Waste Isolation Pilot Plant

Compliance Certification Application

Reference 81

Bredehoeft, J.D., Riley, F.S., and Roeloffs, E.A. 1987
Earthquakes and groundwater. Earthquakes and Volcanos, Vol 19, no. 4, pp. 138-146.

Submitted in accordance with 40 CFR §194.13, Submission of Reference Materials.

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DATE: 02/28/96
DELIVERY DUE: 03/18/96

WESTINGHOUSE ELECTRIC CORPORATION
WASTE ISOLATION DIVISION
P.O. BOX 2078
CARLSBAD, NM 88221

PURCHASE ORDER PO 72919

PAGE: 1 of 3

VENDOR: 156085
Information Express

3250 Ash St.
Palo Alto, CA 94306

PAYMENT TERMS: 1% 10 NET 30 DAYS
FOB: Destination Prepaid & Not Allowed
SHIP VIA: UPS GROUND

This Order is issued under Westinghouse Prime Contract DE-AC04-86AL31950 with the U.S. Dept. of Energy. DPAS DO-E2 rating applies.

SHIP TO: Westinghouse Electric Corp.
Waste Isolation Division
For the U.S. Dept. of Energy
WIPP Site
30 Miles Southeast of Carlsbad
Carlsbad, NM 88220

BILL TO: Westinghouse Electric Corp.
Waste Isolation Division
Accounts Payable Dept.
P.O. Box 2078
Carlsbad, NM 88221

NOTE: RECEIVING HOURS - 7:30 A.M. TO 3:00 P.M. MONDAY THRU FRIDAY

SB-SDB/WO Sol? : SB
P.O. Coding : EXI2
QA Code : N40
West Commodity : GDR
Acct Commodity : 42

Line Nmbr	Item ID / Description	Quantity Ordered	U/M	Unit Price	U/M	Total Price
1	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BELL, J.T., D.A. COSTANZO, AND R.E. BIGGERS 1973B PLUTONIUM POLYMERIZATION - II KINETICS OF THE PLUTONIUM POLYMERIZATION JOURNAL OF INORGANIC AND NUCLEAR CHEMISTRY VOL. 35: 623-628	10.00000	EA	18.000	EA	180.00
2	71510 00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BELL, J.T., C.F. COLEMAN, D.A. COSTANZO, AND R.E. BIGGERS. 1973A PLUTONIUM POLYMERIZATION -- III THE NITRATE PERCIPITATION OF PU (IV) POLYMER [illegible] NUCLEAR CHEMISTRY VOL. 35: 629-632	10.00000	EA	18.000	EA	180.00
3	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BREDEHOEFT, J.D., RILEY, F.S., AND ROELOFFS, E.A. 1987 EARTHQUAKES AND GROUNDWATER EARTHQUAKES AND VOLCANOS, VOL. 19, NO.4, PP. 138-146	10.00000	EA	9.000	EA	90.00
[illegible]	[illegible] PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. CHAPPELL, J., AND N.J. SHACKLETON 1986 OXYGEN ISOTOPES AND SEA LEVEL NATURE VOL. 324, NO.609 137-140 REFERENCE CONTROL NUMBER 5205143547	10.00000	EA	21.000	EA	210.00
5	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. DAVIES, P.B. 1984 DEEP-SEATED DISSOLUTION AND SUBSIDENCE IN BEDDED SALT DEPOSITS PH.D. DISSERTATION STANFORD, CA DEPARTMENT OF APPLIED EARTH SCIENCES STANFORD UNIVERSITY PALO ALTO, CA PUBLISHED IN ENGINEERING GEOLOGY, VOL. 27, #44, 12/89 PG.467	10.00000	EA	20.000	EA	200.00
6	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. HARTMAN, W.K. 1965 TERRESTRIAL AND LUNAR FLUX OF LARGE METEORITES IN THE LAST TWO BILLION YEARS ICARUS VOL. 4, NO.2, PP. 57-166	10.00000	EA			
7	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. IMAN, R.L., AND W.J. CONOVER, 1982 A DISTRIBUTION-FREE APPROACH TO INDUCING RANK CORRELATION AMONG INPUT VARIABLES	10.00000	EA			

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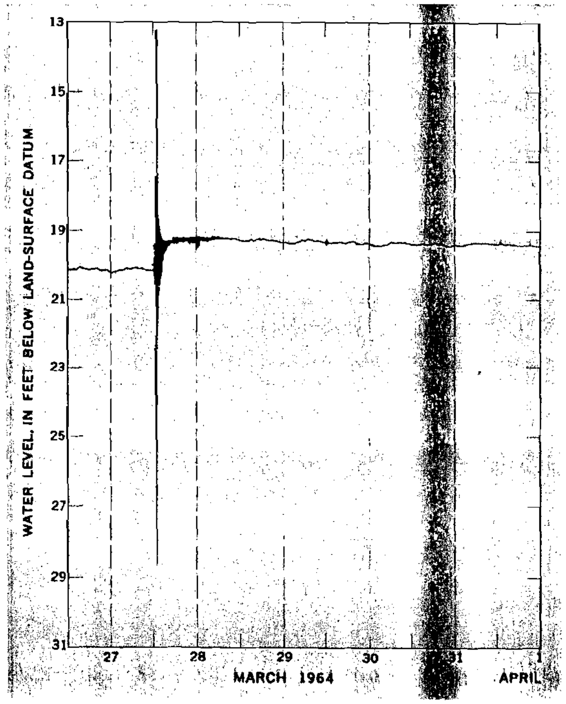
Earthquakes and Groundwater

by
J. D. Bredehoeft, F. S. Riley, and E. A. Roeloffs
U.S. Geological Survey Menlo Park, CA

As part of the U.S. Geological Survey prediction experiment at Parkfield along the San Andreas fault in California, a network of water wells is being monitored. This network consists of wells that are situated at seven sites that were drilled by the Geological Survey for the express purpose of monitoring water levels. These wells have turned out to be very sensitive volume strain meters. The scientific rationale for the wells as strain meters is explained in some detail below.

Water wells can respond rather dramatically to earthquakes. This phenomenon was perhaps best studied in North America following the Good Friday Alaskan earthquake of 1964. Water in a well in northern Florida fluctuated approximately 17 feet during the passage of the Rayleigh surface waves from the Alaskan earthquake. Bob Vorhis, a USGS hydrogeologist, assembled data on 1,450 wells in North America, along with numerous other wells scattered throughout the rest of the world—some as far away as the Phillipines, Africa and Australia—in which a response to the Alaskan earthquake was observed.



Hydrograph of a well near Perry, Florida, showing fluctuation caused by the Alaskan "Good Friday" earthquake March 27, 1984.

It had been known before 1964 that a well could respond to the passage of a seismic wave. Elmer Rexin had been observing earthquakes in a well at the Nunn Bush Shoe Company factory in Milwaukee for a number of years. He had speeded up his recorder and was observing fluctuations in the well which greatly resembled conventional long-period seismograms; he had published these results in the early 1950's. The Alaskan earthquake, because of the number of wells which responded, triggered a serious review of the phenomenon.

The response of a water well to an earthquake is best understood if we distinguish (1) the dynamic response, the fluctuation due to passage of a seismic wave—often a Rayleigh wave, and (2) the static response, the response due to the static deformation produced by an earthquake. Because a well responds both dynamically and statically it could, in principle, be utilized both as a seismograph and as a strain meter. While in reality one theory explains both the dynamic and static response, it is, we believe, conceptually simpler to treat these responses separately. The fact that a water well is a sensitive strain meter provides some interesting geophysical opportunities, as is explained below.

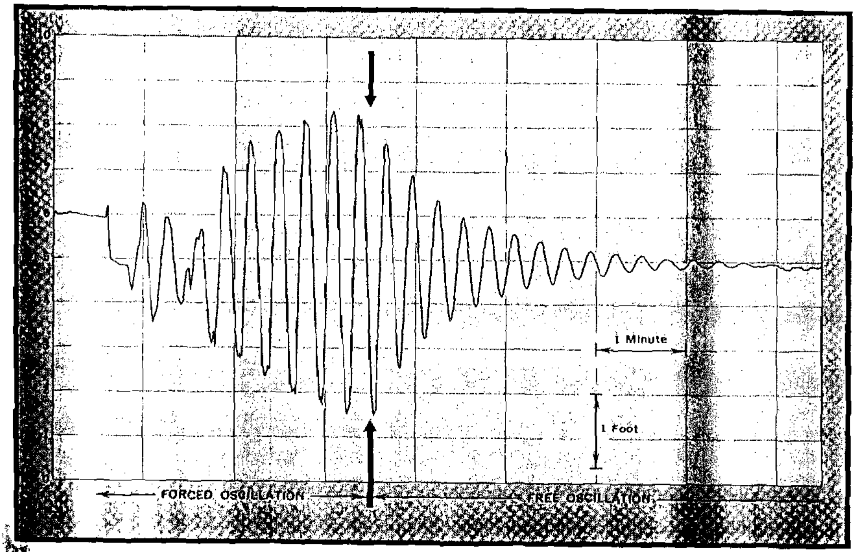
An observation well penetrating a deep confined aquifer is best understood as a simple manometer. The water level in the well is such that the height and weight of the fluid column is sufficient to equal the fluid pressure in the layer it penetrates. Any change in pressure in the aquifer causes fluid to flow into, or out of, the well until the height of the fluid column again is sufficient to balance the pressure in the aquifer.

Dynamic Response

Certain seismic waves, especially Rayleigh waves, cause a volume change in the rock. A volume change in an aquifer produces a pressure change in the fluid. A Rayleigh wave produces a fluctuating fluid pressure in an aquifer, or fluid reservoir rock. The fluid level in an open observation well will try to go up and down in an attempt to balance pressure fluctuations in the aquifer. The dynamics of the oscillation in the well involve further complications.

As frequencies approach those of the Rayleigh waves (periods from 8 to 30 seconds) the open water well behaves as a simple harmonic oscillator. In elementary physics the classic simple harmonic oscillator is a spring with a suspended mass. When disturbed, the mass will tend to oscillate up and down with the motion gradually decaying away. Some water wells behave in a similar manner. An experiment was performed in the Florida well in which the water level fluctuated 17 feet during the Alaskan earthquake. What is interesting is the free oscillation which follows the period of forced oscillation. The forcing, which was near the natural frequency of the well, built the oscillation; the oscillation then died away following the forcing.

If you remember back to freshman physics, you may recall that simple harmonic oscillators could be overdamped or underdamped. When disturbed, underdamped ones oscillate; overdamped ones do not oscillate but simply return with an exponential motion to their original resting place. Hilton Cooper and some colleagues at the USGS in the mid-60's developed the theory for the water well as a simple harmonic oscillator. The mass is provided by the height of the water column in the well; the damping depends on the ease with which water can move in and out of the well. In a highly permeable aquifer, water moves readily in and out of the well; if the permeability is sufficiently high, the well behaves as an underdamped oscillator. If the permeability is low, water can not move in and out of the well readily; the well is overdamped and the oscillation at the well is smaller than the pressure-head fluctuation in the aquifer. In particularly "tight" (less permeable) formations, the well may not respond at all to seismic-pressure fluctuations in the aquifer.



Hydrograph of the well near Perry, Florida, during an experiment in which water in the well was forced to oscillate (indicated as forced oscillation on the graph) and then allowed to oscillate freely (indicated as free oscillation). The vertical scale is arbitary.

The Florida well, which fluctuated so dramatically during the Alaskan earthquake, was excited by a Rayleigh-wave-pressure change very close to the natural resonant frequency of the well. A "sympathetic" response occurred; because of the inertia of the fluid column, the actual fluctuation of the water well was larger than the pressure-head change in the aquifer.

Static Response

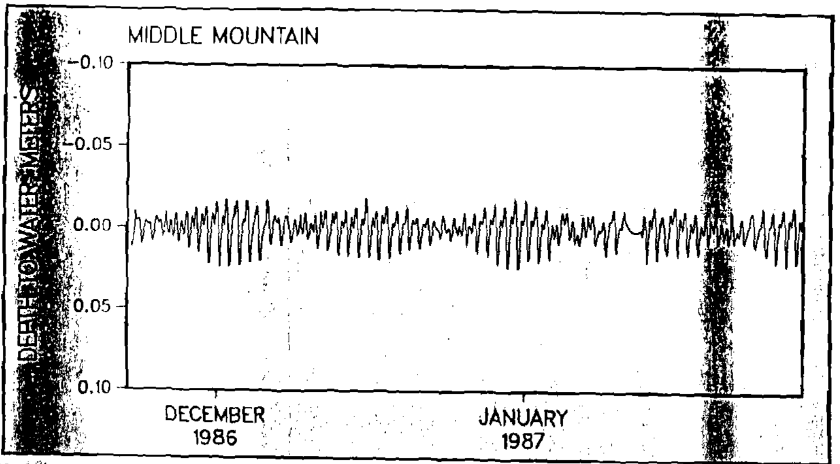
The static response of a well to an earthquake is much less complicated than the dynamic response. The simplest geophysical model of an earthquake is a displacement along a finite rupture plane in an elastic material.

Using this simple elastic conceptual model, a dislocation along a finite rupture in an elastic space requires that the elastic material strain accommodate the displacement along the rupture plane. Frank Press showed, following the Alaskan earthquake, that the simple model predicted measurable strains to large distances, perhaps to several thousand kilometers or more, for great earthquakes. The size of larger earthquakes is more or less correlated with the length of the fault which ruptures during the earthquake. The measurable strain field also depends upon the size of the rupture plane.

The Well as a Strain Meter

A dislocation in an elastic space (the upper part of the crust is often viewed geophysically as an elastic "half-space" because of the effect of the Earth's surface) produces a volume strain. A volume strain in a porous fluid-filled medium creates a fluid pressure change. Because both water and rock are rather incompressible, a small volume strain produces a measurable fluid pressure change.

In terms of strain, one of the most interesting geophysical phenomena observed in many water wells tapping confined aquifers is the earth tide. (This is the response of the solid Earth to the same forces that produce sea tides.) George and Romberg demonstrated in the mid-1940's that wells had an earth-tide fluctuation. One of our Parkfield wells shows a clear tidal fluctuation.



Hydrograph of the Middle Mountain Parkfield observation well showing the tidal response of this well. The data have been high-frequency filtered to eliminate frequencies higher than several cycles per day. Zero on the water level in the well is arbitarily chosen to represent the mean water level in the well.

The solid-earth tide produces a volume strain. The wavelength of tidal strain is roughly half the circumference of the Earth (the tide is approximately semi-diurnal). Because of the long wavelength, the strain is controlled by deep crustal as well as by mantle properties, and the volume strain is of the order of 1 part in 10 billion (10^{-8}) everywhere it has been carefully measured.

The fact that many water wells have earth tide fluctuations of the order of one to several centimeters or more means that these can give a measure of the sensitivity of the well to volume strain. If we can identify an earth-tide signal in the well hydrograph, we know the well is observing volume strains of the order of 10^{-8}. The tidal strain can be used to calibrate the well response.

Wells not only respond to earth tides, they also respond to changes in barometric pressure and seasonal recharge events, as well as man-made effects, such as pumping. Assuming that these effects can be filtered out, it is possible that volume strains of the order of 1 part in a billion (10^{-9}) might be observable in an ordinary water well. A water well can thus be a very sensitive volume strain meter.

Returning to the simple elastic dislocation model of an earthquake, the model suggests that the strain depends on the depth and size of the rupture-plane as well as the amount of slip on this plane. Volume strains on the order of the earth-tide strain might be produced to distances of perhaps 5 to 10 times the length of the rupture plane. For example, an earthquake that produces a rupture on a plane, 1 kilometer by 1 kilometer, which extends from the Earth's surface downward, with a slip of 3 cm, produces a volume strain on the order of the earth-tide volume strain, at distances out to 10 kilometers.

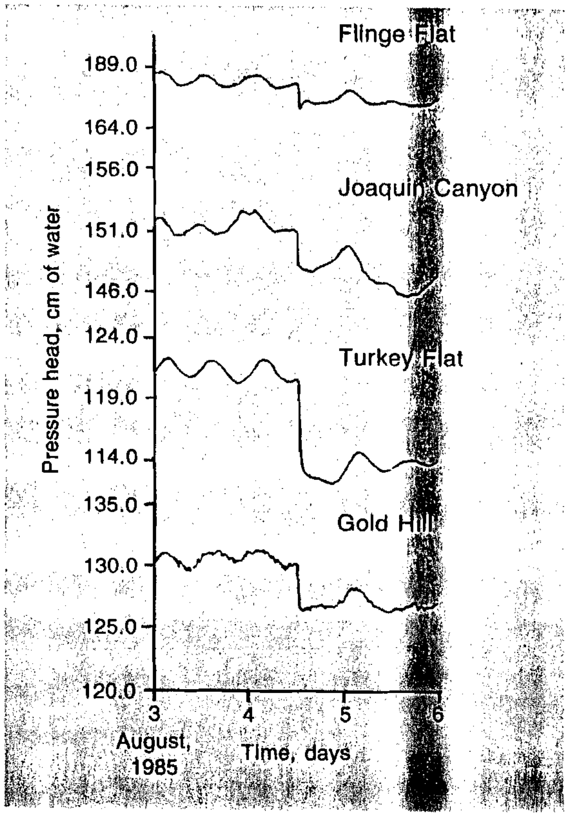
Given these conceptual ideas, it is not surprising that the Japanese, and the Chinese in particular, have reported anomalous water-level events in wells, both before and following earthquakes. By far the biggest success in earthquake prediction was the evacuation of the Chinese city of Haicheng prior to an earthquake on February 4, 1975. Numerous well-documented water-level anomalies preceded this earthquake for a period of approximately 6 to 8 weeks prior to the event. The Tangshan earthquake, a larger event that occurred 19 months after Haicheng, was not predicted by the Chinese. However, a review of continuous hydrographs of wells in the area show what appear to be precursors. So far, no particularly quantitative analysis of either the Haicheng or the Tangchan water-well data has been made.

Parkfield

A regular sequence of six earthquakes, dating back to 1857, has occurred along the San Andreas fault at Parkfield in south central California. The last event occurred in 1966; given the regularity of the 22-year cycle, the next event is expected very soon. The USGS has mounted an extensive earthquake prediction experiment at Parkfield.

A water-well network, expressly designed to continuously monitor volume strain, is an integral part of the Parkfield experiment. Currently, water wells are continuously monitored at seven sites in the vicinity of Parkfield. At all of these sites, water levels are monitored in a deeper horizon, ranging in depth from approximately 88 to 250 meters. Six of the deeper wells show clearly identifiable tidal signals which range from one to several centimeters in amplitude. At five of the locations, a shallow water level, less than 50 meters in depth, is also measured. At these seven locations barometer pressure, rainfall, and water levels are measured every 15 minutes. Data are accumulated for 4 hours and then transmitted, via GOES satellite, over the Water Resources Division data network of the USGS. The data from Parkfield are transmitted to the USGS offices in Menlo Park and are analyzed with the earthquake prediction in mind.

Perhaps the clearest tectonic event we have observed in water well data was an earthquake that occurred in August 1985 at Kettleman Hills, near Coalinga, California. This earthquake was situated approximately 35 to 40 kilometers to the east of the four Parkfield wells that we were operating at that time. A drop in water level at the time of the earthquake was observed in each of the four wells. Using the simple elastic half-space dislocation model, we made a calculation of what we would have expected the water-level change to have been in the four wells. The simple-model calculations computed a response within a factor of two for the observations recorded at all the wells. This response came as something of a pleasant surprise, since the geology between Kettleman Hills and our four wells is quite complex and one of the wells, Flinge Flat, is situated across the active trace of the San Andreas fault from Kettleman Hills.



Hydrographs of four observation wells at Parkfield which show the water-level declines caused by the August 4, 1985, Kettleman Hills earthquake.

The water-well strain network at Parkfield is gradually being expanded. Four or five more wells are planned for the network in addition to the seven currently being observed in real time. One well, a 1,600-meter-deep exploratory oil well (a dry hole), is being reopened by the USGS. It is situated approximately 1,400 meters east of the fault near Parkfield. This well has a substantial well-head pressure, approximately 125 bars (1800 psi).

In addition to the Kettleman Hills coseismic water-level changes, we have observed a number of water-level changes which correlate with observed, surface creep events. One of these events in February 1987 was followed in the succeeding 12 hours by a sequence of small earthquakes in the vicinity of the well. This experience, along with the Chinese experience and a number of fault-mechanics models, suggest that strains may well be precursors to earthquakes. It is these strains which we are attempting to observe. Interestingly, our information on water-well strain from several creep events suggests that the strains may be larger at depth than those observed by the surface creepmeters.

Summary

The most dramatic of the water-well events produced by earthquakes are the water-level fluctuations produced at great distances from the epicenters of large earthquakes. These are dynamic responses produced by elastic transmission of seismic waves. Clearly, some wells could be utilized as long-period seismometers; however, conventional seismometers fulfill this need without some of the complications of the well. The dynamic response is of interest to hydrologists in providing aquifer information, although this information is commonly obtained more directly using other techniques such as pumping tests. The dynamic well response, while dramatic, has not proved very interesting for earth science.

Exactly the opposite is true for the static response of the well. The well is proving to be an interesting volume strain meter. Wells drilled in any number of geologic settings can have good earth-tide fluctuations, indicating good sensitivity to strain. The only requirement is a confined aquifer and enough permeability so that the well will fluctuate at tidal frequencies twice daily. These requirements are not very restrictive. Most of the earth scientists associated with the Parkfield experiment are quite encouraged by our success using water wells as strain meters. This is an exciting development for earthquake prediction, as well as for other aspects of engineering geology and rock mechanics.

CHARLES F. RICHTER (1900-1985)

Charles F. Richter: A Personal Tribute

With the death of Charles Richter in 1985, the seimological community lost a renowned colleague, and many of us lost a close friend and advisor. Charles was born on a farm in Ohio in 1900, received his A.B. from Stanford in 1920, and his Ph.D. from Caltech in 1928. Virtually his entire professional career was spent at the Seismological Laboratory in Pasadena, first as an employee of the Carnegie Institution of Washington and later as a Caltech faculty member. Following his retirement from Caltech in 1970, he was active for several years in the consulting firm of Lindvall, Richter, and Associates. His wife, Lillian, died in 1972, and they had no children. Richter served as President of the Seismological Society of America from 1959 to 1960 and was the second recipient of its medal in 1977.

Meeting Charles Richter was an experience never to be forgotten, for he was a very unusual person—a man of many contrasts. He could be charming or irascible; he could be outgoing or shy; he could be gentle and warm or abrupt and cold; and he was a man with a truly remarkable memory but, at the same time, was renownedly absentminded. In at least two areas, however, he never wavered in his consistency: he was absolutely dedicated to his science, almost to the exclusion of everything else, and he demonstrated utter intellectual honesty. Charles made no pretense of being a diplomat or a politician, and in things scientific, he said what he meant bluntly and precisely—whether it was with regard to earthquake prediction, the safety of high-rise buildings, or the mental competency of selected newspaper reporters! One did not always have to agree with Charles, but certainly one had to respect his opinions.

Most of the members of our Society [Seismological Society of America] will be fully as familiar with Charles' scientific accomplishments as myself. Certainly he is best known, both professionally and publicly, for his introduction of the word "magnitude" into seismological terminology, for his development of the local magnitude scale, and for his subsequent collaboration with Beno Gutenbert in extending the concept to teleseisms. There can be no question of the importance and signficance of this work to our science. But, in my opinion, Charles' greatest contribution to science is his 1958 book *Elementary Seismology.* It is sometimes thought of as a textbook, but it is far more than that; it is a truly remarkable compendium of almost everything seismological, with a strong emphasis on field aspects of the science. Is there a seismologist in the world who does not have this book on his or her shelf? And is there anyone among us who does not refer to it ocassionally, despite its present 30-year age?

On a more personal note, let me recall two very pleasant experiences I had with Charles. When the first galley proofs for *Elementary Seismology* were received from the publisher, Charles was in