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AN OVERVIEW OF PRECAMBRIAN ROCKS IN SONORA

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ABSTRACT

The oldest stratified rocks recognized in NW Sonora (and in Mexico) are deformed muscovite-quartz schists, quartzites, and biotite-quartzofeldspathic gneisses near Caborca, which are cut by calcalkaline intrusives ranging from 1,710 to 1,750 m.y. in age. Southwest of Caborca, upper amphibolite facies layered quartzofeldspathic and amphibolitic gneisses were apparently deformed and metamorphosed at about 1,660 ± 15 m.y. ago, concealing original lithologies and ages. In northeastern Sonora, a younger belt of eugeosynclinal strata, about 1,680 ± 20 m.y. old was tightly folded and metamorphosed to greenschist facies about 1,650 m.y. ago. Numerous granitic plutons intruded into the older Precambrian crust about 1,410 to 1,440 m.y. ago. These major intrusive masses are not known to have been accompanied by regional sedimentation or deformation. Rare, small plutons of micrographic granite added to the Precambrian crystalline complexes about 1,100 m.y. ago, are the youngest Precambrian igneous rocks recognized. They limit the age of a thick miogeoclinal sequence of unmetamorphosed quartzose sandstones, carbonates with numerous stromatolite horizons, and shales which rest nonconformably on them. The sequence is overlain without unconformity by a fossiliferous Lower Cambrian section. The northwestern and northeastern Precambrian suits appear to be separated by a Jurassic magmatic arc and a postulated shear structure of large lateral displacement. Both suites correlate northward into related belts in the SW United States. To the east they are concealed by Phanerozoic cover. Abrupt termination of Precambrian exposures south and west suggets major younger tectonic features which we suspect played important but undefined roles in the apparent absence of Precambrian basement under much of northern and west-central Mexico.

RESUMEN

Las rocas estratificadas más antiguas reconocidas en el noroccidente de Sonora (y en México) son esquistos de muscovita y cuarzo, cuarcita y gneises cuarzofeldespáticos y de biotita deformados, que se presentan en las cercanías de Caborca y los cuales están cortados por intrusivos calco-alcalinos cuyas edades varían de 1,710 a 1,750 m.a. Al surponiente de Caborca los gneises cuarzofeldespáticos y anfibolíticos, estratificados y pertenecientes a la parte superior de la facies de anfibolita, fueron aparentemente deformados y metamorfoseados hace unos 1,660 ± 15 m.a., ocultando litologías y edades originales. En el nororiente de Sonora los estratos eugeosinclinales, pertenecientes a un cinturón más joven y de cerca de 1,680 ± 20 m.a., fueron intensamente plegados y metamorfoseados alcanzando la facies de esquisto verde hace unos 1,650 m.a. Numerosos cuerpos plutónicos graníticos fueron intrusionados en la corteza precámbrica más antigua hace unos 1,410-1,440 m.a. No se sabe si estos cuerpos intrusivos fueron o no acompañados por sedimentación regional o deformación. Esquistos con pequeños cuerpos plutónicos de granito micrográfico se incorporaron a los complejos cristalinos precámbricos hace unos 1,100 m.a. y son las rocas ígneas precámbricas más jóvenes reconocidas. Estas delimitan la edad de una secuencia gruesa miogeoclinal no metamorfoseada, formada por areniscas cuarcíticas, rocas carbonatadas con numerosos horizontes de estromatolitos y por lutitas que descansan sobre éstas con relación discordante. Esta secuencia está cubierta, sin discordancia alguna, por una secuencia fosilífera del Cámbrico Inferior. Los ensambles noroccidental y nororiental del Precámbrico parecen estar separados por un arco magmático jurásico y por una estructura de cizallamiento postulada, de desplazamiento lateral mayor. Ambos ensambles se correlacionan hacia el norte con cinturones relacionados de la parte suroccidental de Estados Unidos. Hacia el oriente están sepultados por la cubierta fanerozoica. La terminación abrupta de los afloramientos precámbricos hacia el sur y hacia el poniente sugiere la presencia de rasgos tectónicos más jóvenes y mayores, los cuales sospechamos que hayan jugado un papel importante, pero aún no definido en la ausencia aparente del basamento precámbrico, distribuido debajo de la mayor parte de México septentrional y centro-occidental.

INTRODUCTION

OBJECTIVES AND DESIGN OF THIS PAPER

Our objective in this paper is to provide an introduction to the geology of Precambrian rocks with emphasis upon their stratigraphic and chronological relationships. Our approach is to give specific examples which reveal our methodology, including a combination of geological mapping and geochronology with associated investigations of structure, petrography and chemistry. Where data is not sufficient to provide this insight, we have synthesized data on a regional basis to provide a complete overview of relationships.

NATURE AND DISTRIBUTION OF EXPOSURES

Outcrops most commonly occur in seemingly disconnected, isolated ranges, surrounded by pediments which slope into broad, shallow alluvial valleys. In western Sonora these ranges, which form part of the basin and range physiographic province, lie within the arid Sonoran desert and in places appear as stark erosional remnants. Vegetation increases somewhat from west to east as does elevation and east of the main road between Nogales and Hermosillo, north-trending parallel ranges and valleys are distinctively more covered.

No systematic distribution of exposures of Precambrian

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rocks exists and no range is known to be comprised exclusively of Precambrian crystalline rocks. The total extent of well-exposed Precambrian crystalline rocks is probably not more than several thousand km^2.

PREVIOUS WORK

Initial investigations of the crystalline rocks were prompted after Gómez and Torres discovered an incomplete sequence of carbonate and clastic rocks, whose ages range from late Precambrian through Paleozoic, and unconformably overlie the crystalline basement (Cooper and Arellano, 1946; Arellano, 1956). Initial radiometric studies were made by Damon and colleagues (1962) on rocks which crop out in ranges between Caborca and Bamori ranch about 40 km south (Figures 1 and 2). Aside from Fries' (1962) geologic summary emphasizing Paleozoic rocks, and more recent reconnaissance mapping by Merriam (1972), no regional studies have focused upon the geology of the Precambrian crystalline rocks. The late Precambrian sedimentary sequence which crops out south of Bamori ranch was studied and subdivided by Eells (1972). A brief paper by T.H. Anderson and Silver (1977) argued for the existence of Precambrian granite basement at Cananea, based upon geochronologic studies of U-Pb isotopic relations in zircon.

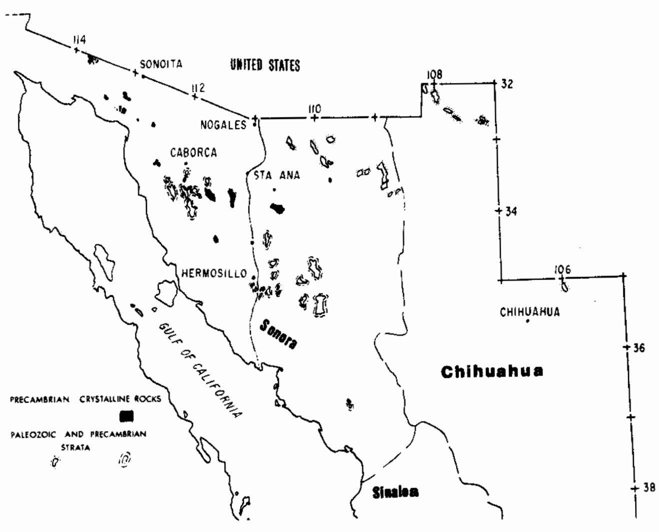

Figure 1.- Distribution of prominent outcrops of basement and pre-Mesozoic cover rocks, Sonora. Black - 1.8 to 1.7 b.y. basement. Gray - 17. to 1.6 b.y. - basement. Solid line with dot border - Paleozoic cover; solid line with dashed-line border - Precambrian and Paleozoic cover.

A synthesis of regional geologic relationships among rocks of inferred Precambrian age by de Cserna (1971) included discussion of the Sonoran basement, as did the compilation of radiometric ages in relation to the metallogenetic chart of Mexico by G. P. Salas (1975).

In north-central Sonora, initial reconnaissance field mapping of a widespread area northwest of Santa Ana by G. A. Salas (1968) revealed the presence of an extensive suite of greenschist-facies rocks comprised mainly of phyllite with subordinate marble, metaconglomerate, quartzite and metagraywacke. In places, mineral assemblages characteristic of the almandine-amphibolite facies occur. G. A. Salas concluded that the layered rocks were composed of two suites, both of which are of Precambrian age. His conclusion was based upon the fact that metamorphism recorded in this region is comparable to that reported from areas of Precambrian crystalline rocks which crop out south of Caborca, further west. To date no paleontologic or radiometric studies which bear directly upon the age of the *layered* rocks have been conducted; however, regional geologic studies do not support a unique Precambrian age assignment for these strata and younger ages cannot be discounted.

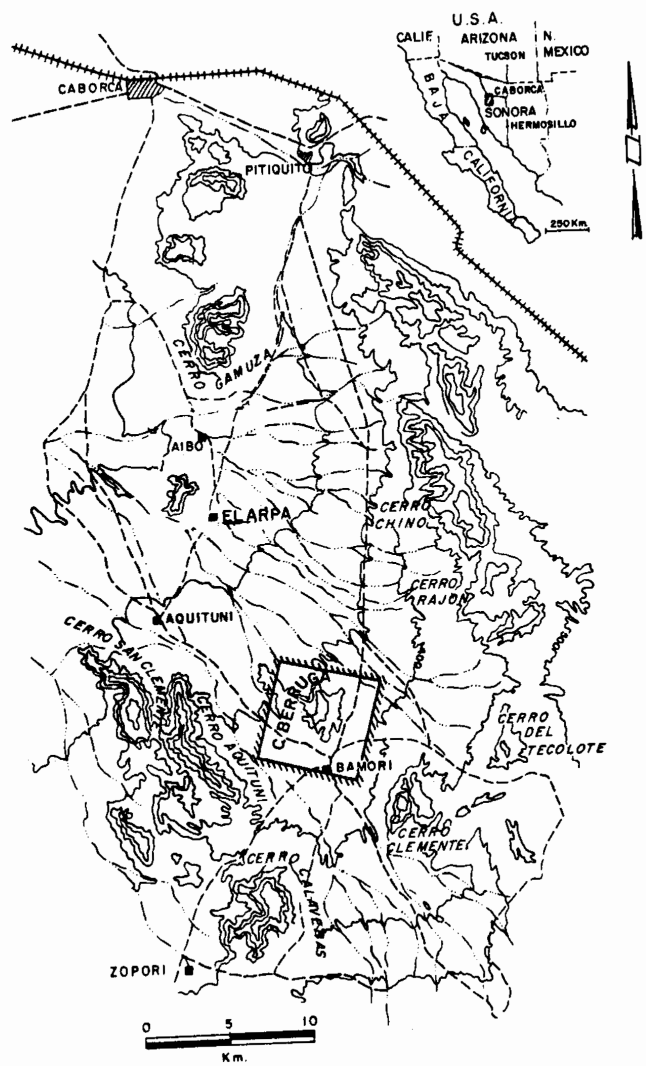

Figure 2.- Topographic map of the Caborca-Bamori region, Sonora, Mexico.

PRECAMBRIAN OROGENIC SUITES IN NORTHWESTERN MEXICO

Major belts of Precambrian crust, which started to form more than 1,800 m.y. ago, and whose framework was completed not later than 1,600 m.y. ago, comprise the fundamental elements of Precambrian basement in northwestern Mexico. Figure 3 shows the distribution of rocks comprising the two older Precambrian cycles in Sonora. The oldest suite, composed of 1.8 - 1.7 b.y. old rocks, includes para - and orthogneisses, quartzose clastic rocks, and sparse schistose units whose silicic character is in contrast to correlative greenstones of central Arizona (Anderson, C. and Silver, 1976). Mineral assemblages characteristic of amphibolite facies are widespread, although south of Caborca greenschist-grade rocks are preserved within a small fault block. These rocks show considerable variation in the degree of deformation. At many places they exhibit banding or foliation which commonly trends northeasterly; however, lack of detailed mapping has precluded the identification of characteristic styles and patterns of folding.

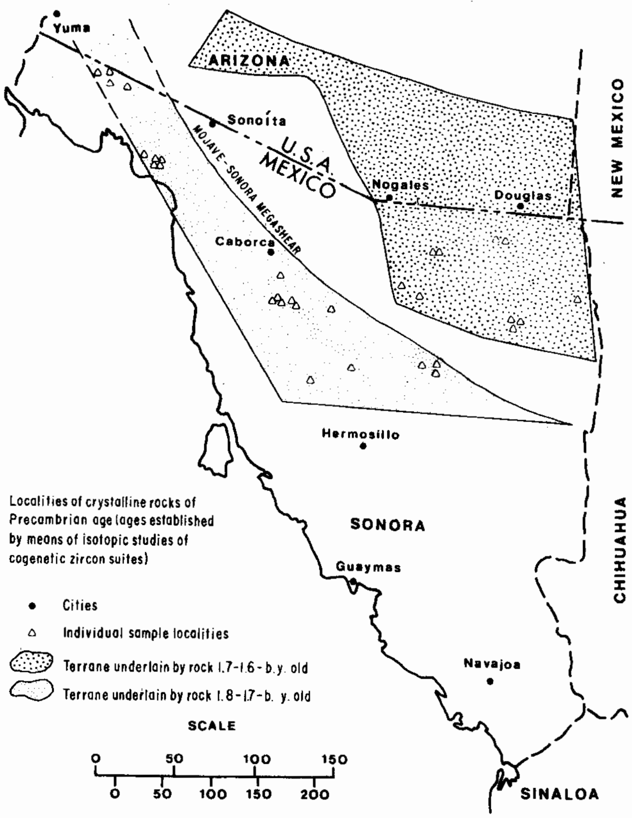

Figure 3.- Extent to Precambrian basement in Sonora, as indicated by the distribution of isotopically studied samples.

Plutons, intrusive into the layered suite, consist of equigranular quartz diorite to quartz monzonite and may be strongly foliated, weakly foliated or unfoliated.

Strongly metamorphosed paragneisses and pegmatites formed during metamorphic segregation yield isotopic zircon ages between 1,645 and 1,685 m.y.

Rocks formed during the interval from about 1,700 to 1,640 m. y. are restricted to northeastern Sonora (Figure 1). In contrast to the gneisses of the older belt, these units are commonly schistose or slaty and distinguished by their greenschist grade of metamorphism. Lithologic similarities between the strata of this area and Pinal Schist are striking and radiometric studies indicate them to be correlative. Preliminary study along the southwestern margin of this belt indicates the presence of distinctly more mafic equivalents.

Numerous, widespread, younger plutons of porphyritic granite, whose ages fall in the interval between 1.5 b.y. and 1.4 b.y., have also been identified as have rare masses of micrographic granite whose ages are consistently about 1,100 m.y. old (Figure 4).

Precambrian basement within the terranes of oldest rocks has been most extensively studied in the Berruga Hills, which will be discussed below in some detail.

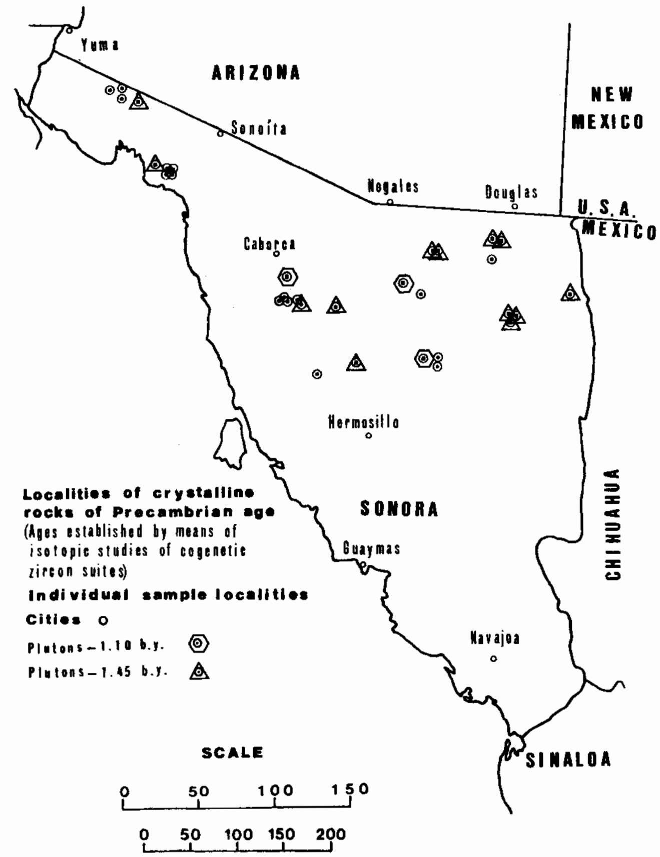

Figure 4.- Distribution of some Precambrian anorogenic plutonic rocks in Sonora, as indicated by U-Pb isotopic studies of cogenetic zircon suites.

GEOLOGY OF THE OLDER PRECAMBRIAN ROCKS OF THE BERRUGA HILLS

Geological setting.- The hills surrounding Cerro Berruga (Figure 2), which must be distinguished from nearby Sierra de la Berruga, comprised dominantly of late Precambrian sedimentary rocks described by Eells (1972), lie just north of Bamori ranch, about 35 km south of the city of Caborca, Sonora. The area is southwest of Tucson, Arizona, about 150 km south of the international border between Mexico and U.S.A.

Elongate ranges between Caborca and Bamori generally trend roughly N-S. Structural attitudes and distribution of rocks of various ages suggest the existence of a regional anticline whose axis is paralleled by a N-S line between Caborca and Bamori, although the structure has been locally strongly modified by younger faults. Near Caborca, late Precambrian carbonate and clastic beds rest nonconformably upon the Aibo micrographic granite and in places are overlain by Paleozoic units. Ranges comprised of these beds delineate, in a gross sense, the north end of the anticline. Farther south, toward Bamori, the west flank is poorly defined by scattered small hills, and ranges on line with the east flank consist of strongly deformed Mesozoic rocks that form steep canyons and jagged peaks more than 1,000 m high. Photo lineations and stratigraphic juxtapositions suggest that these rocks may be allochthonous masses rather than part of an original fold limb.

In the Berruga Hills crystalline basement is locally unconformably overlain by beds whose stratigraphic position and lithology suggest late Precambrian age, although no paleontologic or radiometric data pertaining to their age has been collected at this locality. In the areas west and south of Bamori, ranges consisting of strongly folded late Precambrian and Paleozoic sediments commonly are separated from crystalline rocks by faults.

Berruga Hills are remarkable because of the preservation of a small area of greenschist-grade metamorphic rocks within a regional terrane characterized by upper-amphibolite facies rocks. Prior to metamorphism the layered sequence consisted mainly of quartzose sandstone and siltstone which was intruded by sills and concordant lenticular masses of rhyodacite and hornblende diorite (now hornblende amphibolite). Primary features, such as cross-stratification and igneous contacts and, to a lesser degree original bedding and igneous and sedimentary textures, are preserved in the small area of greenschist-grade rocks located in the southwestern part of the hills (Figure 5). The southeasterly dipping homoclinal sequence is bounded by faults which separate this block from higher grade terrane. Across the faults, although metamorphic grade and intensity of deformation increase markedly, the association of recrystallized quartzite, biotite-muscovite schist, massive quartzofeldspathic gneiss and amphibolite, which shows minor compositional differences from the less-metamorphosed rocks, suggests correlation.

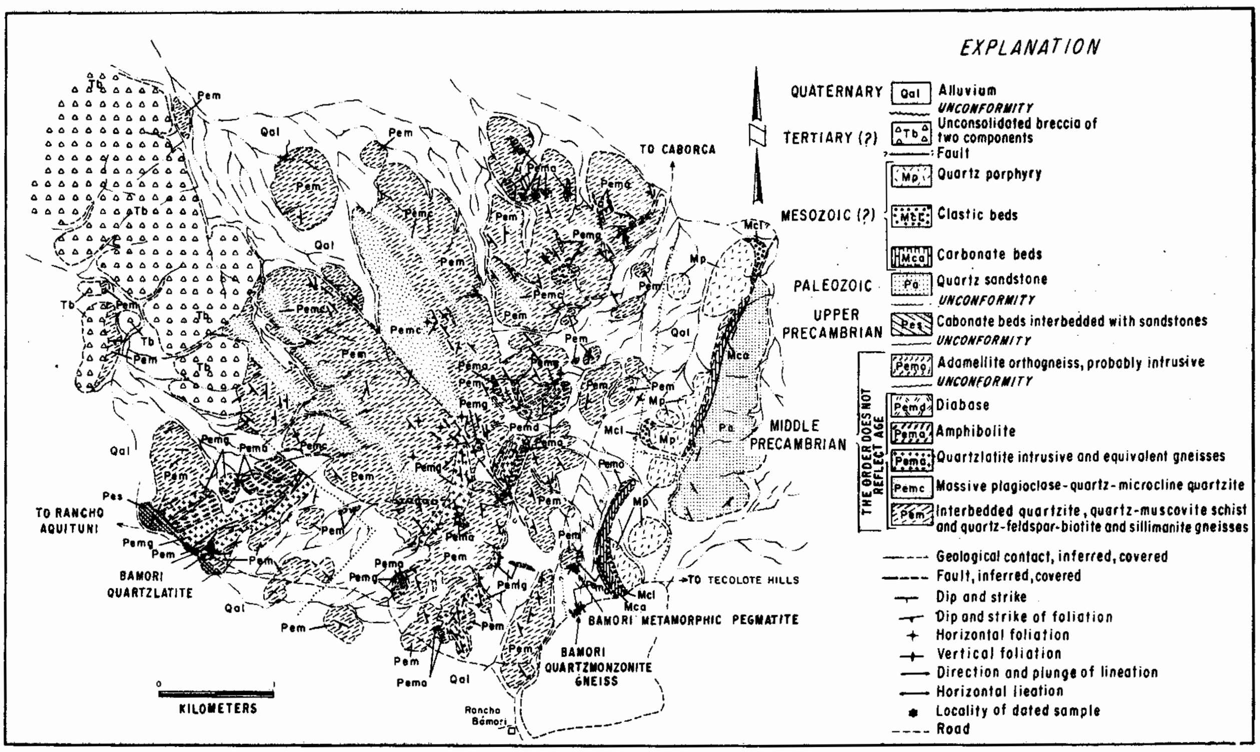

Figure 5.- Geologic map of Berruga Hills.

Metasedimentary rocks.- The most common metasedimentary lithologies are gray quartzite, muscovite metasandstone and quartz-sericite or muscovite schist derived from fine to medium-grained argillaceous quartz sandstone, quartz sandstone, feldspathic sandstone and siltstone. These weather to shades of brown commonly with sparkling flakes of sericite on the bedding planes. No rock fragments were seen in the beds either in the field or during microscope examination. Thin sections reveal abundant quartz grains with less common microcline, altered plagioclase and flakes of sericite, muscovite, biotite and chlorite. The platy minerals are weakly to strongly oriented and define schistosity which is parallel to bedding. Quartzose beds are commonly less than 10 cm, thick but in places may be many centimeters thick. Thickness of beds of sericitic schist is somewhat obscured by schistosity, but is probably similar or less than the quartz-rich beds. In places, individual quartz-grains and cross-stratification are easily recognized in the quartz sandstones, although quartzite may show an incipient gneissic fabric.

Across the faults, that isolate the low grade metamorphic terrane, the increase in metamorphic grade and intensity of deformation is marked. Here, quartzite, quartz-microcline gneiss (with ubiquitous biotite, chlorite and/or muscovite as accessories) and scattered quartz-biotite schist are interlayered with irregular bands of associated hornblende-plagioclase amphibolite and plagioclase-quartz-microcline gneiss. Quartzose gneiss is the most common rock type and scattered beds, as thick as 100 m of clean, massive recrystallized quartzite have been used as stratigraphic markers to delineate structure. Rare conglomeratic beds crop out.

Intrusive rhyodacite.- Brownish-gray porphyritic rhyodacite (Table 1), which weathers reddish-brown with reddish-orange phenocrysts, intruded the sedimentary rocks as concordant sheets with sharp, slightly sheared contacts. The masses are commonly several tens to more than 100 m thick and consist of plagioclase phenocrysts (as much as 10 percent) and distinctly fewer quartz phenocrysts (about 1 percent) in an aphanitic matrix. The euhedral to subhedral plagioclase phenocrysts are about 1 mm to 4 mm long and almost all grains show moderate to intense sericitization. Quartz phenocrysts average about 0.3-0.4 mm and are commonly round or slightly elongate anhedral individuals or mosaics. The groundmass is a very fine-grained intergrowth of recrystallized quartz and feldspar with common opaque grains. Weakly oriented flakes of biotite and chlorite define incipient planes of schistosity. From the interior of the masses outward, schistosity becomes better defined and at the margins it is well-developed. In places, the contact with sedimentary rocks is knife-sharp with almost no textural variation aside from slight increase in abundance of mica flakes which show preferred orientation. Locally, where shearing has been intense along thin, elongate wedges of sedimentary strata trapped between igneous masses, the porphyry may be converted to mica schist where feldspar phenocrysts have been granulated and distinction from sedimentary schist may be difficult.

Table 1.- Chemical and normative analysis of Bamori rhyodacite.

RHYODACITE
(Weight Per Cent)

Chemical Analysis:		C.I.P. W. Norm:	
SiO_2	70.02	Quartz	29.12
Al_2O_3	13.43	Orthoclase	33.37
Fe_2O_3	2.99	Albite	24.41
FeO	1.90	Anorthite	4.95
CaO	1.16	Corundum	0.88
MgO	0.55	Hypersthene	1.65
MnO	0.04	Magnetite	4.37
Na_2O	2.86	Ilmenite	0.96
K_2O	5.60	Apatite	0.30
$H_2O^{(+)}$	0.78		
$H_2O^{(-)}$	0.31		
TiO_2	0.50		
P_2O_5	0.13		
CO2	0.13		
F	0.04		

Analyst: Tadashi Asari

Within the higher-grade terrane masses of plagioclase-quartz-microcline gneiss are interpreted to be correlative with compositionally similar rhyodacite. This correlation is based upon the consistent geographical proximity of amphibolite with feldspar-quartz gneiss, and their outcrop distribution which suggests that they are instrusive (Figure 5). Intense deformation has obscured primary evidence of intrusion such as igneous contacts or xenoliths. However, interfingering amphibolite, plagioclase-quartz-microcline-gneiss and quartz-mica schist and gneiss define more or less coherent, generally concordant belts which suggest relationships similar to those of the less metamorphosed rocks. The composition of the gneiss is mineralogically similar to less metamorphosed rhyodacite (Tables 1-2).

Table 2.- Mineral composition of plagioclase-quartz-microcline gneiss.

	1	2	3	4	5	6	Average
Quartz	32	26	32	22	37	36	31
Plagioclase ($An_{12\text{-}28}$)	37	31	36	39	20	30	32
Microcline	17	32	12	20	21	22	21
Chlorite and biotite	12	9	17	14	20	8	13
Muscovite	--	--	--	--	2	2	1
Opaques	1	3	3	3	1	2	2
Apatite	trace	trace	trace	trace	trace	trace	trace
Zircon	trace	trace	trace	trace	trace	trace	trace
Epidote	--	--	--	--	--	trace	--

* Based upon 1000 points per thin section

Plagioclase-quartz-microcline gneiss commonly weathers pale brown and can be identified in the field on the basis of its lack of stratification, its homogeneous texture, its consistent mineralogical composition and the presence of abundant poorly to moderately defined pale orange porphyroblasts (relict phenocrysts?). Foliation is moderately to well-defined by oriented flakes of mica and some samples show lineation defined by elongate to rod-shaped grains and aggregates. Round or lens-shaped porphyroblasts (?) range from slightly more than 1 mm to almost 5 mm. They consist either of single grains of plagioclase with small patches of microcline and/or quartz inclusions or of grains which no longer consist of coherent plagioclase crystals, but of a mosaic of equidimensional grains of plagioclase and microcline (with less abundant quartz). Recrystallized matrix consists of anhedral plagioclase, quartz and microcline with weakly to strongly oriented flakes of mica.

Rare samples reveal well-preserved igneous textures with phenocrysts of plagioclase and quartz in a fine-grained matrix. Microscopically, relict phenocrysts consist of strongly sericitized poikilitic feldspar with numerous inclusions of quartz in a groundmass of feldspar, altered to sericite, epidote minerals, and quartz.

Amphibolite.- Concordant lenses of amphibolite, in places more than 100 mm thick, parallel the strike of an interfinger with adjacent rhyolite and quartzose sediments. Fresh exposures are greenish black, whereas weathered surfaces show black aggregates of hornblende prisms, commonly more than 1 mm across, in a matrix of small laths of plagioclase and prisms of hornblende. In thin section, anhedral grains of blue-green hornblende are set in a fine-grained matrix of slightly oriented, sericitized plagioclase laths and hornblende prisms with less abundant opaques and rare quartz.

Amphibolite is common throughout the higher grade metamorphic terrane and is found as elongate and irregular masses associated with plagioclase-quartz-microcline gneiss and also in small pods, lenses and nondescript masses in metasedimentary rocks. In fresh exposures it is greenish black and weathers to a dark reddish brown or grayish orange, depending upon the amount of hornblende versus plagioclase. Weathered surfaces show aggregates and small prisms of hornblende imbedded in the lighter colored groundmass. The elongate plagioclase and hornblende do not define foliation but can define distinctive lineation, although some masses show little if any preferred mineral orientation. In thin section anhedral to subhedral yellowish-green hornblende and plagioclase, altered to white mica and clinozoisite, predominate with less abundant quartz, biotite, opaques and apatite.

Adamellite gneiss.- East of the road between Bamori and Caborca and just north of the dam at Bamori ranch, rare exposures of foliated adamellite crop out. Poor outcrops occur on the east side of the first small mound of quartzite on the east side of the road north of the ranch. A short distance to the east across the dry wash, gneiss underlies a low ridge of gray carbonate rocks (Figure 5). In hand specimen the rock consists of interlayered pink and dark gray laminae a few millimeters wide that consist predominantly of potassium feldspar and altered mafic minerals, with less conspicuous quartz and plagioclase. North of the dam, foliation is vertical and trends N 10°-20° W, although the strike varies to N 25° E as one proceeds north. Horizontal lineations are defined by undulations on the foliation planes that parallel color streaks caused by smeared mineral aggregates.

Microscopically, the gneiss consists of almost equal amounts of anhedral grains, some of which are elongate, of plagioclase, potassium feldspar and quartz (Table 3). Grain sizes vary from about 0.75 mm to 2 mm. Moderately oriented chloritized biotite in elongate anhedral to subhedral plates and patches associated with accessory apatite, opaques and zircon define the planar fabric. Fractured grains and narrow granulated zones are numerous. Epidote is present in small veins, irregular patches and as a product of moderate to intense alteration of plagioclase. Potassium feldspar is cloudy.

Table 3.- Mineral composition of Bamori adamellite gneiss and a cross-cutting metamorphic pegmatite.

	Adamellite gneiss	Metamorphic pegmatite
Quartz	28	32
Plagioclase (An_{8-38})	28	37
Orthoclase & Microclase	28	30
Biotite and chlorite	11	1
Opaque minerals	1	trace
Epidote	1	--
Sphene	trace	--
Apatite	1	--
Zircon	trace	trace
Mis. alteration products e.g. calcite, Ti-oxide	2	1

* Based upon 3 thin sections - 1000 points per thin section

The contact with the adjacent metaquartzite is concealed by rubbly float. In places near the contact, gneiss is transitional into foliated amphibolite. Short dikes and pods of aphanitic mafic rock and feldspathic aplitic dikes also crop out, but show no discernable deformational fabric.

Pegmatite.- Intrusive pegmatites, commonly several centimeters to more than half a meter wide, which consist mainly of potassium feldspar, quartz, and muscovite, cut the low grade rocks at scattered localities. Contacts are sharp and in places undeformed pegmatites can be seen to cut foliated quartz latite. The long axes of the major pegmatite minerals are oriented perpendicular to the walls of the pegmatite.

Within the Bamori adamellite gneiss, unfoliated metamorphic pegmatites in zones 15-20 cm wide cut gently across the trend of foliation. The contact between gneiss and pegmatite occurs across a zone a few centimeters wide, where one observes a gradual coarsening of major mineral constituents which include plagioclase, quartz, and potassium feldspar with rare chloritized biotite flakes. This mineralogy is transitional into a quartz-rich core. In thin section (Table 3) the anhedral grains are commonly 3-4 mm wide, although grains as large as 5-6 mm are present. As observed in the gneiss, some grains are fractured and zones of granulated minerals are present.

Pods and lenses of coarse-grained mafic-poor pegmatite are also scattered throughout the terrane of paragneisses. Mineralogy and boundaries which show transition to normal country rock suggest that these pegmatites were generated essentially in place from adjacent beds during the acme of metamorphism.

Structure.- The major fold structure in the Berruga Hills is a northwesterly trending asymmetrical antiform which plunges gently southeast (Figure 5). The flanks of the fold are delineated by massive metaquartzite units (Figure 5). Trends of compositional planes in banded gneisses and foliation in more micaceous beds and linear elements such as trains of smeared mineral grains, finely-rippled surfaces on metaquartzite, and aligned, mafic minerals on foliation planes that parallel the fold axes as well as small folds that indicate flowage of metaquartzite suggest that this fold formed during culmination of Precambrian metamorphism and deformation. The nose of the fold has been broken by faults, some of which parallel and others of which break across the structure. Locally, laminated micaceous beds bounded by quartzose gneiss show tight folds. Cleavage which cuts compositional bands is uncommon, although locally even massive quartzite may show fracture cleavage. In the southwest flank of the antiform, bedding of massive quartzite beds parallels the structural trend; at other localities the intensity of deformation and the lack of stratigraphic markers obscure the relationships between structural surfaces and primary stratigraphic planes.

Faults isolate the area underlain by rocks of greenschist grade from the terrane characterized by almandine-amphibolite facies rocks. In the low-grade area, bedding in metasedimentary rocks and foliation in the igneous intrusive rocks trend northeasterly and dip to the southeast. Cross-beds in quartz sandstone indicate that the homoclinal sequence is right side up. Bedding surfaces of phyllitic units in the northwestern part of this area show intersecting sets of crenulations, but exposures that showed these structures are scarce, and too few measurements were made to determine their role in the deformational history.

During Mesozoic and Cenozoic time regional deformations have been superposed upon the older rocks. In the eastern Berruga Hills, moderately to shallowly dipping faults juxtapose Precambrian orthogneiss, Mesozoic sedimentary rocks, quartz porphyry and worm-burrowed (scolithus tubes?) Cambrian (?) quartzite. Regional observations suggest that the sedimentary units are part of allochthonous sheets which overlie the crystalline Precambrian rocks. As yet it is not known if parts of the basement are included in the allochthonous sheets.

In the westernmost part of the map area crystalline basement is overlain by a veneer consisting of unsorted blocks, some of which are many meters long. Two main lithologies, which are tentatively correlated with units in the late Precambrian sequence, are present; rusty weathering quartz sandstone and gray carbonate with abundant algal mats. Small fragments of crystalline rocks can be found, but are probably derived from adjacent areas or from rare scattered windows through the sheet. The contact between the blocky rubble and underlying basement is horizontal or nearly so. The origin of this debris sheet is unknown.

Metamorphism.- Damon and colleagues (1962) briefly concluded that initial metamorphism was of the hornblende-hornfels facies and that a later somewhat lower-grade event resulted in retrograde effects. Although mineral assemblages in the examined thin sections reveal effects of retrograde metamorphism, a persistent relict assemblage in the quartzose metasedimentary rocks of the hornblende-hornfels facies includes quartz-microcline-plagioclase-biotite-sillimanite, with an unidentified totally altered accessory (garnet?) in some beds. This relict accessory occurs as irregular, elongate poikiloblastic grains which show ubiquitous alteration to a fine grained mixture of chlorite and white mica. Its form and alteration characteristics distinguish it from plagioclase which shows less intense, less pervasive alteration.

Pervasive retrograde metamorphism has affected all the rocks. Quartz and microcline are unscathed; biotite has been moderately to strongly altered to chlorite and muscovite; sillimanite is everywhere sheathed by plates or fibrous pseudomorphs of muscovite; plagioclase also shows weak to intense alteration mainly to sericite or less commonly to epidote minerals. As mentioned above, one mineral species has been replaced beyond recognition by chlorite and white mica. In the small, fault-bounded area, initial metamorphism was of the middle greenschist facies, as suggested by oriented biotite which defines foliation in the silicic instrusive rocks.

Muscovite is a ubiquitous constituent of all quartzose rocks examined. However, it is probably predominantly a product of retrograde effects rather than a participant in the primary mineral assemblage. This is suggested by its replacement of the borders of fibrous masses of sillimanite, by its replacement of biotite, and in some rocks by its presence as flakes formed in plagioclase by coalescence of fine-grained micaceous alteration. Commonly, subhedral rectangular plates of muscovite lie athwart the foliation defined by biotite. These plates can be several millimeters long and enclose shreds of chloritized biotite, quartz inclusions and opaques. Randomly oriented muscovite, formed by replacement and perhaps by growth of new flakes, is particularly abundant and well-developed adjacent to the margins of igneous quartz-feldspar-muscovite pegmatites that cut across foliated rocks of the greenschist-grade terrane.

Geochronological conclusions.- In an effort to establish time of accumulation, metamorphism, deformation and plutonism for the older Precambrian crystalline rocks of the area, we collected samples of igneous and metamorphic rocks which have been dated by means of isotopic analyses of uranium-lead ratios in zircons from Cerro Berruga and from nearby outcrops. This work complements initial studies in the area by Damon and colleagues (1962).

We interpret the upper intercept age of 1,755 ± 20 m.y. for the Bamori rhyodacite to be the time of original crystallization. This age provides a minimum for the accumulation of the sedimentary beds in the Berruga Hills. The well-preserved original igneous texture of the intrusive and the fine, internal zoning and inclusions of the zircons argue convincingly that this is a primary crystallization age, although metamorphic effects have been superficially recorded by the zircon crystals. Furthermore, on the basis of previously noted geological observations and comparisons, it is suggested that the well-preserved intrusive quartz latite is correlative with the plagioclase-quartz-microcline gneiss in the more intensely metamorphosed and strongly deformed parts of the terrane.

Although suffering somewhat more severe external metamorphic effects than the rhyodacite, analyzed zircons from the Bamori adamellite gneiss and the Tecolote granodiorite gneiss, indicate the age of crystallization of the plutonic bodies to be 1,745 ± 20 m.y. Lack of overgrowths, inclusions, and scattered zoned grains, and lack of contrary geological evidence suggest that the zircons record crystallization during the emplacement of plutons which followed, after a short geologic interval, the accumulation of a sedimentary pile. Unfortunately, in the Berruga Hills geologic observations do not provide independent confirmation of the chronological relationships, although in other regions correlative rocks clearly show the intrusive relationship.

Finally, the ages of 1,635 ± 20 m.y. and 1,680 ± 20 m.y. of zircons derived from the metamorphic pegmatites are interpreted as a time interval during which newly-formed zircon crystallized in favorable environments in response to temperatures and pressures accompanying metamorphism. The nature of the geological relationships between the foliated orthogneisses and the undeformed, cross-cutting pegmatites, combined with inherent characteristics of the cogenetic zircon suites, which include internal zoning; rare zoned overgrowths enclosing zircons which resemble those of the orthogneisses; different habits and uranium content than zircons from the orthogneisses; and absence of faceting caused by metamorphism suggest that the pegmatites formed and crystallized after the enclosing gneiss. The age of the zircons from the pegmatites is interpreted to be the time of the last strong, regional, thermal culmination until Mesozoic time, when multiple metamorphic events were recorded in other areas. We have recognized this strong Precambrian metamorphism and deformation in other parts of Sonora and they have been identified previously to the north in Arizona (Silver, 1964; Pasteels and Silver, 1965).

Scattered, pink, feldspar-quartz-muscovite intrusive pegmatites cut the moderately foliated metamorphosed sequence within the small area of greenschist-grade rocks. Near these pegmatites, flakes of muscovite without preferred orientation are scattered throughout the country rock. Although past-deformational plutons have been studied at many localities in Arizona (Silver and Deutsch, 1963; Silver, 1964; Silver, 1968), no large masses of 1,600-1,700 m.y. old plutonic rocks have been identified in Sonora, and these pegmatites may have emanated from nearby centers of strong metamorphism.

OTHER 1.8-1.7 B.Y. OLD ROCKS

Reconnaissance geology and geochronology have enabled us to determine the extent of the terrane composed of Precambrian crystalline rocks correlative with those forming Berruga Hills. Correlation is based upon the presence of layered gneisses, generally characterized by mineral assemblages of amphibolite facies metamorphism, cut by granitic plutons which may or may not be foliated and consistently yield ages close to 1,750 ± 25 m.y. At localities where we were able to date metamorphic pegmatites and/or paragneisses whose mineral assemblages indicate highest amphibolite to granulite facies metamorphism, zircons yield ages close to 1,675 m.y.

We have not discovered interstratified volcanic materials which will enable us to determine the time of accumulation of the layered rocks. However, most ranges have received little attention and several ranges in western Sonora (Figure 1) have extensive mountainous exposures in addition to widespread sediment surfaces possibly underlain by crystalline rocks which no doubt can yield considerable additional information.

GEOLOGY OF THE OLDER PRECAMBRIAN ROCKS OF NORTHEASTERN SONORA

Known outcrops of distinctively schistose, micaceous sediments which bear strong resemblance to some of the rocks called Pinal Schist in Arizona are restricted to northeastern Sonora (Figures 1 and 3). Precambrian rocks are known from Sierras San Jose, Maiderabachi, Los Ajos, Nacozari, Anibacochi and Magallanes.

The dominant lithology observed in the course of our reconnaissance is muscovite schist with common interstratified slaty, sandy beds and volcaniclastic units rich in quartz and feldspar.

East and west of the zone of layered rocks, known Precambrian basement is comprised of younger intrusive granitic plutons.

ANOROGENIC PLUTONS OF PRECAMBRIAN AGE

Following the incorporation of the older Precambrian suites with the margins of previously existing crust, two subsequent periods of Precambrian plutonism occurred (Figure 4). The older plutons, whose ages fall within the interval 1,460-1,410 m.y., comprise an anorogenic, apparently consanguineous suite which is volumetrically one of the major elements of Precambrian basement (e.g. Anderson, T. H. and Silver, 1977). These intrusives, which invade both older terranes, are consistently medium- to coarse-grained granodiorite to granite with conspicuous, large, pink, feldspar megacrysts which commonly show rapakivi texture. They are generally undeformed, although locally they may be foliated.

In contrast to the abundant 1.4 b.y. old plutons, 1.1 b.y. old intrusives are rare. However, these younger masses are also lithologically distinctive. The three known representatives are readily distinguished because they are all medium-grained brick-red granite, with micrographic intergrowths, sparse, altered mafics, and cloudy feldspar.

No layered sequences of volcanic or sedimentary rocks are known to be associated either spatially or chronologically with these plutonic episodes, and other than local contact metamorphic effects, no regional deformation or metamorphism is contemporaneous or nearly contemporaneous.

BOUNDARIES OF THE PRECAMBRIAN CRYSTALLINE BASEMENT

The western limit of the Precambrian crust in Sonora coincides with the apparent southward extension of the San Andreas fault system. Although not established as a fault in Sonora, the western boundary of known basement rocks defines a straight line for at least 150 km (Figure 3).

South of Hermosillo, no Precambrian rocks are known. Basement rocks appear to end along a crudely defined east-west line, about 50 km north of Hermosillo and the abruptness of the contact suggests a tectonic boundary.

Paleozoic beds, composed of interbedded carbonate and clastic units as old as Cambrian and quartz sandstone and paludal sediments of Upper Triassic - Lower Jurassic, are known south of the limit of Precambrian basement and crop out in ranges east and south of Hermosillo. The basal contacts of these sequences have been obliterated by Mesozoic plutons and basement for these beds is unknown.

In easternmost Sonora and adjacent Chihuahua, extrusive rocks cover much of the region and the distribution of basement rocks in this region is unknown.

In northern Sonora, significant areas of no basement exposure crudely define a zone, in places several tens of kilometers wide (Figure 3). This belt separates blocks of Precambrian crust along a northwesterly- trending trace coincident with the hypothetical Mojave-Sonora megashear (Silver and Anderson, T. H., 1974).

LATE PRECAMBRIAN SEDIMENTARY ROCKS

Outcrops of late Precambrian beds are found resting unconformably upon Precambrian basement composed of 1.8-1.7 b.y. orogenic rocks and younger plutons. In northeastern Sonora, Cambrian-age Capote Quartzite overlies rocks similar to Pinal Schist, with no intervening section.

The Gamuza beds consist of several thousand feet of carbonate and quartzose clastic strata some of which contain stromatolites. The unconformable relationship of this section to distinctive 1,110 m.y. Aibo granite and the lithologic and fossiliferous characteristics of the strata indicate that these units are probably correlative with pre-*Olenellus* formations in the Death Valley - Inyo Mountains region of the southern Great Basin. The rocks cannot be correlative with the Apache Group of central and southern Arizona.

According to Arellano (1956) and Cooper and Arellano (1946), the Gamuza beds consist of at least 1,500 m and possibly more than 2,000 m of carbonate and clastic beds. Cooper and Arellano (1946) lithologically subdivided this sequence into three units:

> "The lowest division, about 450 meters thick, consists of fine-grained sandy shales, thin-bedded limestone and fine-grained sandstone with some heavy layers of white quartzite at the top. . . Overlying the uppermost quartzite of the lower group occur 150-200 meters of dark gray dolomite abounding in Cryptozoa in the upper 65 meters. Above the cryptozoan bed occurs the third division of the Precambrian, a section of more than 1,000 meters consisting of thin bedded, commonly brecciated gray dolomite with thick channels of clean, white quartzite."

The lowest member is well exposed in the Arpa Hills, south of Caborca, where it consists of a distinctively colored series of alternating gray limestone; yellow, orange and brown dolomite and sandy dolomite; reddish-orange to brown shale and siltstone and brown calcareous sandstone. The bottom 2-3 m of this member, above the granite, are characterized by gray, pink, or reddish-brown, fine-to-coarse-grained thin-bedded quartz sandstone. The top of this zone is marked by a few resistant, gray quartz sandstone beds less than one meter thick. Above this basal zone, the member consists of alternating limestone and dolomite with scattered clastic interbeds. This part of the Gamuza beds is about 450 m thick and is correlative with Cooper's lowest subdivision with the exception of his upper white quartzite beds. These were not measured because their thickness was obscured by a fault zone which separates the lowest member from the middle dolomite member. They are probably at most a few tens of meters thick. These beds provide a distinctive marker unit which consists of gray or white, clean, vitreous quartzite that weathers brown or light brownish-gray.

Younger beds of the Gamuza sequence crop out in Gamuza Hills (also called Gachupín Hills) just north of Arpa Hills and in the range north of rugged Chino-Rajón Mountains area to the east. On the basis of outcrops at Caborca, Arellano (1956) suggested that the contact between the Gamuza beds and the established Paleozoic section is probably transitional, although no outcrops showing this relationship were seen in the field. However, in Cerros Aquituni, San Clemente, Calaveras and Clemente, where Eells (1972) subdivided the upper parts of the sequence into 12 mappable units, the relationship is locally well-exposed.

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