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MID-TERTIARY VOLCANO-TECTONIC DEVELOPMENT OF THE SOUTHWESTERN CORDILLERA OF NORTH AMERICA

Final Report

NASA/ASEE Summer Faculty Fellowship Program--1987

Johnson Space Center

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Date:	August 21, 1987
Contract Number:	NGT 44-001-800

Abstract

In the Southwestern Cordillera (SC) of North America, volcanic style changed from dominantly calcalkaline stratovolcanoes to caldera-related magmatism during the mid-Tertiary. The dominant tectonic process affecting the region during this time was convergence of the Farallon and North American Plates. The calderas are spatially overprinted on the earlier calcalkaline volcanics and, in some instances, there is a temporal overlap between the two contrasting styles of volcanism. The change in style of volcanism indicates a change in the operative stress regime: compressional for the earlier calcalkaline volcanism and tensional for development of the calderas.

The major volcanic centers in the region are the Sierra Madre Occidental (Mexico), Trans-Pecos Province (Texas), Mogollon-Datil field (New Mexico), San Juan Volcanic Field (Colorado) and the Marysvale Volcanic Field (Utah). We have compared the development of these centers to 1) evaluate the volcano-tectonic relationship of caldera development within and between centers and 2) determine the relationships between the earlier calcalkaline and later caldera-style volcanism.

The calderas exhibit three distinct stages of development that are closely associated with the East Pacific Rise/trench collision. Calderas formed prior to impact tended to be small both in number and size. The largest and most numerous calderas developed close to impact of the rise. After impact of the rise, an abrupt decrease in caldera development occurred. Variation in convergence rates between the Farallon and North American Plates significantly influenced the style of volcanism. Extremely rapid convergence rates (>15 cm/yr) resulted in compressive stress and formation of stratovolcanoes. At ~40 ma, convergence rates slowed, causing an increase in dip of the Benioff and establishment of an extensional regime. The spatial and temporal association of the calcalkaline and caldera-related volcanism argues for the SC representing a region of continued arc magmatism in which the style of volcanism varied in response to differences in regional stresses.

Introduction

During the mid-Tertiary, there was extensive caldera-related volcanism in the Southwestern Cordillera (SC) of North America. The primary caldera centers in this region are the Marysvale, San Juan, Mogollon-Datil, Trans-Pecos and Sierra Madre Occidental volcanic fields. In excess of 3 million cubic km of ignimbrites were erupted from these centers during the Oligocene-Early Miocene.

Although this region is the largest terrestrial caldera field known and has been intensively studied, there is no general agreement upon the tectonic environment of caldera formation. Some authors favor caldera development in a back-arc region [1,2] while others believe that the calderas formed in the area of the primary arc [3] or intra-arc [4]. We have examined the volcano-tectonic history of the various centers in the SC in order to 1) better understand the relationship between the calderas and subduction processes and 2) better delineate the tectonic setting of both the earlier calcalkaline and later caldera-related volcanism.

Regional Setting

The SC is defined here as the area from the Sierra Madre Occidental in western Mexico through and including the Marysvale Volcanic field of Utah (Fig. 1). The major centers in this region are the Sierra Madre Occidental (SMO), Trans-Pecos Province (TP), Mogollon-Datil (MD), San Juan Volcanic field (SJ) and Marysvale Volcanic field (MV). These centers were chosen as they 1) mark the eastern boundary of Tertiary-age magmatism in the SC, 2) have associated caldera development and 3) represent distinct geographical provinces, thus facilitating comparison of regional variations. Data used to characterize these fields was acquired from a number of sources [5-14] which greatly aided our regional synthesis. A comparison of pertinent features of each of the centers is given in table 1.

The SC of North America was volcanically active from approximately 80 ma to the present [15]. During this time however, volcanism changed from subduction-related to extensional (Basin and Range and Rio Grande Rift). The precise timing of this transition is uncertain, but inception of Basin and Range tectonism at 32 to 30 ma in the southern portion of this region [16-18] followed by a northward migration of extension related activity is generally agreed upon.

Volcanic activity can be separated into three main periods. Early magmatism in the region was primarily

Figure 1. Distribution of Caldera Fields in the Southwestern Cordillera

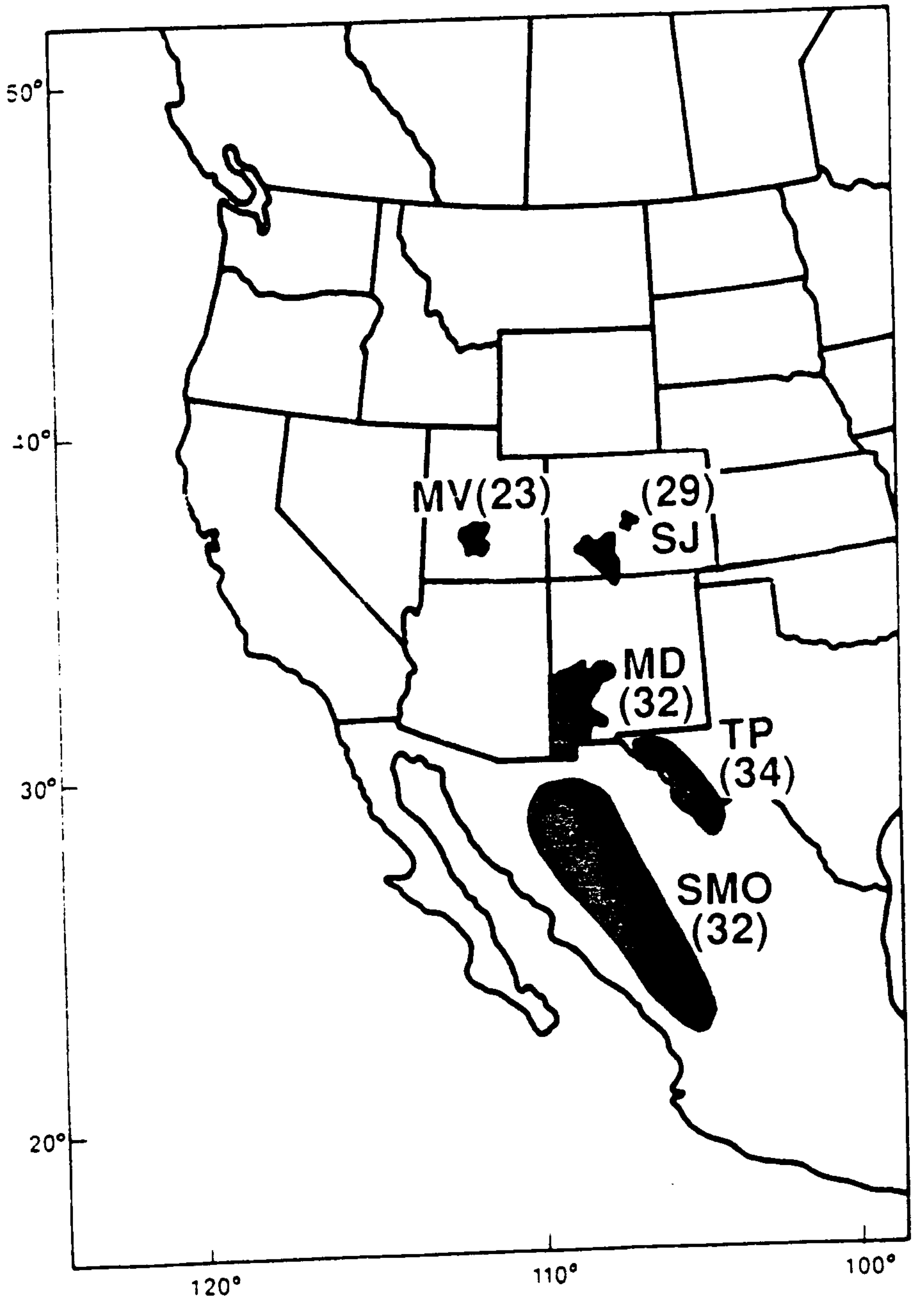


Table One. Comparison of Caldera Centers in the Southwestern Cordillera.

Center	Location	Age [1]	Caldera [2]	Batholith	Earlier Volcanism
Marysvale	Utah	23	6	Yes	Andesitic Stratovolcanoes
San Juan	Colorado	29	16	Yes	Andesitic Stratovolcanoes
Mogollon-Datil	New Mexico	32	28	Yes	Andesitic Stratovolcanoes
Trans-Pecos	Texas	34	12	No	Basaltic Flows
Sierra Madre Occidental	Mexico	32	12/300	Yes	Andesitic

[1] Average age of caldera field based on reported age dates.

[2] These numbers represent minimum values. More detailed mapping in each field may facilitate recognition of more caleras. For instance, in the Sierra Madre Occidental, 12 calderas have been located although in excess of 300 are thought to be present.

References: Swanson et al., 1978; Cameron et al., 1980; Elston, 1984; Henry and Price, 1984; Lipman, 1984; Steven et al., 1984; Swanson and McDowell, 1984; Varga and Smith, 1984.

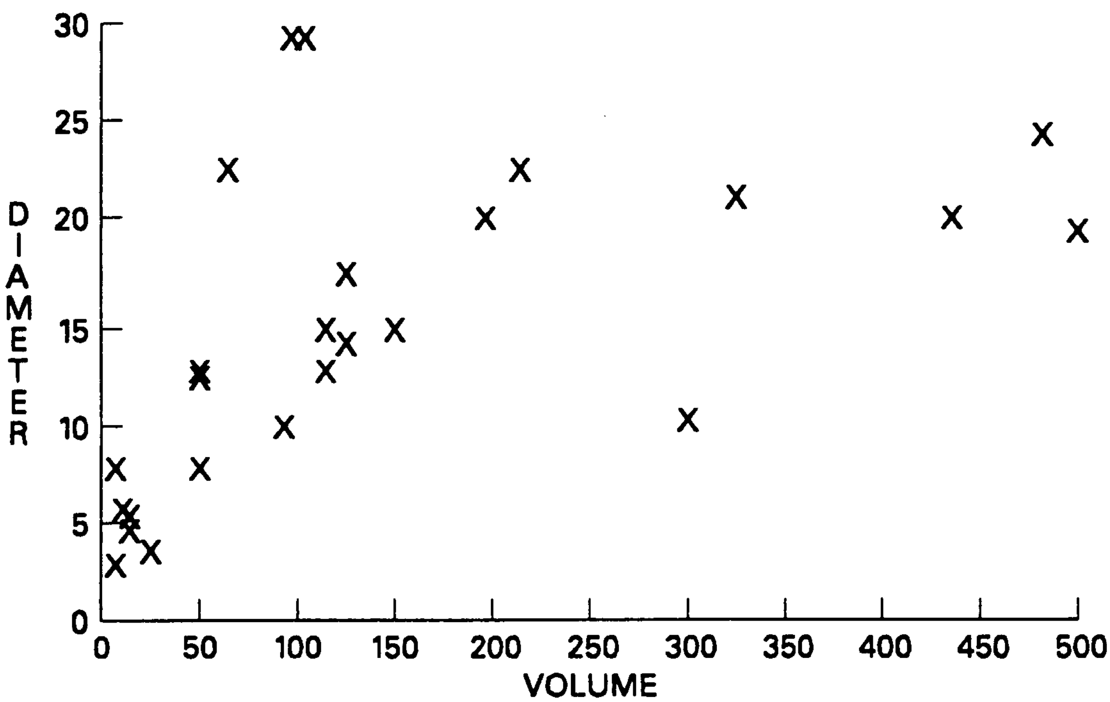
calcalkaline in composition, dominated by andesitic to dacitic stratovolcanoes, cones and domes. Widespread caldera development followed the main period of calcalkaline activity, although there was some overlap between the two phases of magmatism in some centers [1,12].

Ignimbrites erupted during this time varied compositionally from alkaline to calcalkaline in composition. The final period of volcanism is characterized as bimodal. Compositionally, basalts, basaltic andesites and high-silica rhyolites are the dominant eruptive products [e.g. 19]. The two initial stages of volcanism are believed to be related to subduction processes, while the later stage is related to extensional tectonics [4,20].

The caldera activity was transitional between the early arc volcanism and later extensional Basin and Range/Rio Grande Rift activity. Several individuals have noted that a "magmatic lull" existed between the stage of caldera development and extensional volcanism and that the calderas are cut by Basin and Range faulting [1,3]. Therefore, we regard the development of calderas in the SC as significant in the timing of transition of volcanic and tectonic activity in the region.

To better evaluate the volcano-tectonic development of the SC, we have taken a regional approach and gathered data from over 75 calderas in the major caldera centers. Data on caldera age, diameter, volume, distance from trench, latitude, longitude, previous volcanic activity and elemental and isotopic composition were compiled There is not a complete data set available for many of the calderas, which limits the degree of intra and intercenter comparisons. For a significant number or calderas, there is a lack of data regarding the volume of eruptive products. There are three main reasons for the paucity of data for this parameter. First, significant erosion has occurred since emplacement and volume calculations are minimum estimates. Secondly, in some areas, field mapping is not complete and the actual distribution of ignimbrite sheets is unknown. Finally, several calderas in the SMO have been identified exclusively through remote sensing techniques. As a result, we have volume data on less than half of the calderas in the SC centers. Volume, is an important parameter as the volume of erupted products approximates the size of the magma chamber beneath the caldera. For our data set, a positive correlation between diameter and volume for calderas up to 20 km in diameter exists (Fig. 2). For calderas above this size, small changes in caldera diameter can result in very large changes in erupted volume. The correlation between

Figure 2. Relationship between caldera volume and diameter.



diameter and volume is not unique to the calderas we evaluated as other workers have noted similar relationships [21,22]. To work with a complete data set, we will use diameter as an approximation of volume and consider those two parameters jointly in the remaining discussion.

Tectonic Setting

The primary tectonic control on volcanism in the SC between 80 and 30 ma was convergence between the Farallon and North American Plates [e.g. 23]. Convergence rates between these two plates are believed to have been quite rapid (>15 cm/yr) between 60 and 40 ma [24,25] which caused volcanism to migrate a significant distance landward as the Benioff dip shallowed [26]. At approximately 40 ma, subduction slowed to less than 10 cm/yr in response to the Farallon Plate being younger, hotter and therefore, more difficult to subduct. This resulted in a steepening of the Benioff. The decrease in convergence rate continued until the East Pacific Rise (EPR) intersected the trench causing a cessation of subduction along that portion of the continental margin. This places tight constraints on the timing of volcanism and the volcano-tectonic relationships. The majority of the primary arc volcanoes were emplaced during periods of rapid convergence, while the majority of the calderas developed after convergence rates had slowed. This suggests a very intimate relationship between development of caldera volcanism and convergence rates existed.

Discussion

At subduction zones, a continuum between compressional and extensional tectonics exists. A possible mechanism for creating the shift in stress regime is a decrease in orogenic stresses resulting from the slowing of convergence rates [27]. Initially fast rates of convergence and shallow dip angles favors establishment of volcanism landward. Once convergence slows and the dip angle increases, extensional stress regimes can be established. This would lead to crustal thinning on the continent. The process of subduction hinge migration outlined above is generally cited as an important mechanism for opening of the back-arc [e.g. 28] but is evidently applicable in the SC.

Crustal thinning in response to decreased convergence rates would enhance the emplacement of magma chambers at shallow depths. The development of extensional regimes allows more mantle magma access to the continental crust, promoting subcrustal heating of the lower crust which may lead to the development of initial abundant silicic volcanics [22]. Further, modeling of lithospheric magmatism by other authors support the mechanism of crustal thinning as important in the formation of caldera development [29].

If the relationship between crustal thinning and slowing of subduction is related to caldera formation, there should be a correlation between caldera age and development of extensional stress regimes. To evaluate this, we have defined a parameter termed here as normalized age, $(AGE)_n$. This parameter normalizes the age of a given caldera to the timing of the EPR/trench collision. An age of 30 ma was chosen for the collision based on models of plate reconstructions [20,23]. The age of 30 ma is not precise as intersection of the EPR varied both temporally and spatially, but is a reasonable approximation for the majority of the SC, considering processes at the trench will not be felt instantaneously on the continent. Values of $(AGE)_n$ >1 indicate a caldera formed prior to intersection of the EPR, while values <1 indicate caldera formation postdates the collision. When $(AGE)_n$ is plotted against caldera diameter for calderas in the SC, three consistent stages of caldera development are observed (Fig. 3). The earliest calderas (stage 1) formed in the SC tend to have small diameters (<15 km). Caldera diameters reach their greatest size (>25 km) during stage 2 when $(AGE)_n$ is 1.1 to 0.9. Stage 2 also correlates with the most intense period of caldera development/volcanism. Caldera development decreased abruptly during stage 3. The relationships outlined above are not an artifact of scatter from plotting several different centers as the trends are characteristic of individual centers as well (Fig. 4 a,b).

We believe that the data support the model outlined previously and illustrated in figure 5. Stage 0 reflects rapid convergence rates and compressional tectonics, represented by the formation of dominantly calcalkaline stratovolcanoes and cones. As subduction slowed (stage 1) a relaxation of compressive stresses at the trench caused development of neutral to mildly extensional stresses inland. Under these conditions, small magma chambers were emplaced at shallow levels in the crust, hence small calderas were developed. Stage 2 represents the continual slowing of subduction until impact of the EPR at the trench. This would correlate with further development of extensional regimes (increased crustal thinning) and the shallow emplacement of larger magma chambers, perhaps of

Figure 3. Covariation of (AGE)n and diameter for all calderas in the SC caldera centers.

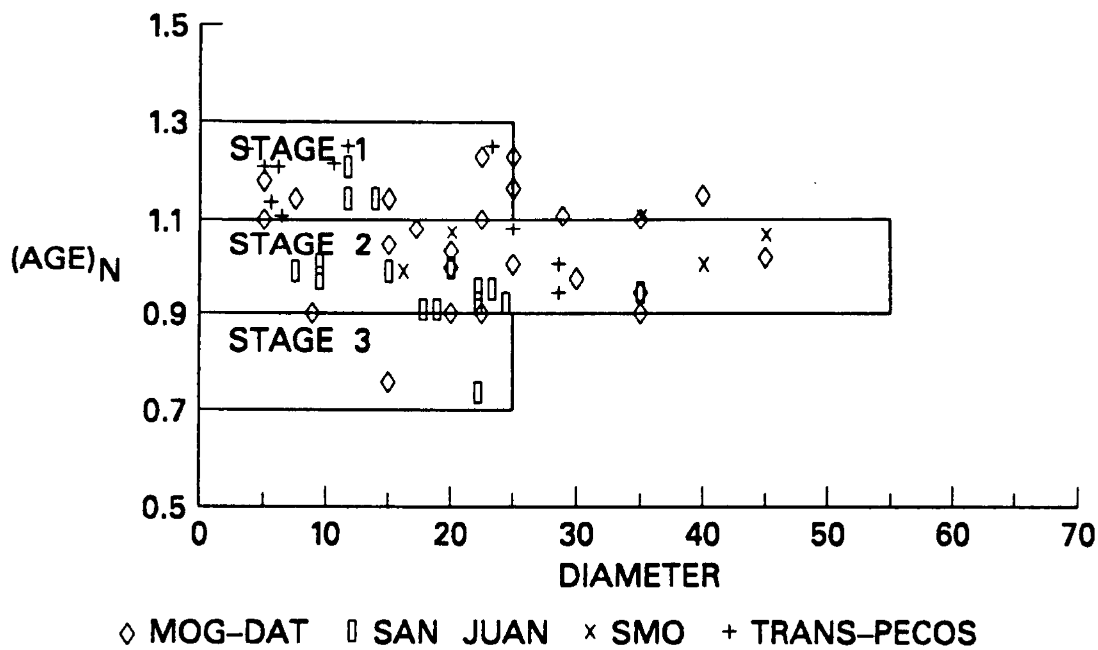


Figure 4. (AGE)n vs. diameter for a) the San Juan Calderas and b) the Mogollon-Datil calderas.

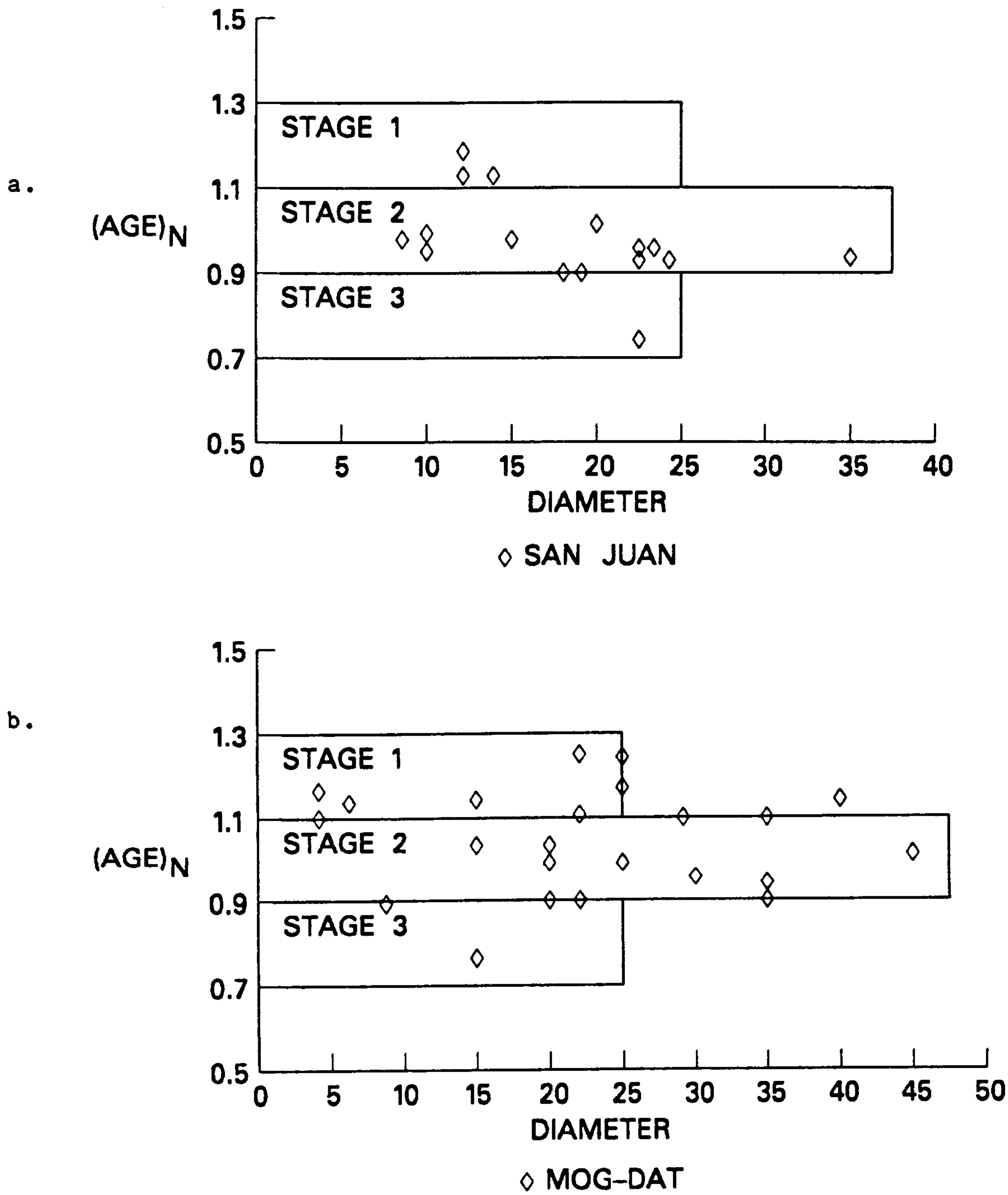
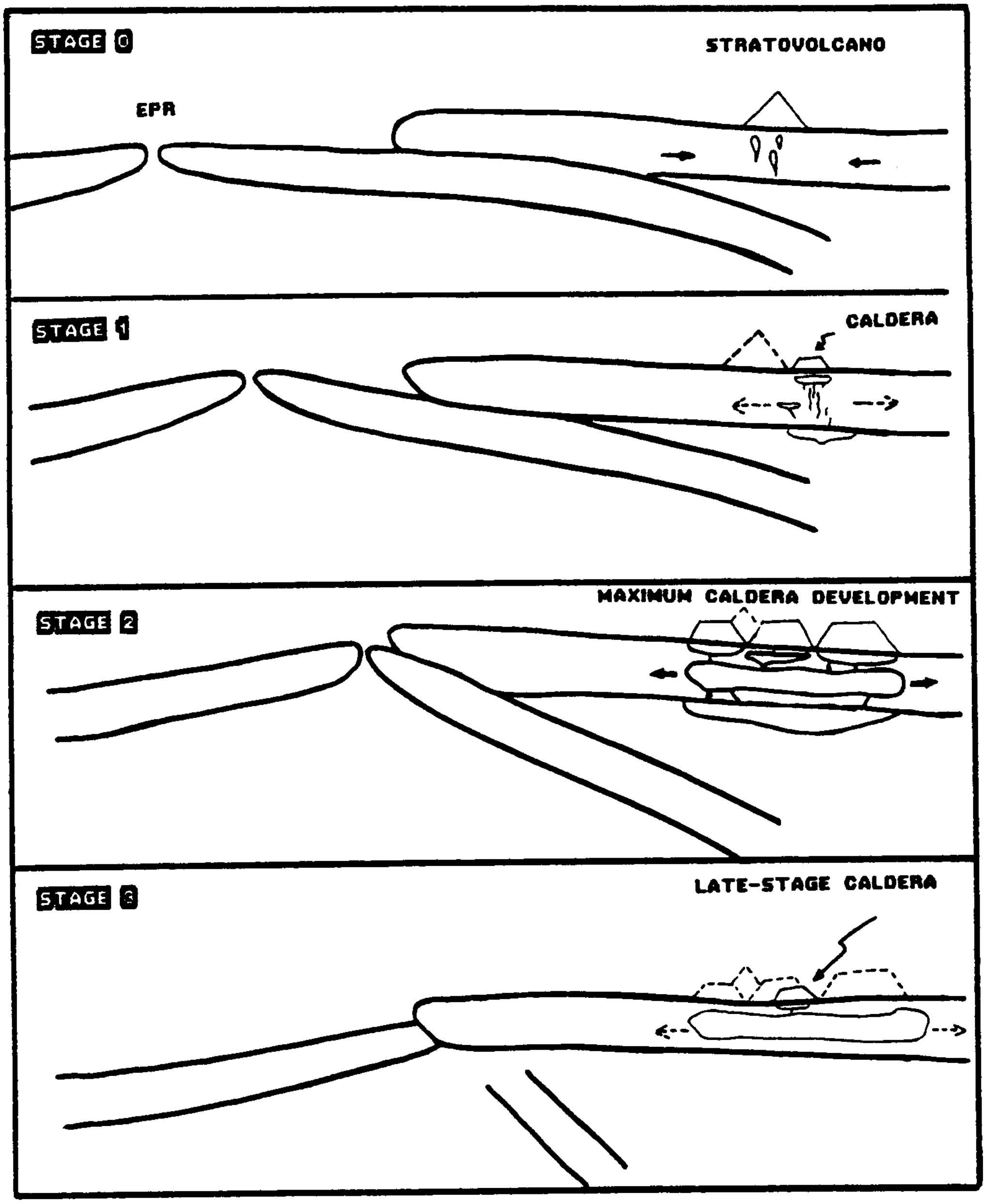


Figure 5. Variations in volcanic development in response to variable stress regimes in the primary arc. Explanation in text.



batholithic proportions. After impact of the EPR at the trench, subduction along that portion of the continental margin ceased (stage 3). One might expect that the transition from late stage 2 to stage 3 would be marked by development of smaller calderas. There are very few data points falling on or below the boundary between of stage 2 and 3. Those that do fall in this range are, for the most part, less than 25 km in diameter. Some of these stage 3 calderas may be young enough to be related to later extensional tectonics (e.g. Lake City Caldera, Ref. 10). However, others falling in this group are cut by later faults, indicating they developed prior to Basin and Range or Rio Grande Rift processes.

Two mechanisms, possibly interrelated, may be responsible for the decrease in late-stage caldera development. First, as subduction initially slowed, then ceased, the role of the subducted slab in the generation of magma would have been significantly reduced (refer to Fig. 5). A decrease in magma generation could account for the presence of smaller magma chambers and a lessening of volcanic activity. Alternatively, the extensional stress associated with the slowing of subduction would not be maintained once subduction had stopped. In this scenario, even if large magma bodies were present at depth, they would not have been able to easily ascend if extensional stresses were not great.

Several authors have noted that there is a relationship between the calderas and shallowly emplaced batholiths in the SC [e.g. 8,10]. These batholiths are believed to represent large-scale chambers which supplied magma to the calderas. Importantly, late-stage calderas are dominantly found within clusters of older calderas, indicating that the younger calderas are also related to the batholiths and may have exploited previously established magmatic conduits. The abrupt cessation of volcanism and the relationships between batholiths and calderas argue for the stress regime exerting the major control on caldera development. The presence of the batholiths indicates magmas must have been present throughout the history of the caldera field, but were most successfully tapped during stages of extensional stress.

As a final point, the presence of both compressional and extensional tectonics and magmatism in the SC has been a point of controversy for some time. It has been argued that the SC represents either a primary arc [e.g. 3], back arc [e.g. 1] or intra-arc extension [e.g. 4]. We believe that the distinction is basically one of semantics.

As distance from the trench remained constant, it is to consider an area initially an arc and then a back arc based solely on the change in volcanic style resulting from differences in stress regime. Further, if the calderas represent a back-arc assemblage, there is no complimentary "primary arc" positioned trenchward. One problem in accepting the SC volcanic centers as primary arc components has been the great distance (up to 1000 km) that both the calcalkaline volcanoes and calderas are found from the trench. However, much of this distance may have been acquired during or post emplacement of the SC volcanics through processes of accreted terranes and pre- and post-Basin and Range extension [2,4,30,31]. If the combined effect of these processes are accounted for, the position of the SC would be much closer to the trench. The temporal and spatial association of calcalkaline volcanism to the calderas is more consistent with the entire volcanic suite representing the primary arc. The term intra-arc spreading seems most appropriate as it implies that the primary site of arc volcanism remained fixed while the change in volcanic style resulted primarily from a change in tectonic stresses (compressional to extensional).

The only center that does not fit the general scheme outlined above is the TP province. It is anomalous in that it lacks a well defined calcalkaline assemblage and has no associated batholith [8]. Also, the average age of the TP calderas is older than any of the other centers. Based on both chemical and geographical trends, it has been suggested that the TP is closely associated with the SMO field [e.g. 32-34] and may represent a back arc assemblage. As stress orientations indicate that the bulk of the TP calderas were emplaced under compressive stresses and it also has been suggested that the TP are part of the primary continental arc [3]. Under conditions of large convergence rates and a low Benioff dip angle, compression will occur in the back-arc [35]. Since the SMO are trenchward from the TP and chemical gradations between the two provinces exist, we believe that the TP calderas were formed in the back-arc environment and that the SMO-TP represent one large volcanic province.

Conclusions

The volcano-tectonic development of the SC reflects the change in convergence rates between the Farallon and North American Plates. Rapid convergence rates and compressional stresses favored development of a calcalkaline magmatic arc. As subduction slowed in response to subduction of progressively hotter and younger portions of the Farallon Plate, an extensional stress regime was established in the arc area and caldera development was initiated.

The variation in caldera size and activity is related to the amount of extension that was experienced in the arc. The timing of the EPR/trench collision apparently marked the maximum convergence-related extension felt on the continent and is associated with the most numerous and voluminous period of caldera development.

The temporal and spatial relationships between the calcalkaline volcanoes and calderas indicates that the site of magmatism remained fixed. Therefore, the changing volcanic styles do not represent arc vs. back-arc assemblages. Rather, they reflect volcanic development in an arc environment that varied in response to changes in regional stresses.

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