

sional midpoint. It was marked by the abrupt disappearance of *Elvinia* and the appearance of *Irvingella*, accompanied by the disappearance of typical trilobites of the *Elvinia* zone and the associated acrotretid brachiopod *Linnarssonella* and the appearance of the distinctly different trilobite and brachiopod assemblage of the *Irvingella major* subzone. Here, as at the M/P boundary, our iridium data show no indication of a concentration anomaly, nor is there any obvious change in the amount of acid-insoluble residue or in the concentration ranges of the elements. However, thin-section analysis revealed a distinct hardground at the boundary, indicating a slight unconformity or hiatus. Thus, the absence of a geochemical anomaly could be a result of missing sediments.

In summary, we have found no significant iridium enrichments at either the M/P or the P/P biomere boundaries; the concentrations of this element are consistently in the range of picograms per gram of whole rock, the concentration characteristic of the earth's crust. Nor do the concentrations of any of the other elements measured exhibit exotic values. Impact of a large achondrite (known to contain less iridium than other meteorites) or of a comet would be less likely to produce an iridium signal detectable above crustal background. The dominant rock at both boundaries is limestone, with variations characteristic of terrestrial processes. Both of these biomere boundary sequences were deposited in shallow water, where wave and tidal action could have dissipated local concentrations of fallout material. Moreover, we have examined only one sampling site. Thus, although the iridium abundances that we have observed are typical of average crustal rock, we cannot definitely conclude that these two Cambrian extinctions were not associated with impacts of large extraterrestrial bodies. We believe that this possibility can be excluded only by iridium measurements on these two biomere boundaries at other distant locations characterized by abundant fossils and continuous deposition. There exist locations in the continental United States, for example, in Arizona, Texas, and Tennessee (9), that may prove suitable for these studies.

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Seismic Detection of the Summit Magma Complex of Kilauea Volcano, Hawaii

Abstract. *Application of simultaneous inversion of seismic P-wave arrival time data to the investigation of the crust beneath Kilauea Volcano yields a detailed picture of the volcano's heterogeneous structure. Zones of anomalously high seismic velocity are found associated with the volcano's rift zones. A low-velocity zone at shallow depth directly beneath the caldera coincides with an aseismic region interpreted as being the locus of Kilauea's summit magma complex.*

For a number of years the Hawaiian Volcano Observatory (HVO) has operated a seismic network to monitor the thousands of earthquakes that occur annually beneath Kilauea Volcano and the surrounding region. These earthquakes are caused by the volcanic and tectonic forces that build and shape the shield volcanoes of Hawaii. The seismic activity provides a means of probing the deep structure of Kilauea. For example, the spatial distribution of magma-related seismic events has been used to map the structure of Kilauea's magmatic passageways (1, 2). Furthermore, an aseismic zone directly beneath the Kilauea caldera has been interpreted as being the volcano's summit magma reservoir (1).

Seismic wave travel time has also been utilized to map the subsurface structure of Kilauea, both with refraction (3, 4) and teleseismic (5) data. All these studies provide clear evidence for the laterally heterogeneous seismic velocity structure of the crust beneath Kilauea. This report presents a three-dimensional model for the P-wave velocity structure of the crust beneath Kilauea, determined by the inversion of local earthquake P-wave arrival times recorded by the HVO seismic network. The data set and method used permit the resolution of structure on a spatial scale of 3 to 4 km. Extreme lateral variations in velocity are revealed, particularly in the contrast be-

tween nonrift (relatively low velocities) and rift and summit areas (high velocities). In addition, a zone of low velocity is detected that coincides with the aseismic region beneath the caldera, confirming this to be a zone of low rigidity.

The use of local earthquake arrival time data to determine a model for three-dimensional seismic structure has proved successful in probing the earth's crust and upper mantle (6-10). In early studies of this type a method was used that involves simultaneous inversion for earthquake locations and velocity structure in a single step (6). Two recently developed techniques have made iterative three-dimensional inversion practical. One is parameter separation (7, 11), a procedure for decomposing the simultaneous inversion problem into a set of equations involving velocity model perturbations only. As a result, the computational size of the inversion problem can be kept manageably small no matter how many earthquakes are included. The second is approximate ray tracing (ART) (8, 9, 12), which takes advantage of Fermat's principle to derive approximate ray paths and travel times in an arbitrary velocity structure. ART is far faster computationally than existing three-dimensional ray tracing algorithms, making it practical to determine an iterative solution to the nonlinear simultaneous inversion problem. Both parameter sepa-

ration and ART are incorporated in our inversion algorithm.

Another distinguishing feature of our approach concerns the representation of the velocity structure. The choice of velocity model parameterization was dictated by the desire to model arbitrary structures while maintaining a practical problem size for computational purposes. Thus a flexible three-dimensional

grid system was adopted with velocities defined at variably spaced nodes and interpolated in between with a simple trilinear function (8). Perturbations to these velocity values and the earthquake hypocenters and origin times are determined in a "progressive" manner (13), with the *F*-test being used to terminate the iterative procedure.

Kilauea's intense, well-distributed

seismicity is ideal for applying the simultaneous inversion method. To take advantage of the distribution of both the seismicity and the HVO network stations, a 20 by 30 km area encompassing the Kilauea caldera was chosen for study (Fig. 1). An initial velocity structure for the inversion was based on a model derived specifically for southern Hawaii (14). The spacing between grid points in the velocity model was 4 km in the *x* direction and 3 km in the *y* and *z* directions. Eighty-five earthquakes from 1980 and 1981 were selected for the inversion. Earthquakes selected had well-constrained epicenters and were observed by a large number of stations, including a station within a focal depth of the epicenter so that the earthquake depth was also well constrained. Arrival times for two 1976 near-summit explosions (man-made) were also included.

A composite model for the P-wave velocity structure beneath Kilauea was constructed from the results of a series of inversions for which the grid spacing remained fixed but the grid as a whole was systematically shifted 1 to 2 km in the *x*, *y*, and *z* directions. Typically, the inversions achieved an 80 percent reduction in the data variance after three iterations. Unweighted root-mean-square residuals for individual events were generally reduced to 0.04 or 0.05 second, close to the estimated data error. Estimated standard errors and resolution (diagonal elements) for velocity parameters averaged 3 percent and 0.7, respectively.

Figure 2 shows a map view of four grid layers of the composite model, positioned 1 km above and 2, 5, and 8 km below sea level (stations are modeled at their true elevations). In the top layer (Fig. 2A), there is a velocity high directly beneath the caldera, corresponding to the roof of the summit magma complex, and velocity highs exist along the upper east and southwest rift zones (see Fig. 1). Looking deeper into the crust, we see a continuation of the velocity highs along the rift zones down to 2 km below sea level (Fig. 2B). The nonrift areas, especially the Kaoiki region, have significantly lower seismic velocities.

Two other important features are visible at this depth. A high-velocity area along the Koae fault system indicates the presence of dense, probably competent, intrusive rock. Recent episodes of intrusive activity in this area have been documented (15), particularly at the northeastern and southwestern boundaries of the fault system where it intersects the major rift zones. We also find a velocity low beneath the caldera, coinciding with the inferred location of Kilauea's summit

Fig. 1. Map of principal geologic features and HVO seismic stations (triangles) in the study area on the southern coast of Hawaii.

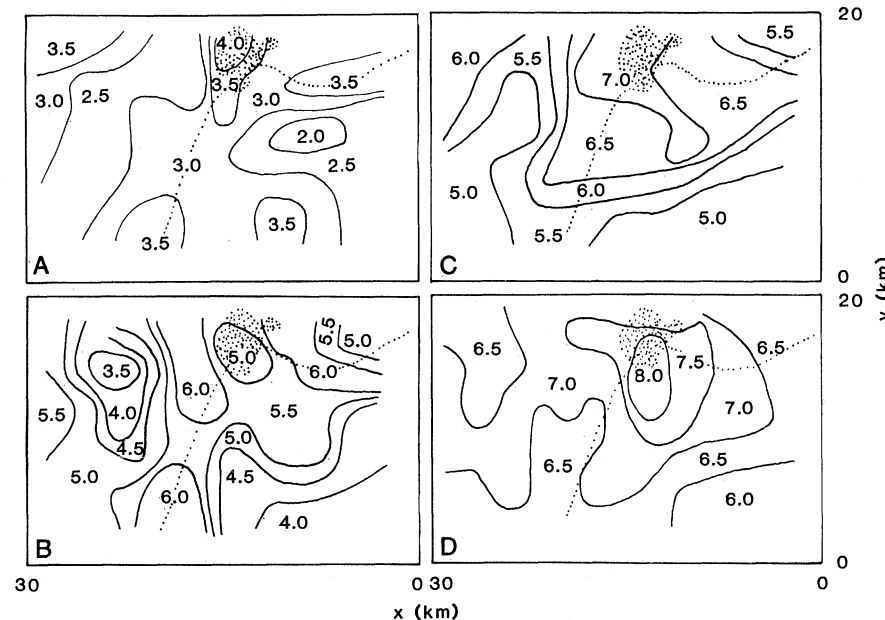
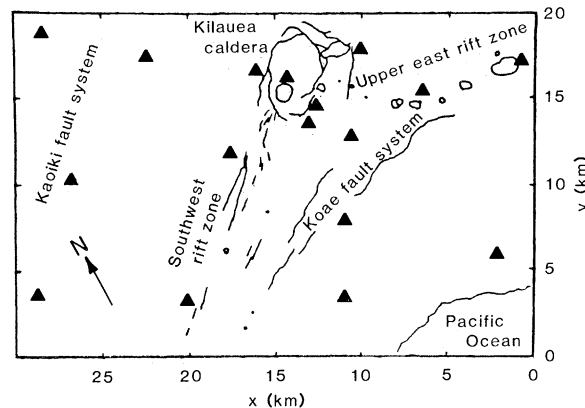
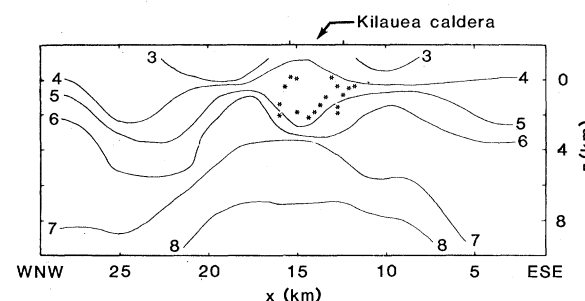


Fig. 2. Four layers of the composite velocity model for Kilauea Volcano, positioned at depths of -1.0 (A), 2.0 (B), 5.0 (C), and 8.0 (D) km with respect to sea level. Velocity is contoured at intervals of 0.5 km/sec. Stippling indicates the position of the caldera and its rift zones.

Fig. 3. West-northwest-east-southeast cross section (at *y* = 16 km) through the caldera, showing the association of the aseismic region [outlined by earthquake hypocenters (asterisks)] with the zone of low seismic velocity. For clarity, only shallow earthquakes in the immediate vicinity of the caldera are shown in the cross section. Many additional events were included in the inversion. Velocity contours are in kilometers per second.



magma complex. At a depth of 5 km (Fig. 2C), the high-velocity core of Kilauea is clearly evident, extending along the upper east and southwest rifts and intruding into the Koae area. Kaoiki and other nonrift areas continue to display rather low velocities. By 8 km the model resolution has become somewhat poor, but the high velocities of the volcano core are still evident, apparently with a slight southward shift from the shallower levels. The very high velocity (> 8 km/sec) directly beneath the caldera is consistent with the results of a previous refraction study (3).

An east-west cross section through the caldera (at $y = 16$ km; Fig. 3) shows the association between the velocity structure and seismicity in the caldera area. Earthquakes cluster around the low-velocity zone directly beneath the caldera at shallow depth. The aseismic zone coincides precisely with the zone of low P-wave velocity. Thus the summit magma complex of Kilauea is detectable in the seismic velocity structure. The low velocity is most likely due to a combination of elevated temperature and the presence of partial melt and pockets of magma.

To summarize, starting with the caldera area, we find near-surface high velocities underlain by a zone of relatively low velocity that displays a slight southward shift with increasing depth. We interpret this as the roof and main body of Kilauea's summit magma complex. The low-velocity zone coincides with an aseismic zone beneath the caldera. The surrounding volume is characterized by rather high velocities, corresponding to the core of the volcano. Systematically high velocities are also observed along the upper east and southwest rift zones. High velocities along the Koae fault system are clear evidence for intrusive activity there. The nonrift areas, especially around the Kaoiki fault system, display almost uniformly low velocities. These findings are generally consistent with previous refraction (3, 4) and teleseismic (5) studies, but indicate the power of the simultaneous inversion method to reveal three-dimensional structure on a finer scale than can be obtained otherwise.

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Calcium-Promoted Protein Phosphorylation in Plants

Abstract. *Phosphorylation of several polypeptides in corn coleoptiles was promoted by adding calcium. Chlorpromazine, a calmodulin inhibitor, reduced calcium-promoted phosphorylation, suggesting that the phosphorylation was modulated by calmodulin. This is evidence for the role of calcium in protein phosphorylation in plants and could serve as an experimental approach to understanding the molecular mechanism by which calcium modulates various physiological processes in plants.*

In order to adapt efficiently to the changing environment, all living organisms have built-in regulatory mechanisms that can be controlled in response to external stimuli. Extensive information from animal systems indicates that hormonal and neural stimuli are the two most important means by which individual cells respond to messages from the rest of the organism. The message received on the surface of individual cells is transmitted to the metabolic machinery of the cell by second messengers, such as adenosine 3',5'-monophosphate (cyclic AMP) and calcium. Attempts have been made to explore the role of cyclic AMP as a second messenger in plants. Although convincing evidence was obtained for the existence of cyclic AMP in plants, sufficient evidence could not be obtained for its physiological role as a second messenger (1). Therefore, there is increasing interest in defining the possible role of calcium as a second messenger in plants (2).

Calcium affects several physiological processes in plants. For example, it has been implicated in geotropism (3), cell elongation, cell division, protoplasmic streaming, senescence, abscission, α -amylase secretion, and several other processes (4). In animals, calcium has been shown to regulate various biochemical processes after binding to proteins like calmodulin (5).

Occurrence of calmodulin in plants has been well documented, and calcium- and calmodulin-modulated activation of enzymes such as nicotinamide

adenine dinucleotide (NAD^+) kinase, Ca^{2+} -activated adenosinetriphosphatase (ATPase), and isofluidoside phosphate synthase has been reported from plant systems (6). Studies with calmodulin inhibitors suggest the possible involvement of calcium and calmodulin in various hormonal responses and geotropism (7). Recently, evidence has been obtained for the presence of endogenous calmodulin inhibitors in plants that could regulate calmodulin activity in vivo (7). Protein phosphorylation is now emerging as the major mechanism by which calcium and calmodulin regulate biochemical events inside the cell in response to external stimuli (8). Many protein kinases that are activated by calmodulin in the presence of calcium have been reported from animal cells. However, only limited information is available about the role of calcium and calmodulin in the phosphorylation of proteins from plant systems (9). We now report evidence for the role of calcium in the phosphorylation of soluble and membrane proteins of corn coleoptiles. Phosphorylation of thylakoid proteins, nuclear proteins, wheat germ proteins, and cytokinin receptors from plants have been reported (9); however, we know of no evidence for the role of calcium in the phosphorylation of those proteins.

Soluble and membrane proteins were isolated from corn coleoptiles in a buffer containing 0.2 mM EGTA (10). Phosphorylation of proteins was performed in the presence of $[\gamma\text{-}^{32}\text{P}]\text{ATP}$. Phosphorylated proteins were analyzed by poly-