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Depressions surrounding volcanic fields: A reflection of underlying batholiths?

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ABSTRACT

The eastern Klamath Mountains of northern California are cut sharply by an arcuate scarp that forms the west wall of a depression containing Pliocene to Holocene lava rocks. This depression may have formed by collapse along hidden concentric fractures over a batholith and, if so, reflects the shape and areal extent of the body. Large depressions enclosing other volcanic fields are evident on small-scale satellite imagery. If such depressions overlie still hot or even molten batholithic bodies, analysis of satellite imagery might delineate the areal extent of associated geothermal resources.

INTRODUCTION

If it were possible to approximate the shape and areal extent of a batholith that is the source of magma for an active or dormant volcanic field by using surface geology and physiography, it would be easier to evaluate the geothermal resources of that area. A distant view of the volcanic field and surrounding area via small-scale satellite imagery and maps may provide some answers to this problem.

The Mount Shasta–Medicine Lake region of northern California is an area affected by Pliocene to Holocene volcanism. The Medicine Lake Highland, located east of Mount Shasta, is a broad basaltic shield volcano with a central caldera and is capped with numerous andesite, dacite, and rhyolite domes and flows (Anderson, 1941; Eichelberger, 1975).

The volcanic field overlaps the boundary between two geologic provinces: the Klamath Mountains, consisting of deformed Ordovician to Cretaceous sedimentary and volcanic rocks, ultramafic bodies, and intrusive granitic stocks (Irwin, 1966), and the Modoc Plateau basaltic lava rocks (Macdonald, 1966).

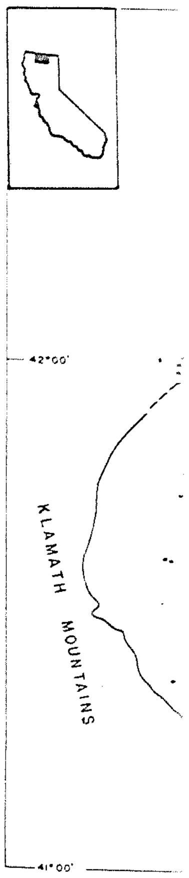
SHASTA VALLEY DEPRESSION

The Klamath Mountains of northern California extend from the Pacific Coast to the Central Valley and north into Oregon. They are highly dissected, with a remarkable accordance of summit levels between elevations of 1,500 and 2,100 m that Kinkel and others (1956) interpreted as a Miocene or Pliocene erosion surface.

The eastern Klamath Mountains of northern California are cut sharply by an arcuate scarp that forms the west wall of a depression containing Pliocene to Holocene lava rocks and pyroclastic rocks (Figs. 1, 2). East of this line is a depression, with a difference in elevation of about 1,000 m between accordant summits of the Klamaths located near the scarp and the floor of Shasta Valley. In the Modoc Plateau the depression is far less obvious, although the trends of some normal faults turn sharply north or northeast in the area corresponding to an extension of the depression boundary into the plateau (Fig. 1). The trend of normal faults appears to be bent around the eastern edge of the depression (Fig. 1). Thus, the resulting 100-km-diameter circular structure is outlined in the west by the topography and in the east by structural trends; it includes both the Mount Shasta and Medicine Lake volcanic fields.

Very few faults are visible in the western half of the circular depression. A linear trend of volcanic vents extends from the southern flank of Mount Shasta across the summit and into Shasta Valley on the north flank. This has been interpreted by Williams (1934) as an indicator of a north-trending fault beneath the mountain. Topographically high blocks of prevolcanic terrane crop out along this trend, both north and south of Mount Shasta (Fig. 2); perhaps there is a structural high or horst in line with the vent areas. The semicircular scarp, which forms the western edge, may indeed be a fault scarp if the depression has a volcano-tectonic origin. In the compilation of geologic maps of the area by Strand (1964), the scarp was not interpreted as a fault.

v. 4, p. 568-572, SEPTEMBER 1976



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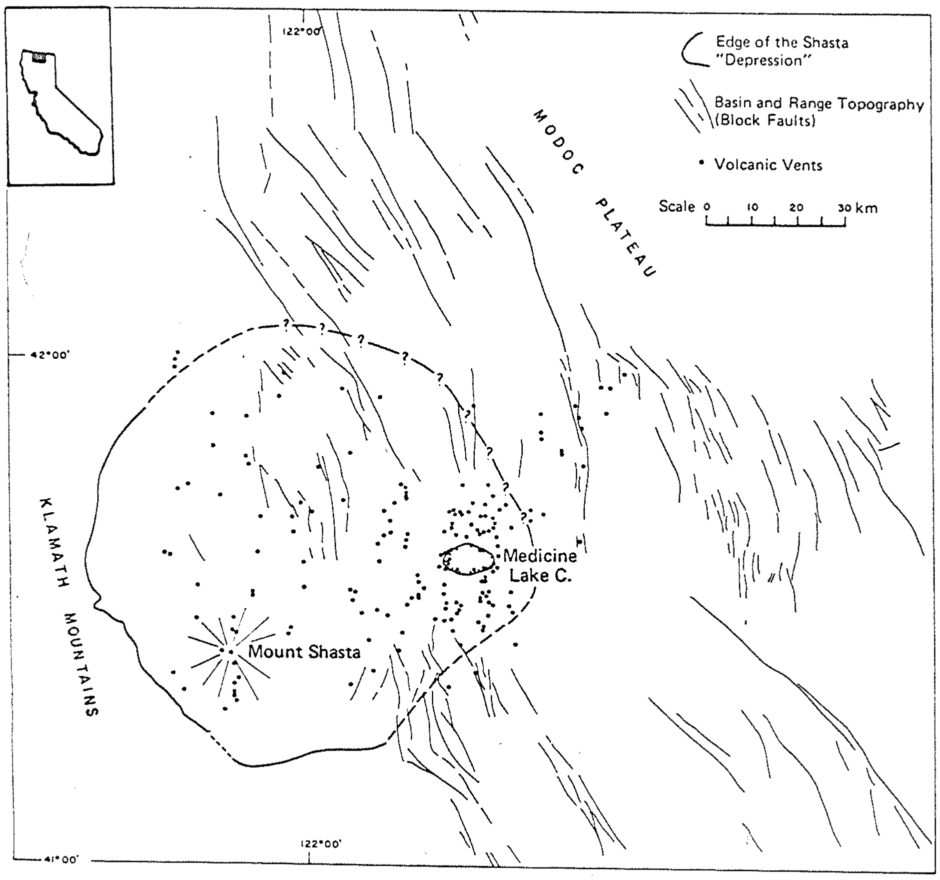

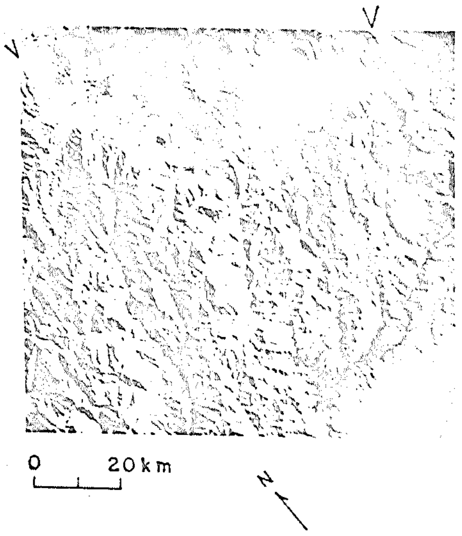

Figure 1. Left, Shasta depression; structure and locations of volcanic vents. Location is indicated on index map of California. Right, satellite photograph of southwestern portion of Shasta depression, illustrating scarp that forms west wall. Mount Shasta is peak near top-center; Shasta Lake is in lower right corner. (Skylab photograph SL3-25-053.)

The eastern part of the depression is cut by northwest-trending normal faults characteristic of the Modoc Plateau.

Volcanic Vents

In the southwestern part of the depression, volcanic vents are sparse (an average of 1 vent per 51 km^2), with the highest concentration across Mount Shasta, as noted previously by Williams (1934). Silicic rocks (andesite, dacite) here are more voluminous than basaltic lavas. There are more volcanic vents (cinder cones, domes, dacite flows) in the eastern part of the depression, with a minimum of 1 vent per 13.5 km^2, and basalt is the predominant rock type.

Origin of the Shasta Depression

Since several late Cenozoic volcanic fields lie within the depression, it may be that the origin of the depression is due to collapse following extrusion of lavas from a large magma chamber or a series of interconnected chambers within a batholith. Farther north in the western Cascade Range, there are stocks exposed along a north-south trend, underlying and contemporaneous with late Tertiary volcanic rocks (Fiske and others, 1963; Erikson, 1969). If we assume that the Klamath Mountains once extended across the depression, the volume involved in subsidence is about 2,800 km^3 (volume measurements from the scale 1:250,000 topographic maps). The base of the volcanic rocks is roughly defined by outcrops of prevolcanic terrane at the south end and north-northwest of Mount Shasta (Fig. 2). The volume of volcanic rock overlying prevolcanic terrane is about 2,700 km^3, which is consistent with the idea of collapse resulting from extrusion of these rocks. (The volume was estimated using presently available geologic maps and planimetric measurements of the scale 1:250,000 topographic maps. The estimated error is 15 to 20 percent.)

The location and shape of the Shasta depression is based entirely on small-scale topographic maps and satellite imagery (Landsat, Skylab). Interpretation of this imagery led to the hypothesis that the depression may reflect the outline, and possibly the areal extent, of a batholith underlying the volcanic fields. This interpretation is supported by the gravity measurements of LaFehr (1965). In Figure 3, the residual Bouguer gravity map is superimposed on the outline of the depression as indicated in Figure 1. The circular, -10-mgal anomaly corresponds remarkably well with the depression. According to LaFehr (1965), an anomalously low density mass of rock or melt exists at 4 to 10 km below the depression, with a density contrast of about 0.2 g/cm^3.

Assuming that the depression is underlain by a batholith, the location of vent areas should be an expression of the fracture system generated by the intrusion, the regional tectonic stresses, or both. Cone sheets and ring dikes have been observed elsewhere above intrusions (Anderson, 1936; Cloos, 1936). Theoretical studies by Koide and Bhattacharji (1975) suggests that steeply dipping concentric fractures will develop above an intrusion owing to stress concentration around its apex. Their

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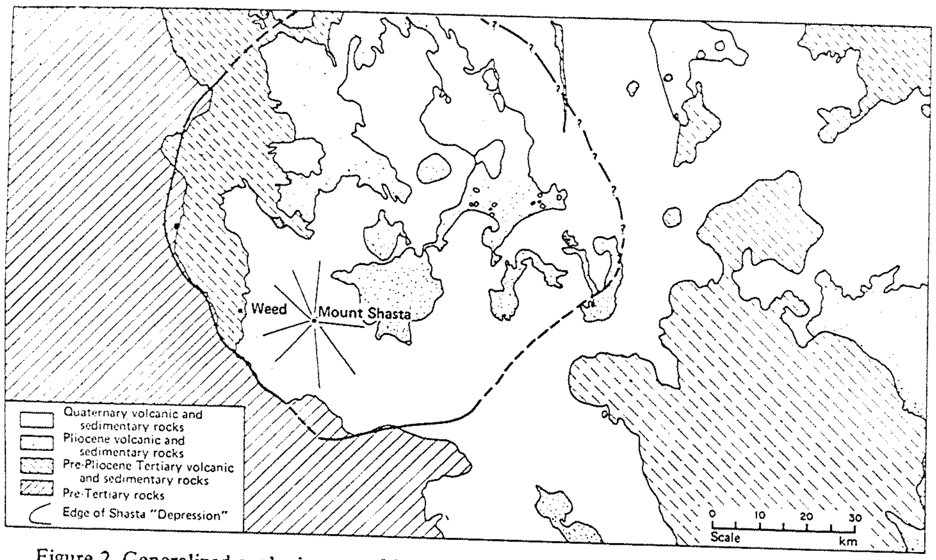


Figure 2. Generalized geologic map of Shasta depression, from Gay and Aune (1958) and Strand (1964).

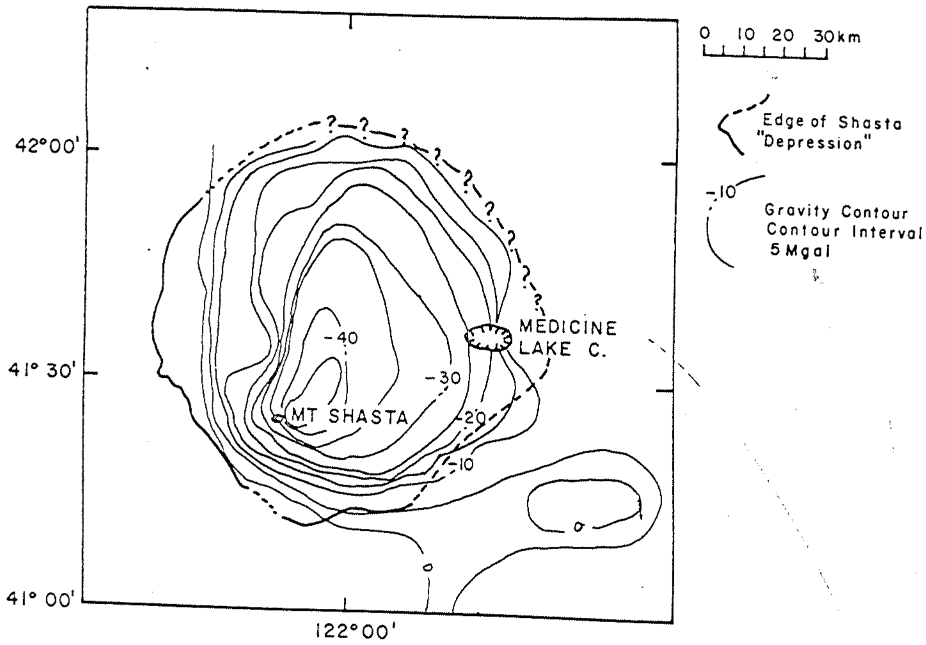


Figure 3. Residual Bouguer gravity map of Shasta–Medicine Lake region of northern California (LaFehr, 1965), superimposed on outline of Shasta depression.

calculations are supported by field studies of fracture patterns around the Silverton caldera, Colorado (Burbank and Luedke, 1968), which may be related to a vertically elongated magma chamber and high magma and hydrothermal fluid pressures. The only surface expression of concentric fracturing in the area of this study is the semicircular wall of the Shasta depression, along which there has been subsidence. If there are concentric or radial fractures or faults within the depression, they are buried by volcanic rocks. A gravity gradient of 8 mgal/km across the southern boundary of this depression (LaFehr, 1965) suggests a strong density contrast, as might be generated by intermediate or silicic magma intruded along concentric faults into rock units similar to those of the adjacent Klamath Mountains.

Why is there such a contrast in the spacing of vent areas across this depression? One possible answer is that the normal faults of the Modoc Plateau interact with concentric fractures developed over a batholith. For a simple model of this, assume that concentric fractures above the intrusion are spaced 2 km apart at ground surface (at Ardnamurchan, Scotland, a structure 25 km in diameter, the spacing is 1 km). The observed normal faults are spaced about 2.5 km apart where not buried by sediment or lava. The intersection of the normal faults with hypothetical concentric fractures developed over the intrusion would produce a fault plane intersection every 11 km^2. This is surprisingly close to the observed vent density of 1 per 13 km$_2$ in the eastern half of the depression. A perturbation of the gravity contours within the Medicine Lake area (Fig. 3) may reflect the denser spacing of basaltic vents.

Summary

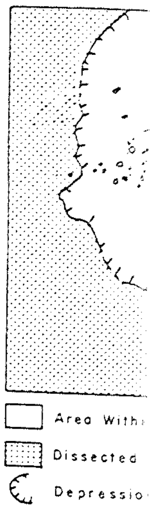
The Klamath Mountains are cut sharply by an arcuate scarp, forming the west wall of a depression with a radius of about 50 km; the eastern edge of the depression is outlined by changes in fault trends. The nearly circular depression also coincides with a negative gravity anomaly. I propose that the depression formed by collapse, along concentric fractures, over a batholith and reflects the shape and areal extent of the batholith. No faults or fault zones have been observed along the scarp; they are inferred on the basis of the topographic change. If the concentric fractures have lower dip angles—for example, 60° to 70° rather than near-vertical—then the areal extent of the batholith is considerably less than that of the depression.

Normal faults cut across the eastern half of the circular structure. The density of volcanic vents is far greater where normal faults intersect the depression. It is possible that the vents are along intersections of northeast-trending normal faults with concentric faults formed over the apex of a batholith. In the western half of the depression, uncut by normal faults typical of basin-and-range topography, vent areas are sparse.

Seismic data may help identify the present state of the proposed batholith. If the basaltic lavas of the eastern half of the depression rose to the surface through a lower density body along extensional faults, then the body must have been rigid enough for brittle fracture. It is also possible that the differences in vent density and magma type between the two halves of the depression are related to heterogeneous or multiple plutons. Further studies of the lavas within the depression may provide clues to the state of the proposed batholith.

LARGE-SCALE DEPRESSIONS AROUND OTHER VOLCANIC AREAS

Much is known about volcanic collapse features within a single volcanic pile, but very little about larger depressions sur-



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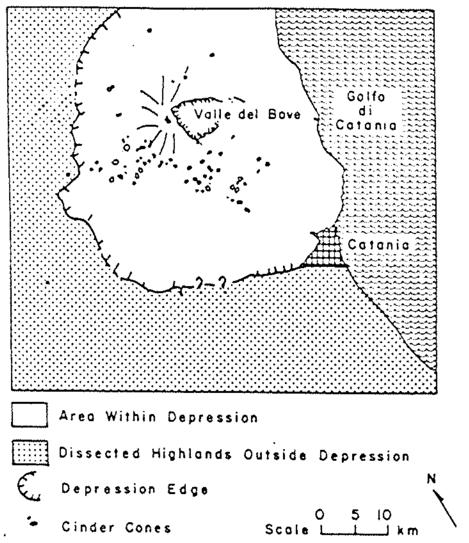

Figure 4. Sketch map of Mount Etna, Sicily, and surroundings; from Skylab photographs SL3-87-354 to SL3-87-356.

rounding volcanic regions. Such depressions have been observed on satellite photographs or images of many parts of the Earth.

Mount Etna, Sicily. The massive shield volcano Etna is located in a 33 × 39 km depression within uplifted and dissected Eocene and Miocene sedimentary terrane (Fig. 4; Servizio Geologico d'Italia, 1961). The depression is still visible, although it is nearly filled with lava flows and pyroclastic rocks. The summit of Etna is near the center of the depression (this is best seen on Skylab III photographs SL3-87-354 to SL3-87-356).

Kamchatka, USSR. The active volcanoes of Kamchatka, from Avachinsky to Gamchen, are located in an overlapping chain of circular to ovoid depressions within older, dissected terrane (Fig. 5). These are interpreted as volcano-tectonic depressions and constitute the "caldera line" of Kamchatka; cupolas of granitic intrusions are exposed in this area (Vlasov, 1964). If the depressions reflect underlying batholiths, they are similar in geometry and scale to batholiths exposed by erosion, such as the Coastal batholith of Peru (Myers, 1975; Fig. 5). The Kamchatkan depressions are best seen on ERTS images 1117-23581, 1189-23574, and 1189-23571.

Huzi (Fuji) and Hakone Volcanoes, Japan. The volcanoes Huzi and Hakone, on the island of Honshu, occupy a depression within older, dissected rocks. The depression appears to be made up of two overlapping depressions, with combined dimensions of about 55 × 30 km (ERTS-1145-00542; Fig. 6).

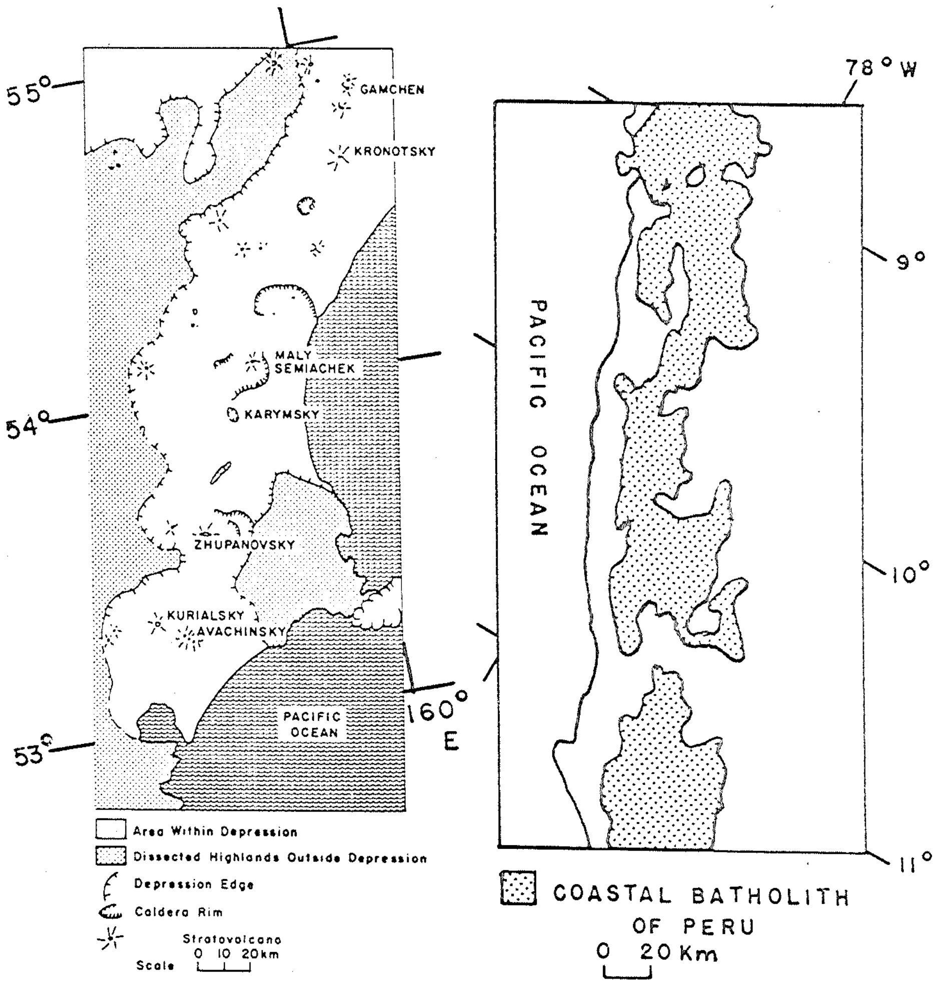

Figure 5. Left, sketch map of 2.3° segment of volcanic terrane along the east coast of Kamchatka, USSR, with outlines of large depressions surrounding volcanic fields (based on ERTS images 1117-23581, 1189-23571, and 1189-23574). Right, to compare depressions in Kamchatka with areal extent and geometry of a batholith, this sketch map of the Coastal batholith of Peru is presented at same scale (adapted from Myers, 1975).

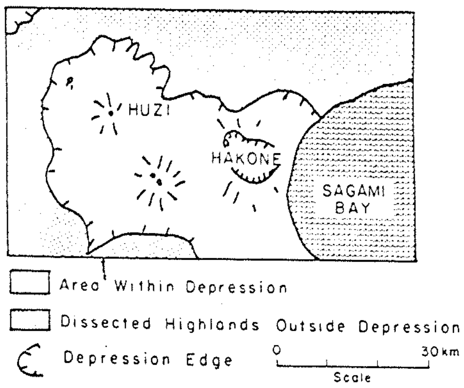

Figure 6. Sketch maps of Huzi and Hakone volcanoes, Japan, based on ERTS image 1145-00542.

Kyushu, Japan. An oblique view of the island of Kyushu, Japan, provides an excellent overview of the volcanic centers of Kirisima, Aso, and Kuzyu (Fig. 7).

A nearly circular depression, 50 km in diameter, encloses the active Kirisima volcanic field and laps over the upper part of Kagosima Bay. The nearly circular shape of the depression seems not to be controlled by the northeast-southwest tectonic trend prevalent on the island.

In contrast to the circular depression at Kirisima, the volcanic fields of Aso and Kuzyu are within a troughlike depression parallel to the structural trends of the island. The depression is bounded by Silurian to Jurassic sedimentary rocks, granitic intrusive rocks, and metamorphosed volcanic rocks (Takai and others, 1963). The depression is from 25 to 40 km wide and traverses the entire island of Kyushu, a distance of 100 km (Skylab photograph SL4-139-3942 and ERTS-1132-01240.

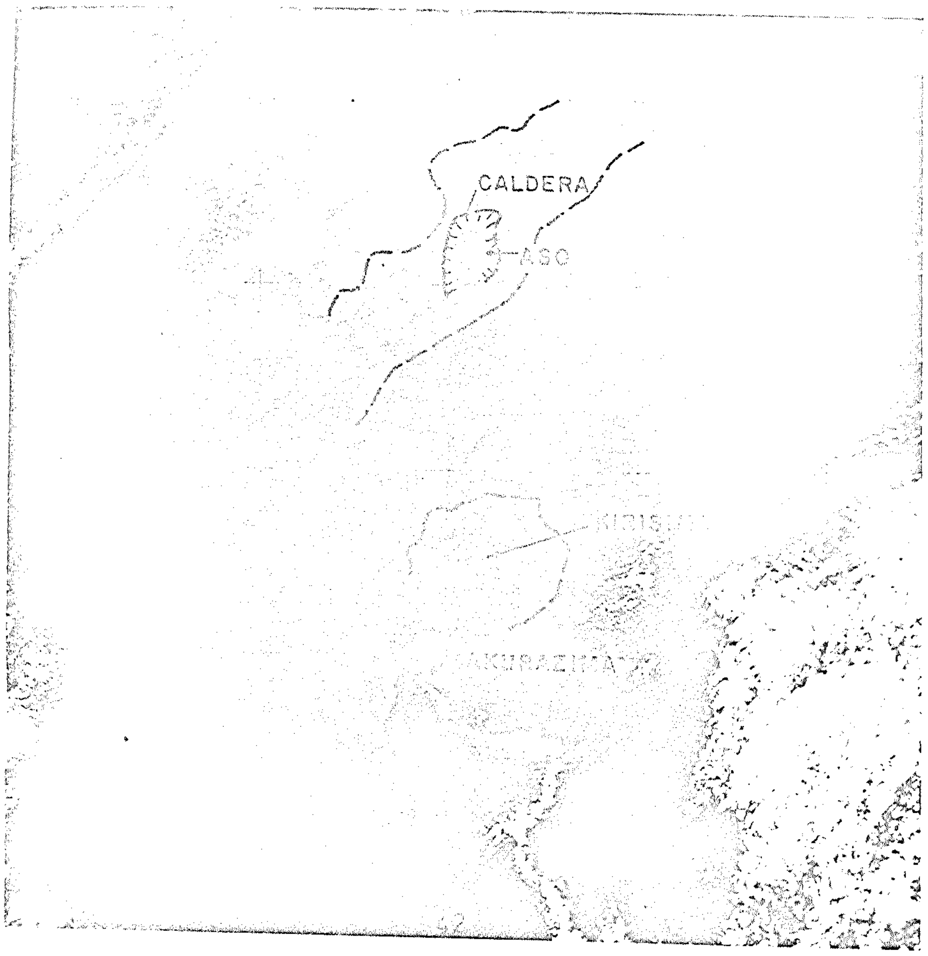

Figure 7. Oblique view of the island of Kyushu, Japan, showing depressions around volcanic fields of Aso, Kirisima, and Kuzyu (Skylab photograph SL4-139-3942).

CONCLUSIONS

It has been well known for some time that ring-fracture systems form over large intrusions (Anderson, 1936; Koide and Bhattacharji, 1975) and that collapse occurs along these fractures in some instances. The surface depression may be circular or elongate, depending on the degree of control by a regional tectonic fabric. The broad depressions are most easily seen on satellite photographs; they may reflect the shape and size of batholiths underlying active volcanic fields and should therefore aid in the planning of geophysical and geologic exploration of geothermal areas.

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ACKNOWLEDGMENTS

Reviewed by Wendell Duffield, John Eichelberger, and Wolfgang Elston.

Supported by ERDA Contract W7405ENG36.

This work was performed under the auspices of the U.S. Energy Research and Development Administration.

MANUSCRIPT RECEIVED APRIL 12, 1976

MANUSCRIPT ACCEPTED JUNE 21, 1976

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