Reports

Yellowstone: Seismic Evidence for a Chemical Mantle Plume

Abstract. *Arrivals of P waves from a recent event at the Nevada Test Site, recorded at a distance of 15.3°, passed beneath the Yellowstone caldera at depths of 200 and 400 kilometers. The travel time anomalies are modeled by a vertical cylindrical structure with a high-velocity core and a low-velocity collar as compared with the more normal mantle. The velocity structure and vertical extent of this feature are consistent with a chemical mantle plume beneath the Yellowstone caldera.*

The Yellowstone caldera has recently been shown to be the surficial expression of a deep-seated lithospheric structure (*1*). Delays in P wave arrivals from teleseismic sources recorded within 50 km of the caldera have been modeled by a body with a seismic velocity 10 percent lower than that of the normal mantle. The diameter of this structure increases with depth from 30 km at the surface to 70 km at a depth of 100 km. Severe attenuation of seismic rays passing through the upper regions of the caldera, consistent with a partial-melt and low-velocity structure, has been reported (*2*). The extent of volcanics and the apparent depth of this structure have led many investigators to propose that the Yellowstone caldera caps a localized, columnar upwelling of hot mantle material, variously called a hot spot or plume (*3*). Additional teleseismic P delay data, recently collected by the U.S. Geological Survey, suggest that this feature extends to depths of 200 km and continues to increase in diameter with depth (*4*). However, the exact definition of the anomaly has not yet been resolved.

A recent event at the Nevada Test Site (NTS) on 28 October 1975, local magnitude (M_L) 6.3, provided a unique opportunity to study the mantle beneath Yellowstone from a new azimuth and potentially to resolve the velocity structure below a depth of 200 km. Seventeen stations centered near Regina, Saskatchewan, and deployed in a fan configuration from NTS (Δ = 15.3°, arc length = 300 km), recorded this event (Fig. 1). Two arrivals, direct P waves (P_{200}, bottoming depth = 200 km) and the reflection from the 400-km discontinuity (P_{400}), passed beneath the Yellowstone caldera (Δ = 8.5°). Unlike the teleseismic studies of P delay that record energy traveling nearly vertically within the anomaly (*5*), the recorded arrivals traveled nearly horizontally through the structure.

The 17 recording units deployed in this experiment were high-gain, short-period vertical seismographs, 14 of which had an identical frequency response and recorded with either a pressurized ink system or a stylus on a smoked drum. The other three units had a much larger dynamic range and recorded on magnetic tape. Timing for four units depended on a quartz-crystal, temperature-compensated clock calibrated both before and after the NTS event. The other seismographs recorded radio WWVB [World Wide Time Boulder (U.S. Bureau of Standards)] simultaneously with the seismic signal. The timing accuracy is estimated to be 50 msec. Stations were spaced about 20 km apart and were within 2 km of being equidistant from NTS. Three station arrays were deployed radially both at the center and at the northwest end of the fan in order to obtain $dt/d\Delta$ corrections. All data were time-shifted by an amount appropriate to equalize stations to a common distance (Δt < 0.2 second).

As compared with P waves recorded elsewhere in North America at similar distances from other NTS events (*6*), the first swing of the P wave was unexpectedly and severely attenuated at all stations. Indeed, several stations appear to have recorded a dilatational first motion. In addition, stations 10, 11, and 12 (Fig. 2) recorded a weak signal, possibly the result of either attenuation or strong interference from multiple ray paths. The amplitude of the emergent first arrival increased until the dynamic range at most stations was exceeded. Fortunately, four stations (stations 1, 3, 8, and 13) spread across the fan recorded the wave shape of P_{200} and P_{400} (Fig. 2). Within the 5.5 seconds separating the two arrivals, the amplitude of P_{200} had decayed to 10 percent of the peak amplitude of P_{400}. Because of the emergent first arrival and the ambiguity of picking an arrival for P_{400}, the records were digitized at approximately 50-msec intervals, and we determined the relative arrival times with the aid of a computer by cross-correlating several cycles of the signal. Although P_{400} clipped at many stations, the frequency and phase of this arrival are not expected to be seriously shifted by the P_{200} coda. A numerical experiment suggests that at the dominant period of the recorded phases an average apparent time shift of less than 0.03 second is expected, assuming a signal-to-noise ratio of 5.

Figure 3 shows the relative arrival times derived from the cross-correlation of adjacent stations. By randomly cross-correlating stations, we obtained a check on systematic apparent time delays artificially introduced by the cross-correlation of adjacent stations. In general, relative arrival times derived from either

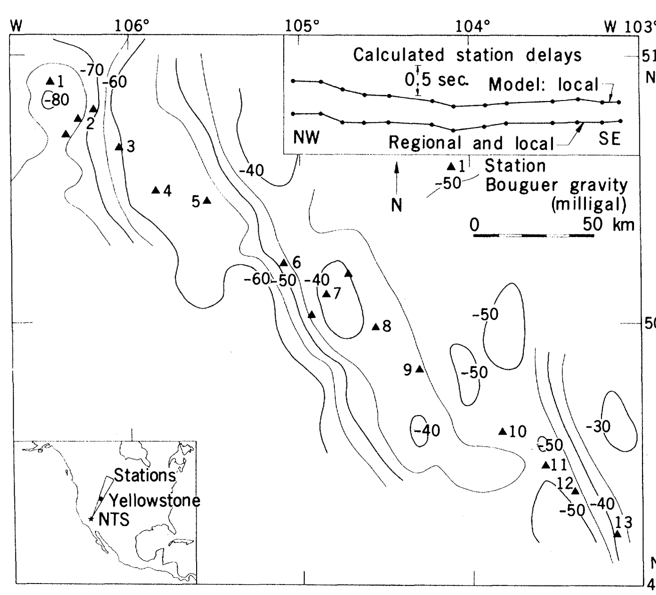

Fig. 1. The locations of stations that recorded the NTS event. Contours represent the Bouguer gravity anomaly and are used to estimate local station delays. The expected delays are calculated on the basis of two different assumptions about the origin of the observed gravity anomalies: (i) "local" reflects only local accumulations of sediments; (ii) "regional and local" results from a smooth transition in crustal structure superimposed on local accumulations of sediments.

cross-correlation technique agreed to one digitization interval, 50 msec. The error bars in Fig. 3 are estimates of the uncertainty in the correlation function and include any timing ambiguities.

Local station delays resulting from either accumulations of soft sediments or changes in local crustal structure are difficult to ascertain. The earth's gravity field should locally reflect accumulations of unconsolidated, low-density and low-velocity sediments (Fig. 1) (*7*). An expected P delay can be estimated by comparing both gravity and P delay data from known sediment-filled basins. In this comparison, delays across the fan are calculated from the observed gravity field and the assumption that perturbations in the field result solely from local basin structures. The expected delays increase from east to west by 0.3 second (Fig. 1; local model). A second interpretation is that local structures are superimposed on a regional gradient resulting from a transition in the structure of the crust (*8*). The maximum delay calculated from this assumption is 0.1 second and again increases from east to west (Fig. 1; regional and local model). Relatively small, uniform station delays are also suggested by the relief on the Precambrian basement. The topography of the contact between the Upper Cretaceous marine sediments and the basement changes linearly by less than 1 km across the 300-km array (*9*). Corrections for station elevations have not been included as the region is topographically flat. The lack of correlation between observed delays and possible local delays suggests that the relative arrival times are not simply near-station effects.

Although not correlated with the known gravity data, the travel time anomalies could still be attributed to lateral variations beneath the receivers. Differencing the two arrivals, $P_{400} - P_{200}$ (Fig. 3c), should remove any near-station effects and emphasize variation where the two ray paths diverge. These differential times show that the center of the anomaly, relative to the sides, is about 0.15 second faster at 400 km than at 200 km. If the precise velocity structure at 200 km can be resolved by other investigations, these data can be used to extend or limit the depth of the plume to 400 km. Conversely, if no travel time anomaly is present at 400 km, then the differential travel times reduce to the anomaly at 200 km and the effect of local station delays is completely removed. Those P waves traveling through the center of the anomaly, relative to the sides, are delayed by 0.15 second. The shape of the anomaly may be modeled by a cylindrical body 100 km in diameter and with a velocity slower by 1.2 percent than that of the adjacent normal mantle (Fig. 3c).

Interpreting the observed delays as arising from the continuation of the proposed Yellowstone plume to depths in excess of 200 km requires a very different structure from that previously reported for shallower depths (*5*). Seismic rays passing through the sides of the plume are delayed by as much as 0.5 second (Fig. 3, a and b). However, rays passing through the center of the anomaly show little delay at 200 km and appear somewhat advanced at 400 km when compared with rays passing through the more normal mantle as recorded at the extreme ends of the array. The simplest model consistent with these delays is a cylindrical body with a low-velocity collar around a high-velocity core. As the rays passed nearly horizontally through the plume, a two-dimensional ray tracing program was used to determine appropriate parameters for this model. For any given station, the path with the least travel time may arise from three different seismic rays. The first ray travels around the anomaly, the second passes through the low-velocity collar, and the third travels through both the low-velocity collar and the high-velocity core. The transit times were normalized by the travel time of the anomaly-free ray path. The problem is largely nonunique, as velocity contrasts and dimensions are closely related. A simple, radially symmetric model was constructed that matches the data and does not require large velocity anom-

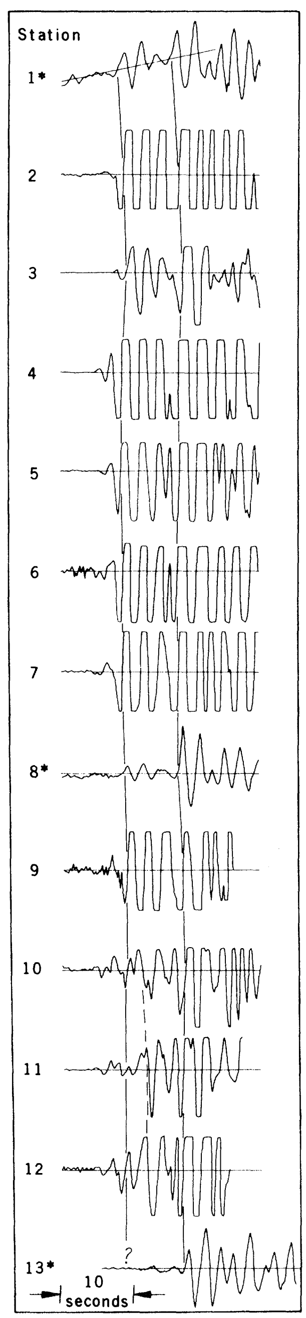

Fig. 2. Recorded P wave arrivals corrected for $dt/d\Delta$, where $\Delta t < 0.2$ second. The stations marked with asterisks recorded on magnetic tape and had a slightly different frequency response from that of the other stations. The relative arrival times were defined as the maximum of the cross-correlation of the P wave coda of adjacent stations at approximately the time alignment indicated by the light vertical lines.

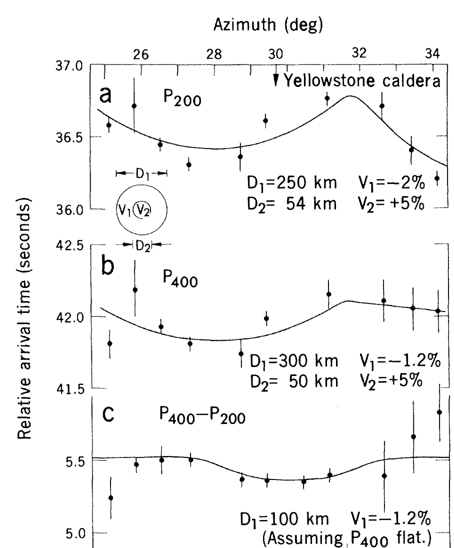

Fig. 3. Relative arrival times for (a) P_{200}, (b) P_{400}, and (c) $P_{400} - P_{200}$ derived from cross-correlating several cycles of the recorded P wave coda. The three lines are calculated from the model parameters listed below each graph. The model parameters are as follows: D_1, outer diameter of the low-velocity collar; D_2, diameter of the high-velocity core; V_1 and V_2, the percentage change in velocity from the normal mantle for D_1 and D_2, respectively. The model in (c) is calculated on the assumption that no anomaly exists at 400 km. The differential travel times, $P_{400} - P_{200}$, are independent of local station delays and reduce to the anomaly at 200 km. Only data points obtained from instruments with identical frequency response characteristics are plotted.

alies (Fig. 3, a and b). The structure of the high-velocity core is nonunique. Possible models range from a diameter of 50 km and a seismic velocity 10 percent higher than that of the normal mantle to 85 km and 4 percent, respectively. The rapid decrease in the observed travel time for P_{200} between the azimuths 32° and 34° (Fig. 3a) is well modeled by the ray that travels around the anomaly. Hence the diameter of the low-velocity collar at a depth of 200 km is fairly well constrained at 250 ± 30 km. The velocity contrast between the collar and the normal mantle must be as large as 2 percent in order to delay sufficiently the ray passing through the collar. However, an upper bound on the velocity contrast cannot be determined. At 400 km, the rapid decrease in travel time between 32° and 34° is absent. The smoother anomaly is modeled by the ray that travels through the collar. The respective diameter is at least 300 km, and the velocity contrast appears to be less than 2 percent. For both models the center of the structure is shifted approximately 40 km northwest from the center of the caldera.

The simple structure described above is inadequate to completely model the anomaly. Rays passing through the center of the anomaly are advanced and rays passing through the collar or around the anomaly are delayed with respect to the model. We expect that a more complete model that we are developing, employing radial velocity gradients within the plume, will remove this defect. Finally, the structure does not appear to be entirely symmetrical. The southeast shoulder of both the P_{200} and the P_{400} anomalies (Fig. 3, a and b) appears to be somewhat broader than the northwest shoulder. This asymmetry implies a differing collar radius between the northwest and southeast sides of the structure.

Anderson (*10*) has recently discussed a chemical plume model that essentially predicts the observed travel times. In his model, conduits through the mantle contain residuals from the differentiation of the primitive earth. The chemical plume is enriched with CaO, Al_2O_3, TiO_2, and the refractory elements including U and Th. The CaO-Al_2O_3-TiO_2 assemblage and the refractory elements are expected to have higher seismic velocities than normal ferromagnesian silicates. Thermal perturbations from the decay of the radioactive refractory elements would depress the seismic velocities in the mantle surrounding the plume. The resulting structure would be a cylindrical body with a relatively high-velocity core and a low-velocity collar. The velocity structure and the vertical extent of this feature is consistent with a chemical mantle plume beneath the Yellowstone caldera. The asthenosphere above the chemical plume is more extensively molten than elsewhere, thereby giving lower velocities. The thermal plume hypothesis gives the same result in this region but predicts quite different results at depths greater than about 200 km. Within the lithosphere both the chemical plume and the thermal plume hypotheses give the same result. Melting is expected to be extensive, seismic velocities are reduced, and attenuation is increased.

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Snowfall Observations from Natural-Draft Cooling Tower Plumes

Abstract. *During the winter of 1975–1976, snowfall from the plumes of large natural-draft cooling towers of power plants has been observed. Snow accumulations up to 2.5 centimeters have been found on the ground at extended distances from the cooling towers, and visibility has been restricted to less than 1600 meters in the tower plume near ground level.*

Five American Electric Power System (AEP) power plants in Kentucky, Ohio, and West Virginia are equipped with natural-draft cooling towers (Fig. 1). In this area there are several rivers capable of supplying condensing water for power plants of the size that were being installed in the early 1950's. In the last 20 years, however, the increase in the size of the power plants combined with concern over the potential effects on the rivers has led to a shift from direct, once-through systems to cooling towers, as shown in Table 1.

In view of the prospect of cooling towers capable of discharging 1.25×10^9 kg-cal per hour, studies of plume rise and persistence under various meteorological conditions were undertaken by the American Electric Power Service Corporation and Smith-Singer Meteorologists, Inc., at the Muskingum River and Big Sandy power plants during the fall of 1968. From 1968 through 1970 these studies consisted of visual observations and photographs of the plumes taken from the ground; temperature, humidity, and wind measurements were also recorded. By the third year of this exploratory study, we became convinced that airborne observations were necessary to study plume behavior accurately and to establish firm relationships with meteorological conditions. During the last three winters (1973 through 1976) measurements of ambient temperature and humidity were recorded from light aircraft. Each test also included visual and photographic records of the geometry of the visible plumes, and wind data were obtained from aircraft drift measurements.

Table 1. Growth of AEP generating capacity.

Period	Additional capacity installed during period (Mw)	Percentage of new capacity using cooling towers
1950–1954	1980	0
1955–1959	1920	23
1960–1964	1970	25
1965–1969	2510	53
1970–1974	5570	100

Up to March 1975, no significant environmental effects had been found at any of the natural-draft towers studied. Data from the 1973–1975 flight tests (*1*) indicated that no precipitation or fog was induced at ground level by these towers. On the contrary, all of the visible plumes, a few of which traveled 25 km or more from the plants, remained at least 450 m above ground.