TECTONIC CONTROLS ON MESOZOIC ARC MAGMATISM IN NORTH CHILE

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RESUMEN: Complejos plutonicos Jurasicos (*c.* 190 Ma and *c.* 153-138 Ma) se ubican escencialmente al oeste del Sistema de Falla Atacama (SFA), emplazados en el basamento metasedimentario y los complejos plutonicos anteriores. El SFA corresponde a una zona de fractura a escala cortical con una larga y compleja historia de desplazamientos desde el Jurasico-Cretacico (*c.* 158 Ma, *c.* 132-126 Ma) al Reciente. Complejos plutonicos Cretacicos se urbican a lo largo (*c.* 127 Ma) y al este (*c.* 106 Ma) del SFA emplazados en volcanitas andesiticas Cretacicas, ya que durante el Cretacico, el foco de la actividad magmatica migro hacia el este.

KEY WORDS: Ar ages; dip-slip faulting; Mesozoic arc magmatism; strike-slip faulting; syn-kinematic plutonism; transtension.

INTRODUCTION

One perplexing feature of arc systems relates to the relationship between the apparently continuous nature of subduction processes and the episodicity of regional magmatic events. Such episodicity suggests that the rates of tectonic processes must be relatively rapid. Also, the relationship between arc-related strike-slip faults and magmatism is uncertain. Arc-parallel trench-linked strike-slip faulting is common along convergent margins and is particularly important in continental arc systems. As a result, fore-arc slivers typically are stranded between strike-slip faults and trenches. Trench-linked strike-slip faults, in addition to accommodating the horizontal component of oblique subduction, cut and may localize arc intrusions and volcanic rocks. One major question is whether relative thermal 'softening' within an evolving magmatic arc is required for development of strike-slip fault systems or whether development of strike-slip fault systems facilitates the ascent and emplacement of arc-related magma? One aim of our ongoing research in North Chile is to understand better the spatial and temporal development of plutonic complexes and associated tectonic structures within an eroded continental arc system to provide data to evaluate more fully these issues.

GEOLOGICAL SETTING

The major geological features of the western South American continental margin are a manifestation of the longevity of subduction along this regional plate boundary. Evolutionary stages have been influenced by the direction and magnitude of plate convergence vectors. In North Chile, upper Paleozoic back-arc basin and fore-arc sedimentary sequences (including an extensive accretionary prism) formed during rollback of subducting oceanic lithosphere. These successions host a broad Permian-Triassic magmatic arc. The metasedimentary basement/arc complex comprised a country rock terrane for subsequent Lower Jurassic, Upper Jurassic and Lower Cretaceous magmatic arcs which presently are exposed in the Coastal Range. Mesozoic arc complexes are transected by a trench-linked strike-slip fault system: the Atacama Fault System (AFS). The AFS extends for at least 1000 km between La Serena and Iquique within the Coastal Range of North Chile. It has been active from at least the Upper Jurassic, with displacement continuing intermittently into the Upper Miocene. The trend of the system is sub-parallel to the continental margin, but the major faults within it change orientation systematically to define three arcuate segments. We are concerned with the relationship between magma emplacement and fault displacement in the southern part of the AFS between Taltal and Copiapo, which has been referred to as the El Salado segment. Between 25°00'S and 27°30'S, in the El Salado segment of the AFS, steep foliations in ductile simple shear belts have been reworked by brittle fault zones. To the east, inboard of the arc rocks, sedimentary and volcanic rocks of a Mesozoic back-arc basin are exposed. This Mesozoic back-arc basin formed part of a system extending throughout Chile. The major contractional event east of the AFS in North Chile occurred in the late Oligocene - early Miocene when Paleocene and older rocks of the Mesozoic back-arc basin were thrust to the east.

During the Jurassic and early Lower Cretaceous South America appears to have been essentially static, which likely allowed development of the behind-arc basins as a consequence of subduction zone rollback and syn-subduction extension. Plate reconstructions for the Lower Cretaceous suggest that the Aluk plate subducted southeastward at an oblique angle relative to the South American continental margin. This kinematic setting appears to have been maintained until the late Upper Cretaceous, when the Farallon plate was tectonically juxtaposed along the plate boundary of North Chile.

THE CHANARAL REGION (25°00'-27°30'S)

In the Chanaral Region, Upper Paleozoic sedimentary sequences and granites of a broad Permian-Triassic magmatic arc formed the crust into which Lower Jurassic (LJ), Upper Jurassic (UJ) and Lower Cretaceous (LC) magmatic arc rocks were emplaced. Each of these arcs is composed of an expanded range of compositions from gabbro-diorite through tonalite to granodiorite (Brown, 1991). LJ plutonic complexes have equant outcrop patterns and are located west of the AFS, whereas the UJ and LC plutonic complexes are elongate north-south and their emplacement clearly was controlled by the geometry of the Atacama Fault System. Plutonic complexes younger than *c.* 100 Ma are emplaced into the marginal basin behind the arc during structural inversion of the basin and here again plutonic complexes have equant outcrop shapes. Individual plutons within these Mesozoic complexes display field, textural and petrological characteristics which reflect upper crustal levels of magma emplacement and associated rapid post-magmatic cooling. Al-in-hornblende barometry across the UJ and LC arcs on rocks with the appropriate full phase assemblage suggests *c.* 2 kbar load pressure during emplacement of plutonic complexes along the AFS. Several dike swarms were emplaced during the development of the Mesozoic arcs and account for east-west dilation of up to 15%. They show that the arc was extending during emplacement of arc magmas.

Magmatism appears to have been episodic as revealed by peaks in a histogram of number of ages (published, various sources, all methods) *v.* geologic series (*c.* 30 Ma interval), by published U-Pb zircon data, which reflect crystallization ages, and by new $^{40}Ar/^{39}Ar$ hornblende plateau and isotope correlation ages. The rapid cooling implied by a shallow crustal level results in intracrystalline mineral argon systems recording isotopic ages very similar to the time of initial magma emplacement. Thus our precise $^{40}Ar/^{39}Ar$ dates also reflect crystallization ages. Peaks of activity occurred in the Lower Permian (LP), the Triassic (T), the LJ, the UJ and the LC. Using the $^{40}Ar/^{39}Ar$ method, we have determined precise emplacement ages of individual plutonic complexes both along strike and across strike within each of the Mesozoic arcs. On the west side of the Coastal Range, $^{40}Ar/^{39}Ar$ hornblende isotope correlation ages of *c.* 190 Ma characterize the LJ arc suite along more than 1° of latitude. Ages of 153, 139 and 138 Ma have been determined on hornblende from samples W to E across the UJ arc suite, and ages of *c.* 127 and 106 Ma have been determined on hornblende from localities across the LC suite. These ages indicate that as the locus of magmatic activity stepped successively E, each previous arc cooled. Furthermore, whole rock $^{40}Ar/^{39}Ar$ ages of 156 and 154 Ma from calc-alkaline basaltic andesite dikes indicate emplacement of the earliest magmas of the UJ suite in an extensional environment.

The geochemical features of granitoid (> 63% SiO_2) samples from the LJ, UJ and LC plutonic complexes from the Coastal Range include enrichment in Rb, Th, U and K and depletion in Ba, Ta, Nb, Sr, P and Ti, characteristic features of continental margin granitoids, and relative enrichment in the LREE relative to the HREE. Normalized values for Y of *c.* 5 suggest shallow magma sources. For the expanded range of compositions, K/Rb and Rb/Sr do not change dramatically with increasing SiO_2 until very high SiO_2 contents, features that are consistent with fractional crystallization as the dominant control of the chemical variation. The low on average Ba/La ratios exhibited by the rocks suggest low alkali earths in the source region and argue for limited subduction zone enrichment within the mantle wedge. This is confirmed by low Ba/Nb ratios at low SiO_2 contents.

THE ATACAMA FAULT SYSTEM

In the El Salado segment, the AFS transects intrusive and volcanic rocks of the Upper Jurassic and Lower Cretaceous magmatic arcs. At El Salado, and for 20 km to the S, the AFS contains three principal fault zones where distinct brittle faults have reworked rocks that display an earlier record of penetrative ductile strain. For much of its length, the western fault zone juxtaposes Jurassic diorite/tonalite to the W with Cretaceous tonalite/granodiorite to the E. This brittle fault contact is located within a *c.* 800 m wide ductile shear zone which appears to have initiated during upper amphibolite facies conditions. A variety of kinematic indicators all indicate east-side-down displacement (Brown *et al.*, 1993). Because field relations constrain at least an early Lower Cretaceous age for ductile displacement, the AFS could have initiated within a fault system responsible for Jurassic - Lower Cretaceous subsidence in the Mesozoic marginal basin to the E. Jurassic plutonic rocks exposed west of the main shear zone are cut by small-scale shear zones which again display amphibolite facies mineral assemblages, and which may have formed during the early stages of development of the AFS. The eastern fault zone of the AFS marks a boundary between Cretaceous volcanic rocks and Cretaceous tonalite/granodiorite to the E. Cretaceous plutonic rocks adjacent to the boundary are penetratively ductilely deformed in a 700-1400m wide belt of steep east-dipping mylonites. Kinematic indicators indicate sinistral displacement across the high ductile strain zone (Brown *et al.*, 1993). Field relations suggest Lower Cretaceous movement, and intrusive rocks of the UJ and LC magmatic arcs are elongate parallel to the AFS.

Further W than the main AFS, ductilely-deformed metasedimentary rocks and leucogranites occur at the west margin of the Upper Jurassic plutonic complexes, east of Flamenco. Poorly defined kinematic indicators are consistent with vertical displacement. $^{40}Ar/^{39}Ar$ plateau ages on muscovite of *c.* 159 and 156 Ma suggest that the earliest ductile displacement recorded within the Mesozoic plutonic complexes is of Upper Jurassic age.

Hornblende from two samples of mylonitic diorite from within the western fault of the AFS both display well-defined $^{40}Ar/^{39}Ar$ plateaus and yield isotope correlation ages of *c.* 132-130 Ma, interpreted to date cooling through the appropriate argon closure temperature following deformation under amphibolite facies conditions within the AFS. This provides a minimum age for the down dip component of ductile displacement on the AFS. Hornblende from a foliated mylonitic diorite from within the east fault of the AFS displays a well-defined $^{40}Ar/^{39}Ar$ plateau and yields an isotope correlation age of *c.* 126 Ma, interpreted to date greenschist facies ductile deformation during strike-slip displacement on the AFS.

The upper amphibolite facies, east-side-down shear zones along the west fault of the AFS are interpreted to have formed in the wall-rocks of Lower Cretaceous intrusions during emplacement. The shear zones dip steeply at the surface but may become low-angle at depth. Ductile deformation was promoted by heat supplied from the arc plutons which were emplaced at dilational jogs in this extensional shear zone system. The east fault of the AFS represents a boundary to the extensional domain. The mylonites were reworked by successively lower temperature, sinistral strike-slip ductile-to-brittle faults.

CONCLUSIONS

Our preliminary $^{40}Ar/^{39}Ar$ data on plutonic complexes suggest that arc magmatism is partly episodic. A significant time gap exists between the Lower Jurassic plutonic complexes and Upper Jurassic plutonic complexes. Smaller, possibly significant time gaps occur within the Upper Jurassic and Lower Cretaceous plutonic complexes.

The Atacama Fault System likely was initiated *c.* 160 m.y. ago and was characterized by extension until *c.* 130 Ma. Since plate kinematic reconstructions suggest south-east directed subduction during this interval, due to the expansion of the Pacific Ocean Basin while South America remained essentially static in a mantle reference frame, it is likely that the AFS represents a transtensional fault during the Upper Jurassic. The outcrop shape of plutonic complexes, spacing of emplacement at *c.* 30 m.y. interval and the plate kinematic framework all indicate that in the interval 190 Ma to 160 Ma subduction zone rollback initiated a transtensional regime which at 160 Ma controlled pluton emplacement. In addressing the question of whether relative thermal 'softening' of an evolving magmatic arc is required for development of a strike-slip fault system or whether the development of a strike-slip fault system facilitates the magmatism associated with the arc, our data suggest that thermal weakening during pluton emplacement at 190 Ma and extensional stresses generated by subduction zone rollback allowed initiation of the AFS at *c.* 160 Ma and subsequent growth of the AFS during the next 30-m.y. period to *c.* 130 Ma. Magmatism and thermal weakening likely precede initiation of arc-parallel fault systems at active continental margins, although in detail each intrusion likely was associated with weakening of the arc that allowed ductile deformation followed by a ductile-brittle transition during cooling. Once established, arc-parallel fault systems at active continental margins may control ascent and emplacement of magma, as evidenced by the UJ and LC plutons.

The $^{40}Ar/^{39}Ar$ results from the Atacama Fault System suggest a polyphase history of ductile displacement. The data suggest a change from down-dip ductile displacement under amphibolite facies conditions to strike-slip ductile displacement under greenschist facies conditions during the interval 130-126 Ma. The transition from down-dip to strike-slip may correspond to a decrease in depth and may reflect exhumation on the evolving fault system. These data permit two interpretations of arc tectonics. Either extension and magma emplacement occured together with sinistral strike-slip on the AFS but partitioned from it in a transtensional regime, or extension associated with emplacement of arc magmas preceded strike-slip displacements on the AFS during the waning stages of arc magmatism. In the second interpretation, cooling due to arc abandonment, rather than exhumation, may have contributed to the ductile-brittle transition.

REFERENCES

BROWN, M., 1991. Relationship between magmatism and tectonics in northern Chile. Geochemical evidence from 25°30'-27°00'S. *6 Congreso Geologico Chileno,* Actas, **1**, 631-634.

BROWN, M., DIAZ, F., and GROCOTT, J., 1993. Displacement history of the Atacama Fault System 25°00'S-27°00'S, northern Chile. *Geological Society of America, Bulletin,* **105**, in press.