Reports

Volcanic Activity and Great Earthquakes at Convergent Plate Margins

Abstract. *Volcanoes are unusually quiet for periods of a few years to a few decades prior to great shallow-thrust earthquakes. This is the most obvious part of an apparent pattern of volcanic activity related to the occurrence of great earthquakes at some convergent plate margins.*

At most convergent plate margins large segments of the plate interface are occasionally ruptured by great shallow-thrust earthquakes that have rupture zones which extend for several tens to several hundreds of kilometers (*1*, *2*). In many areas apparently similar great earthquakes have recurred in the same segments at intervals of from tens to hundreds of years (*3*). A few volcanoes have erupted a few hours to a few months after a great shallow earthquake has occurred near the volcano (*4*). Furthermore, a systematic pattern of volcanic activity seems to occur before large predominantly strike-slip earthquakes in the Sagami Trough region of Japan (*5*). Since some evidence exists for a relation between volcanic activity and great earthquakes, I systematically examined the pattern of volcanic activity before and after great shallow-thrust earthquakes in the circum-Pacific region.

I defined volcanic activity as the number of volcanoes within a given rupture zone that were in eruption during 1- or 2-year time intervals. Eruption data were taken from standard lists (*6*). Questionable eruptions or incidents of solfatara activity were excluded. Rupture zones, times, and magnitudes of great earthquakes were taken from Kelleher and his co-workers (*2*) and from Carr and Stoiber (*7*) for some Central American data.

The method used to associate volcanic activity and great earthquakes in the Central American region is shown in Fig. 1. This region was perhaps the most difficult to interpret because there have been many large earthquakes whose rupture zones commonly overlap rather than a few giant earthquakes whose rupture zones do not overlap. Figure 1a shows some relatively well defined rupture zones and the locations of volcanoes active during the period from 1820 to 1976. Several other large shallow-thrust earthquakes have occurred in this region during the period considered. The less well defined rupture zones of these earthquakes are estimated (Fig. 1b) by means of vertical bars, dashed where uncertain. Figure 1b is a space-time plot. Volcanic activity is shown by closed circles. No attempt was made to quantify the size of eruptions. Associations of seismic and volcanic activity are summarized in Fig. 1c, which is a group of histograms made by plotting all the volcanic activity which occurred in a given rupture zone on the same time line. In the other convergent plate margins considered (Figs. 2, 3, and 4) only these summary histograms are shown.

Volcanoes in southern Chile (Fig. 2b) are divided into three groups based on the three major rupture zones (1906, 1928 through 1938, and 1960). In Kamchatka, Russia (Fig. 3), there are four groupings of volcanoes. Some volcanoes are included in more than one group because the two smaller rupture zones, 1959 and 1971, overlap parts of the larger rupture zones, 1923 and 1952. In the northern Antilles (Fig. 4b) there is just one volcano grouping which includes all volcanoes within the rupture zone of the 1843 earthquake. All of the eruptions in this area since 1880 have been eruptions of the Soufrière Volcano on Guadeloupe Island.

I assumed that the only volcanoes likely to be affected by a particular earthquake were the ones within or immediately landward of the rupture zone of that earthquake. This assumption seems to be true in most regions but may not be true in Kamchatka. The 1923 and 1952 earthquakes seem related to periods of low volcanic activity throughout the region (Fig. 3b).

At the convergent plate margins described above there have been similar patterns of volcanic activity that accompany great shallow-thrust earthquakes. The patterns have three parts: a precursory increase in volcanic activity, quiescence preceding the earthquake,

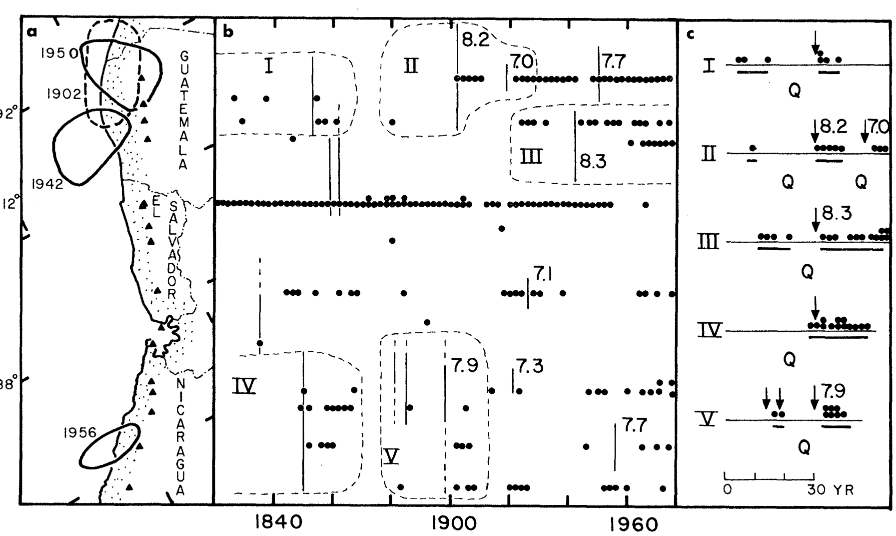

Fig. 1. (a) Map of Central American volcanoes active since 1820 (closed triangles) and rupture zones and times of some recent great earthquakes (areas encircled by solid and dashed lines). (b) Space-time plot of volcanic eruptions (closed circles) and great earthquakes (vertical lines, dashed where uncertain). The magnitudes of earthquakes are indicated if known. The vertical axis is the position along the arc projected from the adjacent map. Dashed lines enclose regions where volcanic activity and great earthquakes are associated. (c) Histograms of volcanic activity in particular rupture zones versus time. Each circle represents a volcano active at any time during a 2-year period. Arrows mark the times of great earthquakes; *Q*'s mark periods of low volcanic activity that precede great earthquakes. Horizontal bars mark periods of high volcanic activity that precede or follow periods of low volcanic activity.

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and an increase in volcanic activity near the time of the earthquake. The most characteristic part of these patterns is the period of quiescence (*Q*) or low volcanic activity that begins several years to a few decades before the great earthquake and continues until near the time of the earthquake. These periods of low volcanic activity have occurred in association with most large shallow earthquakes in these regions although there are exceptions such as the 1906 earthquake in central Chile (Fig. 2b) and the 1959 and 1971 earthquakes in Kamchatka (Fig. 3b).

Periods of increased volcanic activity flanking the quiescence are not always present, and the increase is sometimes slight. The periods of activity I interpret as increased or anomalously high are underlined in Figs. 1c, 2b, 3b, and 4b.

The first or precursory period of increased volcanic activity marks the start of anomalous volcanic behavior. Although there are few clear examples, the time interval between the beginning of this increased activity and the earthquake is generally less than 15 years for earthquakes with magnitudes less than 8 and more than 15 years for earthquakes of magnitude 8 or greater. These intervals are compatible with the relation between precursor time interval and magnitude derived by Scholz *et al.* (*8*) for several earthquake precursors.

The second period of increased volcanic activity begins near the time of the earthquake, either a few years before or after the earthquake. This last part of the pattern of volcanic activity related to great earthquakes is usually present but is highly variable. For example, in southernmost Chile periods of increased activity began a few years before the 1837 and 1960 earthquakes and lasted only a few years. In Central America, on the other hand, periods of increased activity have generally begun a few months or years after the earthquake and continued for a decade or more.

In the northern part of the Antilles arc (Fig. 4b) and in parts of Central America and Chile most historic volcanic eruptions have occurred in association with large earthquakes. Since the background level of volcanic activity is these areas is essentially complete quiescence, the quiescence between the precursory and subsequent periods of increased volcanic activity is not remarkable. In these areas of generally low volcanic activity the periods of increased volcanic activity are much more apparent.

The large-scale deformation of convergent plate margins before, during, and after great earthquakes seems capable of raising (precursory activity), lowering (quiescence), and raising again (activity near time of earthquake) the level of magma in active volcanoes. How this is accomplished is not clear. Deformation of the crust may affect shallow magma chambers and conduits. Magma may be generated near the part of the inclined seismic zone that lies directly beneath volcanoes (*9*). In many instances

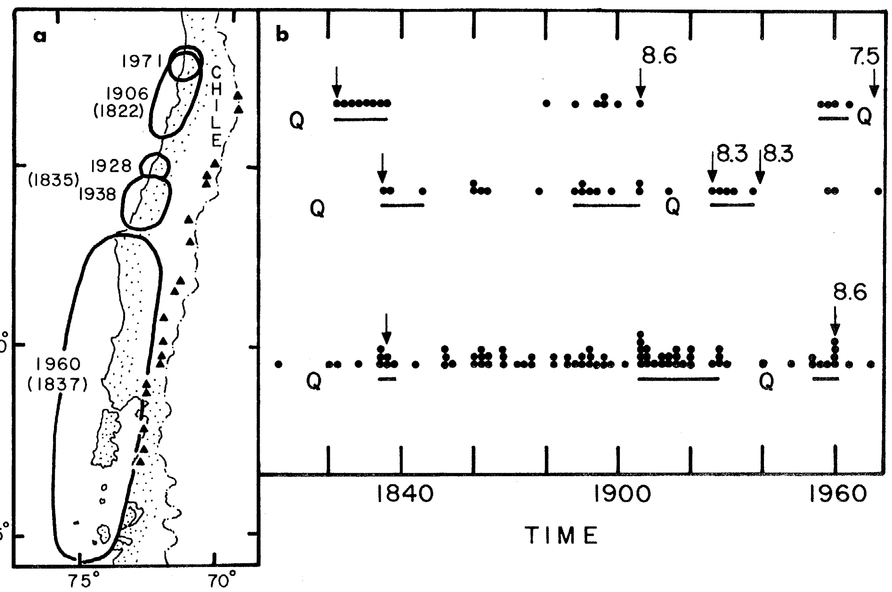

Fig. 2. (a) Map of active volcanoes and rupture zones of great earthquakes in southern Chile. Symbols are as in Fig. 1a. (b) Histograms of volcanic activity within the three main rupture zones versus time. Symbols are as in Fig. 1c. Class interval, 2 years.

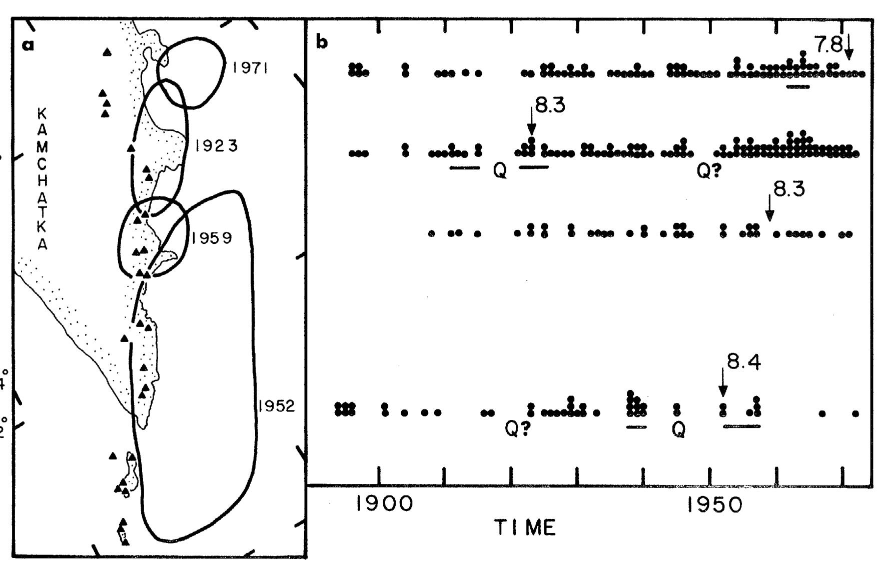

Fig. 3. (a) Map of active volcanoes and rupture zones of great earthquakes in Kamchatka. Symbols are as in Fig. 1a. (b) Histograms of volcanic activity within the four main rupture zones versus time. Symbols are as in Fig. 1c. Class interval, 1 year.

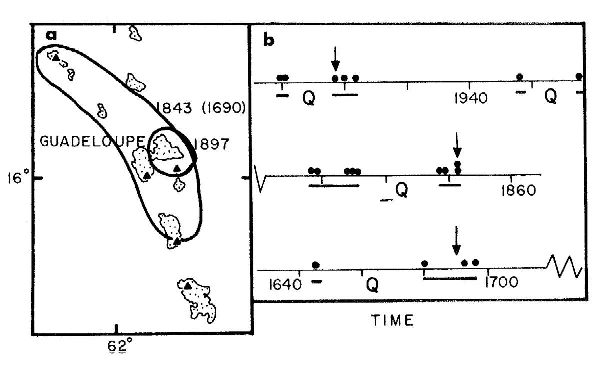

Fig. 4. (a) Map of active volcanoes and rupture zones of great earthquakes in the northern Antilles arc. Symbols are as in Fig. 1a. (b) Histogram of volcanic activity versus time within the rupture zone of the 1843 earthquake. Symbols are as in Fig. 1c. The zigzag in the time axis represents a hiatus (1720 through 1780) in seismic and volcanic activity. Class interval, 2 years.

the hypocenters of great shallow-thrust earthquakes are located near the deepest, most landward extent of their rupture zones (*2*). These hypocenters are only a few tens of kilometers from regions of possible magma generation. Therefore, deformation in the hypocentral region may affect the production or rise of magma from its source region. Dilatancy in the hypocentral region and diffusion of a vapor phase from the region of magma generation is a more speculative cause.

The concept of interrelated seismic and volcanic activity cannot yet be evaluated everywhere. A systematic examination of the occurrence parameters of great earthquakes is not yet available for many regions (Indonesia and most of the southwestern Pacific island arcs). In other regions volcano catalogs either do not exist (Aleutian arc) or do not extend back more than a few decades (most of the southwestern Pacific).

In many areas there is no clear association of volcanic and seismic activity. A few segments of convergent plate margins have neither large earthquakes nor active volcanoes (northern Peru–southern Ecuador, Tonga from 23°S to 28°S) (*10*). Many segments have active volcanoes but infrequent large earthquakes (northern Ryukyus, Izu-Bonin-Marianas, Indonesia from 106°E to 122°E) (*10*). Other segments have great earthquakes but little or no recent reported volcanic activity (Nankai Trough, Peru, Mexico, southern Kuriles, southern Ryukyus). Northern Honshu and Ecuador have both large earthquakes and active volcanoes but no obvious volcanic sequence related to great shallow earthquakes, perhaps because the rupture zones in these areas are a great distance from the volcanic chain.

Qualitative forecasts of varying levels of reliability can be made from the associations described here. It is fairly certain that in Central America volcanic activity near the rupture zones of future large shallow-thrust earthquakes will be unusually high for about a decade after the earthquakes. In the past the two largest eruptions in Central American history (Cosigüina in 1835 and Santa Maria in 1902) occurred within months after nearby great earthquakes.

The pattern of volcanic activity can suggest regions that might be preparing for a large shallow-thrust earthquake and therefore deserve careful study. Two such regions are suggested here. One is central and western El Salvador in Central America (Fig. 1), which is a prominent seismic gap (*7*). The volcanoes of this region have been dormant since 1955 with the exception of one small eruption in 1966. Before 1955 there was essentially continuous volcanic activity in this region. The other region deserving attention is the Guadeloupe arc of the northern Antilles (Fig. 4), where the current pattern of volcanic activity is very similar to the volcanic activity which preceded the large earthquake of 1897.

The crude method of evaluating volcanic activity used here probably masks some relations between volcanic and seismic activity. For example, it does not reveal the relation between earthquakes and volcanic activity in the Sagami Trough region of Japan which is made clear only by a detailed study of the eruption pattern of a particular volcano in that region (*5*). Such detailed studies of active volcanoes may have great value in the long-range forecasting of large shallow earthquakes.

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Catechol Estrogens: Presence in Brain and Endocrine Tissues

Abstract. *Catechol estrogens have been identified and measured in rat brain and various endocrine tissues with the use of a sensitive radioenzymatic assay. The specificity of this assay was confirmed by thin-layer chromatography and mass spectral analysis of the reaction products. The concentration of catechol estrogens in the hypothalamus and pituitary are at least ten times higher than reported previously for the parent estrogens. Catechol estrogens have potent endocrine effects and, because of their normal occurrence in the hypothalamic-pituitary axis, they may have an important role in neuroendocrine regulation.*

Although the catechol estrogens, including 2-hydroxyestradiol ($2OHE_2$) and 2-hydroxyestrone ($2OHE_1$), have been recognized as major urinary metabolic products of estrogen for over 20 years (*1*), their presence in tissues has never been established. The instability of catechol estrogens, as well as the relatively low concentrations of estrogens in tissues in general, has hampered previous attempts at identifying catechol estrogens in situ (*2*). Recent evidence indicates that catechol estrogens are not only metabolic end products, but possess potent biological and endocrine activities of their own (*3–6*). For this reason, we undertook a series of studies designed to identify catechol estrogens in tissues and to measure their concentrations in brain and other neuroendocrine organs.

Several years ago our laboratory described the formation of a stable radioactive *O*-methylated derivative of catechol estrogen following the incubation of estradiol with liver microsomes, reduced nicotinamide-adenine dinucleotide phosphate, catechol-*O*-methyltransferase (COMT; E.C. 2.1.1.6) of rat liver, and [^{14}C]methyl-*S*-adenosylmethionine (*7*). Since COMT specifically *O*-methylates dihydroxylated phenols, such as the catecholamines (*8*) and catechol estrogens (*9*), it seemed feasible to utilize this enzyme to form a stable methoxy derivative for the measurement of catechol estrogens in biological materials. By employing a radioactive methyl donor of high specific activity ([^{3}H]methyl-*S*-adenosylmethionine), a partially purified preparation of COMT, and selective solvent extraction with nonpolar solvents, an extremely sensitive (< 10 pg) assay for catechol estrogens was developed (*10*). We now report the presence of catechol estrogens in various brain and endocrine tissues of the rat; and in concentrations that exceed those of their parent estrogens.

Female Sprague-Dawley rats (180 to 200 g) were obtained from Zivic-Miller and housed with free access to food and