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$^{40}Ar/^{39}Ar$ AND U–Pb EVIDENCE FOR LATE PROTEROZOIC (GRENVILLE-AGE) CONTINENTAL CRUST IN NORTH-CENTRAL CUBA AND REGIONAL TECTONIC IMPLICATIONS

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Abstract

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Central Cuba is composed of fault-bounded tectonostratigraphic terranes juxtaposed and deformed during plate collision and subsequent transform motion between the Caribbean and North American plates in the Late Mesozoic-Cenozoic. One of these, the Las Villas terrane, contains crystalline basement rocks thought to be pre-Upper Jurassic on stratigraphic grounds. The Socorro Complex occurs in the northwestern Las Villas terrane, and consists of marbles and siliciclastic metasedimentary rocks, and the Río Caña Granite. An $^{40}Ar/^{39}Ar$ plateau date of 903.5 ± 7.1 Ma for phlogopite from a marble corroborates previous K-Ar dates from this unit, and establishes unambiguously a Late Proterozoic age for high-grade metamorphism. Discordance of the $^{40}Ar/^{39}Ar$ age spectrum can be reliably attributed to diffusive Ar loss, which if modeled as an episodic thermal event implies a reheating age that closely coincides with the Late-Cretaceous–Paleogene collision between the Caribbean and North American plates. U-Pb zircon data indicate an intrusive age of 172.4 Ma for the Río Caña Granite, and reveal an inherited zircon component with an age of ~ 900 Ma. Radio-isotopic data from the Socorro Complex display no evidence of Pan-African age thermal overprinting. These observations, combined with constraints provided by published results from nearly Pangean landmasses, suggest that the complex lay substantially to the southwest (present-day co-ordinates) during the Early Paleozoic. Following its genesis in the mid-Mesozoic, the Caribbean plate evidently transported fragments of an extensive Grenville-age belt that spanned the Americas during the Late Proterozoic.

Introduction

The tectonic evolution of the Caribbean plate and its northern boundary zone has been studied extensively in the last decade (e.g., Pindell and Dewey, 1982; Sykes et al., 1982; Wadge and Burke, 1983; Mattson, 1984; Duncan and Hargraves, 1984; Burke et al., 1984; Pindell, 1985),

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during which time considerable progress has been made in understanding the Cretaceous and younger geologic history of the region in terms of plate tectonic processes. The pre-Late Jurassic history of the northern Caribbean region remains much more poorly understood because rocks known to be this old are relatively rare and are generally not well dated. Collision between the North American and Caribbean plates during the Late Cretaceous–Eocene has produced intense deformation that obscures earlier stratigraphic and structural relationships. Post-Eocene sinistral transform motion between these plates has produced major rotations (e.g., Gose and Eby, 1987) which further complicate geologic relations. The effect of this motion in Cuba is largely unknown, but preliminary paleomagnetic data (P.R. Renne, unpublished data) suggest that parts of central Cuba have undergone $\sim 80°$ of post-Early Cretaceous counterclockwise rotation with respect to the North American plate.

The origin of the Caribbean plate as a tectonic entity, as envisaged by Pindell and Dewey (1982) and most subsequent investigators, followed the rifting apart of Pangea in the Middle Jurassic. Shortly thereafter, the northeastern margin of the Caribbean plate was the site of the Cretaceous magmatic arc(s) of the Greater Antilles, marking the zone of convergence between the Caribbean and North American plates. The nature and age of the basement upon which this arc was constructed are poorly constrained, as is the location of its origin.

The pre-rift tectonic history of the Caribbean region has obvious implications for the relationship of the North and South American continents prior to the Middle Jurassic. This paper presents data that provide constraints on the nature, age and original location of crustal fragments that eventually were transported by the Caribbean plate. Some applications of these constraints to the paleotectonic relationship of the Laurentian and Amazonas cratons of North and South America respectively, during the Late Proterozoic are presented in the following.

Regional geology of central Cuba

Central Cuba comprises several distinct tectonostratigraphic terranes (used in the non-genetic sense of Howell et al., 1985), shown in Fig. 1, that are imbricated along WNW–ESE trending faults. As discussed by Somin and Millán (1977, 1981), Millán and Somin (1981, 1985) and Hatten et al. (1988), these terranes contain lithologic suites characteristic of convergent plate margins, including volcanic and plutonic arc-related rocks (Zaza and Manicaragua terranes), ortho-amphibolites (Manicaragua terrane), high pressure–low temperature (blueschist and eclogite facies) tectonites (Escambray terrane), ophiolite fragments (Zaza terrane), and serpentinite melanges (especially along thrusts within and between terranes). The imbrication of these terranes, and much of the deformation and metamorphism of rocks composing them, took place during the Late Cretaceous–Paleogene collision of the Caribbean and North American plates (Hatten et al., 1988). Evidence reviewed by Mattson (1984), Burke et al. (1984) and Pindell (1985) implies that these terranes originated on the Caribbean plate. The active plate boundary in this area since ~ 36 Ma ago has been the Cayman trough, south of Cuba (Pindell and Dewey, 1982; Burke et al., 1984), suggesting that Cuba was sutured to the North American plate during the collision.

The Las Villas terrane

The Las Villas terrane (Hatten et al., 1988) comprises a belt of highly deformed Late Jurassic to Early Eocene sedimentary rocks unconformably overlying diverse types of crystalline basement. In the southeastern Las Villas terrane defined by Hatten et al. (1958, 1988), basement complexes include (from oldest to youngest) the Perea metabasites, the San Marcos Troctolite and the Tres Guanos granitoids. Cross-cutting relationships discussed by Hatten et al. (1958, 1988) permit the delineation

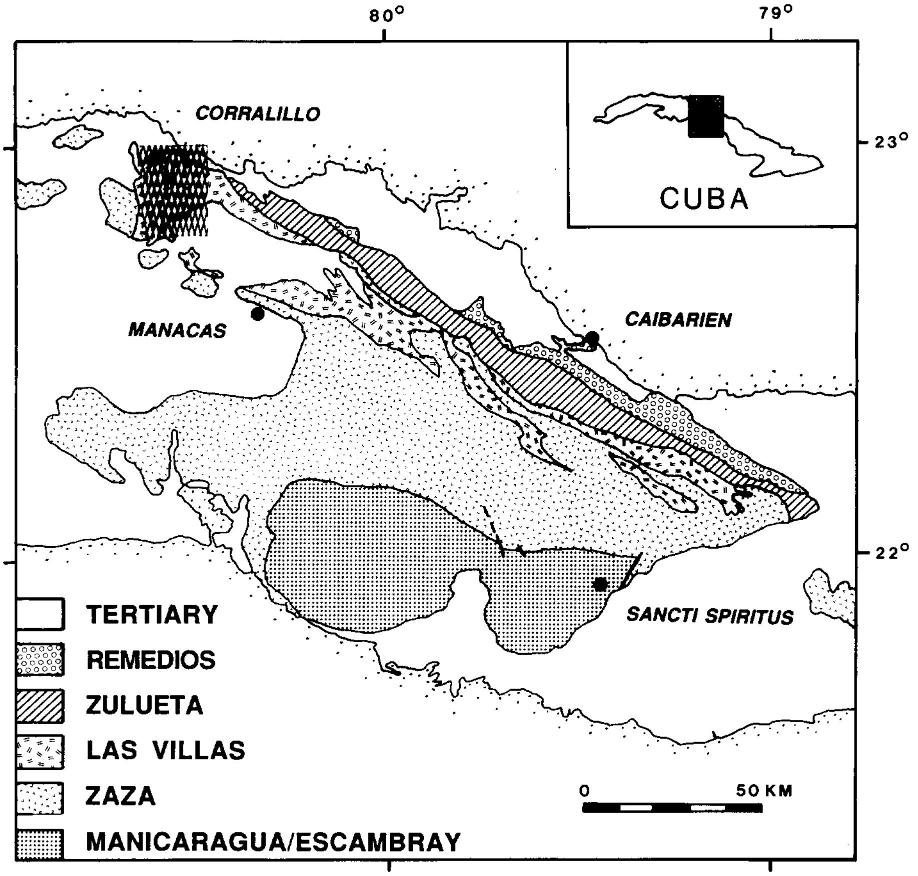


Fig. 1. Tectonostratigraphic terranes of central Cuba, modified from Hatten et al. (1988) and discussed in text. Contacts between terranes are faults. Cross-hatched area is shown in Fig. 2.

of relative ages of these units. K–Ar dates of 79 ± 2 Ma on whole rock (Somin and Millán, 1981) and 61 ± 1 Ma on biotite (Meyerhoff et al., 1969) samples have been reported for the Tres Guanos quartz monzonite, but Hatten et al. (1958, 1988) presented stratigraphic arguments that this granitoid has a pre-Tithonian (pre-152 Ma; Palmer, 1983) intrusive age, and speculated that the K–Ar dates reflect a tectonothermal overprint, presumably related to plate collision.

Somin and Millán (1981) considered the Perea metabasites, San Marcos Troctolite and Tres Guanos quartz monzonite to be part of an Upper Jurassic(?)–Cretaceous ophiolite association, but several factors weigh against this interpretation:

(1) The San Marcos 'Troctolite' (as observed in the Jarahueca Fenster) is actually a leucogabbro with anorthositic affinity, much more reminiscent of anorthosite complexes or layered basic intrusions than of ophiolites;

(2) The Tres Guanos granitoids are compositionally distinct from the typical plagiogranites of ophiolite suites. Further research (in progress) on these rock units is needed before their age and tectonic significance can be addressed.

Basement of the northwestern Las Villas terrane, the focus of this paper, is herein referred to as the Socorro Complex, consisting of deformed granitic and metasedimentary rocks described below.

Socorro Complex

The Socorro Complex is exposed in the area shown in Fig. 2, where it crops out poorly in a region of subdued topography. This complex comprises the Río Caña Granite and Sierra Morena Marbles discussed by Somin and Millán (1977, 1981). Best exposures of the complex occur in streambeds of the area (particularly the Río Caña and its tributaries), but even in these the exposure is discontinuous and lithologic relationships are often obscured. Relationships among the various lithologic units shown in Fig. 2 are poorly exposed and thus may be subject to slightly different interpretations. Our observations and mapping strongly suggest that the Socorro Complex is allochthonous, its northeastern border resting with tectonic discordance on highly deformed thin-bedded Late Jurassic carbonates of the Veloz Formation and Early Cretaceous cherts of the Amaro Formation. To the southwest, the crystalline complex

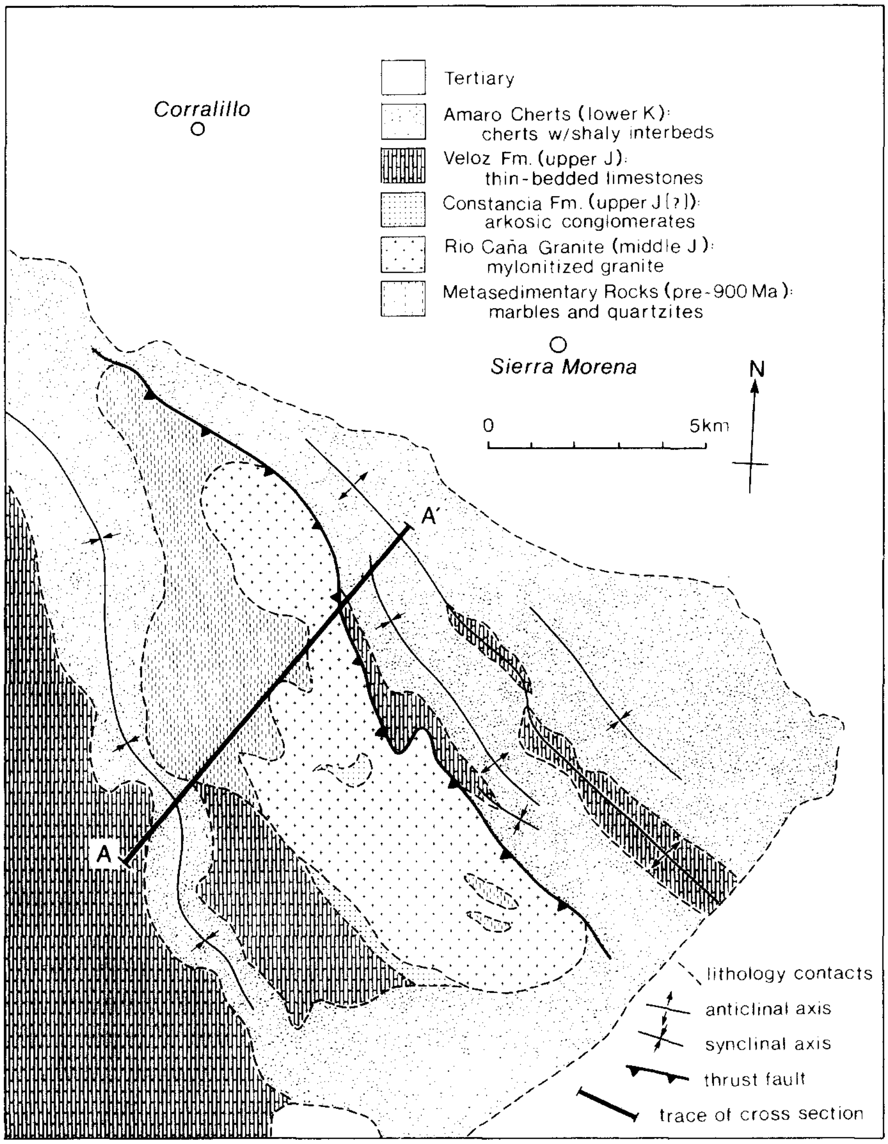


Fig. 2. Geologic map of the Río Caña Area showing the Socorro Complex.

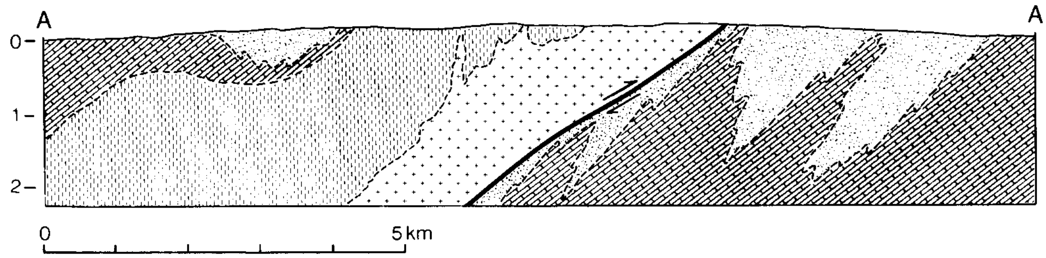


Fig. 3. Interpretive cross-section along A–A′ in Fig. 2.

appears to be overlain unconformably by the Veloz and Amaro Formations (Hatten et al., 1958; Pszczolkowski, 1986). Arkosic conglomerates of the Constancia Formation, derived from the complex, occur discontinuously between the Río Caña Granite and the Veloz Formation along this unconformity (Hatten et al., 1958; Pszczolkowski, 1986). Pardo (1975) also considered the Socorro Complex (Sierra Morena) to represent allochthonous pre-Neocomian basement outcrops. Pszczolkowski (1986) interprets the complex to comprise pre-Tithonian basement fragments between thrust sheets. Our structural interpretation portrays the Socorro Complex as a basement uplift, thrust from southwest to northeast, as shown in Fig. 3.

The distribution of the Socorro Complex in surface outcrops is limited, but similar rocks occur elsewhere in evaporite diapirs (discussed below) and as clastic components in arkosic sediments of the Upper Cretaceous (Campanian–Maastrichtian) Bacanayagua Formation along the Gulf coast in Habana and Matanzas provinces (Somin and Millán, 1981). Thus the Socorro Complex may have been much more widely exposed in the Cretaceous.

Río Caña Granite

The Río Caña Granite (Hatten et al., 1988) of the Socorro Complex is a coarse-grained, pink-colored granite, consisting of perthitic microcline, plagioclase, quartz, biotite, apatite and zircon. A chemical analysis of a sample of the granite reported by Somin and Millán (1981) includes 68.32% SiO_2, 14.94% Al_2O_3, 1.89% CaO, 4.63% K_2O, and 3.90% Na_2O by weight. Locally, the granite is highly deformed and commonly possesses a cataclastic texture featuring porphyroclasts of feldspars and strained quartz in a comminuted matrix of feldspars, quartz, and biotite (see Plate 1(a)). Plagioclase porphyroclasts are often kinked or broken. Biotite is frequently chloritized, and the feldspars contain sericitic alteration products. Irregular pods of greenish breccia, possibly brecciated mafic xenoliths, occur within the granite.

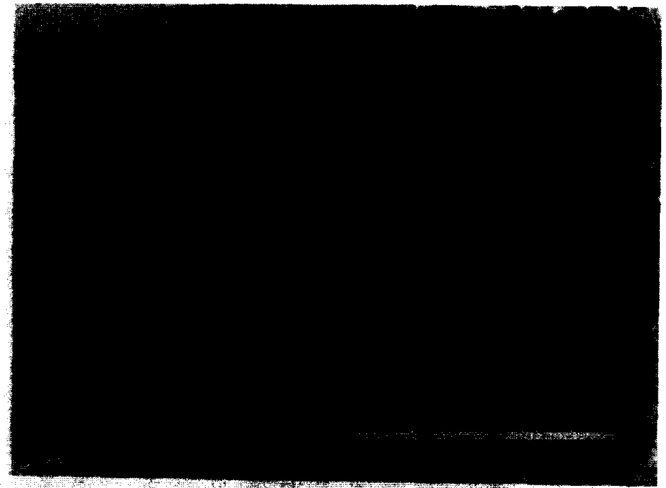
Contact relations of the granite with the Mesozoic sedimentary rocks are not well exposed, but it appears to be overlain unconformably by arkosic conglomerates of the Constancia Formation, which is in probable depositional contact with the overlying Veloz Formation in the southern portion of the complex (Fig. 2). These inferred relationships suggest a pre-Late Jurassic age for the Río Caña Granite. Somin and Millán (1981) reported whole-rock K–Ar dates of 150 ± 5, 139 ± 5 and 140 ± 2 Ma for two samples of the granite. Interpretation of these data must accommodate the observations that:

(1) the granite contains 30–60 vol.% microcline, whose high K content implies that a whole-rock K–Ar date is probably in effect a microcline date;

(2) the microcline is generally sericitized, quite strongly in many cases.

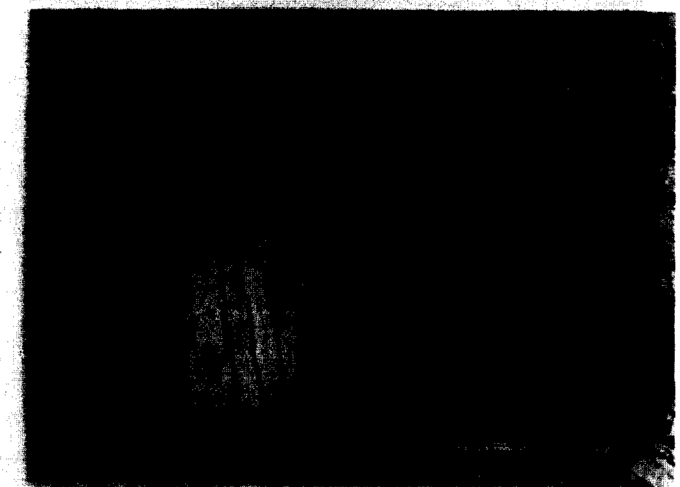
The K–Ar dates thus may reflect the most recent cooling of the granite through the blocking temperature ($\sim$100–200°C; Berger and York, 1981; Harrison and McDougall, 1982) of Ar in K-feldspar. The K–Ar dates may also reflect the

(a) Photomicrograph of Rio Caña Granite. K = perthitic microcline, Q = quartz, P = plagioclase. Shear zone from upper left to lower right of photo contains comminuted grains of these minerals plus chloritized biotite. Crossed Nicols. Scale bar is 1.0 mm.



(b) Zircon crystal in thin section of Rio Caña Granite, with inclusions of smaller, rounded pre-existing zircon grains. Plane polarized light. Scale bar is 0.2 mm.

(c) Rounded and embayed zircon crystals in thin section of Rio Caña Granite. Plane polarized light. Scale bar is 0.2 mm.



(d) Photomicrograph of Sierra Morena Marble. Porphyroblasts of phlogopite (left) and serpentine pseudomorph after forsterite (right) in a matrix of calcite. Plane polarized light. Scale bar is 1.0 mm.

Plate 1. Photomicrographs of features in (a–c) the Río Caña Granite and (d) the Sierra Morena Marble.

age of sericitization. Considering the evidence for widespread overprinting of K–Ar systematics (implying greenschist grade or higher metamorphism) in basement rocks elsewhere in Cuba during the Late Cretaceous–Paleogene (Meyerhoff et al., 1969; Somin and Millán, 1977, 1981; Hatten et al., 1988), it is somewhat surprising that microcline and/or sericite were apparently not reset during this time interval, but more detailed analyses of these rocks with $^{40}Ar/^{39}Ar$ techniques (in progress) are needed to evaluate better their thermal histories.

Metasedimentary rocks

Associated with the Río Caña Granite are metasedimentary rocks, dominantly marbles (Sierra Morena Marble of Somin and Millán, 1977, 1981) and quartzites, whose contacts with the granite are obscured by poor exposure. The quartzites are generally fine grained, but the marbles range from fine to very coarse grained; in the latter case the rock may resemble skarn. Textures of the metasedimentary rocks are typically granoblastic or porphyroblastic, but are locally schistose in thin, discrete shear zones which may be genetically related to cataclastic textures developed in the granite. Traces of molybdenite occur locally associated with quartz in irregular veins in the clastic rocks.

Samples of marble collected for this study contain variable proportions of calcite ± diopside ± phlogopite. Equant patches (up to 5 mm diameter) of serpentine are locally abundant, resembling pseudomorphs after forsterite. Vesuvianite was also reported in some of these rocks by Somin and Millán (1977). These assemblages are indicative of high-grade metamorphism in either the pyroxene-hornfels or upper amphibolite/granulite facies of contact or regional metamorphism, respectively (Turner, 1981). Their bulk compositions indicate that dolomitic carbonate rocks were the protoliths for the marbles. Although field and petrologic data are consistent with the contact metamorphism of the metasedimentary rocks by the intrusion of the Río Caña Granite, the geochronologic data presented below are inconsistent with this. Shearing and cataclasis of both rock units apparently occurred under brittle conditions, and thus are probably unrelated to the intrusive event.

The biostratigraphic ages of the Veloz and Amaro Formations (Hatten et al., 1958; Pszczolkowski, 1986), which appear to be in unconformable depositional contact with the Socorro Complex to the southwest, suggest a pre-Late Jurassic metamorphism of these rocks. This constraint cannot be considered rigorous, however, as the nature of the contact (depositional or tectonic) is ambiguous. K–Ar analyses of different portions of a single coarse phlogopite crystal from a marble have yielded apparent dates of 945 ± 25 and 910 ± 25 Ma (Somin and Millán, 1977). Somin and Millán (1977) concluded on this basis that the marbles were substantially older than the Río Caña Granite, and related their genesis to the Grenville orogeny. The significance of these K–Ar dates is not entirely clear. Phlogopite closes to thermally activated Ar diffusion at ~350–400°C (Giletti and Tullis, 1977), and thus is more resistant to resetting than feldspars and other micas, and might not be outgassed by low greenschist facies metamorphism. However, the K–Ar technique does not permit the recognition of excess Ar, particularly problematic in metamorphic rocks, which can produce spuriously old K–Ar dates (e.g., Lanphere and Dalrymple, 1976).

Geochronologic data

Despite some uncertainties about their significance, published geochronologic data suggest that the Socorro Complex has a substantial pre-Cretaceous history, and its study is therefore relevant to understanding the early tectonic evolution of the Caribbean region. In order to resolve some ambiguities posed by existing K–Ar dates, the following $^{40}Ar/^{39}Ar$ and U–Pb data have been obtained as part of our continuing geochronologic, petrologic and tectonic studies of Cuba.

Analytical procedures

A phlogopite-bearing marble (shown in Plate 1(d)) collected ~1 km from the contact with the Río Caña Granite was crushed and sieved. Phlogopite crystals were hand picked from the 1–2-mm size fraction, which is the approximate size range of phlogopite porphyroblasts in this sample. Crystals were rinsed in distilled water for 30 min in an ultrasonic cleaner, then dried, and 0.040 g was packaged in Al foil for irradiation in the McMaster University nuclear reactor. After irradiation, 0.035 g was degassed in 15 temperature steps and the purified Ar from each extraction analyzed with a Varian-MAT GD150 mass spectrometer at Princeton University. Details of instrumentation, temperature control, gas purification, data collection, background and mass discrimination corrections, corrections for interfering nucleogenic isotopes and decay of ^{37}Ar and ^{39}Ar, decay constants, age and error calculations were similar to those reported by Onstott and Peacock (1987). K/Ca and K/Cl atomic ratios were calculated from corrected $^{39}Ar/^{37}Ar$ and $^{39}Ar/^{38}Ar$ ratios using the data reported by Onstott and Peacock (1987) for the McMaster reactor.

A sample of the Río Caña Granite was crushed, and zircons separated by conventional methods. Microscopic examination of the zircon population reveals a high proportion of clear, euhedral grains, plus some possibly rounded or corroded grains (Plate 1(c)), some of which appear to have partial, euhedral overgrowths (Plate 1(b)). After acid washing in hot HCl, followed by hot HNO_3, non-magnetic coarse and fine size fractions were purified by hand picking and analyzed by methods modified after Krogh (1973). Details of the analytical procedures and error analysis are described by Mattinson (1987). Mass spectrometric analysis was on the UCSB MAT-261 multicollector instrument, allowing simultaneous collection of all the relevant Pb or U isotopes.

$^{40}Ar/^{39}Ar$ data on phlogopite (metasedimentary rocks)

Data from the step heating experiment are summarized in Table I, and the corresponding apparent age spectrum is shown in Fig. 4a. The age spectrum (corrected for atmospheric Ar having $^{40}Ar/^{36}Ar = 295.5$) shows young apparent ages at low extraction temperatures, increasing monotonically from 153.4 Ma at 600°C to a plateau which begins with the 950°C fraction at 898.6 Ma. The plateau spans ~67% of the total ^{39}Ar released, and the volume-weighted age calculated from these steps is 903.5 ± 7.1 Ma. The pattern of discordance shown in Fig. 4a is suggestive of either (1) partial diffusive Ar loss, such as may occur during a reheating event (Turner, 1968) or (2) a mixture of two phases having different ages and degassing behavior.

An isotope correlation diagram (Fig. 5) aids the characterization of several components of Ar. Low-temperature fractions (600–700°C) define a parabolic trajectory whose intercept on the $^{36}Ar/^{40}Ar$ axis is indistinguishable from present-day atmospheric Ar. This strongly suggests that all the gas fractions are composed of a mixture between an atmospheric component and a radiogenic component. Non-linearity of the array indicates a variable $^{39}Ar/^{40}Ar$ for the radiogenic component of each fraction. As the non-radiogenic component appears to be of uniform atmospheric composition, the $^{39}Ar/^{40}Ar^*$ ratio ($^{40}Ar^*$ is radiogenic ^{40}Ar) of any fraction is thus the intercept on the $^{39}Ar/^{40}Ar$ axis of a line connecting each datum point with the atmospheric $^{36}Ar/^{40}Ar$ value.

Examination of $^{37}Ar/^{39}Ar$ and $^{38}Ar/^{39}Ar$ ratios (Fig. 4b and c) shows that the low-temperature extractions are correlated with relatively high Ca/K and Cl/K, which monotonically decrease to uniform values as this component is exhausted (by 950°C). The plateau values of

TABLE I

$^{40}Ar/^{39}Ar$ analytical data: CUH-4 phlogopite

T (°C)	$f(39)$	f_1 ($\times10^{-3}$)	f_2 ($\times10^{-2}$)	Atmospheric (%)	$^{40}Ar^*$ (E-6 cm^3 STP)	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	Date (Ma) (±1 S.D.)
600	0.0093	−4.173	1.053	89.59	0.356	6.4103	0.443	153.4±24.4
650	0.0154	−0.955	0.826	65.75	0.385	1.4677	0.329	247.7±17.3
700	0.0233	−0.568	1.006	39.39	0.759	0.8729	0.270	364.2±14.6
750	0.0359	−0.303	1.557	11.87	2.056	0.4657	0.263	579.1±8.0
800	0.0729	−0.108	2.307	2.21	8.795	0.1652	0.246	791.2±1.5
850	0.1737	−0.052	2.565	0.87	26.599	0.0792	0.238	861.9±2.9
900	0.3342	−0.036	5.104	0.29	44.256	0.0558	0.217	892.5±1.0
950	0.5474	−0.028	3.743	0.31	59.306	0.0432	0.225	898.6±1.0
975	0.6574	−0.026	3.424	0.31	30.718	0.0399	0.225	901.3±1.1
1000	0.7303	−0.029	4.169	0.28	20.513	0.0452	0.225	906.4±1.1
1025	0.7963	−0.029	2.383	0.50	18.375	0.0445	0.210	898.8±1.6
1050	0.8603	−0.019	0.792	0.98	17.889	0.0286	0.223	902.6±1.2
1075	0.9154	−0.017	0.889	0.79	16.701	0.0262	0.222	907.5±1.4
1100	0.9718	−0.020	3.543	0.23	14.798	0.0306	0.222	911.0±1.4
1180	1.0000	−0.032	1.143	1.10	8.211	0.0488	0.197	931.5±1.3

Sample mass = 0.035 g. Average J-value = 0.023833 ± 0.000031. Integrated date = 870.1 ± 1.0 Ma. Plateau date = 903.5 ± 7.1 Ma.

Uncertainty in extraction temperature is ±2°C. $f_1 = 1/[1-(^{37}Ar/^{39}Ar)_{Ca}/(^{37}Ar/^{39}Ar)_M]$, and $f_2 = f_1[1-(^{36}Ar/^{39}Ar)_{Ca}/(^{36}Ar/^{39}Ar)_M]$, where $()_{Ca}$ = Isotope ratio of Ar extracted from irradiated Ca salts (from Onstott and Peacock, 1987), and $()_M$ = isotope ratio of Ar extracted from irradiated unknown. Atmospheric (%) = % of ^{40}Ar that is of atmospheric composition. $^{40}Ar^*$ is radiogenic Ar, corrected for atmospheric Ar ($^{40}Ar/^{36}Ar = 295.5$), with ^{36}Ar corrected for nucleogenic $^{36}Ar_{Ca}$. $f(39)$ is the cumulative fraction of ^{39}Ar released in each step. $^{37}Ar/^{39}Ar$ and $^{38}Ar/^{39}Ar$ reflect interference- and decay-corrected values of nucleogenic $^{37}Ar_{Ca}$, $^{38}Ar_{Cl}$, and $^{39}Ar_K$. Date calculated using decay constants and isotopic abundances of Steiger and Jager (1977). Error calculations according to Onstott and Peacock (1987).

$^{37}Ar/^{39}Ar$ and $^{38}Ar/^{39}Ar$ correspond to Ca/K = 0.060 and Cl/K = 0.048 (using the data of Onstott and Peacock, 1987), indistinguishable within error from ratios (Ca/K = 0.047 ± 0.018 and Cl/K = 0.037 ± 0.015) determined from electron microprobe analysis of a phlogopite crystal from the same hand sample. Microprobe data indicate that K, Ca and Cl are homogeneous over all but the outermost 10–20 μm of the crystal, where marginal serpentinization results in K-depletion while Ca and Cl are unchanged. Initial high Ca/K and Cl/K may thus reflect the contribution of marginal serpentine, although the volume fraction of serpentine calculated from the above is <0.2%, much less than the amount required to generate the $^{39}Ar_K$ associated with Ca/K and Cl/K anomalies. The anomalously high initial Ca/K may also reflect contamination from calcite incompletely removed during mineral separation, e.g., possibly present along cleavages or cracks.

The release patterns of individual isotopes, shown as a function of extraction temperature in Fig. 6, are consistent with a single mineralogic source for $^{39}Ar_K$ and $^{40}Ar^*$. In contrast, the bimodal release pattern for $^{37}Ar_{Ca}$ supports a low-temperature contribution from a high-Ca phase which dominates $^{37}Ar_{Ca}$ in the first three or four gas fractions. This phase does not contain significant $^{39}Ar_K$ or $^{40}Ar^*$; thus calcite is further implicated as a contaminant. The release pattern of $^{38}Ar_{Cl}$ reveals a minor Cl anomaly in the 600°C, and possibly in the 700°C fractions, whose source is unknown. Thus, despite evidence for additional phases besides phlogopite reflected in the low-temperature gas fractions, these phases do not appear to contribute to the $^{39}Ar_K$ or $^{40}Ar^*$ budget and the age

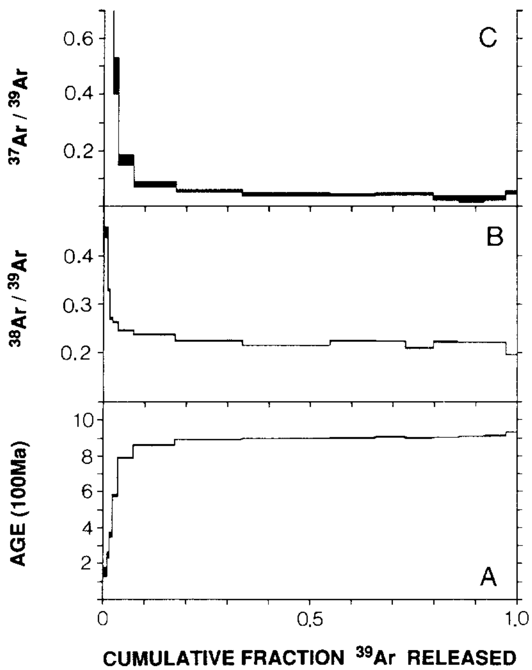


Fig. 4. Results of incremental heating experiment, showing the following values as a function of cumulative fraction of total ^{39}Ar released: (A) apparent age, calculated from corrected ^{40}Ar*/^{39}Ar ratios; (B) $(^{38}Ar)_{Cl}/(^{39}Ar)_K$, the nucleogenic ratio of Cl-derived ^{38}Ar to K-derived ^{39}Ar; (C) $(^{37}Ar)_{Ca}/(^{39}Ar)_K$, the nucleogenic ratio of Ca-derived ^{37}Ar to K-derived ^{39}Ar.

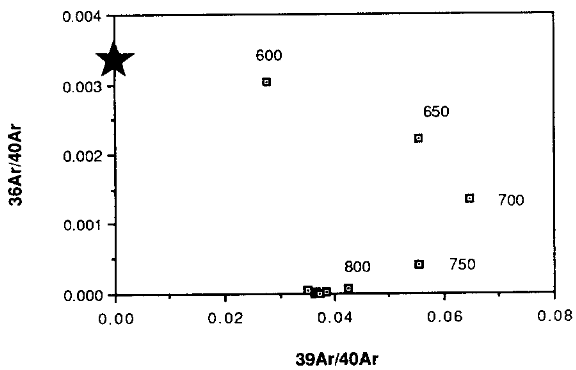


Fig. 5. ^{36}Ar/^{40}Ar versus ^{39}Ar/^{40}Ar correlation diagram. Numbers refer to extraction temperatures. Star corresponds to present-day atmospheric Ar. Symbols are > 1S.D. errors.

spectrum may be confidently interpreted as the product of volume-diffusive loss of Ar.

The correlation diagram, Fig. 5, shows that the non-radiogenic Ar component of the low-temperature fractions has atmospheric composition, hence the apparent ages of these fractions are meaningful and can be used to model the pattern of discordance. If this Ar-loss was due to a single reheating event, the algorithm of Hall and York (1982) can be applied to the theory of Turner (1968) to calculate the age of this event for a given diffusion geometry and fraction of gas lost. In this model, the age calculated from the first increment of gas released, 153.4 ± 24.4 Ma, is an upper limit on the possible age of the secondary event. For the present case, with 3.7% ^{40}Ar* loss (per cent difference between the total gas age and the plateau age) and cylindrical diffusion geometry, a model age (t_m) of 59.5 ± 9.4 Ma is calculated for the reheating event and 905.8 ± 9.8 Ma for the phlogopite's primary cooling age. For small fractional Ar loss (L), as in this case, model reheating ages calculated by this method are very sensitive to small perturbations in the value of L: for $L = 0.036$, $t_m = 24.9 \pm 9.9$ Ma; for $L = 0.038$, $t_m = 91.5 \pm 9.0$ Ma. The present limited data do not warrant detailed interpretation of this model overprint age, but we note that the results cited above are consistent with partial outgassing during the pervasive Cretaceous–Paleogene tectonothermal activity previously discussed.

The K–Ar dates (910 ± 25 and 945 ± 25 Ma) reported by Somin and Millán (1977, 1981) from a Sierra Morena Marble (discussed above) are slightly older than the ^{40}Ar/^{39}Ar plateau date reported herein. This may reflect the much larger grain size (hence higher blocking temperature if the scale of Ar diffusion approaches the grain dimensions) of the phlogopite used in the K–Ar analyses, or may be a result of excess Ar contamination*.

* Note added in proof: Seventeen ^{40}Ar/^{39}Ar laser probe spot analyses made on the {001} face of a single phlogopite crystal (~0.4 cm diameter) yield dates ranging from 952 ± 12 Ma to 718 ± 9 Ma. Older dates are more common near the center of the grain.

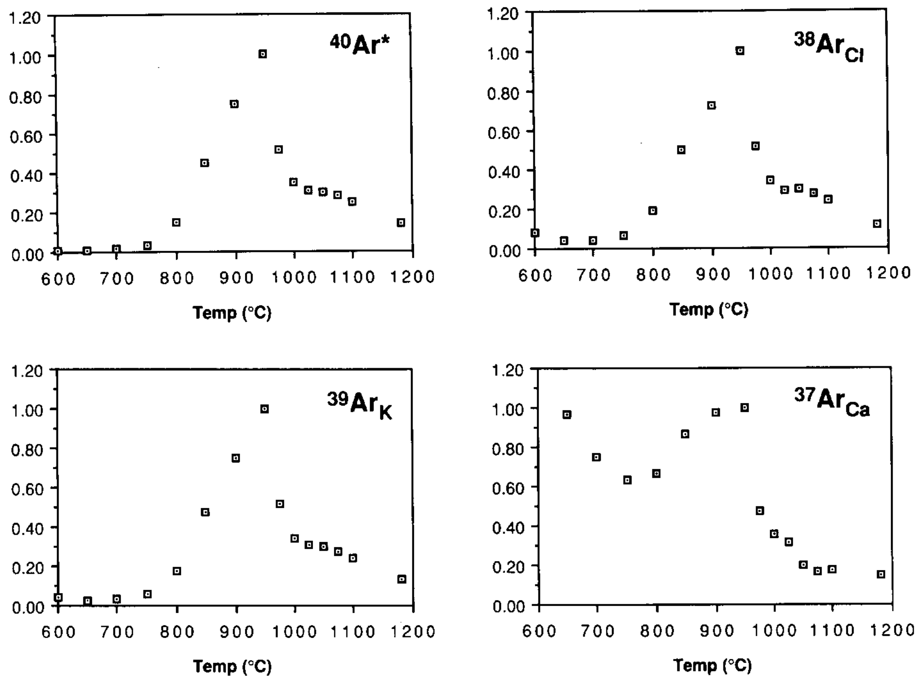


Fig. 6. Release patterns of individual Ar isotopes as a function of laboratory extraction temperature. Values plotted on vertical axes are atomic abundances normalized to the abundance in the 950°C extraction.

TABLE II

Río Caña Granite zircon data

Sample[a]	F201 Zir f	F201 Zir c
^{238}U (ppm)	320.6	286.6
$^{206*}Pb$ (ppm)	8.231	7.711
$^{208}Pb/^{206}Pb$[b]	0.1955	0.1826
$^{207}Pb/^{206}Pb$[b]	0.05879	0.05609
$^{204}Pb/^{206}Pb$[b]	0.000495±3	0.000244±2
$^{206*}Pb/^{238}U$ (Ma)[c]	188.4±0.4	197.3±0.4
$^{207*}Pb/^{235}U$ (Ma)[c]	194.2±0.7	206.2±0.6
$^{207*}Pb/^{206*}Pb$ (Ma)[c]	265±5	309±3

[a]c and f designate coarse and fine size fractions, respectively. Zircon analytical methods after Mattinson (1987).
[b]Observed isotopic ratios corrected for mass fractionation of 0.125% per mass unit, based on replicate analyses of NBS Pb standards. Two-sigma errors are shown for last digit of the 204/206 ratio. Errors on the 208/206 and 207/206 ratios are <0.1%.
[c]Ages calculated using decay constants of Jaffey et al. (1971). Error analysis after Mattinson (1987).

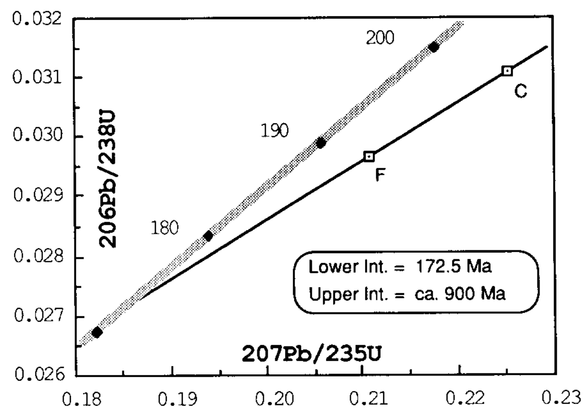


Fig. 7. Expanded portion of U-Pb concordia, with data from the Río Caña Granite. The concordia curve (virtually a straight line for this small segment) is shown for ~170–200 Ma by the heavy stippled line. Fine (F) and coarse (C) fractions of zircon define a discordia line with a lower intercept of 172.5 Ma, and an upper intercept (not shown) of ~900 Ma.

U-Pb data on zircon (Río Caña Granite)

The two zircon fractions have moderately low U contents (~300 ppm–see Table II), and show a strong pattern of 'normal' discordance. On a concordia plot (Fig. 7), the two fractions define a discordia trajectory with a lower intercept of ~172.5 Ma, and an upper intercept of ~900 Ma. Both points plot close to the lower intercept, which is therefore tightly constrained. Because of the long projection, and the fact that only two data points define the chord, the upper intercept is much less well constrained. Additional fractions, in progress, will allow more rigorous statistical analysis, with meaningful errors on the upper and lower intercepts. The coarser fraction has a lower U concentration, and plots higher on the discordia trajectory than does the finer fraction. In general, the overall pattern of discordance of the zircons (i.e., plotting close to the lower intercept) is typical of that for igneous rocks containing older inherited zircons (for example, see Fig. 4 of Mattinson and James, 1985). The finer fraction contains a larger proportion of newly crystallized zircons (plus possibly a greater proportion of Pb loss from the inherited component) and the coarser fraction contains a greater fraction of inherited zircons, possibly as cores (seed crystals) upon which igneous zircon nucleated.

The most straightforward interpretation of the zircon data is that the lower intercept on concordia at ~172.4 Ma represents the time of magmatic emplacement of the granite, and that the upper intercept on concordia at ~900 Ma represents the minimum age of the inherited zircons. Thus, the granite was emplaced in the Jurassic, and derived in part by anatexis or assimilation of (probably) continental >900 Ma source rocks, or sedimentary or metasedimentary rocks derived from a >900 Ma source.

A possible alternate interpretation is that the granite was emplaced and crystallized at ~900 Ma, and that the observed discordance is the result of a Jurassic thermal event. This would require the loss of almost 98% of the Pb from the fine-grained zircons during the Jurassic. In light of the evidence for chiefly cataclastic (cold) deformation of the granite (see earlier description), and the relatively low U concentrations in the zircons (and thus low accumulation of radiation damage, an important factor in susceptibility to Pb loss — see Silver, 1963), this second interpretation seems highly unlikely.

Conclusions from geochronologic data

$^{40}Ar/^{39}Ar$ and U–Pb data summarized herein clearly show evidence of Late Proterozoic continental crust in the Las Villas terrane. $^{40}Ar/^{39}Ar$ data indicate that phlogopite from a Socorro Complex marble cooled through its Ar closure temperature at ~903.5 Ma ago, following high-grade metamorphism. Additionally, a minor secondary thermal event at ~60 Ma ago is suggested by modeling of the step heating data. The U–Pb data indicate that the Río Caña Granite was emplaced and crystallized in the Early–Middle Jurassic, at ~172.4 Ma, but that the source of the granite was, at least in part, continental crustal rocks containing 900-Ma-old zircons. The clastic metasedimentary rocks associated with the marble, or similar rocks at greater depth, are a likely source for these inherited zircons. The whole-rock K–Ar ages of 150–139 Ma reported for the granite by Somin and Millan (1981) evidently reflect either simple cooling of the granite (through ~100–200°C as discussed earlier) or a separate, later thermal disturbance.

Partial outgassing of the phlogopite, indicated by the low-temperature part of the $^{40}Ar/^{39}Ar$ age spectrum, may also reflect the emplacement and cooling of the granite, although this outgassing is more reasonably modeled as a later event. An additional problem with the latter interpretation is that heat flow considerations (Jaeger, 1957; discussed by Turner, 1981, pp. 18–24) suggest that a pluton of this size and general composition should have produced a temperature ≥400°C at a distance of 1 km from the contact. This almost certainly should have been sufficient to outgas >3.7% of the Ar from phlogopite, whose Ar blocking temperature is <372°C, the value calculated for a 1.0 mm diffusion radius and a cooling rate of 1000°C Ma^{-1} from the diffusion data of Giletti and Tullis (1977) using the formulation of Dodson (1973). Because of the poorly exposed contact relationships, however, we cannot be sure that the present relative positions of the marble and granite reflect their relative positions when the granite was intruded. A tectonic contact somewhere between the two units is possible, and the marble sampled for this study may have originally been further from the granite, possibly explaining the apparent absence of thermal effects from the intrusion on Ar isotopic systematics of the phlogopite.

Somin and Millán (1981) reported fragments of rocks resembling some Socorro Complex lithologies from the San Adrian gypsum diapir (Meyerhoff and Hatten, 1968), located ~40 km east of the city of La Habana. Among these are arkosic sandstones (resembling those of the Constancia Formation) and phlogopitic marbles. Fine-grained phlogopite separated from one of the latter yields a K–Ar date of 123±5 Ma (Somin and Millán, 1981). If this rock was indeed derived from the Socorro Complex, then the K–Ar date reflects a more complete outgassing of this phlogopite than observed in the sample reported above, probably a result of either its smaller grain size or variable thermal conditions during the reheating event, or both.

Regional tectonic implications

The Socorro Complex apparently represents a fragment of continental crust, whose history includes:

(1) pre-900 Ma deposition of dolomitic carbonates and siliciclastic sedimentary rocks;

(2) high-grade metamorphism of these rocks, probably at mid-crustal depth, at ~900 Ma;

(3) intrusion of the Sierra Morena Granite at ~172 Ma;

(4) uplift and erosion of the complex (represented by the Constancia Formation) prior to the Late Jurassic deposition of the Veloz Formation;

(5) a minor Late Cretaceous–Paleogene reheating event;

(6) cataclastic deformation of both the granite and the metasedimentary rocks, which is constrained only to be post-172 Ma.

The Socorro Complex contains a significantly older geologic record than is known from anywhere else in the Greater Antilles. Its tectonothermal history is markedly discordant with respect to those of the oldest known nearby rock units to the north and east, including those from DSDP holes 537 and 538A and peninsular Florida, which preserve a record of pervasive Pan-African (~650–500 Ma) age intrusion and metamorphism (Dallmeyer, 1984, 1987a, 1989; Dallmeyer et al., 1987). Neither the $^{40}Ar/^{39}Ar$ nor the U–Pb data presented herein show any evidence for Pan-African tectonothermal activity superimposed on rocks that were metamorphosed at ~900 Ma, which is remarkably similar in age to biotite K–Ar cooling dates from the Grenville belt (e.g., Berger and York, 1981; Dallmeyer, 1987b) and Llano Province

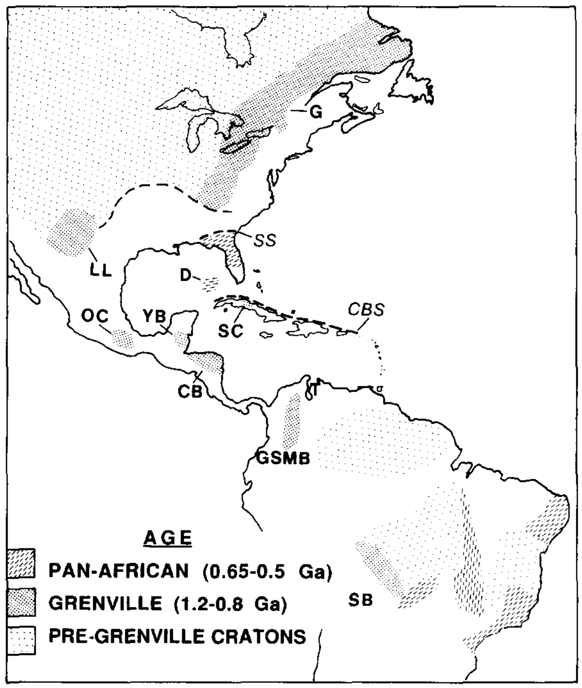


Fig. 8. Present-day distributions of Grenville (~1200–800 Ma) and Pan-African (~650–500 Ma) age orogenic complexes. Sources in text. G = Grenville Province, LL = Llano Province, D = DSDP holes 537 and 538A, OC = Oaxaca Complex, YB = Yucatan Block, CB = Chortis Block, SC = Socorro Complex, GSMB = Garzón–Santa Marta Belt, SB = Sunsas Belt, SS = Suwanee Suture, CBS = Caribbean-Bahamas Suture.

(Denison et al., 1984) of North America. Figure 8 shows the distribution of rocks strongly affected by the Grenville and Pan-African events, illustrating the apparent discordance across the Caribbean–Bahamas suture.

Grenville-age high-grade metamorphic rocks seemingly unaffected by Pan-African tectonothermal events occur in a discontinuous belt (Fig. 8) that extends from the Llano Province southward through the Yucatan block (Gomberg et al., 1968), Chortis block (Horne et al., 1976), and Oaxaca Complex (Ruiz et al., 1988; Ballard et al., 1989) of Central America; and the Garzón–Santa Marta belt of the Colombian Andes (Alvarez, 1981; Kroonenberg, 1982; Priem et al., 1989). The Sunsas belt of the western Amazonian craton may also be genetically related to the foregoing, although 1280–950 Ma thermal activity in the Sunsas orogen was dominated by voluminous granitoid intrusion and lower-grade metamorphism (Priem et al., 1971; Litherland and others, 1986) than amphibolite–granulite-facies metamorphism common to the other complexes mentioned above. The Sunsas belt further differs from these in being truncated to the southeast by a Pan-African (Brasiliano) mobile belt.

The Socorro Complex thus may represent part of an extensive Grenville orogen, characterized by high-grade metamorphism ± plutonism, which spanned the Americas during the Late Proterozoic. Correlations between the Grenville Province and the Garzón–Santa Marta belt of Colombia have been proposed before (Kroonenberg, 1982, and references therein), but the possible role of Caribbean and Central American terranes in such correlations have yet to be considered. A speculative reconstruction of part of the expanded Grenville orogenic belt, immediately prior to the Mesozoic rifting apart of Pangea, is shown in Fig. 9. This reconstruction places all the Central American/Caribbean crustal blocks (Chortis, Yucatan, Oaxaca and Socorro Complex) together in a landmass herein termed 'Caribbeana', bounded to the northeast by the Sonora–Mojave Megashear and to the southeast by the Colombian Andes. In this scenario, Caribbeana was subsequently fragmented and dispersed during the birth and motion of the Caribbean plate, beginning in the Middle Jurassic and continuing to the present. It must be emphasized that Fig. 9 does not attempt to reconstruct the Grenville (sensu lato) Belt at the time of its origin 1.2–0.8 Ga ago, but rather depicts its remnants just prior to the Mesozoic rifting of Pangea.

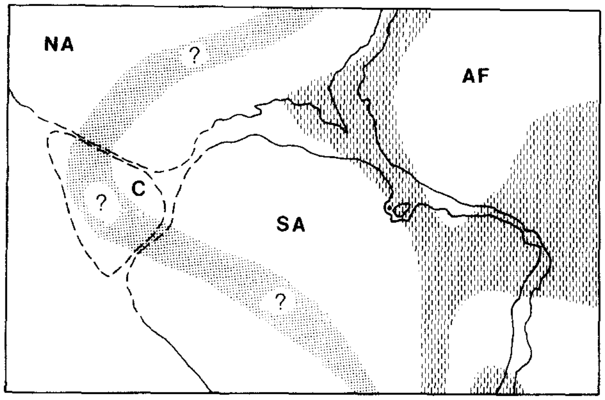


Fig. 9. Diagrammatic reconstruction of Pangea at ~180 Ma, showing Pan-African Orogens and postulated Grenville (sensu lato) Belt (queried where existence uncertain) discussed in text. NA = North America, AF = Africa, SA = South America, C = 'Caribbeana'.

The potassic Río Caña Granite is compositionally akin to intra-cratonic rift-associated granites, and its intrusion in the Middle Jurassic may have accompanied the rifting apart of Pangea. Uplift and erosion of the Socorro Complex by the Late Jurassic is not consistent with a simple post-rifting subsidence history beyond the Late Jurassic, but may instead reflect an earlier episode of plate collision prior to the widely recognized Late Cretaceous–Paleogene event. The age of subsequent cataclastic deformation in the Socorro Complex is poorly constrained, but this may have coincided with the thermal event indicated by $^{40}Ar/^{39}Ar$ data discussed previously. The rather poorly constrained age (~60 Ma) of this event is consistent with its occurrence during the Late Cretaceous–Paleogene collision of the Caribbean and North American plates.

The reconstruction depicted in Fig. 9 differs from most (e.g., those of Pindell and Dewey, 1982; Burke et al., 1984; Pindell, 1985) in that a much tighter fit between North and South America is obtained by removing the intervening crustal blocks which we place in Caribbeana. Details of the distribution of these blocks in a Pangea reconstruction is a major source of discrepancy between various published tectonic models, and their transport history during the early evolution of the Caribbean plate is not well understood. More quantitative data, particularly from geochronologic and paleomagnetic studies, are needed to help delineate the individual tectonothermal histories and tectonic motions of these fragments in order to help evaluate the foregoing speculations.

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