Two-Billion-Year Granulites in the Late Precambrian Metamorphic Basement Along the Southern Peruvian Coast

B. Dalmayrac, J. R. Lancelot, A. Leyreloup
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Abstract. Uranium-lead data indicate that the high-pressure granulitic and charnockitic nuclei within the medium-grade metamorphic complex of the Peruvian coastal area must be related to an orogenic event \(2 \times 10^9\) years ago. As in western Africa and Brazil, this old granulitic basement is reworked by Late Precambrian orogeny. Its presence along the Peru-Chile Trench must be taken into account in interpreting the anomalously high strontium isotopic ratios of recent calc-alkaline volcanism.

The Peruvian Andes between the Brazilian shield and the Peru-Chile Trench are a complex mountain system made up largely of rocks deformed by Precambrian, Hercynian, and Andean orogenies. Precambrian rocks exposed in the eastern Andean cordillera and along the southern Peruvian coast (Fig. 1) form part of a single Late Precambrian orogenic belt (3-5). They are characterized by the same overall lithology and polyphase deformation and by two metamorphic events (6), the first of intermediate pressure and the second of low pressure. From place to place, and especially along the southern coast, these medium- to high-grade mobilized metamorphic rocks are associated with older granulites and charnockites.

The medium- to high-grade metamorphic Precambrian terranes of the southern Peruvian coast are composed of a thick lower metasedimentary sequence, interbedded with basic gneisses, and an upper series of prasinitic schists. These rocks were strongly deformed during two periods of Precambrian isoclinal folding.

The oldest and most important deformation is contemporaneous with the first prograde metamorphism. The second is associated with the general retrograde metamorphism, the regional cleavage, and the fold lineation transverse to the coast. Two later compressive events that produced chevron folds and kink bands end the Late Precambrian orogeny. The first prograde metamorphism seems to increase in grade toward the south. It is generally characterized by biotite-staurolite, garnet–kyanite-sillimanite–potassium feldspar relict associations of a medium-pressure type with cordierite in catazonal paragenesis. By comparison with similar Precambrian rocks of the eastern cordillera (6), the metamorphic gradient is typically Barrovian. The second metamorphism, of a low-pressure type (chlorite-muscovite-epidote-cordi-
compute lead loss starting at $T_1$ ($1.9 \times 10^6$ years $\approx T_1 \approx 2 \times 10^6$ years) and stopping at $T_2$ ($0.6 \times 10^6$ years $\leq T_2 \leq 0.66 \times 10^6$ years). Good fits (Fig. 2) of the calculated discordia curves with experimental points are obtained in these cases, but the best fits are obtained if multistage models are used (19) (Fig. 3) with the sequence: (i) continuous lead loss from $T_1$ to $T_2$; (ii) episodic lead loss at $T_2$; and (iii) a closed system from $T_2$ to the present time.

We thus prefer the latter interpretation, and we assign an age of about $1.95 \times 10^6$ years to the granulite-facies metamorphism; from this time to about $0.6 \times 10^6$ years the granulite-facies rocks remained in the deep zone of the continental crust and underwent a strong continuous lead loss. Uplift and retro-gneiss metamorphism occurred during Late Precambrian orogenesis, producing a slight episodic lead loss.

These results have three important implications:

1) An orogenic event $1.9 \times 10^6$ to $2.1 \times 10^6$ years ago that produced granulite charnockite rocks, reworked as nuclei in the Late Precambrian without evidence of an intermediate event $1 \times 10^6$ years ago, seems to be a widespread phenomenon in South America, as well as in west and central Africa. In western Ahaggar (Algeria), for example, the granulite metamorphism of the In‘Ouzzal formation, which is a basement unit occurring in the Pan-African orogenic belt, limited by large shear zones, has been dated at $2.05 \times 10^6$ years on the basis of old uranium decay constants (14, 20). Furthermore, data from zircons studied grain by grain and from whole-rock rubidium-strontium studies (21) have shown that these metasedimentary sequences derive from rocks that are $3.1 \pm 0.1 \times 10^9$ years old. A similar sequence is known in Brazil, where, for example, the parametamorphic granulite of Paraiba do Sul produced $2 \times 10^6$ years ago (22) was reworked during the Late Precambrian orogeny (Serra dos Orgaos gneisses) (23). These granulite rocks from Brazil also seem to have been derived from terranes $3.1 \times 10^9$ years old (Mantiqueira and Barbacena gneisses) (25).

2) The Late Precambrian thermal event deduced from lead loss models (Figs. 2 and 3) is also in agreement with the potassium-argon data of $642 \pm 16 \times 10^6$ and $679 \pm 12 \times 10^6$ years (5) obtained for the Arequipa granite and basic gneisses. Furthermore, a potassium-argon age of $647 \times 10^6$ years has been reported (26) from orthogneiss xenoliths included in Tertiary volcanites from northwestern Bolivia; these orthogneisses could possibly belong to a southeastern extension of the Arequipa

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Table 1. Uranium and lead contents of the granulitic and charnockitic nuclei. Common lead values used for blank correction: $^{206}Pb/^{204}Pb = 18.5$; $^{207}Pb/^{204}Pb = 15.5$; $^{208}Pb/^{204}Pb = 38.0$. Mean calculated errors: 0.9 percent for ($^{207}Pb/^{235}U$); 1.1 percent for ($^{206}Pb/^{238}U$). Samples: PB 159, enderbite; PB 167, charnockite; PB 174, charnockite paragneiss; PB 173, khondalite; ppm, parts per million.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample weight (g)</th>
<th>U (ppm)</th>
<th>Pb (ppm)</th>
<th>$^{207}Pb/^{235}U$ (measured)</th>
<th>$^{207}Pb/^{235}U$ (corrected)</th>
<th>$^{206}Pb/^{238}U$ (corrected)</th>
<th>$^{208}Pb/^{232}U$ (corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB 159 (200 mesh)</td>
<td>0.00207</td>
<td>449</td>
<td>140</td>
<td>3436</td>
<td>0.11213</td>
<td>0.2939</td>
<td>4.5413</td>
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<tr>
<td>PB 167 (200 mesh)</td>
<td>0.00106</td>
<td>543</td>
<td>163</td>
<td>1478</td>
<td>0.1123</td>
<td>0.2925</td>
<td>4.5280</td>
</tr>
<tr>
<td>PB 174 (200 mesh)</td>
<td>0.00213</td>
<td>232</td>
<td>159</td>
<td>4365</td>
<td>0.10466</td>
<td>0.2375</td>
<td>3.4187</td>
</tr>
<tr>
<td>PB 174 (200 mesh)</td>
<td>0.00308</td>
<td>230</td>
<td>58</td>
<td>5768</td>
<td>0.10464</td>
<td>0.2386</td>
<td>3.4404</td>
</tr>
<tr>
<td>PB 174 (100 mesh)</td>
<td>0.00100</td>
<td>257</td>
<td>64</td>
<td>1600</td>
<td>0.10372</td>
<td>0.2376</td>
<td>3.3959</td>
</tr>
<tr>
<td>PB 173 (300 mesh)</td>
<td>0.00033</td>
<td>273</td>
<td>53</td>
<td>1408</td>
<td>0.09401</td>
<td>0.1884</td>
<td>2.4463</td>
</tr>
</tbody>
</table>

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Fig. 2 (left). Concordia diagrams, $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$. The line labeled 2 represents the best straight line obtained by a two-error regression treatment. The diffusion curve (labeled 1) is obtained by assuming a continuous lead loss ($\lambda_{2}$) from $1.95 \times 10^6$ to $0.6 \times 10^6$ years and a closed system from $0.6 \times 10^6$ years until now.

Fig. 3 (right). Concordia diagram, $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$. A multistage model is assumed with continuous lead loss between $T_1 = 1.95 \times 10^6$ years and $T_2 = 0.6 \times 10^6$ years, episodic lead loss at $T_2$, and a closed system between $T_2$ and the present time. Variations in parameter $\lambda$ (19) permit determination of the relative importance of episodic and continuous lead losses. For $0.001 < A < 0.01$ (models 3 and 4) the episodic lead loss is negligible as compared to the continuous lead loss; the inverse is obtained for $A = 1$ (model 6). For model 5, which shows a good fit to the data, $A = 0.1$. 
complex. Farther to the south, rubidium-strontium whole-rock ages between 600 ± 50 x 10^6 and 500 ± 55 x 10^6 years have been reported (27) from the Pampean ranges of northwestern Argentina. They could also be related to the Late Precambrian orogeny, if we consider that the numerous Hercynian granitoid intrusions in this area have produced thermal effects that may have opened the rubidium-strontium system of the Late Precambrian rocks with quite high rubidium-strontium ratios (28).

3) The presence of the granite-charnockite complex 2 x 10^8 years old along the Perú-Chile Trench must be taken into account in genetic models of Andean volcanism. James et al. (29) and Hamet et al. (30) have suggested crustal contamination as a possible explanation for the variation of 87Sr/86Sr isotope ratios (0.7055 to 0.7080) in recent calc-alkaline lavas (Arequipa and Barrosso units) erupted through the thick Peruvian continental crust; these data contrast with lower isotopic ratios (0.7030 to 0.7042) generally found in similar rocks of the same continental crust; these data contrast with lower isotopic ratios (0.7030 to 0.7042) generally found in similar rocks of the same continental crust; these data contrast with lower isotopic ratios (0.7030 to 0.7042). Consequently, the presence of the granulite-charnockite complex is consistent with the idea of crustal contamination.

Note added in proof: While this report was in press, a paper by Cobbing et al. about similar Rb/Sr studies was published (33).

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References and Notes
7. The term "khondalite-kinzigite sequence" is used for a suite of high-pressure granulitic aluminous paragneisses (quartz, mesoperthitic plagioclase, feldspar, orthopyroxene, garnet, almandine, rutile, sapphire, zircon, monazite, ore) varying from a quartz-or-thoclasic (khondalite) pole to a plagioclasic (kinzigite) pole (8).
9. The term "enderbitic gneiss" is used for hypersthene-bearing dioritic gneisses.
15. Using old decay constants: \(\lambda_{\text{Sr}} = 0.1357 \times 10^{-10} \text{year}^{-1}\) and \(\lambda_{\text{Sr}} = 0.9722 \times 10^{-10} \text{year}^{-1}\); \(T_1 = 1946 \pm 36 \times 10^6 \text{years}\) and \(T_2 = 725 \pm 29 \times 10^6 \text{years}\) (A. H. Jaffey, K. F. Flynn, L. E. Oleninhen, W. C. Bentley, A. M. Essling, Phys. Rev. 4, 1889 (1973)).
30. J. Hamet et al., Geology, in press.
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