Carboniferous tholeiitic dikes in the Salada unit, Acatlán Complex, southern Mexico: a record of extension on the western margin of Pangea

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ABSTRACT

A suite of mafic dikes intrudes polydeformed, greenschist facies, metapsammites and metapelites of the Salada unit in the eastern part of the Acatlán Complex, southern Mexico. The age of the dikes is constrained by the youngest detrital zircon in the Salada host rocks (352±3 Ma) and the Early Permian age of the overlying Tecomate formation, which is devoid of such dikes. The mafic rocks are generally composed of amphibole, chlorite, feldspar, epidote and accessory opaque minerals. Their chemistry resembles rift-related tholeiites with ~50 wt.% SiO₂ and Mg# ~0.40–0.60. Their chondrite-normalized REE patterns resemble N-type MORB with (La/Sm)n mostly ~0.5–0.6, and their mantle-normalized patterns are relatively flat with no negative Nb anomaly and a low Th/La ratio indicating the absence of both subduction-related fluids and crustal contamination. Their chemistry resembles N-type MORB. Their intrusive relationships with the continentally-derived clastic rocks suggests that they were emplaced in thin continental crust. Shallow-water, Mississippian fauna in the adjacent Oaxaquia terrane, with Mid-Continent (USA) affinities, indicate that Pangea had already amalgamated by this time. In this context, the tholeiitic dikes are inferred to have formed during extension on the western margin of Pangea that was synchronous with extrusion of high-pressure rocks above an active subduction zone.

Key words: Acatlán Complex, geochemistry, Pangea, Carboniferous, Mexico.

RESUMEN

Se estudia una serie de diques mágicos que intruyen metapelitas y metapsamitas polideformadas de la unidad Salada y que se hallan en condiciones metamórficas de esquistos verdes. Esta unidad aflora en el sector oriental del complejo Acatlán, en el sur de México. La edad de los diques está limitada por los circones detríticos más jóvenes de las rocas de caja de la unidad Salada (352±3 Ma) y por la edad del Pérmo Temprano de la formación Tecomate sobreyacente, en la cual no se ha hallado ese tipo de diques. Los diques mágicos están compuestos generalmente por anfibol, clorita, feldespato, epidota y minerales opacos. Su composición geoquímica los clasifica como rocas toleíticas originadas por extensión (rift) con contenidos de sílice en torno al 50% en peso y Mg# entre 40 y 60. Los espectros de tierras...
INTRODUCTION

The mafic dikes that form the topic of this paper occur in the Xayacatlán area within the eastern part of the Acatlán Complex, Mixteca terrane (Figure 1). They intrude metapsammites and metapelites that were polydeformed under greenschist facies conditions. They were previously assigned to the Cosoltepec Formation, which was interpreted as a Cambro-Ordovician accretionary prism by Ortega-Gutiérrez et al. (1999, and references therein). However, the presence of Devonian detrital zircons (youngest detrital zircon age of ~376 Ma or ~410 Ma youngest population) in the type Cosoltepec Formation led Talavera-Mendoza et al. (2005) and Vega-Granillo et al. (2007) to suggest that the Cosoltepec Formation was deposited as a Devonian-Carboniferous passive margin bordering Gondwana and that it was subsequently caught in the collision zone between Gondwana and Laurentia during the amalgamation of Pangea. On the other hand, Keppie et al. (2008a, and references therein) have proposed that the Mixteca terrane lay on the active western margin of Gondwana during the Carboniferous. In an attempt to shed light on the Late Paleozoic tectonic setting of the Mixteca terrane, we present geochemical data for some Carboniferous mafic dikes in the eastern part of the Acatlán Complex.

GEOLOGICAL SETTING

The Acatlán Complex (Mixteca terrane) is bounded on three sides by faults and shear zones (Figure 1a): 1) along its eastern side the north-trending, Permian, dextral Caltepec fault zone separates it from the ~1 Ga Oaxacan Complex (Elias-Herrera and Ortega-Gutiérrez, 2002), which forms the basement of the Oaxacan (Oaxaquia) terrane (Keppe, 2004); 2) to the south, the east-west, Cenozoic, dextral La Venta-Chacalapa Fault (Tolson, 2007; Solari et al., 2007) juxtaposes it against the Xolapa terrane; and 3) to the west, the NNE-trending, late Mesozoic-early Cenozoic, westerly-vergent Papalutla thrust places the Acatlán Complex on top of the Cretaceous Morelos platform (Cerca et al., 2007). The northern boundary of the Mixteca terrane is obscured by over lain Mesozoic-Cenozoic rocks of the Mixteca terrane cover and the Trans-Mexican Volcanic Belt (Gómez-Tuena et al., 2007) (Figure 1a). The geological history of the eastern Acatlán Complex has recently been summarized by Keppie et al. (2008a) as follows (Figure 2):

1) Ordovician deposition of rift-passive margin clastic rocks and intrusion of a rift-related, bimodal suite of igneous rocks;

2) latest Devonian-Carboniferous, polyphase deformation attributed to rapid exhumation of the high pressure (HP) rocks that was synchronous with deposition of sedimentary rocks, including the Salada unit; Mississippian eclogite facies (HP) metamorphism and polyphase deformation;

3) Early Permian intrusion of arc-related plutons into periarc sedimentary rocks (including the Tecomate formation) synchronous with low grade polyphase deformation; and

4) Late Permian-Triassic deposition of the siliciclastic rocks (Chazumba and Magdalena units) in a foredeep in front of S-vergent thrusts; and

5) Jurassic migmatization associated with polyphase deformation of the Chazumba and Magdalena units.

Remapping of the Xayacatlán area has distinguished three greenschist facies, clastic units (Figure 3), from west to east (Morales-Gámez et al., 2008): 1) the Ordovician Huerta unit composed of polydeformed metapsammites and metapelites; 2) the pre-450 Ma Amate unit consisting of polydeformed meta-arkoses and metapelites; and 3) the Carboniferous Salada unit made up of metapsammites and metapelites cut by mafic dikes. An older limit for the age of the mafic dikes that intrude the Salada unit is provided by the 352±3 Ma age of the youngest detrital zircon (Morales-Gámez et al., 2008). These dikes do not occur in the overly ing, Lower Permian Tecombe formation. A reconnaissance of the geochemical characteristics of mafic rocks associated with the greenschist facies clastic rocks revealed that they are predominantly tholeiitic MORB-type rocks associated with minor alkaline varieties of uncertain age (Keppie et al.)
Figure 1. Location of the Xayacatlán map shown on (a) terrane map of Middle America (modified after Keppie, 2004), and (b) geological map of the Acatlán Complex (modified after Keppie et al., 2008a).
Further research has indicated that the clastic rocks can be assigned to, at least, two different ages: Ordovician (Huerta and Amate units and correlatives) and Carboniferous (Salada unit and correlatives) (Keppie et al., 2008a; Ramos-Arias et al., 2008; Morales-Gámez et al., 2008; Grodzicki et al., 2008; Hinojosa-Prieto et al., 2008). Mafic dikes and flows associated with the Ordovician clastic rocks appear to be continental rift tholeiites formed in a rift-passive margin environment (Keppie et al., 2008b). The Carboniferous mafic pillow lavas in the western Acatlán Complex also have within-plate tholeiitic affinities (Grodzicki et al., 2008).

In order to determine the tectonic environment during the Carboniferous (passive or active margin), the geochemistry of mafic dikes that intrude the Salada unit was undertaken and is presented in this paper.

PETROGRAPHY

Nine geochemical samples of the Salada Unit were collected in the northern part of the area, and one sample from the south (Figure 3). All the samples are from different NNE-trending mafic dikes and display the same structural history as the host rocks. In places, the dikes cut the bedding in the host rocks. In thin section the mafic rocks are composed of amphibole, chlorite, feldspar, epidote and accessory opaque minerals. The metasedimentary rocks are made up of quartz, muscovite, chlorite and accessory opaque minerals. These mineral associations indicate metamorphism under greenschist facies conditions. The fact that the amphiboles are aligned indicates that this metamorphism was synchronous with deformation.

GEOCHEMISTRY

Ten samples were analyzed for major and some trace elements (Rb, Sr, Ba, Ga, Zr, Y, Nb, V, Ni, Co and Cr) by X-ray fluorescence spectrometry in the Department of Earth Sciences of University of Ottawa, Canada. Eight representative samples were selected from this set for analysis of other trace elements (rare-earth elements [REE], Th, Nb, Ta, Zr and Hf) by ICP-MS at the Department of Earth Sciences, Memorial University of Newfoundland. The analytical error of the trace element determinations is 2–10% and <2% for major elements. Where available, ICP-MS data were preferred because of their better quality at low concentration levels.
Figure 3. Geological map of the Xayacatlán area showing locations of mafic dikes sampled for geochemistry.
Analytical results for these rocks are presented in Table 1. The major and trace element compositions of these rocks are similar to those of modern volcanic rocks. This suggests that the rocks are the metamorphic equivalents of such rocks and that they retain, to a large degree, their magmatic composition. Unlike sedimentary rocks, they have high Cr/Th (>400) and low Th/La (<0.1) ratios (Rollinson, 1993), and according to a procedure of Leake (1964), they resemble metamorphosed basalts. The rocks have a composition corresponding to subalkaline basalts (Figure 4) with SiO$_2$ (volatile-free basis) ranging between 47.5 and 51.5 wt. % and Mg# (=Mg/(Mg+Fe$_{tot}$)) between 0.40 and 0.60, and display tholeiitic characteristics (Figure 5). According to their normative compositions, the rocks are mostly olivine-normative tholeiites. Cr and Ti abundances are typical of rift-related tholeiites (Figure 6). The chondrite-normalized REE patterns of most of the rocks show a minor depletion of light REE (Figure 7) and their patterns

Table 1. Geochemical data for mafic dikes cutting the Salada unit, Acatlán Complex, southern Mexico.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SAL-1</th>
<th>SAL-2</th>
<th>SAL-3</th>
<th>SAL-4</th>
<th>SAL-5</th>
<th>SAL-6</th>
<th>SAL-7</th>
<th>SAL-8</th>
<th>SAL-9</th>
<th>SAL-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long.</td>
<td>97°57'39&quot;</td>
<td>97°55'29&quot;</td>
<td>97°55'11&quot;</td>
<td>97°55'00&quot;</td>
<td>97°54'54&quot;</td>
<td>97°54'51&quot;</td>
<td>97°54'18&quot;</td>
<td>18°17'02&quot;</td>
<td>18°17'04&quot;</td>
<td>18°17'05&quot;</td>
</tr>
<tr>
<td>Lat.</td>
<td>18°13'16&quot;</td>
<td>18°16'44&quot;</td>
<td>18°16'44&quot;</td>
<td>18°17'04&quot;</td>
<td>18°17'05&quot;</td>
<td>18°17'02&quot;</td>
<td>18°17'04&quot;</td>
<td>18°17'05&quot;</td>
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</tr>
</tbody>
</table>

SiO$_2$ (wt.%) 47.66 45.39 45.34 44.93 46.28 43.67 46.50 45.27 47.44 49.21
TiO$_2$ 0.99 1.59 1.31 2.43 1.23 1.48 1.49 2.06 1.44 1.24
MgO 6.63 8.86 5.54 6.51 8.66 7.79 8.31 4.54 7.59 7.84
CaO 9.93 8.03 13.31 11.06 8.01 9.01 10.49 11.09 9.35 8.63
Na$_2$O 3.07 2.64 2.89 1.13 1.80 1.78 2.03 1.11 3.33 2.77
K$_2$O 0.02 0.10 0.25 0.04 0.17 0.39 0.14 0.13 0.08 0.19
P$_2$O$_5$ 0.08 0.13 0.12 0.22 0.10 0.12 0.14 0.33 0.13 0.11
LOI 4.10 6.00 7.30 5.40 7.40 9.20 3.50 8.00 4.70 4.40
Total 99.37 99.92 99.44 100.06 100.32 100.73 99.37 100.08 100.59 100.25
Mg# 0.56 0.59 0.52 0.49 0.60 0.57 0.58 0.40 0.53 0.56
Cr (ppm) 234 360 167 261 221 126 244 43 170 175
Ni 98 84 78 62 122 98 99 20 90 66
Co 44 45 41 40 47 49 46 9 10 5 0
V 251 321 275 400 275 290 304 325 359 333
Zn 72 88 74 93 85 97 90 114 100 91
Rb 32 32 39 26 39 55 37 56 66 45
Sr 371 148 153 226 119 166 190 76 123 97
Ga 16 17 14 19 14 17 19 16 15 16
Ta 0.28 0.14 0.10 0.24 0.08 - 0.14 - 0.22 0.21
Nb 4.2 2.4 1.8 4.4 1.5 - 2.1 - 4.0 3.4
Hf 1.66 2.46 1.87 4.45 1.82 - 2.45 - 2.11 1.71
Zr 64 98 75 117 68 91 93 152 82 70
Y 17 29 24 48 22 38 29 46 25 23
Th 0.27 0.17 0.17 0.53 0.08 - 0.10 - 0.19 0.16
La 3.29 2.95 2.37 5.44 2.05 - 2.59 - 2.82 2.41
Ce 7.77 9.32 6.86 16.33 6.15 - 8.16 - 7.94 6.79
Pr 1.25 1.66 1.25 2.86 1.10 - 1.49 - 1.33 1.20
Nd 6.51 9.29 7.20 15.78 6.22 - 8.71 - 7.54 6.74
Sm 2.10 3.11 2.45 5.23 2.19 - 2.90 - 2.58 2.34
Eu 0.83 1.21 0.92 1.77 0.83 - 1.18 - 0.96 0.87
Gd 2.86 4.58 3.73 7.52 3.55 - 4.61 - 4.09 3.71
Tb 0.51 0.84 0.67 1.34 0.63 - 0.82 - 0.78 0.68
Dy 3.46 5.78 4.64 9.18 4.36 - 5.76 - 5.30 4.80
Ho 0.67 1.19 0.96 1.93 0.87 - 1.20 - 1.04 0.94
Er 2.04 3.53 2.89 5.73 2.65 - 3.48 - 3.06 2.74
Tm 0.286 0.514 0.392 0.823 0.399 - 0.502 - 0.449 0.413
Yb 1.99 3.37 2.83 5.41 2.60 - 3.29 - 3.10 2.72
Lu 0.284 0.472 0.394 0.761 0.357 - 0.452 - 0.479 0.425

FeO$_{T}$ = total Fe as Fe$_2$O$_3$; Mg# = Mg/(Mg+Fe$_{T}$).
Carboniferous tholeiitic dikes in the Salada unit, Acatlán Complex

are similar to N-type MORB with (La/Sm)_n mostly ~0.5–0.6. The absolute concentration of REE varies slightly but the shape of the patterns remains the same: these variations are consistent with low-pressure fractional crystallization. The mantle-normalized trace element patterns of the rocks (Figure 8) are relatively flat without a Nb depletion relative to La and Th suggesting that the rocks have not been modified by subduction-related fluids and that the rocks were not significantly contaminated by crustal material. The absence of a Nb anomaly and a low Th/La ratio suggest an asthenospheric source without any suprasubduction imprint or crustal contamination. The high Ti and Cr content also rules out formation in an arc environment. The rocks resemble N-type MORB. The geochemical characteristics suggest that the rocks are either rift-related oceanic basalts or continental tholeiite emplaced in rather thin crust without significant crustal contamination: the latter is most likely as the mafic dikes intrude continentally-derived clastic rocks.

DISCUSSION

The Carboniferous, rift-related tholeiitic dikes in the Xatacatlán area may be correlated with within-plate, rift-related tholeiitic pillow basalts interbedded with clastic metasedimentary rocks (Coatlaco unit) in the western part of the Acatlán Complex, which have yielded a 357 ± 35 Ma detrital zircon age (Grodzicki et al., 2008). Deposition of the Salada and Coatlaco units was also contemporaneous with deposition of the Patlanoaya Group, which, in turn, was synchronous with exhumation and deformation of high-pressure rocks (Ramos-Arias et al., 2008), and the earliest deformation of the Salada unit (Morales-Gámez et al., in press). This deformation has been related to extrusion of the high-pressure rocks into the upper plate above an active subduction zone (Keppie et al., 2008a).
Talavera-Mendoza et al. (2005) and Vega-Granillo et al. (2007) place the Mixteca terrane in the collisional suture zone between southern Laurentia and Gondwana (Figure 9a). That this collision had already taken place by the Mississippian is suggested by the presence of shallow water Mid-Continent (USA) fauna in the Santiago Formation that lies above the ~1 Ga Oaxacan Complex in the adjacent Oaxaquia terrane (Navarro-Santillan et al., 2002). Although the presence of Carboniferous, within-plate, rift-related tholeiites could be explained by gravitational collapse of a collisional orogen, it is inconsistent with paleomagnetic data, which indicate that, in the Permian, the Mixteca terrane lay roughly at its present position relative to Laurentia (Alva-Valdivia et al., 2002). The latter position places the Mixteca terrane on the Pacific margin of Pangea (Figure 9b). On the other hand, Carboniferous rift-related tholeiites synchronous with deformation, and extrusion of high-pressure rocks in an active margin setting, is more consistent with a location along the western margin of Pangea, well south of the Laurentia-Gondwana suture zone (Figure 9b) (Elias-Herrera and Ortega-Gutiérrez, 2002; Keppie et al., 2008a).

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Figure 9. Permo-Carboniferous reconstructions: (a) after Talavera-Mendoza et al. (2005) and Vega-Granillo et al. (2007), and (b) modified from Keppie et al. (2008a).

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Morales-Gámez et al.

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