uplift may be caused by residual volcanic activity rather than renewed activity. Heat may be transferred through the flow of gases to the water-saturated pyroclastic formations which increase in volume by thermal expansion of pore spaces.

McKee, C.O., Lowenstein, P.L., De Saint Ours, P., Talai, B., Itikaral, I.; Mori, J.J., 1984, Seismic and ground deformation crises at Rabaul Caldera: Prelude to an eruption?: Bulletin Volcanologique, v. 47-2, p. 397-411.

September 1983 marked the beginning of a period of increased seismicity and increased ground deformation at Rabaul Caldera. These events are interpreted as indications of higher rates of magma injection beneath the caldera.

Minakami, T., 1960, Fundamental research for predicting volcanic eruptions, Part I. Bulletin of the Earthquake Research Institute., v. 38, p. 497-544.

The relationship between earthquakes and deformation caused by volcanic activity and tectonic earthquakes is discussed. Examples of deformation at Usu Volcano are used. The emphasis is on comparing tectonic and volcanic seismic activity.

Minakami, T., 1974, Prediction of volcanic eruptions: In: Civetta, L., Gasparini, P., Luongo, G., and Rapolla, A., eds., Physical Volcanology: Elsevier, Amsterdam, p. 313-333.

A good summary of volcanic precursors is provided. Discussions of elevated seismicity, surface deformation, variations in geothermal temperatures, geomagnetic fields and gravity fields are included.

Minakami, T., Ishikawa, T., and Yagi, K., 1951, The 1944 eruption of Volcano Usu in Hokkaido, Japan: Bulletin Volcanologique, v. 11, tome 11, p. 45-157.

Seismic, geodetic, geomagnetic, petrologic, and geochemical studies of Usu Volcano are described. The geologic history and chronology of past eruptions are included. In 1910, at the north foot of the cone, 150 m of uplift in an area 3 km long and .75 km wide was caused by the intrusion of a cryptodome. Precursory activity resumed with an earthquake felt on December 28, 1943. Noticeable deformation (upheaval, cracks, and dislocations) began in January, 1944. Uplift in the form of a dome reached 50 m by the time of the first explosion on June 23, 1944.

Miyazaki, T., 1988, Vertical ground deformation in the summit caldera related to the 1986 eruption of Izu-oshima Volcano: Kagoshima International Conference on Volcanoes, Proceedings, p. 324-326.

Precise leveling has been repeated annually since 1982. The inner caldera is continuously subsiding in relation to the flanks of the volcano. This may be caused by loading and the compaction of erupted materials. Prior to the 1986 eruption, the central cone did not inflate. Rapid deflation occurred after the eruption due to the increased load of the newly erupted material.

Mogi, K., 1958, Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them.: Bulletin of the Earthquake Research Institute, v. 36, p. 99-134.

This is the classic paper describing the Mogi model that relates a pressure source, ground deformation, and volcanic phenomena. Deformation data from Usu, Sakura-jima, and Kilauea are examined.

Mori, H. Y., Miyamachi, H., Suzuki, A., Maekawa, T., and Okada, H., 1988, Geodetic research at volcanoes in Hokkaido, Japan: Proceedings, Kagoshima International Conference on Volcanoes, p. 342-345.

The 1977 eruption of Usu was accompanied by the emplacement of a cryptodome which uplifted the crater floor 180 m and thrust it to the northeast about 250 m. Deformation continued until March, 1982.

There was no significant line length change at Tarumia during the phreatic activity of 1978-1981. Leveling measurements since 1983 indicate vertical fluctuations at the summit.

No significant changes were detected with the EDM at Tokachidake prior to the small phreatic eruption in 1985.

Murata, K.J., Dondoli, C., and Saenz, R., The 1963-65 eruption of Irazu Volcano, Costa Rica (The period of March 1963 to October 1964): Bulletin Volcanologique, v. 29, 765-793.

The March 1963 eruption of Irazu produced ash and other pyroclastic material. This paper describes the extent of the deposits and the floods, landslides, and lahars that followed the eruption.

Leveling conducted in May 1964 showed that there had been 11 cm of uplift of the upper part of the volcano since 1949. Releveling in September 1964 showed subsidence to the 1949 level.

Newhall, C.G., 1984, Short-term forecasting of volcanic hazards: Proceedings of the Geologic and Hydrologic Hazards Training Program, U.S. Geological Survey Open File Report 84-760, p. 507-592.

Provides an overview of volcano eruptive mechanisms and monitoring techniques. Written to be understood by the non-scientist.

Newhall, C.G., and Dzurisin, D., 1988, Historical Unrest at Large Calderas of the World, v. 1 and 2: U. S. Geological Survey Bulletin 1855, 1108 p.

This two volume report is an excellent overview of unrest at calderas. It describes possible precursors to eruption, summarizes trends of caldera unrest, and describes historical activity at large calderas. The authors have included a bibliography and maps for each caldera described.

Nishimura, S., Abe, E., and Katsura, K., 1988, The secular changes of gravity and its gradient around Sakurajima, southern part of Kyushu: Kagoshima International Conference on Volcanoes, Proceedings, p. 258-264.

Gravity surveys have been conducted at Sakurajima since 1965. Gravity values at the summit increased slightly from 1973 to 1977 and decreased after 1984. The values of vertical gravity gradient gradually decreased after 1975 and may be related to the increasing frequency of eruptions since 1974.

Okada, H.M., 1983, Comparative study of earthquake swarms associated with major volcanic activities, in Shimozuru, D. And Yokoyama L., eds., Arc Volcanism, Physics and Tectonics, Tokyo, Japan, p. 43-61.

The relationship between seismicity and both deformation and sector collapse is described. Seismicity and deformation rates rise proportionally. Episodic deformation is accompanied by large earthquakes with a maximum magnitude around 5. Usu and Mt. St. Helens are used as examples.

Okada, H., 1988, The 1977 eruption of Usu and the observational results: Kagoshima International Conference on Volcanoes, Proceedings, p. 29-32.

Precursors (seismic) lasted only 32 hours. A new cryptodome, Usu-shinzan, "was formed in the summit crater basin which was upheaved 180 m above its original level and pushed to the northeast." Deformation was episodic.

Okamura, A.T., 1988, Water-tube and spirit-level tilt data, Hawaiian Volcano Observatory, 1958-1986: U.S. Geological Survey Open-file Report 88-237, 219 p.

Results from portable long-base water-tube tiltmeters and spirit-level systems are compared and their respective precisions are determined.

Okamura, A.T., Dvorak, J.J., Koyanagi, R.Y., and Tanigawa, 1988, Surface deformation during dike propagation in Wolfe, E.W., ed., The Puu Oo eruption of Kilauea Volcano, Hawaii: Episodes 1 through 20, January 3, 1983, through June 8, 1984: U.S. Geological Survey Professional Paper 1463, 165-181.

Tilt changes recording the intrusion of a dike at the onset the 1983 Puu Oo eruption are documented, analyzed, and compared to the seismic record of dike emplacement. The data suggest that the advancing dike tip intersected a body of magma stored in the east rift zone.

Omori, F., 1911, The Usu-san eruption and earthquake and elevation phenomena: Bulletin Imperial Earthquake Investigative Committee, v. 5, p. 1-38.

The explosive activity of 1910 was followed by ground deformation in the form of 155 m of uplift. Precursory deformation is not mentioned. If precursory deformation occurred, it may not have been detected due to the limited monitoring techniques available at the time.

Omori, F., 1913, The Usu-san eruption and the elevation phenomena. II. [Comparison of the bench mark heights in the base district before and after the eruption.]: Bulletin of the Imperial Earthquake Investigative Committee., v. 5, p. 105-107.

A brief history of past eruptions and a detailed account of the 1910 eruption are included. The southern coast of Toya Lake rose 21.1 m one month after the start of the eruption. A 2700 m x 600 m tract of land uplifted 155 m (1.5 m/day) to form New Mountain.

Omori, F., 1914, The Usu-san eruption and the earthquake and elevation phenomena. III. Results of precise levelings in 1905-1919, with accounts of the observations relating to the level change of the Lake of Toya.: Bulletin of the Imperial Earthquake Investigative Committee, v. 8, p. 1-34.

The 1910 eruption was followed by uplift and the formation of New Mountain. Volcano Bay, over 6 km away from the center of uplift, was uplifted 1 foot.

Otway, P.M., 1982, Tilt-leveling in the Taupo Volcanic Zone, New Zealand: Informal Report, pp. 6.

Otway's informal report discusses history of precise leveling in New Zealand, the design of the deformation networks, and methods of leveling.

Otway, P.M., Grindley, G.W., and Hull, A.G., 1984, Earthquakes, active fault displacement, and associated vertical deformation near Lake Taupo, Taupo volcanic zone: New Zealand Geological Survey, Report 110, 73 p.

In 1983, two earthquake swarms affected the northern part of Lake Taupo and were accompanied by tilt changes. Observed displacement was 50 mm down to the west and about 30 mm of extension. Earthquake swarms occur regularly and indicate the widening of the Taupo Volcanic Zone and the emplacement of magma at deeper levels.

Pingue, F., and Scarpa, R, 1987, Ground deformation monitoring and modelling at some Italian volcanoes: Vesuvio, Lipari-Vulcano, and Campi Flegrei, in King, Chi-Yu and Scarpa, Roberto, eds., Modeling of volcanic processes: Friedr. Vieweg and Sohn, Weisbaden, Germany, 208 p.

The present status of ground deformation in three volcanic areas in Italy is reviewed. Each area behaves differently. A comprehensive explanation of the activity is lacking.

Reilinger, R., Oliver, J., Brown, L., Stanford, A., Balazs, E., 1980, New measurements of crustal doming over the Socorro magma body, New Mexico: Geology, v. 8, p. 291-295.

Leveling measurements conducted in the Socorro area indicate that approximately 7,000 square km have been uplifted at least 10 cm since 1934. Maximum uplift near the center of this zone has reached 20 cm. A crustal discontinuity located 20 km below the central zone is presumed to be a magma body. Uplift between 1909 and 1979 has averaged 5 mm/year.

Rymer, H., Brown, G.C., 1987, Causes of microgravity change at Poas Volcano, Costa Rica: An Active but non-erupting system: Bulletin of Volcanology, v. 49, p. 389-398.

The authors have concluded that gravity changes at Poas are due to a change in the average density of magma at depths below 500 feet. An average of 1% fluctuation in the volume of gas in a crystal-free magma accounts for the changes.

Sanderson, T.J.O., Berrino, G., Corrado, G., and Grimaldi, M., 1983, Ground deformation and gravity changes accompanying the March 1981 eruption of Mount Etna: Journal of Volcanology and Geothermal Research, v. 16, p. 299-315.

The results of deformation measurements from August 1980 to August 1981 are modeled.

Savage, J.C., Prescott, W.H., Chamberlain, J.F., Lisowski, M., and Mortensen, C.E., 1979, Geodetic tilt measurements along the San Andreas Fault in central California: Bulletin of the Seismological Society of America, v. 69, no. 6, p. 1965-1981.

Annual or semi-annual spirit-level surveys were initiated to check the long-term stability of the continuously recording borehole tiltmeters located along the San Andreas Fault. Procedures on siting stable benchmarks in soil rather than bedrock are noted.

Scandone, R., 1981, Models of volcanic processes: a review and some new ideas: Bulletin Volcanologique, v. 44, no. 3, p. 257-268.

Models of pre-eruptive magmas are examined to determine factors involved in triggering eruptions. Magma behavior is heavily influenced by the rise velocity and interaction with pore fluids.

Schimozuru, D., 1981, Magma reservoir systems inferred from tilt patterns: Bulletin Volcanologique, v. 44-3, p. 499-504.

Tilt patterns at Kilauea and Krafla volcanoes are compared. The tilt data from Kilauea show an irregular pattern; the Krafla data show a very regular saw-tooth pattern. The differences are attributed to differences in the magma-reservoir systems. The Kilauea system is composed of a main reservoir and a group of smaller interconnected chambers. The Krafla system consists of one large-volume reservoir.

Schomaker Lt. M.C., and Berry, R.M., 1981, Geodetic leveling: NOAA Manual NOS NGS 3, National Oceanic and Atmospheric Administration, National Geodetic Survey, Rockville, Maryland.

Instructions and background information for establishing and maintaining vertical control are presented. The manual includes general specifications for reconnaissance, bench-mark setting, geodetic leveling, water and valley crossings, and data processing in the field. Data for inclusion in the U.S. National Geodetic Vertical Network should be gathered according to these instructions.

Shepherd, J.B., Aspinall, W.P., Rowley, K.C., Pereira, J., Sigurdsson, H., Fiske, R.S., Tomblim, J.F., 1979, The eruption of Soufriere Volcano, St. Vincent, April-June 1979: Nature, v. 282, p. 24-28.

Tilt changes suggested inflation of the volcano, but the measurements were within the limits of standard error. Therefore, tilt results alone could not be considered as conclusive evidence of volcano inflation. Elevated seismicity confirmed the elevated state of unrest, and the authorities were notified.

Shepherd, J.B., Tomblin, J.F., and Woo, D.A., 1971, Volcano-seismic crisis in Montserrat, West Indies, 1966-67: Bulletin Volcanologique, v. 35, p. 135-163.

Seismic and solfataric activity increased in 1966. Measurements obtained using water-tube tiltmeters showed that an area 2-3 km southeast of Soufriere Hills uplifted until January 1967, subsided between January and March 1967, and slowly uplifted again between March and September 1967.

Sindrason, S., and Olafsson, H., 1978, A magnetoresistor geotiltmeter for monitoring ground movement: Nordic Volcanological Institute 7806, 7 p, 8 figs.

This instrument was developed to be compact, sturdy, and to be suited for borehole installation. The magnetoresistors register a change in the magnetic field. Sensitivity of the instrument was found to be 0.14 mV/microradian.

Smith, R.B., Reilinger, R.E., Meertens, C.M., Hollis, J.R., Holdahl, S.R., Dzurisin, D., Gross, W.K., and Klingele, E.E., 1988, What's moving at Yellowstone?: Eos, Transactions of the American Geophysical Union, v. 70, no. 8, p. 113-125.

In 1987, a baseline network for systematic measurement of vertical and horizontal displacements was established in the Yellowstone-Hebgen Lake region using GPS (Global Positioning System), leveling, precision gravity, and trilateration. An understanding of the causes of uplift in the region will help answer questions concerning complex regional tectonic relationships. Geologic history and seismic background are outlined. Benchmark site selection and field methods are discussed for each method of measurement.

Suzuki, S., and Kasahara, M., 1979, Seismic activity immediately before and in the early stage of the 1977 eruption of Usu Volcano, Hokkaido, Japan: Journal of the Faculty of Science, Hokkaido University, Ser. VII, v. 6, p. 239-254.

Earthquakes began 32 hours before the eruption. The early stages of the eruption were followed by more seismicity and ground deformation including "the formation of new mountains in the area around the summit and horizontal compression in the northeastern foot of the volcano."

Swanson, D.A., 1986, Measurements of ground deformation to forecast and predict eruptions: EOS Transactions of the American Geophysical Union, v. 67, no. 16, p. 397.

Each volcano has a different pattern of deformation. Emphasis is placed on making baseline measurements during periods of quiet. In the event of a volcanic crisis, measurements can be compared and decisions can be made quickly.

Swanson, D.A., Casadevall, T.J., Dzurisin, D., Holcomb, R.T., Newhall, C.G., Malone, S.D., and Weaver, C.S., 1985, Forecasts and predictions of eruptive activity at Mt. St. Helens: Journal of Geodynamics, v. 3, p. 397-423.

Terminology concerning forecasting and predicting eruptions is clarified. A factual statement describes observations or data. "A forecast is a comparatively imprecise statement of the time, place, and nature of the expected activity." A prediction, on the other hand, "is a comparatively precise statement of the time, place, and ideally, the nature and size of impending activity." Monitoring studies of seismicity, ground deformation, gas emissions, thermal changes, and historical behavior are considered together to form a basis for forecasting and predicting eruptive activity. Change in eruptive style may result in an inaccurate prediction.

A summary of activity at Mt. St. Helens is presented including examples of forecasting and prediction successes and failures.

Swanson, D.A., Casadevall, T.J., Dzurisin, D., Malone, S.D., Newhall, C.G., Weaver, C.S., 1983, Predicting eruptions at Mt. St. Helens, June 1980 through December 1982: Science, v. 221, p. 1369-1376.

Thirteen eruptions between June 1981 and December 1982 were predicted days to weeks in advance on the basis of seismic, deformation, and gas-emission data.

Swanson, D.A., Duffield, W.A., and Fiske, R.S., 1976, Displacement of the south flank of Kilauea Volcano: The result of forceful intrusion of magma into the rift zones: U.S. Geological Survey Professional Paper 963, 39 p.

A review of deformation data collected since 1896 is presented. The authors believe that long-term displacements are the summation of smaller episodes of deformation. Examples of deformation related to specific eruptions are cited in support of this idea. During this century, the north flank of the volcano has remained stable. Displacement of the south flank correlates directly with the number and proximity of rift eruptions in a given time period and is interpreted as a result of the forceful intrusion of magma into the rift zone.

Swanson, D.A., Duffield, W.A., Jackson, D.B., and Peterson, D.W., Chronological narrative of the 1969-71 Mauna Ulu eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 1056, 55 p.

The 1969-1971 Mauna Ulu eruption, which occurred on the upper east rift zone of Kilauea, can be divided into four stages, based on eruptive style. Water-tube tilt and EDM measurements record patterns of deformation at Kilauea's summit as the eruption evolved.

Swanson, D.A., Jackson, D.B., Koyanagi, R.Y., and Wright, T.L., 1976, The February 1969 east rift eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 891, 30 p.

The eruption was preceded by a 4 month period of inflation at the summit and along the upper east rift zone. Summit deflation and uplift near the vent areas accompanied the eruption. Lateral migration of the centers of deformation occurred in response to the filling and emptying of the reservoir system.

Swanson, D.A., Lipman, P.W., Moore, J.G., Heliker, C.C., Yamashita, K.M., 1981, The 1980 eruption of Mt. Saint Helens, Geodetic monitoring after the May 18 Eruption, in Lipman, P.W. and Mullineaux, D.R., eds., The 1980 eruptions of Mt. St. Helens: U.S. Geological Survey Professional Paper 1250, p. 157-168.

After the May 18 landslide and eruption, the volcano subsided slightly. Thereafter, it expanded days to 3 weeks before most magmatic eruptions and major periods of gas discharge.

Sylvester, A.G., 1975, History and surveillance of volcanic activity on Jan Mayen Island: Bulletin Volcanologique, v. 39, no. 2, p. 313-335.

Jan Mayen is an Arctic basaltic island along the mid-Atlantic ridge. It is currently being monitored for seismicity and deformation. Deformation monitoring includes a tide gauge, a 4 km leveling line, gravity measurements, and 6 tiltmeter stations, all operational by 1974. Two years of results are reported. There was no evidence of deformation.

Sylvester, A.G., 1985, Shortcomings of monitoring volcano deformation by dry tilt surveying: EOS, Transactions of the American Geophysical Union, v. 66, no. 46, p. 854.

Due to lack of uniformity of benchmarks, survey procedures, and thermal influences, caution must be used when tilt rates are less than hundreds of microradians over several months.

Tada, T., and Hashomoto, M., 1988, Recent crustal deformation around the Aira Caldera, Kagoshima, Japan, and its relation to the volcanism of Sakurajima Volcano: Kagoshima International Conference on Volcanoes, Proceedings, p. 284-287.

Leveling, distance surveys, and tide gauge measurements at Sakurajima are analyzed . Crustal uplift occurred from 1914 to 1975. Subsidence has been occurring since 1979. The authors conclude that the magma reservoir inflated from 1914 through 1978, and began to deflate in 1979.

Taylor, G. A., 1963, Seismic and tilt phenomena preceding a Pelean type eruption from a basaltic volcano: Bulletin Volcanologique, Tome 26, p. 5-11.

Manam, in Papua, New Guinea, has been intermittently active since December, 1956. Eruptive activity includes lava flows and pyroclastic flows. Precursors include tectonic seismic activity, elevated local seismicity, and ground tilt. Eruption timing is tied to the influences of earth tides.

Thatcher, W., Savage, J.C., 1982, Triggering of large earthquakes by magma-chamber inflation, Izu Peninsula, Japan: Geology, v. 10, no. 12, p. 637-640.

Three large earthquakes on the Izu Peninsula were preceded by 1 to 3 years of aseismic uplift.

Tilling, R.I., Christiansen, R.L., Duffield, W.A., Endo, E.T., Holcomb, R.T., Koyanagi, R.Y., Peterson, D.W., and Unger, J.D., 1987, The 1972-1974 Mauna Ulu eruption, Kilauea Volcano: An example of quasi-steady-state magma transfer, in Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 405-469.

A chronological narrative of the eruption and lava lake activity is described. Summit tilt data show two periods of oscillation, each lasting at least 8 months, but very little net summit inflation. This record of very little net change is interpreted to reflect a quasi-steady-state movement of magma from a mantle source to the summit reservoir and to the upper east rift zone.

Tryggvason, E., 1968, Measurement of surface deformation in Iceland by precision leveling: Journal of Geophysical Research, v. 73, no. 22, p. 7039-7050.

Grabens in southwest Iceland show continuous historical subsidence similar to the average rate during the last 9,000 years.

Tryggvason, E., 1973, Surface deformation and crustal structure in the Myrdalsjokull area of South Iceland: Journal of Geophysical Research, v. 78, no. 14, p. 2488-2497.

The amount of tilt measured near the edge of the Myrdalsjokull ice field is dependent on the amount of snow present. The underlying crustal plate is estimated to be 6.5 to 8.5 thick, much thinner than in other parts of the world.

Tryggvason, E., 1982, The N.V.I. Magnetoresistor tiltmeter results of observations 1977-1981: Nordic Volcanological Institute 8203, p. 1-44.

The results of monitoring the Krafla and the Vestmannaeyjar areas in Iceland by the N.V.I. magnetoresistor tiltmeter are presented here. Results are compared to those of a water-tube tiltmeter and the relative merits of the two instruments are discussed.

Wadge, G., 1976, Deformation of Mount Etna, 1971-1974: Journal of Volcanology and Geothermal Research, v. 1, p. 237-263.

EDM, tilt, and leveling data for the period 1971-1974 are modeled to explain the observed deformation of Mt. Etna during that period. The favored model involves horizontal radial strain about an open, cylindrical magma column.

Wadge, G., 1983, The magma budget of Volcan Arenal, Costa Rica from 1968 to 1980: Journal of Volcanology and Geothermal Research, v. 19, p. 281-302.

The 1968 eruption of Arenal resulted in the effusion on the western slope of a block lava flow which has continued to be active to the present. Four spirit-level tilt stations were installed in October 1976. Repeated measurements over 2 years indicated a downward tilting of the volcano's summit by as much as 80 urads with the greatest magnitude of tilt close to the volcano. Two models were suggested to explain the tilt: a) evacuation of magma at the summit reduces reservoir pressure and volume, thereby deflating the volcano, and b) the upper slopes are depressed by the increased loading of the lava flow. The second model could produce the observed changes and is favored.

Walsh, J.B., and Decker, R.W., 1971, Surface deformation associated with volcanism: Journal of Geophysical Research, v. 76, no. 14, p. 3291-3302.

A change in magma pressure in a vertical column up to a point about 1.5 km below the center of uplift can explain the vertical and horizontal uplift at Kilauea.

Walsh, J.B., and Rice, J.R., 1979, Local changes in gravity resulting from deformation: Journal of Geophysical Research, v. 84, no. B1, p. 165-170.

Gravity changes are proportional to local elevation changes. A model is developed to calculate the gravity changes due to a center of dilation and a long thrust fault.

Watanabe, H., 1983, Changes in water level and their implications to the 1977-1978 activity of Usu volcano: in Shimozuru, D., and Yokoyama, I., eds., Arc Volcanism, Terra Scientific Publishing Co., Tokyo, p. 81-93.

The water level in a well was found to have risen 37 m after the August 1977 pumice eruption. By comparing the deformation data with the water-level data, the authors conclude that the increase in water level may have been caused by an eastward thrust of the summit.

Westphal, J.A., Carr, M.A., Miller, W.F., and Dzurisin, D., 1983, An expendable bubble tiltmeter for geophysical monitoring: Review of Scientific Instruments, v. 54, p. 415-418.

Principles of electrolytic-bubble tilt sensors, designed for use in the crater of Mt. St. Helens, are explained. Installation procedures, accuracy and calibration of the tiltmeters are discussed. They are inexpensive and rugged.

Wolfe, E.W., Garcia, M.I., Jackson, D.B., Koyanagi, R.Y., Neal, C.A., and Okamura, A.T., 1987, The Poo Oo eruption of Kilauea Volcano, episodes 1-20, January 3, 1983, to June 8, 1984, in Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 2, 471-508.

This well-documented eruption is the longest and most voluminous Hawaiian eruption of historical time. The eruption began as intermittent fissure eruptions and changed into an episodic central-vent eruption in the east rift zone of Kilauea Volcano. Continuous tilt measurements show gradual inflation of the summit and in the rift zone accompanied by a repose period, followed by abrupt deflation and an eruptive episode. This trend indicates that magma reservoirs recharged during repose periods, and rapidly discharged during fountaining episodes. Recharge during inflationary periods balanced discharge and deflation. This indicates that the eruptions began and ended in response to pressure in the magma system. The report includes a review of recent activity, geologic structure, and the magmatic plumbing system at Kilauea.

Yamamoto, E., Kumagai, T., 1988, Precursory tilt changes of the 1986-1987 volcanic eruption of the Izu-oshima Volcano obtained by continuous crustal tilt observations: Kagoshima Conference on Volcanoes, Proceedings, p. 308-311.

Continuous tilt observations have been made at Izu-oshima since 1983. Summit and flank eruptions occurred from November 15 through November 21, 1986. Anomalous tilt changes occurred when the 1986 eruption began. The pressure source, according to a Mogi model, is at a depth of 2 km.

Yamashita, K.M., 1981, Dry tilt: A ground deformation monitor as applied to the active volcanoes of Hawaii: U.S. Geological Survey Open File Report 81-523.

The author describes dry-tilt station installation, estimation of error, interpretation of the data, and various leveling instruments. Also included is an equipment list with approximate costs as of 1979. This paper has been tranlated into Spanish.

Yamashita, K.M., Doukas, M.P., 1987, Precise level lines at Crater Lake, Newberry Crater and South Sister, Oregon: U.S. Geological Survey Open File Report 87-293.

Bench mark descriptions, data for the 1985-1986 surveys, maps, and photos are presented.

Yokoyama, I., 1971, Gravimetric, magnetic, and electrical methods: in, The surveillance and prediction of volcanic activity, a review of methods and techniques, Paris, UNESCO, p. 75-101.

The author discusses theory, techniques, problems, and examples of gravimetric monitoring at active volcanoes. In addition, magnetic and electrical methods of monitoring are discussed.

Yokoyama, I., 1971, A model for the crustal deformation around volcanoes: Journal of the Physics of the Earth, v. 19, no. 3, p. 199-207.

Yokoyama offers an alternative to the Mogi (1958) model to explain crustal deformations around volcanoes. The Mogi model assumes a spherical pressure source while the Yokoyama model assumes a thrust pressure source.

Yokoyama, I., 1985, Volcanic processes revealed by geophysical observations of the 1977-1982 activity of Usu Volcano, Japan: Journal of Geodynamics, v. 3, p. 351-367.

Precursory earthquakes and deformation began abruptly only 30 hours before the onset of the eruption of Usu in 1977.

Yokoyama, I., 1989, Microgravity and height changes caused by volcanic activity: four Japanese examples: Bulletin of Volcanology, v. 51, p. 333-345.

Microgravity and leveling data are analyzed for four volcanoes. Microgravity changes at one benchmark at Usu Volcano during the 1977-1982 activity were caused by deformation of the ground and aquifers near the mark. Local gravity changes around the eruptive fissures during the 1983 activity of Miyakejima volcano were due to magma intrusions. Gravity changes and elevation changes were poorly correlated during the 1986 eruption of Ooshima. Microgravity changes and elevation changes at Sakurajima suggests that magma has been accumulating beneath the volcano for eight years.

Yokoyama, I., Yamashita, H., Watanabe, H. and Okada, H.M., 1981, Geophysical characteristics of dacite volcanism; The 1977-1978 eruptions of Usu Volcano: Journal of Volcanology and Geothermal Research, v. 9, p. 335-358.

The eruption of Usu volcano was accompanied by earthquake swarms and 160 m of uplift. Pre-eruption deformation was slight, beginning only a few days before the eruption. Most of the uplift occurred in the 9 months following the onset of eruption.