Report on

1:250 000 Scale Geological and Metallogenic Maps
Sierras de Las Minas, Chepes and Los Llanos

Provincia de La Rioja

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GEOSCIENTIFIC MAPPING OF THE SIERRAS PAMPEANAS ARGENTINE-AUSTRALIAN COOPERATIVE PROJECT

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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ABSTRACT

Geology

The map area covers most of the Sierras de Chepes, de Los Llanos and de Las Minas. The oldest rocks exposed are metasediments and meta-igneous rocks of the Olta Metamorphic Complex. The metasediments are interpreted as being deposited on the passive margin of western Gondwana, developed during intracontinental rifting and break-up of Laurentia from Gondwana and opening of the Iapetus Ocean in the Early Cambrian. Based on U-Pb dating of zircons, the minimum provenance age of the metasediments is about 540 Ma, and the minimum age limit of sedimentation is about 530 Ma. Following sedimentation and minor magmatic activity, the western margin of Gondwana continent was subjected to compressive deformation (D1) and regional metamorphism (M1) of the Pampean cycle. The age of the Pampean cycle is about 530 Ma (Early Cambrian).

In the early Ordovician, closure of the Iapetus Ocean and eastward subduction beneath the western margin of Gondwana was accompanied by the formation of a large continental margin magmatic arc. During this early phase of the Famatinian cycle the dominantly calc-alkaline granitoids and minor intermediate and mafic plutonic rocks of the Chepes Igneous Complex were emplaced. These rocks represent the infrastructure of the magmatic arc, and because of the high heatflow, the country rock of the Olta Metamorphic Complex was subjected to low pressure/high temperature metamorphism and migmatisation (M2) overprinting the earlier phase of regional metamorphism (M1). U-Pb dating of zircons of the granitoids of the Chepes Igneous Complex yield crystallizaton ages ranging from ~491 to ~477 Ma (early Ordovician).

During the late Ordovician the Cambrain basement and continental margin magmatic arc underwent east-west, non-coaxial compressive deformation (D2) at regional greenschist-facies metamorphic conditions (M3). A weakly to strongly penetrative north to north-northwest trending foliation has affected the rocks of both the Olta Metamorphic and Chepes Igneous Complexes, and retrogressive metamorphism was widespread. In zones of high strain, up to 1 km wide, mylonitic shear zones were formed within and bounding the sierras, but also, as indicated by airborne geophysics, in the basement rocks underlying the plains. The ductile shear zones are mostly east-dipping and kinematic indicators show orthogonal, westerly directed thrust movement. ^{40}Ar-^{39}Ar dating of muscovite from mylonitised granite exposed in the southeast part of the Sierra de Chepes has produced an age of about 455 Ma for the shearing.

Peraluminous to slightly peralkaline and zoned granite plutons of the Devonian Achalian cycle are widespread east of the project area in the Córdoba and San Luis project areas. The granite bodies were emplaced in country rock during and following east-west compressive deformation. In the map area there are no outcrops evident of felsic magmatism and deformation at this stage, but airborne magnetics suggest the presence of zoned granite bodies beneath Cainozoic sediments in the plain west of the Sierra de las Minas, and southeast of the Sierra de Los Llanos. During the later stage of the Achalian cycle, east-west compression produced a regionally widespread conjugate system of rectilinear brittle-ductile, vertical, northwest- and northeast-trending strike-slip faults and fractures. The orientation and conjugate relationship of the faults indicate a continuation of the east-west compressive tectonic regime. In the Sierra de Las Minas this fault system

is particularly well developed, and is associated with sericite - pyrite ± chlorite alteration and quartz vein-type Au ± Cu mineralisation, resulting from mesothermal hydrothermal activity. ^{40}Ar-^{39}Ar isotopic dating of sericite associated with the hydrothermal alteration has produced a crystallization age of about 390 Ma.

Following peneplanation of the Cambrian to Devonian basement, continental sediments with rare marine incursions (from the west) were deposited in the Carboniferous to Triassic Paganzo Basin, a large cratonic basin which covered the west and central areas of Argentina. In the project area remnants of late Carboniferous and Early Permian sediments of the Paganzo Group are preserved in graben structures.

During the Cainozoic, the peneplained Paleozoic basement and preserved overlying sediments of the Sierras Pampeanas were deformed into north-south oriented, elongate fault blocks forming the present characteristic topography of rugged sierras separated by broad intermontane basins. The Sierras de Las Minas, de Chepes and de Los Llanos were uplifted and tilted by reverse faults which in places have reactivated Paleozoic mylonitic shear zones. Locally these sierras are traversed by graben structures parallel and transverse to the regional north-south structural grain.

Metallogeny

Three principal Paleozoic metallogenic cycles are recognised in the southern Sierras Pampeanas. The first two metallogenic stages are closely related to the Famatinian (early Ordovician) tectonic and magmatic cycle, and the third major period of mineralisation occurred during the Achalian (Devonian) tectonic cycle. Only the latter cycle is significant in the Sierras de Las Minas and Chepes.

Metallic mineral deposits broadly correlated with the Achalian (Devonian) tectonic cycle constitute the third metallogenic phase in the southern Sierras Pampeanas. It is characterised by diverse deposits of Au, W, Ag, Pb, Zn, Cu, and a second period of pegmatite-related mineralisation including Be, Li, Nb, Ta, U, REE, Th and F. The Achalian metallogenic cycle is represented in the Sierras de Las Minas and Chepes by mesothermal shear-related Au±Cu.

New ^{40}Ar-^{39}Ar dating of white mica hydrothermal alteration associated with shear-related Au±Cu suggests mineralisation occurred from ~390 to ~360 Ma. This metallogenic phase commenced during the period of Devonian felsic magmatism. These granites are fractionated, peraluminous to borderline-metaluminous, oxidised to weakly reduced, magnetic to non-magnetic S- and I-types and form zoned ovoid plutons that were emplaced at relatively high crustal levels synchronous with compressive deformation. Granite data are taken from elsewhere in the Sierras Pampeanas as no Devonian granites crop out in the sheet area, although magnetics indicate they exist beneath Cainozoic cover units. Oxygen and hydrogen isotope compositions of alteration and veins minerals are compatible with input of evolved meteoric fluids with or without a minor component of magmatic or metamorphic waters in the formation of these Au±Cu, W and Ag-Pb-Zn deposits.

Regional mapping and metallogenic modelling have defined zones of potential for Au±Cu mineralisation in the sierras de Las Minas and Chepes. The zones of Au±Cu potential are focussed on a conjugate set of northwest and northeast trending Devonian shear zones characterised by sericite-pyrite and hematite alteration. These are evident in the aeromagnetic imagery as magnetic ‘lows’, within a regional domain of demagnetisation(?) of Ordovician granitoid rocks, and extend to the west of the Sierra de Las Minas beneath Cainozoic cover.

Sediment hosted uranium mineralisation in Carboniferous and/or Permian clastic sedimentary rocks in the sierras de Las Minas and Chepes region has not been investigated extensively. This mineralisation style may be part of a separate metallogenic cycle of Carboniferous or younger age. Potential areas for U have been outlined in a metallogenic model.

PREAMBLE

Funded by the Government of the Argentine Republic, the Geoscientific Mapping of the Sierras Pampeanas Argentine-Australian Cooperative Project is a collaborative program between the Australian Geological Survey Organisation and the Servicio Geológico Minero Argentino of the Subsecretaría de Minería de la Nación. The project aims to update the geoscientific knowledge base, provide a modern framework for resource assessment, and promote exploration and development in the region. Training of Argentinian geoscientists and technology transfer are key components of the project.

The pilot 'second generation' mapping program involved integrated geological, geophysical and metallogenic mapping totalling 27 000 km^2 in three selected areas of the southern Sierras Pampeanas, a Paleozoic basement terrane in central Argentina (Figures a and b). The three areas, in the provinces of La Rioja, Córdoba and San Luis, were selected to provide key sections of the major tectono-stratigraphic packages comprising the southern Sierras Pampeanas. The region is well known for its resources of industrial and construction materials. Additionally, a range of metallic mineral deposits containing Au, W, Ag, Be, Li, Ni, Cu, Pb, Zn, Nb and Ta, among other commodities, are represented in the region.

Mapping in the three survey areas, *Sierras de Las Minas, Chepes y Los Llanos* (Provincia de La Rioja); *Sierras Septentrionales de Córdoba* (Provincia de Córdoba), and the *Sierras de San Luis y Comechingones* (provincias de San Luis y Córdoba), was undertaken in 1995 to 1996 (Stuart-Smith and Lyons, 1995; Stuart-Smith and others, 1996b, 1996c). A major program of high resolution airborne magnetic and gamma-ray spectrometric surveys was carried out (Chambers, 1996; Figure b), and interpretation completed (see 1:250 000 scale *Interpretación Aeromagnetica* maps and accompanying reports: Hungerford and others, 1996a, 1996b, Hungerford and Pieters, 1996). Fieldwork and map compilation were supported by Landsat TM imagery, airborne geophysics, ground-based geophysical data, GPS located field sites, aerial photography, and geochronological, geochemical and stable isotopic studies. Airborne geophysical data and preliminary interpretations of the geology based on Landsat TM imagery were released to the public in mid-1996. Preliminary assessment of the regional geology and prospectivity of the La Rioja project area was documented by Pieters and Skirrow (1996). Analytical, petrological and geochronological results of the project were reported by Lyons and others (1996), Lyons and Skirrow (1996), Sims and others (1996), Camacho and Ireland (1997) and Camacho (1997).

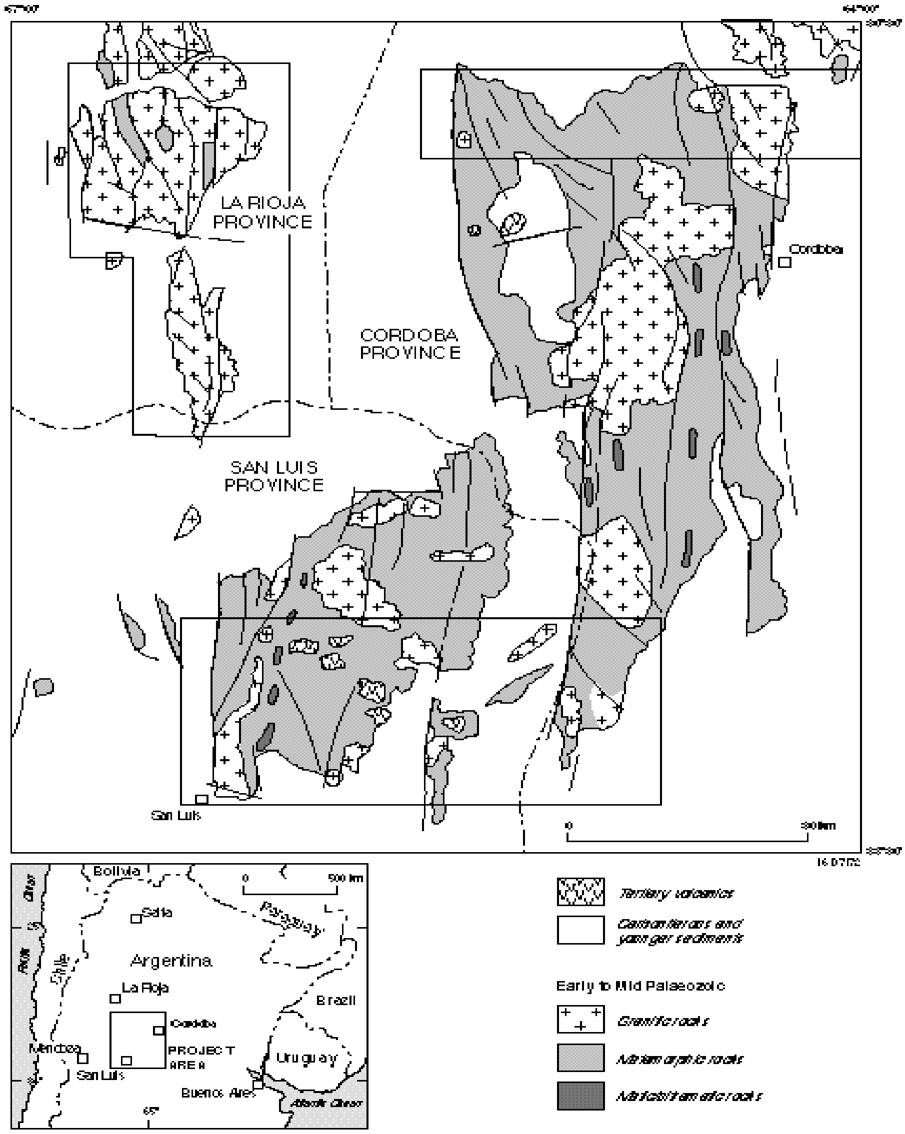

Figure a. Location of the three project areas and simplified regional geology of the southern Sierras Pampeanas

Over Page
Figure b. Total magnetic intenstity images of the three project areas

Magnetic Image

Syntheses of the geological, metallogenic and geophysical results of the project are presented in 1:250 000 scale *Hoja Geológica* and *Hoja Metalogenética* and accompanying reports for each of the three areas (Pieters and others, 1997; Lyons and others, 1997; Sims and others, 1997). A series of eighteen 1:100 000 scale geological and eighteen mineral occurrence maps constitute some of the principal datasets of the project. They are accompanied by reports on the geology and mineral deposits, including output datasheets from the ARGMIN mineral deposit database (Skirrow and Trudu, 1997). An Arcinfo-based Geographic Information System (GIS) of the Sierras Pampeanas project contains all major geoscientific map datasets (Butrovski, 1997). Selected datasets from the GIS along with metallogenic models of mineral potential have been compiled at 1:400 000 scale in the *Atlas Metalogenético* for the southern Sierras Pampeanas (Skirrow and Johnston, 1997).

This report covers the Geology and Metallogeny of the *Sierras de Las Minas, Chepes y Los Llanos* 1:250 000 scale map sheet in the Province of La Rioja. The report is divided into two sections*: Geology, and Economic Geology. The 1:250 000 scale *Hoja Geológica* and *Hoja Metalogenética* are contained in pockets at the back of the report.

***Recommended bibliographic citation:**

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SKIRROW, R.G., 1997. Economic Geology of the Sierras de Las Minas, Chepes and Los Llanos 1:250 000 map sheet. *In:* PIETERS, P., SKIRROW, R.G. and LYONS, P., 1997, Report on Geology and Metallogeny of the Sierras de Las Minas, Chepes and Los Llanos 1:250 000 map sheet, Province of La Rioja. Geoscientific Mapping of the Sierras Pampeanas Argentine-Australian Cooperative Project, Australian Geological Survey Organisation, unpublished report.

SECTION I: GEOLOGY

By Peter Pieters and Patrick Lyons

1. INTRODUCTION

1.1 LOCATION AND ACCESS

The map area dealt with in this report covers the Sierras de Chepes, de Las Minas and de Los Llanos and the surrounding plain which fall mostly in the southern part of the La Rioja Province, and, in the extreme south, also in the San Luis Province (Figure 1). The map area is bounded by latitudes 30°40’ S and 32°00’ S, by longitude 66°00’ W in the east, by longitude 66°45’ W in the west, north of latitude 31°20’ S, and by longitude 66°30’ W in the west, south of latitude 31°20’ S. The area includes parts of the 1:250 000 scale Chamical (3166-I) and Chepes (3166-IV) sheets, and covers the following 1:100 000 scale sheets: Corral de Isaac (3166-33), Ulapes (3166-27), Desiderio Tello (3166-21), Santa Rita de Catuna (3166-15), the eastern half of Ñoquebe (3166-20), and the eastern half of Malanzán (3166-14).

The area is easily accessible from Córdoba by Ruta Nacional 38 and Ruta Provincial 32, from La Rioja by Ruta Nacional 38 and Rutas Provinciales 27, 28 and 29, and from San Juan by Ruta Nacional 141. The nearest regularly serviced airport is located at La Rioja.

The main centre of population, logistics and commerce is Chepes on Ruta Nacional 141 (Fig. 2) located between the Sierra de Chepes and Sierra de Las Minas (outside the map area). The Sierra de Chepes is separated from the Sierra de Las Minas to the south by a topographic low formed by shallow valleys and the plain. In the north the Sierra de Chepes is divided from the Sierra de Los Llanos by the westerly trending valley of Rio Malanzán in the west, and the east-southeast oriented valleys of Rio de Solca and Rio de

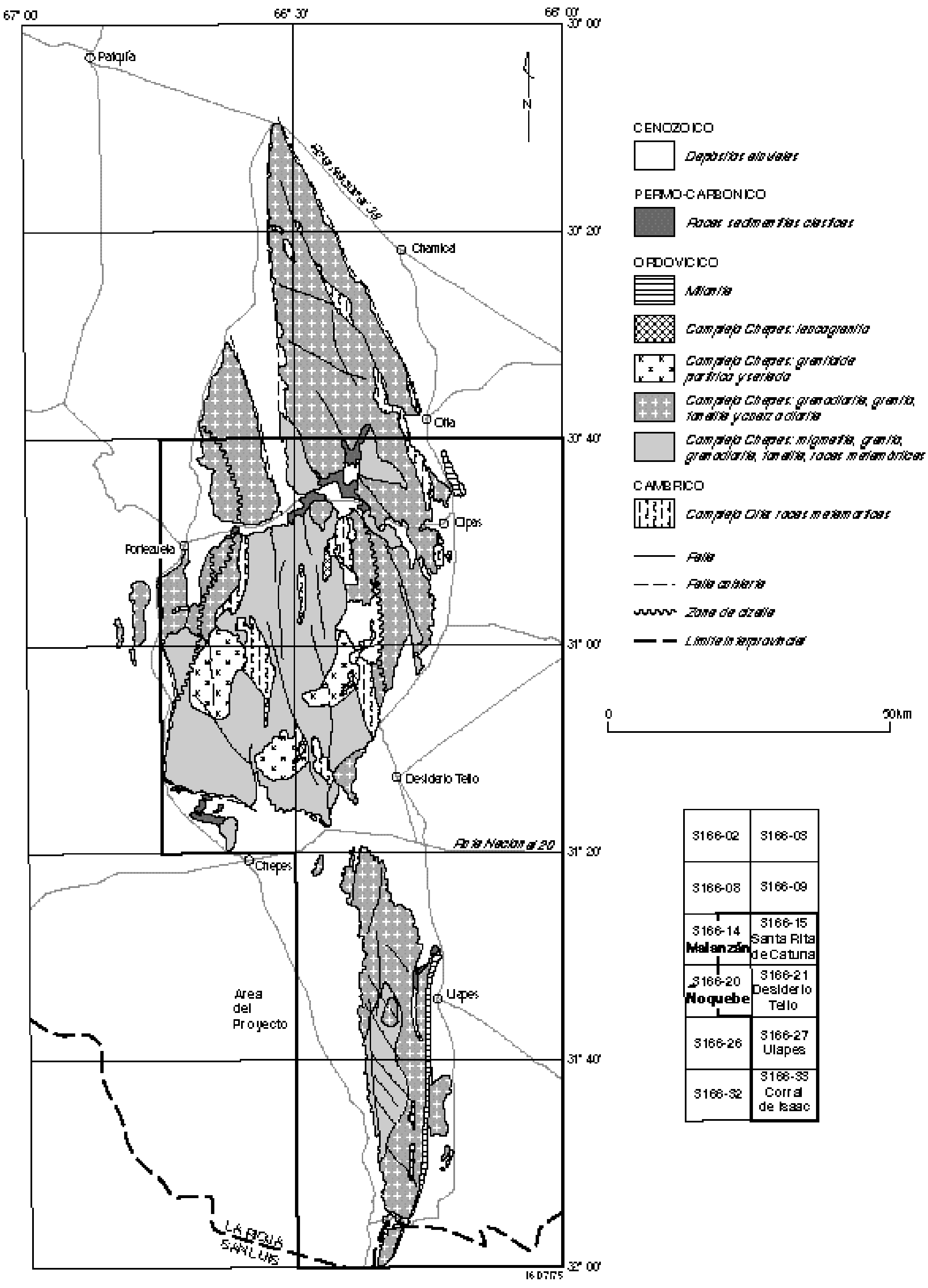
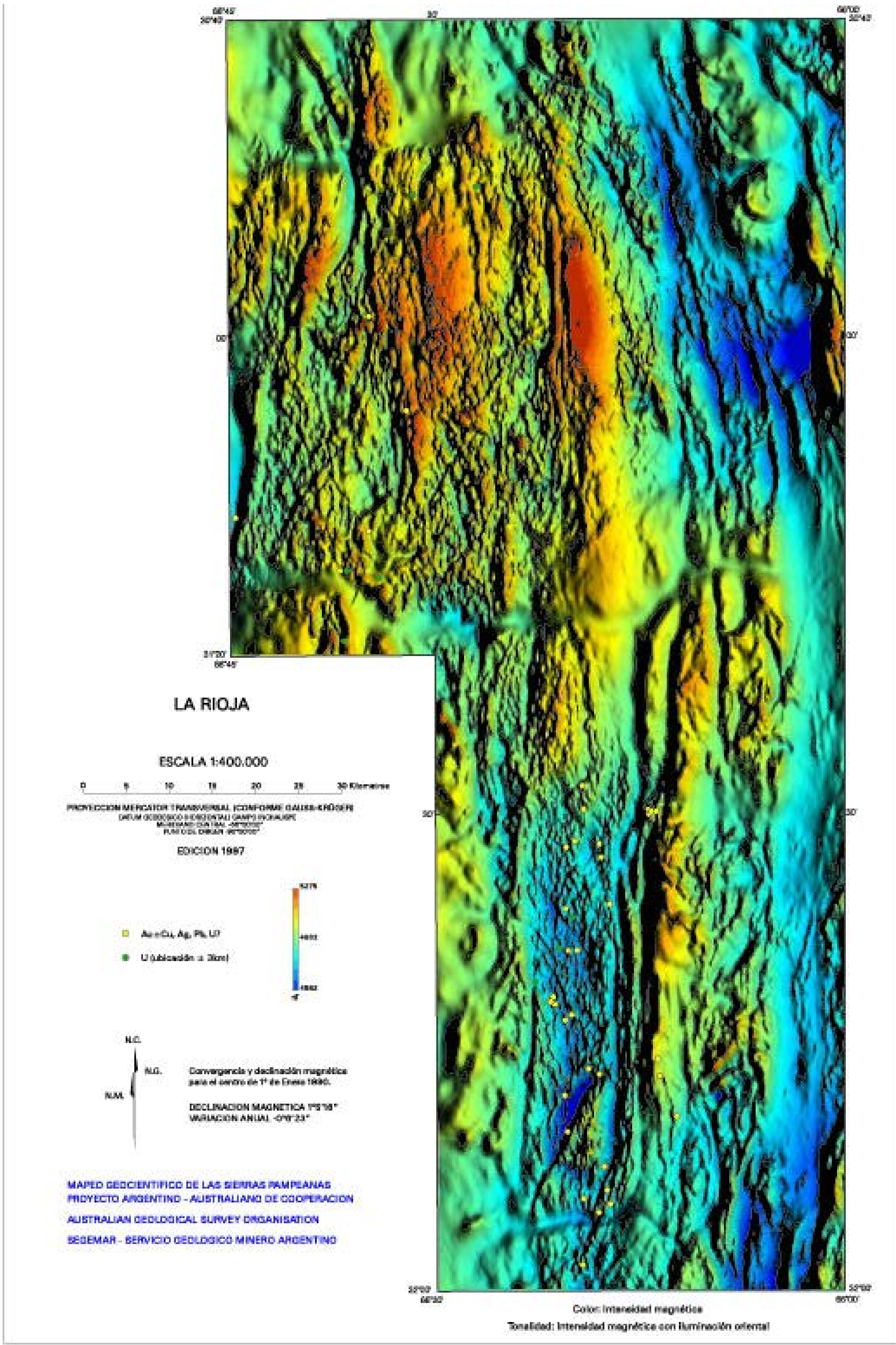


Figure 1. Location of the 1:250,000 scale Sierras de Las Minas, Chepes and Los Llanos map area in La Rioja Province with generalised regional geology. Graticule shows location and name (where available) of 1:100,000 scale map sheets.

Landsat TM image



Anzulón in the east. In the western part the Sierra de Los Llanos is divided by a northerly trending up to 4 km wide valley, and the western range (sierra) is also commonly known as the Sierra de Malanzán.

1.2 NATURE OF WORK AND PREVIOUS INVESTIGATIONS

Mapping of the Sierras de Chepes, de Las Minas and de Los Llanos was carried out in 1995 and 1996 under the Geoscientific Mapping of the Sierras Pampeanas Argentina - Australia Cooperative Project by geologists of the Australian Geological Survey Organisation (AGSO) and the Subsecretaría de Minería (DNSG). The mapping employed a multidisciplinary approach using the newly acquired high-resolution airborne magnetic and gamma-ray spectrometric data, Landsat TM imagery, and 1:45 000 scale (approximate) black and white air photos. All geological maps were compiled on topographic bases produced at photo-scale from rectified Landsat images controlled by field GPS sites. Subsequently the geological and topographic maps were scanned and digitised, and the data were transferred into GIS Arc/Info. From the GIS six 1:100 000 scale maps, combining geology and topography, were produced, and the 1:250 000 scale geological/topgraphic map accompanying this report was constructed by scale reduction and seamless edge matching of the 1:100 000 scale maps. Geologists involved in the fieldwork were P.E. Pieters and P. Lyons (AGSO), and O. Cravero, J. Ríos-Gómez, G. Vujovich, S. Page and O. González.

Although regional geological reconnaissance and specialist studies in the area of the Sierras de Chepes, de Las Minas and de Los Llanos have been carried out since 1873 (for example: Bodenbender, 1911 and 1912; Bracaccini, 1946 and 1948; Frengüelli, 1946, 1949 and 1950; Turner and de Alba, 1968), the first systematic mapping of the Sierra de Las Minas was conducted in 1967 by R. Caminos (Caminos, 1979), and of the southern part of the Sierra de Chepes by V. Ramos (Ramos, 1982).

Figure 2 (previous page). Landsat-5 TM image of the map area with locations of known mineral occurences and some culture.

A program of regional stream-sediment geochemistry (Cu, Pb, Zn) accompanied by geological observations and air photo interpretation was carried out in 1972 by the Subsecretaría de Estado de Minería (La Rioja) and led to the production of an unpublished series of 1:50 000 scale geological maps covering the entire area of the Sierras de Chepes, de Las Minas and de Los Llanos. From 1993 to 1995 the Metal Mining Agency of Japan and the Subsecretaría de Estado de Minería, financially sponsored by the Japan International Cooperation Agency (JICA), carried out a program of gold exploration including diamond drilling of ten holes in the Sierra de Las Minas (JICA, 1993, 1994 and 1995). Systematic mapping of the Chamical and Chepes 1:250 000 sheet areas is currently undertaken by the DNSG.

1.3 GEOPHYSICS

As part of the cooperative project between AGSO and DNSG, a high resolution airborne geophysical survey was carried out over the map area. For this survey, magnetic and radiometric (U, K, Th) data were obtained by World Geoscience along flight lines spaced 500m apart, from a nominal height of 100m. To assist the aeromagnetic interpretation, magnetic susceptibilities of most exposed rock-types were measured during field work. Magnetic data from the airborne survey were processed by Hungerford Geophysical Consultants (HGC) and radiometric data were processed by AGSO. The data were interpreted by HGC and geoscientists from AGSO at 1:100 000 scale and have been reported separately (Hungerford and others, 1996).

The aeromagnetic data (Figure 3), indicate a variety of north-south trending elongate domains associated with granitoid bodies and outcrops of metasediments. The domains in the Sierra de Chepes and southern Sierra de Los Llanos are much more magnetic than the domains in the Sierra de Las Minas, and there is evidence that a large swath of the granitoids in the Sierra de Las Minas is either remanently magnetised or is underlain by very low magnetic granitoids and/or metasediments.

Northerly trending, curvilinear non-magnetic zones in both the northern and southern sierras are interpreted to be major shear zones. In the east beneath the plains the presence of an east-dipping half-graben is interpreted from a steep increase in depth to magnetic basement followed, in the extreme east, by the reappearance of shallow magnetic units. A prominent, broad low magnetic zone strikes roughly east-west and separates the Sierra de Chepes from the Sierra de Las Minas. Similar magnetic features separate the Sierra de Chepes from the Sierra de Los Llanos and cut across the Sierra de Las Minas in the extreme south.

In the Sierra de Las Minas northwest non-magnetic linears correspond with shear zones which are clearly defined on Landsat images and airphotos. These shear zones form part of a conjugate shear system of which the northeast-trending set is poorly developed, and they contain locally gold bearing quartz veins.

In the extreme northeast, and west of the central part of the Sierra de Las Minas occur circular magnetic trends and anomalies beneath sedimentary cover which are possibly associated with relatively young (?Devonian) granitoid intrusions emplaced after the main phases of deformation.

Over Page
Figure 3. Total magnetic intensity image of the map area, reduced to the pole, with location of known mineral occurrences.

AEROMAG IMAGE

2. STRATIGRAPHY

2.1 Regional relationships

The Sierras Pampeanas are a distinct morphotectonic province of early to middle Paleozoic, low to high-grade metamorphic and felsic to mafic plutonic rocks that form a series of block-tilted, northerly oriented ranges separated by intermontane basins. The ranges are bounded by escarpments developed on moderate to steeply dipping normal and reverse faults developed during the Cainozoic Andean uplift (Jordan and Allmendinger, 1986).

Recent geological and geophysical surveys conducted by the Cooperative Argentine-Australian Project in the Sierras Pampeanas show that the Paleozoic basement of the southern Sierras Pampeanas contains a number of distinct lithological and structural domains which are traversed by major shear zones. There are two principal domains: an Early Cambrian Pampean domain, and an early Ordovician Famatinian domain, which are juxtaposed in a complex way. Both domains share a common geological history since early Ordovician time.

In the map area the Cambrian metasediments and meta-igneous rocks of the basement are grouped together in the Olta Metamorphic Complex, and belong to the Pampean domain. These metamorphic rocks are intruded by early Ordovician granitoid and minor mafic bodies of the Chepes Igneous Complex, and at the same time were subjected to high-temperature/low pressure metamorphism and anatexis. The intrusives and migmatite make up the Famatinian domain which was formed during a phase of westward subduction beneath the Pampean terrane. Both domains were subjected to compressive non-coaxial deformation and retrogressive metamorphism in the late Ordovician. Subsequently, the domains were intruded by Devonian granites (not exposed but interpreted from airborne magnetics), and covered by Carboniferous and Permian continental sediments and Cainozoic continental sediments.

2.2. CAMBRIAN BASEMENT

Olta Metamorphic Complex (€o)

Distribution

The Olta Metamorphic Complex is exposed in elongate, northerly trending areas, up to 18 km long and 4 km wide, in the Sierras de Los Llanos and de Chepes. Throughout these Sierras and also in the Sierra de Las Minas the plutonic rocks and, particularly, migmatite of the Chepes Igneous Complex contain inclusions and enclaves of Olta Metamorphic Complex lithologies; however, generally the outcrops are small and unmappable at 1:100 000 scale.

Nomenclature, stratigraphic relations and age

The unit has been desribed as the Olta Formation by Furque (1968), Caminos (1979) and Ramos (1982). It is proposed in this report to change the name to Olta Metamorphic Complex, as the lithostratigraphy is mostly obliterated by metamorphism and tectonism. The mineral assemblages indicate metamorphic conditions ranging from greenschist facies to anatexis, and a variety of minor lithologies are included in addition to the widespread metasediments. As yet, only the El Cisco gneiss has been mapped as a unit of the Olta Metamorphic Complex, but detailed mapping at 1:50 000 scale and larger would define the distribution of the smaller units.

The intrusive contact between the Olta Metamorphic Complex and metaluminous granitoids of the Chepes Igneous Complex is sharp, and thermal aureoles are poorly developed. However, the country rock is commonly broken up with small to very large (few cms - 30 m), irregularly shaped fragments embedded in the granitoid. Most of the Olta Metamorphic Complex outcrops form steeply dipping screens between the intrusive bodies. In places, the contact is gently dipping to subhorizontal; for example, in the drainage of Quebrada Porongo (about 3 km west-southwest of Porongo mine) metasediments are overlain by porphyritic granite of the Chepes Igneous Complex.

On the other hand, the contact between the Olta Metamorphic Complex and the migmatite units of the Chepes Igneous Complex is gradational and complex, and difficult, if not impossible, to locate at 1:100 000 scale. The contact with the peraluminous muscovite-biotite granite (Ogm) of the Chepes Igneous Complex is complex and varies from gradational to sharp.

A U-Pb age analysis on detrital zircon grains without metamorphic overgrowths obtained from a metasediment sample (A95PP111A; 66°32.50’W/33°06.40’S) yielded a minimum provenance age of about 545 Ma (Camacho and Ireland, 1997), and is interpreted to represent the maximum age of sedimentation. However, this age may have been affected by post depositional metamorphism causing Pb loss from an older population. The metasediments of the Olta Metamorphic Complex are tentatively correlated with the Tuclame Formation (Stuart-Smith and others, 1997) exposed in the 3166-17 1:100 000 sheet area (Cordoba Province). Zircon and monazite from a sample of Tuclame Formation migmatitic rock gave U-Pb ages of respectively 532 ± 12 Ma and 533 ± 19 Ma (Camacho and Ireland, 1997). These ages are interpreted to indicate the age of the main phase (Pampean cycle) of metamorphism in the Tuclame Formation.

Lithology

The Olta Metamorphic Complex consists dominantly of psammitic and pelitic metasediments ranging from muscovite-biotite bearing quartzite to quartz-rich and mica-rich slate, phyllite and schist. Associated with the metasediments are minor micacaceous quartz-feldspar phyllite, schist and gneiss, hornblende-plagioclase schist and gneiss, and schistose to gneissic granitoid (Figures 4, 5, 6).

The metasediments are medium to dark grey, fine-grained, and characteristically show a parallel metamorphic segregation layering of felsic and mica-rich material ranging in thickness from a few millimetres to 2 cm, and a layer parallel foliation defined by subparallel aligned micas. Locally, a crude layering of 20 cm to 50 cm thick quartz-rich and mica-rich packages is tentatively interpreted to reflect sedimentary bedding. Where observed, the bedding structures are subparallel to the metamorphic layering.

Thin section study shows that the psammitic metasediments have a narrow compositional range comprising the following minerals: 70-85% quartz, 5-20% biotite, 5-15% muscovite, <5% opaques (mostly magnetite), in places <10% feldspar (both plagioclase and microcline), and rarely <2% clinozoisite/epidote and <2% apatite. Accessory microcrystalline zircon occurs in the biotite and is surrounded by pleochroic haloes; tourmaline is another common accessory mineral. The pelitic metasediments are similar and transitional to the psammitic metasediments; they contain 50-70% quartz and 25-40% micas.

The quartz is generally completely recrystallised to a polygonal granoblastic aggregate; only in one greenschist facies siltstone the quartz clasts are partly preserved although the grain margins are strongly abraded and the matrix is recrystallised to very fine biotite and white mica. The quartz (± feldspar) and micas are differentiated into parallel layers or lenses ranging in thickness from 0.5 mm to a few centimetres. However, mica also occurs scattered in the quartz (± feldspar) aggregates. In the layers, the biotite and muscovite occur as solitairy crystals and aggregated in folia which both tend to be orientated parallel to the layering. The metamorphic segregation layering and subparallel aligned micas define a distinct foliation (S1). However, throughout the rocks there are biotite and muscovite flakes randomly oriented, and cordierite porphyroblasts discordant or mimetic with respect to the S1 foliation.

Figure 4. Locality A95PP009 (66°20.73'W/31°07.63'S). Banded metasediments of the Olta Metamorphic Complex deformed by tight D1' folding.

Figure 5. Locality A95PP058 (66°36.39'W/30°49.19'S). Sharp intrusive contact between metasediments of the Olta Metamorphic Complex and leucocratic granite of the granitoid unit (Og) of the Chepes Igneous Complex.

Figure 6. Locality A95PP096 (66°37.33'W/31°05.44'S). Enclave of banded metasediments in biotite sparse granite (migmatite unit Ogm). Sharp hinges in the banding indicate isoclinal (intrafolial) folding (D1) subsequently deformed by small-scale upright folds (D1').

Figure 7. Locality A95PP086 (66°34.63'W/30°58.81'S). Transition between metamorphics of Olta Metamorphic Complex and migmatite of Chepes Igneous Complex. Banded metasediments or meta-ingneous rock invaded by irregular layers and lenses of quartz-feldspar rock and leucocratic granite; strongly deformed by tight to isoclinal ductile folding.

Some rocks contain up to 5% porphyroblastic cordierite, and the assemblage cordierite - chlorite - biotite - muscovite in pelitic metasediments indicates low-pressure/high-temperature metamorphic conditions of the hornblende hornfels facies. Although porphyroblastic andalusite was not detected, the rare presence of this mineral is suggested by irregular patches of fine mica. The assemblage cordierite - andalusite - K-feldspar was observed by Dahlquist and Baldo (1996) providing evidence that metamorphic conditions as high as the pyroxene hornfels facies were reached. Features indicating the onset of anatexis are widespread in the Olta Metamorphic Complex (and in the migmatite of the Chepes Igneous Complex); however, rocks typical of the sillimanite zone with which anatexis is commonly associated are extremely rare and metapelite with the assemblage sillimanite - K-feldspar was again only reported by Dahlquist and Baldo (1996).

With increasing amounts of feldspar the psammitic and pelitic metasediments grade into interlayered grey micacaceous quartz - feldspar metamorphics. These rocks are probably derived from feldspathic or volcaniclastic sediments, or felsic to intermediate volcanics. Compared to the psammitic and pelitic metasediments, the micaceous quartz - feldspar schist/gneiss is considerably lower in quartz (30-60%) and contains 30-60% feldspar (microcline and plagioclase). These rocks also carry 5-20% biotite, 5-35% muscovite and <2% opaques (mostly magnetite), and some contain up to 20% cordierite and <2% epidote/clinozoisite. The generally distinct foliation is defined by fine segregation layering of felsic minerals and mica, and layer parallel aligned micas.

The medium to dark green hornblende - plagioclase schist or gneiss are thought to represent disrupted dykes and other small intrusive bodies emplaced in the metasedimentary sequence, and/or volcanic intercalations of intermediate composition. The compositions and textures of hornblende-plagioclase schist or gneiss and schistose or gneissic granitoid vary considerably depending on the degree of metamorphism and deformation, and the nature of the protoliths ranging from granite to mafic rich quartz - diorite. The rocks contain 25-55% quartz, 0-55% feldspar (plagioclase and microcline), 0-20% biotite, 0-20% muscovite and 0-65% hornblende; minor constituents are magnetite (<5%) and sphene (<2%). Amphibolite was not observed. The weakly to moderately well developed foliation is defined by lenticular quartz segregations, subparallel aligned mica and occasionally hornblende crystals and biotite folia. The mineral assemblage hornblende-plagioclase indicates metamorphic conditions of the hornblende hornfels facies. At locality A95PP130 (66.45806°W/30.93867°S) in the drainage of Quebrada Los Algarrobos, an enclave of the Olta Metamorphic Complex in migmatite consists of psammitic schists interlayered with dark, fine-grained plagioclase-magnetite - clinopyroxene - hornblende - quartz fels, and spotted, medium grey and medium-grained muscovite - biotite - cordierite - microcline - quartz schist/gneiss. The fels contains up to 10% magnetite resulting in magnetic susceptibility values up to 8500 x 10^{-5} SI; the mineral assemblage clinopyroxene - hornblende - plagioclase indicates metamorphic conditions of the pyroxene hornfels facies.

The medium grey schistose or gneissic granitoid represent metamorphosed and deformed felsic to intermediate intrusive rocks which were mostly disrupted prior to or during the main phase of metamorphism. In places, these rocks are difficult to recognise from deformed and metamorphosed granitoids of the Chepes Igneous Complex.

The main foliation (S1) has a northwesterly to northeasterly strike with dips ranging from shallow to steep to the east as well as the west. The rare occurrence of remnants of isoclinal fold hinges contained within the foliation (intrafolial folds) suggests deformation by layer parallel folding. The main foliation is locally deformed by open to tight microscopic to mesoscopic folds which are accompanied by a more or less well developed axial-plane or crenulation cleavage (S1’).

A study of trains of opaque and mica inclusions in poikilitic cordierite pophyroblasts in metasediments by Dahlquist and Baldo (1996) showed the presence of a pre-metamorphic deformational fabric. This early fabric is thought in this report to be associated with the phase of compressional deformation which produced the folding and S1 and S1’ foliations, and which was accompanied by probably greenschist-facies regional metamorphism. Subsequently, the phase of low-pressure metamorphism associated with the emplacement of the Chepes Igneous Complex in early Ordovician time caused recrystallization and grainsize coarsening largely preserving the older deformational fabric. The random orientation of cordierite porphyroblasts and part of the biotite and muscovite flakes support a two stage metamorphic history.

The S1 and S1’ fabrics are regionally deformed by a phase of shearing associated with east-west compression of late Ordovician age. The layering is disrupted and boudinaged, and locally the foliation is rotated into paralellism with vertical to steeply dipping shear planes. During this phase of deformation the rocks were also affected by retrogressive metamorphism with the formation of epidote/clinozoisite, chlorite and white mica, and the recrystallization of quartz. In zones of higher strain, where mylonite is developed, the S1 and S1’ foliations are mostly obliterated by the shearing. The northerly aligned outcrop areas of the Olta Metamorphic Complex tend to coincide with mylonite zones, possibly because they form zones of weakness as screens between the relatively resistant bodies of plutonic rocks of the Chepes Igneous Complex. In these mylonite zones the Olta Metamorphic Complex lithologies are commonly tectonically intermixed with the plutonic rocks.

The Olta Metamorphic Complex is generally characterised by low aeromagnetic anomalies and radiometric response. The majority of the psammitic and pelitic metasediments have a magnetic susceptibilty lower than 40 x 10^{-5} SI; however, some rocks are relatively rich in magnetite (5%) raising the magnetic susceptibilty up to 300 x 10^{-5} SI. The meta-igneous rocks have a wide range of magnetic susceptibilties, up to 2000 x 10^{-5} SI.

Remarks

Detailed mapping by Dahlquist and Baldo (1996) along an east-west transect from Quebrada Las Cañas (30°56’S; 66°37’W) to Tuani (30°56’S; 66°31’W) in the northwestern high-altitude part of the Sierra de Chepes (southeast part of Malanzán (3166-14) 1:100 000 sheet) provided additional information on the controlling factors of metamorphism of the Olta Metamorphic Complex. Along this section, metasediments of the Olta Metamorphic Complex are exposed as steeply dipping screens alternating between granodiorite and migmatite of the Chepes Igneous Complex. From east to west (towards the centre of the Sierra) the lithology of the metasediments changes from phyllite and spotted (chlorite-white mica pseudomorphs after cordierite) phyllite to schist and porphyroblastic (cordierite) schist, and gneiss, migmatite and cordierite-bearing muscovite-biotite granite. Four typical assemblages in pelitic metasediments indicate an increase of metamorphic grade from east to west:

1. biotite zone: biotite - muscovite - quartz - garnet - (cordierite) - (chlorite),
2. cordierite zone: biotite - muscovite - cordierite - magnetite - quartz - (plagioclase),
3. andalusite - K-feldspar zone: biotite - andalusite - K-feldspar - cordierite - magnetite - fibrolite - quartz - (plagioclase) - (secondary muscovite), and
4. anatectic zone: quartz - plagioclase - K-feldspar - cordierite - biotite - magnetite - (sillimanite) - (secondary muscovite).

The successive metamorphic zones are characterised by the common occurrence of cordierite, andalusite remaining stable up to breakdown of muscovite (resulting in the stable association andalusite - K-feldspar), and the absence of garnet in the higher metamorphic grades. The metamorphic textures and assemblages indicate that metamorphism took place at low pressure of no greater than 2.5 kbar (which indicates a depth of about 10 km), and that the temperature increased from 400° C in the biotite zone to 700° C in the zone of anatexis.

In the northeast part of Sierra de Chepes and southeast part of Sierra de Los Llanos the outcrops of the Olta Metamorphic Complex (and the El Cisco Metamorphics) partly merge with a distinct and continuous north-south aligned magnetic domain, which occurs mostly beneath the alluvial plain east of these Sierras and, farther south, the Sierra de Las Minas. This flat and low-magnetic zone is interpreted to be associated with the metasediments of the Olta Metamorphic Complex. West of the faulted western margin of the Sierra de Chepes there occurs beneath the alluvial plain another pronounced, northerly trending magnetic low, which is also thought to be associated with Olta Metamorphic Complex.

El Cisco Gneiss (€c)

Distribution

The only known outcrops of the El Cisco Gneiss occur in the southeast part of a small, isolated and north-northwest elongate sierra, 1-2 km east of the southeast flank of the Sierra de Los Llanos (Santa Rita de Catuna (3166-15) 1:100 000 sheet). The sierra is hilly to mountainous, and is formed on asymmetric tilt block with a steep escarpment in the west. The east-flowing, superposed or antecedent Rio La Ciénaga has cut a gorge, as deep as 150 m, across the south part of the sierra. The El Cisco damsite at the western end of the gorge and the reservoir provide a regular water flow for irrigation.

Nomenclature, stratigraphic relations and age

The name El Cisco gneiss is introduced in this report as an informal unit of the Olta Metamorphic Complex. The name is derived from the El Cisco damsite, and the reference area is south of where the Rio La Ciénaga leaves the range. This unit has been proposed in order to differentiate gneissic metasediments from the mainly finer-grained metasediments and metamorphics derived from igneous rocks of the Olta Metamorphic Complex.

In the reference area, the unit is separated from the Ulapes mylonite in the west by a fault structure which follows a northerly trending, continuous, narrow and linear valley. In the east the unit is onlapped by Cainozoic sediments (Cza) which form cliffs up to 30 m high.

The minimum provenance age of 540 Ma, based on U-Pb dating of zircons without overgrowths, for the metasediments of the Olta Metamorphic Complex is also thought to apply to this unit.

Lithology

The rocks of this unit form a monotonous sequence of quartz-rich psammitic to pelitic gneiss and schist. The main mica is biotite, and white mica (muscovite) occurs as a minor mineral. The metasediments contain a few percent to 20 % feldspar. The magmatic susceptibility is very low.

2.3. CAMBRIAN BASEMENT/ ORDOVICIAN IGNEOUS COMPLEX

Olta Metamorphic Complex, migmatite (€oOmg)

Distribution

In the Sierra de Chepes, the large terrain of migmatite of the Chepes Igneous Complex contains northerly trending, elongate areas, up to 13 km long by 8 km wide, which are underlain by Olta Metamorphic Complex lithologies and migmatite in proportions which may vary between 25% and 75%. Granite, granodiorite and tonalite make up a minor part (<5%) of the unit. At least three large outcrop areas have been mapped based on evidence from fieldwork, and interpretation of Landsat TM imagery, airphotos and also airborne magnetics and radiometrics. These outcrops occur in the central west (Malanzán (3166-14) and Ñoquebe (3166-20) 1:100 000 sheets), northeast (Santa Rita de Catuna (3166-15) 1:100 000 sheet) and southeast (Desiderio Tello (3166-21) 1:100 000 sheet) parts of the Sierra de Chepes.

Nomenclature, stratigraphic relations and age

The unit is poorly defined and is a mixture of lithologies which could not be differentiated at 1:100 000 scale. The contact with the surrounding migmatite of the Chepes Igneous Complex is complex and transitional (Figure 7). On the other hand, the contact of the unit with the porphyritic granitoid of the Chepes Igneous Complex in the central west part of the Sierra de Chepes is abrupt and could be traced from airphotos.

The age of deposition of the Olta Metamorphic Complex lithologies is Early Cambrian, and the age of the migmatite is early Ordovician, as discussed in separate sections on these units.

Lithology

The lithologies of the Olta Metamorphic Complex and migmatite are described in separate sections elsewhere in this report.

2.4. ORDOVICIAN IGNEOUS COMPLEX

2.4.1 Chepes Igneous Complex

Distribution

The Chepes Igneous Complex is by far the dominant basement unit (80% in area) exposed in the Sierras de Chepes, de Las Minas and de Los Llanos.

Nomenclature

Caminos (1979) and Ramos (1982) applied the name Chepes Formation for the unit. These authors recognised the following subdivisions:

- Normal facies,
- Migmatitic facies, and
- Porphyritic facies.

Because of the wide lithological variety, the gradational contacts between the lithological units and also the structural complexity it is proposed to change the name, in accordance with the International Stratigraphic Code, to Chepes Igneous Complex. The broad subdivisions of Caminos and Ramos were confirmed by this survey, but with more detailed information available the Chepes Igneous Complex has been subdivided into nine unnamed informal units, one newly named but informal unit (Quemado norite), and the formal Asperezas Granite and Tuani Granite. The following map units make up the Chepes Igneous Complex:

- Migmatite (Omg),
- Quemado norite (On),
- Tonalite (Ot),
- Granodiorite (Ogd),
- Biotite granite (Ogr),
- Granitoid (Og),

〈 Porphyritic granitoid (Ogp),

〈 Tuani Granite (Otu),

〈 Asperezas Granite (Oa),

〈 Migmatite, granitoid, tonalite (Ox),

〈 Migmatite, 2-mica granite (Omgg),

〈 Chepes Igneous Complex, undivided (Oc).

Stratigraphic relationships within the Chepes Igneous Complex

The order of emplacement of the various plutonic units and the formation of the migmatite of the Chepes Igneous Complex is poorly constrained as the contacts are commonly gradational and complex, and the late Ordovician phase of compressional deformation and metamorphism (see TECTONISM) has obscured the stratigraphic relationships. Furthermore, isotopic age dating indicated that the various magmatic pulses succeeded in a relatively short time span of about 17-20 Ma, and that they at least partly overlap in time (see *Geochronology* below).

The porphyritic granitoid (Ogp), only exposed in the Sierra de Chepes, forms relatively distinct, large plutons which are intruded with sharp contacts in the Olta Metamorphic Complex and the Olta Metamorphic Complex, migmatite (€oOmg) unit. The unit also intrudes the migmatite (Omg) and migmatite, granitoid, tonalite (Ox) units, but the boundaries are less well defined.

In the Sierra de Las Minas, the Asperezas Granite is emplaced within the granodiorite (Ogd) and granitoid (Og) units, but in the southern part its western contacts are gradational with the granite (Ogr) unit. In the Sierras de Chepes and de Los Llanos, the Asperezas Granite forms intrusive bodies in the migmatite (Omg), granitoid (Og) and granodiorite (Ogd) units. In the Sierra de Chepes, bodies of medium to coarse leucogranite, interpreted to belong to the Asperezas Granite, are closely associated with the porphyritic granitoid (Ogp), but contact relationships are not clear. The leucogranite is possibly a highly evolved phase of the magma that produced the porphyritic granitoid.

The granodiorite (Ogd), granite (Ogr) and granitoid (Og) units, characterised by the widespread presence of biotite, hornblende, fine-grained mafic to intermediate xenoliths, paucity of primary muscovite and medium to high magnetic susceptibility, cover large areas in all three Sierras. Only in a few places do they form distinct pluton to stock-size bodies, which, however, are markedly elongate in a north-south direction. The contacts of these units are mostly fault-controlled, and only the intrusive contact with the Olta Metamorphic Complex is sharply defined. The stratigraphic contacts with the migmatite units (Omg, Ox, Oc) are diffuse and extremely complex. Bodies of granodiorite and granite, unmappable at 1:100 000 scale, in the migmatite units are thought to be comagmatic with the granodiorite (Ogd), granite (Ogr) and granitoid (Og) units. The tonalite (Ot) and Quemado norite (On) are thought to be intermediate to mafic phases genetically related to the granodiorite, granite and granitoid units.

The Tuani Granite, characterised by the abundant presence of muscovite in addition to biotite, and locally cordierite, is spatially restricted to the outcrop areas of the migmatite units (Omg, Oc, Omgg, Ox), the Olta Metamorphic Complex (€o), and Olta Metamorphic Complex, migmatite (€oOmg) unit. Most bodies (including neosomes in the migmatite complex) are small with poorly defined boundaries, and only in a few places small stocks were mappable at 1:100 000 scale, for example on the eastern side of the northerly trending valley separating the western and eastern blocks of the Sierra de Los Llanos.

Geochronology

Two sets of recently compiled isotopic age analyses are available for the rocks of the Chepes Igneous Complex. Pankurst and others (1996) carried out a program of Rb-Sr whole-rock dating (Table 1), and Camacho and Ireland (1997) obtained crystallization ages of zircon by the U-Pb method (Table 2). Both sets of data show that the various magmatic phases of the Chepes Igneous Complex were emplaced in a relatively short time span of about 14-19 Ma. However, the Rb-Sr whole-rock ages are consistently, on an average, 23 Ma younger than the U-Pb zircon ages. It is thought that the Rb-Sr system was affected by the regional greenschist facies metamorphism associated with compressional deformation in the late Ordovician (see TECTONICS), and that the ages are partly reset.

The U-Pb zircon ages suggest that the granitoid unit (Og) is slightly older than granitoid and tonalite of similar composition but associated with the migmatite-bearing units (Oc, Ox). Analyses from neosome rocks formed by anatexis, and from the peraluminousTuani Granite are not available. The porphyritic granitoid (Ogp) was dated as being older than the migmatite-bearing units, and the Asperezas Granite is the second oldest unit. These age results conflict with field observations, as both the porphyritic granitoid and Asperezas Granite intrude the migmatite-bearing units and the granitoid. With only five U-Pb zircon age analyses available, the results must be regarded with caution for the following reasons: the age differences of the units are within or close to the error limits, and the time span of Chepes Igneous Complex magmatism is relatively short (about 14 Ma).

The narrow range of crystallization ages (491-477 Ma), geochemical characteristics (see *Geochemistry* below) and the contact relationships in the field indicate that the units of the Chepes Igneous Complex were emplaced during one major magmatic event in the early Ordovician, and that they belong to the same igneous suite (or batholith).

Pankhurst and others (1996) observed that samples of metaluminous porphyritic granitoid (Ogp) and biotite granite (Ogr/Asperezas Granite) as well as the peraluminous 2-mica granite (Tuani Granite) have elevated initial $^{87}Sr/^{86}Sr$ ratios (Table 1) and initial εNd values of -5 to -7 suggesting a significant metasedimentary component in the source rocks of the granitoids.

Geochemistry

Thirty two samples of the Chepes Igneous Complex and one pegmatite sample were collected for major and trace element analyses. The samples cover a wide spectrum of plutonic and migmatitic phases (see Table 3).

Table 1. Rb-Sr whole-rock dating by Pankhurst and others (1996).

Unit (Pankhurst and others, 1996)	Unit (this survey)	Age (Ma)	MSWD	initial $^{87}Sr/^{86}Sr$
Porphyritic Granodiorite	porphyritic granitoid (Ogp)	471±10	0.8	0.7089
		452±9	1.8	0.7111
Tuani Granite (2-mica granite)	Tuani Granite (Otu)	464±5	0.8	0.7089
Tuani Granite (cordierite granite)	Tuani Granite (Otu)			0.7155
El Elefante Granite	biotite granite (Ogr)/ Asperezas Granite (Oa)	469±5		0.7088
El Elefante Granite	biotite granite (Ogr)/ Asperezas Granite (Oa)	459±5		0.7105
El Elefante Granite	biotite granite (Ogr)/ Asperezas Granite (Oa)	456±3		

Table 2. U-Pb zircon age dating by Camacho and Ireland (1997).

Sample	Latitude (S)	Longitude (W)	Unit	Rock type	Age (Ma)
A95PP076A	30°57.98'	66°40.74'	granitoid (Og)	biotite-hornblende granodorite	491±6
A95PP114A	31°06.38'	66°31.85'	Chepes Igneous Complex, undivided (Oc)	biotite granodiorite	477±7
A95PP116A	31°11.08'	66°31.66'	porphyritic granitoid (Ogp)	biotite monzogranite	485±7
A95PP159A	31°26.98'	66°17.49'	Asperezas Granite (Oa)	biotite monzogranite	490±7
A95PP183A	31°40.72'	66°19.31'	migmatite, granitoid, tonalite (Ox)	biotite-hornblende tonalite	480±6

The SiO_2 concentrations of the granite, granodiorite and tonalite samples range from 60% to 78%, and of the norite/gabbro from 43% to 45% (the norite/gabbro phase is not part of the data set used for the following discussion). Binary plots of the concentrations of the major element oxide FeO (total Fe calculated as FeO), MgO, Al_2O_3, CaO and TiO_2, and Sr against SiO_2 concentrations (Figure 8) display well defined linear trends. However, on the Al_2O_3 versus SiO_2 diagram in particular, and to a lesser degree on the MgO and TiO_2 versus SiO_2 diagrams two parallel trends are discernable; the biotite and hornblende-bearing granodiorite and tonalite of both the granitoid (Og) unit and the migmatite units make up one trend, and the more felsic rocks the other one. The concentrations of these elements decrease as SiO_2 concentrations increase. Plots of Na_2O, K_2O and Na_2O+K_2O versus SiO_2 (Figure 9) yield more poorly defined trends than the previous plots. K_2O and Na_2O+K_2O generally increase, but Na_2O of the samples within most units tends to decrease with increasing SiO_2. The

CaO/Na_2O+K_2O ratio is less than one except for a few samples and decreases linearly as SiO_2 concentration increases. The K_2O versus SiO_2 diagram shows that the rocks fall in the high-K series and to a lesser degree in the calc-alkali fields. Plots of ASI versus SiO_2 show that most samples are metaluminous. Generally the granites associated with the migmatite have ASI values very close to 1.1, and one migmatitic granite reaches a value of 1.34. The samples of leocogranite (Asperezas Granite), biotite porphyritic granitoid, biotite granite and granodiorite, and the tonalite associated with the migmatite have mostly values fluctuating around 1.0.

Table 3. Rock samples submitted for major and trace element analyses.

Rock Unit	**Sample**	**Description**
CHEPES IGNEOUS COMPLEX		
Asperezas Granite (Oa)	A95PP159A	biotite monzogranite
	A95PP185C	biotite - muscovite monzogranite
porphyritic granitoid (Ogp)	A95PP078C	biotite granite
	A95PP078D	biotite granodiorite
	A95PP079A	biotite granodiorite
	A95PP116A	biotite monzogranite
biotite granite (Ogr)	A95PP054D	muscovite - biotite monzogranite
	A95PP068B	(muscovite -) biotite monzogranite
	A95PP082A	muscovite syenogranite
	A95PL182B	biotite granite
	A95PL184	leucogranite
granodiorite (Ogd)	A95PL169	biotite granodiorite
	A95PL177B	biotite granite
granitoid (Og)	A95PP007A	biotite granodiorite
	A95PP045A	hornblende - biotite tonalite
	A95PP076A	biotite - hornblende granodiorite
	A95PP138A	biotite granodiorite
	A95PP211A	muscovite - biotite granite
	A95PL163	muscovite - biotite granite
	A95PP173	hornblende - biotite granodiorite
Quemado norite (On)	A95PP133A	norite
	A95PL183	altered norite
migmatite, granitoid, tonalite (Ox)	A95PP179A	biotite - hornblende tonalite
	A95PP183A	biotite - hornblende tonalite
Chepes Igneous Complex, undivided (Oc)	A95PP027A	hornblende - biotite tonalite
	A95PP090A	biotite monzogranite
	A95PP100A	hornblende - biotite tonalite
	A95PP114A	biotite granodiorite
	A95PP139A	biotite - hornblende granodiorite
	A95PP142A	biotite monzogranite
	A95PP193B	muscovite - biotite granite
PEGMATITE, APLITE, MICROGRANITE		
pegmatite, aplite, microgranite (Op)	A95PP056D	muscovite syenogranite

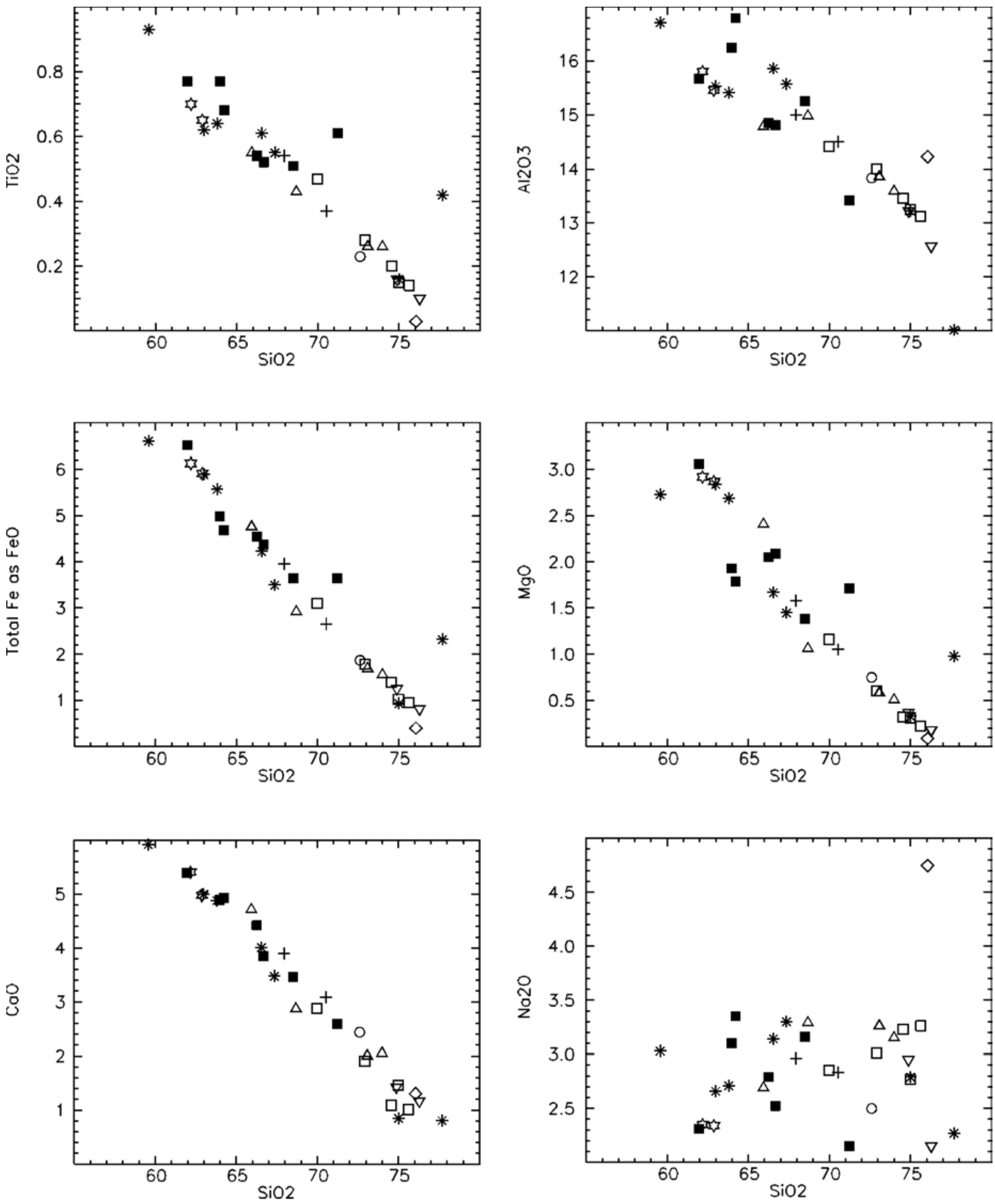


Figure 8. Bivariate plots for wt% major elements versus SiO2 for the Chepes Igneous Complex. Symbols as for Figure 9.

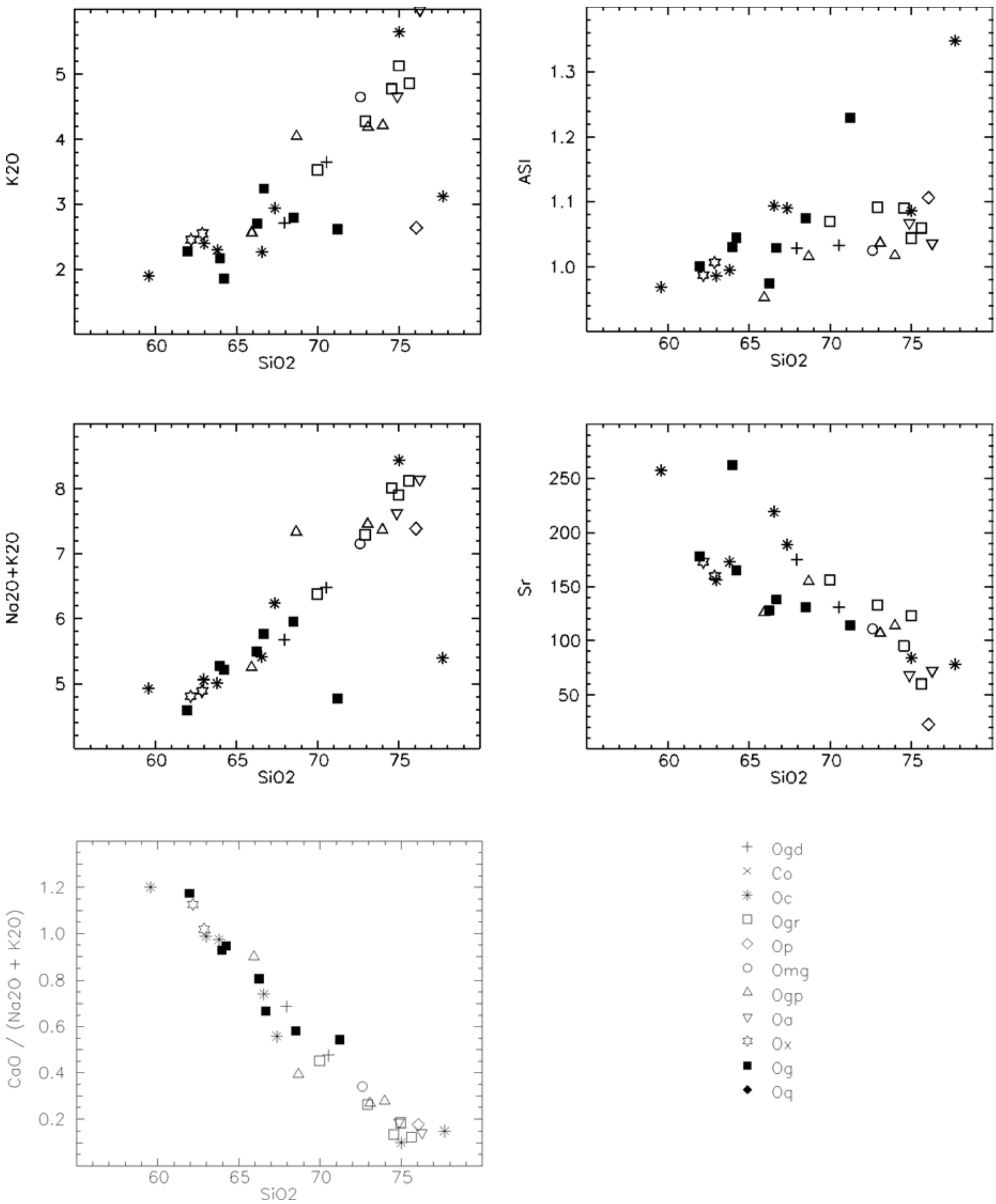


Figure 9. Bivariate plots for wt% major elements and ppm Sr versus SiO2 for the Chepes Igneous Complex.

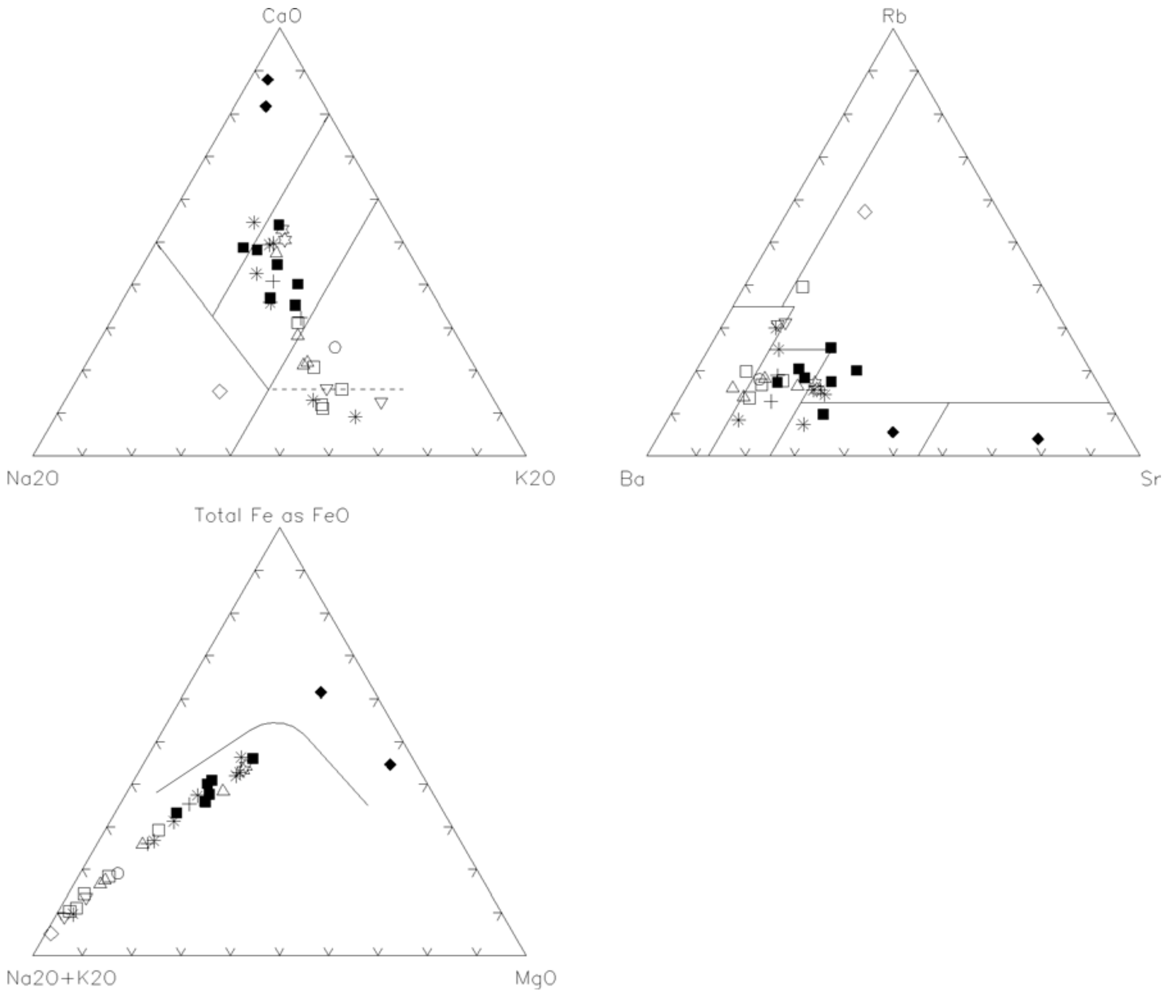


Figure 10. Na2O-K2O-CaO, Ba-Rb-Sr and AFM ternary plots for the Chepes Igneous Complex. Symbols as for Figure 9.

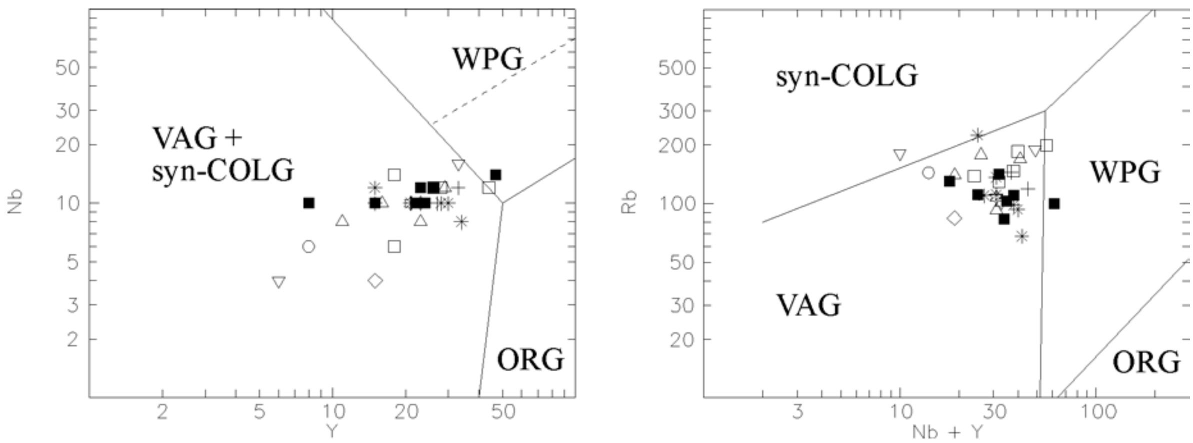


Figure 11. Nb-Y and Rb-(Nb+Y) tectonic discrimination plots for the Chepes Igneous Complex (after Pearce and others, 1984). Symbols as for Figure 9.

On an AFM ternary diagram (Figure 10) the data follow a coherent and decidedly calc-alkaline trend. A Na_2O-K_2O-CaO ternary plot (Figure 10) shows similar ties to the calc-alkaline trend for these oxides as defined by Nockolds and Allen (1953). The Na_2O-K_2O-CaO ternary plot also demonstrates that the larger part of the samples are granodiorite with smaller numbers plotting in the monzo- and syenogranite fields, and the tonalite field.

The samples were plotted on Nb against Y and Rb against Nb+Y diagrams (Figure 11) after Pearce and others (1984) on which they plot dominantly as volcanic-arc granites (VAG).

The samples tend to be enriched in large ion lithophile (LIL) elements (for example, K, Rb, Ba and Th), relative to the high-field-strength (HFS) elements (for example, Nb, Zr, and Y). The resulting high LIL/HFS ratios are typical of magmatic rocks formed by subduction-related processes (Tarney and Saunders, 1979). The low TiO_2 concentrations of the samples, without exception <1%, are also consistent with other arc-derived rocks (Green, 1980).

Migmatite (Omg) of the Chepes Igneous Complex

Distribution

This unit is exposed from north to south over a 20-30 km wide area in the central part of the Sierra de Chepes; farther north, in the central part of the Sierra de Los Llanos, the outcrops are restricted to two northerly trending 4-6 km wide belts, separated by granitoid (Og) of the Chepes Igneous Complex. The rocks mostly underlie a gently sloping to horizontal plateau which represents an old, uplifted erosional surface.

Stratigraphic relations and age

The contact between the migmatite and the Olta Metamorphic Complex is generally gradational and difficult to map at 1:100 000 scale as it passes through a zone where continuous outcrop of the Olta Metamorphic Complex becomes progressively more dismembered and diffuse. The contacts with the igneous units of the Chepes Igneous Complex are both gradational and sharp. The Asperezas Granite occurs as well-defined intrusive bodies, and in places the porphyritic granitoid (Ogp) was observed, either in the field or on air photos and Landsat TM images, to intrude the migmatite. However, in other places the transition from coherent plutonic bodies to the migmatite is across a zone where the different lithologies are intermixed in a complex way.

U-Pb ages of zircon from rocks formed by anatexis are not available. However, a biotite granodiorite sample from the undivided Chepes Igneous Complex (Oc) gave an age of 478±7 Ma, and a biotite-hornblende tonalite sample from the migmatite, granitoid, tonalite unit (Ox) an age of 481±5 Ma (Camacho and Ireland, 1997); in both units the plutonic rocks are spatially closely associated with the migmatite.

Lithology

The unit is made up of a multitude of rock types which mainly form part of the migmatite complex (including remnants of the Olta Metamorphic Complex), while the remainder comprises granitoids and minor intermediate plutonic rocks which are thought to have been emplaced at the time of the migmatisation process (Figures 12, 13, 14, 15, 16, 17). The proportion of migmatite in the unit is at least 50% and commonly between 60% and 70%. The distribution of the various rock types varies considerably from place to place over distances as short as 50 m. The outcrop area of the different rock types is commonly irregular and too small to be mapped at 1:100 000 scale. However, in places with sparse or no vegetation, some of the migmatite phases, and associated granitoids and Olta Metamorphic Complex metasediments, may be recognised on 1:45 000 scale black and white air photos by tonal differences.

Figure 12. Locality A95PP021 (66°34.63'W/31°05.16'S). Paleosome of recrystallised metasediments or meta-igneous rock preserved in fine-grained leucocratic granite. Migmatite unit (Omg) of Chepes Igneous Complex.

Figure 13. Locality A95PP021 (66°34.63'W/31°05.16'S). Layered migmatite (unit Omg) of Chepes Igneous Complex.

Figure 14. Locality A95PP021 (66°34.63'W/31°05.16'S). Finely layered migmatite (unit Omg) of Chepes Igneous Complex.

Figure 15. Locality A95PP026 (66°39.17'W/31°09.95'S). Migmatitic granodiorite (fine-grained, equigranular, anhedral) with parallel aligned biotite-rich schlieren, small irregular pegmatite bodies and microdiorite xenoliths.

Figure 16. Locality A95PP137 (66°27.20'W/30°56.18'S). Migmatite of unit Omg intruded by porphyritic granitoid (Ogp) along subhorizontal contact.

Figure 17. Locality A95PP180 (66°21.14'W/31°39.55'S). Layered migmatite grading into granodiorite; unit Ox of the Chepes Igneous Complex.

A common migmatite type is stromatic migmatite (Mehnert, 1968) where neosome and paleosome are more or less distinctly layered and have contrasting compositions. The layers are less than 5 mm to 50 cm thick and discontinuous with lenticular to pinch-and-swell forms. The layering tends to parallel the northerly structural trend of the Olta Metamorphic Complex metamorphics. At a more advanced stage of migmatisation the rock becomes a schlieren or nebulitic migmatite. In these migmatites the boundaries between the paleosome and neosome are irregular and diffuse, and these phases can only be recognised by the slightly different proportions of their mineral contents. The schlieren have irregular and whispy forms but their long dimensions still follow the regional structural trend. At this stage the migmatite merges into magmatic granitoid.

The paleosome of the migmatite is composed of psammitic, pelitic and feldspathic metasediments (including 2-mica phyllite, schist and gneiss), schistose and gneissic granitoid, and minor hornblende-plagioclase schist and gneiss. These rock types have been described in the section on the Olta Metamorphic Complex, although in the migmatite they tend to be slightly higher-grade and coarser, and the proportion of the psammitic and pelitic metasediments is less than the total of the other rock types. With advanced migmatisation the paleosome and neosome lithologies become progressively more homogeneous eventually forming granitoid in which the original planar fabric elements are only preserved as schlieren. The paleosome of the migmatite commonly contains equant porphyroblasts of plagioclase or K-feldspar, and locally also relatively coarse anhedral cordierite. Feldspar porphyroblasts are even noticable in nebulitic and schlieren migmatite or granotoid where migmatisation has reached an advanced stage of homogenization. Scattered, equidimensional milky to grey quartz segregations measuring 4-10 cm across are a typical feature closely associated with the migmatite complex.

The neosome comprises two types of leucosome: fine to medium-grained muscovite-biotite monzo- or syenogranite and muscovite-bearing pegmatite, and granodiorite. The plagioclase is an- to subhedral, equidimensional and shows very little compositional zoning. The K-feldspar (microcline) is anhedral, relatively coarse and occasionally poikilitic. The quartz commonly occurs in irregular aggregates. The leucosomes are commonly separated from the paleosome by a melanosome forming a thin selvedge of dark grey to black biotite-feldspar-quartz rock which in places also contains hornblende or cordierite. The biotite forms parallel streaky aggregates aligned about the same trend as the layering. The contact with the paleosome is gradational and with leucosome abrupt. The neosome rocks form discontinuous, lenticular bodies up to 50 cm thick. With advanced migmatism the paleosome and neosome become progressively more disrupted, intermingled and intermixed, and eventually it is impossible to differentiate the two phases.

The migmatite lithologies are closely associated with granitoids ranging in composition from monzo- or syenogranite through granodiorite to tonalite. The contacts between the migmatite and granitoids are both sharp and diffuse or gradational, and in places it is not clear whether the granitoids represent an advanced stage of migmatisation or that they form magmatic bodies derived from lower crustal levels. The granitoid bodies which were observed range in size and shape from irregular enclaves 1 to 30 m across to dykes and stocks. At locality A95PP040 (66°25.78'W/30°51.31'S) in the drainage of Rio Nacate, where it debouches from the mountains, the relationships between the migmatite complex and both migmatitic and magmatic granitoid are well exposed. In the mountains east of the wide, northerly trending valley that divides the Sierra de Los Llanos, migmatite and metasediments of the Olta Metamorphic Complex are closely associated with small bodies, including veins and dykes, of peraluminous muscovite-biotite monzogranite. However, in the same area, air photo interpretation and scattered field observations indicate also the presence of a granite stock (Tuani Granite) of the Chepes Igneous Complex.

The main structural fabric in the migmatite is a generally northerly trending foliation defined by the compositional layering, and parallel alignment of biotite and of elongate aggregates or streaks of biotite with or without hornblende and cordierite. This foliation parallels and is mostly, if not all, controlled by the structural fabric of the metamorphics of the Olta Metamorphic Complex. The migmatite layering is only locally deformed by isolated disharmonious or rootless folds, and as there is no evidence of a linear or planar shape fabric formed under medium to high-grade metamorphic conditions it is thought that the metamorphic-magmatic event took place in a passive tectonic setting. The mineral assemblages of the metamorphics of the Olta Metamorphic Complex and migmatite indicate a tectonic setting of low-pressure metamorphism.

The migmatite and granitoid lithologies are altered and deformed under greenschist-facies conditions. Plagioclase is partly altered to sericite, secondary muscovite and epidote/clinozoisite, biotite to chlorite, epidote/clinozoisite and titanite, and quartz is recrystallized to granoblastic-polygonal aggregates. The rocks are locally disrupted by shearing and cut by a spaced foliation, both about a northerly trend, and in zones of high strain they are transformed into mylonite. The spaced foliation is defined by reoriented biotite and by aggregates, lenses and ribbons of recrystallised quartz.

Quemado norite (On) of the Chepes Igneous Complex

Distribution

Norite, gabbro and diorite were mapped in the southern part (Rio del Quemado) and northern part (Rio de Balde) of the Sierra de Las Minas, and in the central west Sierra de Chepes (Pampa del Chañar). Exposures of mafic rock are interpreted from airphotos south of Rio del Quemado and in the southeast part of the Sierra de Los Llanos.

Nomenclature, stratigraphic relations and age

Ramos (1982) reported on the occurrence of mafic plutonic rocks in the Sierras de Chepes and de Las Minas, and assigned this unit as an informal subdivision to the 'Chepes Formation'. The unit is distinct and mappable at 1:100 000 scale, and therefore it is proposed to introduce the name Quemado norite. It is named after the Rio del Quemado in the southern part of the Sierra de Las Minas; in the drainage area of this river the unit is well exposed and easily accessible by vehicle track.

The unit, where mapped as well as interpreted from airphotos, is exposed in topographic lows up to 1000 m across. The subhorizontal or gently dipping upper boundary is overlain by granitoid of the Chepes Igneous Complex, and, in Pampa del Chañar, by metasediments of the Olta Metamorphic Complex; the overlying rocks make up the hills surrounding the depressions.

The unit is cut by a 10 m thick garnet-tourmaline bearing pegmatite body in Pampa del Chañar, and by aplite veins in other places.

Lithology

Mapping of this unit was restricted to the marginal zones where it is in contact with granitoid or metasediments of the Olta Metamorphic Complex. Although medium to locally coarse-grained norite, gabbro and diorite are the characteristic rock types, the rocks in the marginal zone are more variable in composition as well as texture. In both outcrops in the Sierras de Las Minas, where the unit is in contact with granitoid, the compositions of the rocks range from norite/gabbro to quartz diorite and tonalite, and the colour index, grain size and proportion of constituent minerals are highly variable. Compositional and textural (grainsize) layering is common; the layers range in thickness from 4 to 15 cm. Towards the contact with the metasediments of the Olta Metamorphic Complex, norite and gabbro decrease in grainsize from medium with coarse phases of pyroxene or hornblende to medium and fine, and the composition of the mafic rocks becomes hybrid.

In most outcrops the rocks are little tectonised and altered, and massive compared to the surrounding granitoid and metasediments. Jointing and fracturing is commonly wide-spaced, and only locally are the rocks weakly foliated.

In thin section the norite and gabbro consist of plagioclase, orthopyroxene and clinopyroxene with variable amounts of hornblende and very little (<2%) biotite; magnetite is a common accessory. Hornblende commonly forms large, skeletal, poikilitic, optically continuous crystals with enclosed rounded plagioclase, ortho- and clinopyroxene. Replacement of pyroxenes and hornblende by secondary amphibole varies from marginal to pervasive. Other secondary minerals are epidote/clinozoisite, chlorite, actinolite, sericite, and where quartz is present it is recrystallised to a fine polygonal granoblastic aggregate. The nature of the secondary minerals indicates that the rocks were subjected to greenschist metamorphism.

A fine mafic rock collected from the marginal zone close to the contact with metasediments contains, in addition to plagioclase, hornblende and ortho- and clinopyroxene (about 50%), relatively large amounts of recrystallised quartz, K-feldspar and clinozoisite. This hybrid composition is probably the result of reaction with the country rock.

The magnetic susceptibility of the mafic rocks varies from 500 to 5500 x 10^{-5} SI, and in the Rio del Quemado drainage the outcrop area is located in a 10 km long, north-south elongate zone characterised by a strong aeromagnetic signature and very low radiometric signature.

Remarks

From the field observations it is not clear whether the mafic rocks intrude the granitoids and metasediments as discrete bodies (for example sills) or if they form synplutonic mafic bodies emplaced in partially crystallised felsic magma.

As the rocks are commonly coarse-grained, and relatively little altered and deformed they have much potential for high-quality dimension stone.

Tonalite unit (Ot) of the Chepes Igneous Complex

Distribution

The exposure of this unit is restricted to the southern part of the Sierra de Las Minas. However, tonalite is a minor to rare but widespread component of the migmatite units, and the granodiorite and granitoid units of the Chepes Igneous Complex; in these units it is unmappable at 1:100 000 scale. The unit, together with the Quemado norite which it encloses, is characterised by a very high aeromagnetic signature and a low radiometric response, and on airphotos and Landsat TM images it stands out by a relatively dark tone.

Nomenclature, stratigraphic relations and age

Caminos (1979) included this unit in the 'normal facies of the Chepes Formation' consisting of massive granodiorite and tonalite. As discussed in the section on the biotite granite (Ogr) the 'normal facies of the Chepes Formation' is replaced by five informal units.

The unit grades into the surrounding granitoid unit (Og). The contact with the Quemado norite appears to be gradational (see Quemado norite).

Lithology

Although grey, fine to medium-grained tonalite is the characteristic rock type of this unit, it is closely accompanied by, and gradational to, granodiorite. Locally granodiorite makes up about 50% of the outcrop.

The main rock-forming minerals of the tonalite are plagioclase (30-45%), quartz (10-40%), biotite (5-20%), and hornblende (0-35%). The minor constituents include magnetite (<5%), muscovite (<5%), primary epidote (<1%), allanite (<1%), titanite (<1%), and locally orthopyroxene (<1%). The plagioclase tends to be relatively coarse and is commonly tabular subhedral; it shows normal zoning with the composition varying from oligoclase to labradorite. Biotite and hornblende are commonly subhedral. Primary epidote and allanite tend to be interstitial. Where observed the orthopyroxene mantles magnetite.

The rocks are affected by deformation and greenschist facies regional metamorphism. The quartz is recrystallised to a fine, polygonal granoblastic matrix commonly forming parallel aligned ribbons. The plagioclase, particularly the cores, is altered to very fine or microcrystalline epidote/clinozoisite and sericite; biotite is variably replaced by chlorite and epidote/clinozoisite. A weakly to moderately developed foliation is defined by quartz ribbons and trails of recrystallised biotite. In places fine-grained biotite tails trail from medium-grained biotite.

The magnetic susceptibility of tonalite samples collected from all units of the Chepes

Igneous Complex is moderate to high, ranging from 300 to 1500 x 10^{-5} SI.

Granodiorite (Ogd) of the Chepes Igneous Complex

Distribution

This unnamed granodiorite is exposed both east and west of the Asperezas Granite and biotite granite (Ogr) unit in the eastern part of the Sierra de Las Minas, and also occupies most of the northern part and the extreme southern part of the Sierra. Along the east flank of the Sierra de Las Minas the granodiorite is abruply bounded by the eastern border fault. The unit underlies most of the western mountain block of the Sierra de Los Llanos, and occurs along the margins of the north-south elongate valley south of the Dique El Portezuelo. Because of the gradational character of the boundaries the distribution of the granodiorite (Ogd), biotite granite (Ogr) and granitoid (Og) units is based for a large part on their geophysical properties.

Like in the granite country the topography is hilly with low to moderate relief with broad flat-topped or rounded ridges. The rocks are exposed as tors, boulders, pavements and irregular sheets.

Nomenclature, stratigraphic relations and age

Caminos (1979) and Ramos (1982) included this unit in the ‘normal facies of the Chepes Formation’ consisting of massive granodiorite and tonalite. As discussed in the section on the biotite granite (Ogr) the ‘normal facies of the Chepes Formation’ is replaced by five informal units.

The boundaries between the five informal units are gradational, and each unit contains, in widely variable proportions, rock types of the other units. The units are intruded by dykes and veins of aplite and pegmatite.

The plutonic rocks of the Chepes Igneous Complex are genetically related, and therefore the U-Pb zircon ages of 490±5 Ma and 495±7 Ma for the granitoid (Og) unit and

Asperezas Granite (Oa), respectively, provide an age bracket for the biotite granite unit.

Lithology

The rocks are mainly light grey passing to medium grey where they contain relatively high amounts of biotite, and some of the granites are light pink to greyish pink.

The main rock type is granodiorite containing 5 to 20% biotite and in places up to 5% hornblende; on a regional scale the composition grades into monzogranite and tonalite. Compositional and, to a lesser degree, textural changes at outcrop scale range from abrupt to gradational, and show in the field as igneous banding of biotite ± hornblende bearing phases and felsic (with or witout K-feldspar) phases, the occurrence of biotite-rich schlieren in more felsic granodiorite, and irregular shaped enclaves of granite or tonalite in granodiorite.

Xenoliths are widespread and in places they make up 20 to 30 % of the rock. The composition is microdiorite or micro quartz diorite containing 20% to 60% biotite and commonly also hornblende (<10%). Some xenoliths contain fine to medium-grained feldspar phenocrysts. The size of the xenoliths is up to 100 cm with the most common sizes varying between 5 cm and 20 cm. Most contacts with the host rock are sharp but gradational contacts were also observed. In zones of high strain, for example along the western margin of the Sierra de Las Minas, the xenoliths are flattened, predominantly about a northerly strike. Enclaves of migmatite in the granodiorite are rare, for example, at A95RS054 (31°58.37’W/66º19.30’S) in the southernmost part of the Sierra de Las Minas.

The typical granodiorite is made up of quartz (15-30 %), plagioclase (30-50 %), K-feldspar (10-25 %), biotite (10-15 %), hornblende (<10 %), and accessory magnetite and zircon. The quartz is recrystallised to aggregates with polygonal granoblastic textures and/or deformed to grains with strained extinction and sutured boundaries. The plagioclase forms subhedral grains and commonly shows normal zoning; particularly in the cores it is altered to microcrystalline epidote/clinozoisite, fine epidote, sericite and minor to fine muscovite. The K-feldspar, dominantly microcline, is relatively coarse, anhedral and little altered to kaolinite. The biotite and hornblende occur mostly as single crystals but also in clusters; the biotite is variably replaced by chlorite, epidote and sphene, and the hornblende by secondary amphibole. A minor but characteristic phase is made up of primary epidote and allanite. In places the epidote is nucleated on the allanite. The accessory primary epidote is difficult to recognise from the widespread secondary epidote; however, the secondary epidote is usually more pleochroic, intergrown with clinozoisite, and closely associated with plagioclase, biotite, etc., which it replaces. Titanite and zircon are common accessories; zircon commonly occurs in the biotite surrounded by pleochroic haloes.

The strained plagioclase and microcline, recrystallization of quartz, commonly present foliation and shearing, flattened xenoliths and the assemblage of secondary minerals indicate regional scale contemporaneous compressive deformation and greenschist facies metamorphism.

Biotite granite unit (Ogr) of the Chepes Igneous Complex

Distribution

The biotite granite unit is exposed in the eastern part and extreme northwest parts of the Sierra de Las Minas and throughout the Sierras de Chepes and Los llanos. The outcrop areas are generally elongated north-south. Although partly covered by alluvial sediments, the largest body recognisable as a discrete pluton crops out in the north-south trending topographic low in the northeastern part of the Sierras de Chepes where the villages Nacate and El Quemado are located (Santa Rita de Catuna (3166-15) 1:100 000 sheet). This pluton is also typically extended in north-south direction; it is 25 km long and 5 km wide.

The topography of the granite country is typically hilly with low to moderate relief and flat-topped or rounded ridges, and the rocks form tors, boulders, pavements and irregular sheets.

Nomenclature, stratigraphic relations and age

Caminos (1979) and Ramos (1982) included this unit in the 'normal facies of the Chepes Formation' described as massive granodiorite and tonalite. Based on the additional geological and geophysical information collected during the present project the 'normal facies of the Chepes Formation' is replaced by five informal units, namely: biotite granite (Ogr), granodiorite (Ogd), granitoid (Og), tonalite (Ot) and Quemado norite (On).

The unit is transitional to the Asperezas Granite and the comagmatic units mentioned above, and fieldwork data, in combination with airphoto and Landsat image interpretation, only poorly constrain the boundaries. However, the airborne radiometric and magnetic signatures of the unit are more distinct and the position of the boundaries is mainly based on their geophysical properties. The contact with the Olta Metamorphic Complex is clearly intrusive and well defined; the unit is also intrusive in the migmatite (Omg). In the southwestern part of the Sierra de Chepes there occur two irregular, north-south elongate bodies of which the southern one is emplaced in the undivided Chepes Intrusive Complex and the northern one in the porphyritic granitoid. Ramos (1982) assigned these bodies to the Asperezas Granite.

The U-Pb zircon ages of 490±5 Ma and 495±7 Ma for the genetically related granitoid unit (Og) and Asperezas Granite (Oa), respectively, provide an age bracket for the biotite granite unit.

Lithology

The most common rock type is monzogranite which is light pink to light grey, fine to medium-grained, equigranular to seriate with relatively coarse K-feldspar, and homogeneous. In places it grades into, or is cut by veins or dykes of, leucogranite and aplite (partly Asperezas Granite). Granodiorite lithologies were also observed. The monzogranite contains 2-15% biotite. Xenoliths are only locally common; they are round to oval with sharp as well as gradational boundaries and up to 6 cm long, and invariably consist of biotite microdiorite or micro quartz diorite containing up 30-60% biotite. The rocks are deformed and metamorphosed in a similar manner as the

Asperezas Granite.

Granitoid unit (Og) of the Chepes Igneous Complex

Distribution

This unit has a wide distribution in the northeast part of the Sierra de Chepes continuing northward into the southeast part of the Sierra de Los Llanaos, in the northwest part of the Sierra de Chepes (Figure 5), and throughout the Sierra de Las Minas.

Nomenclature, stratigraphic relations and age

The granitoid unit consists of 25-75% granodiorite and 25-75% biotite granite, and minor tonalite and leucogranite which, at 1:100 000 scale, could not be subdivided into separate units by field mapping and interpretation of airphotos, Landsat TM and airborne geophysics.

The contact with the Olta Metamorphic Complex is intrusive and well defined; the contacts with the migmatite unit (Omg) and the migmatite, granitoid, tonalite unit (Ox) are locally sharp but mostly gradational. In places the unit is intruded by the Asperezas Granite.

Based on one U-Pb zircon analysis the age of a biotite-hornblende granodiorite sample is 490±5 Ma.

Lithology

The rock types making up this unit are described in separate sections on the granodiorite (Ogd) unit and the biotite granite (Ogr) unit.

Porphyritic granitoid unit (Ogp) of the Chepes Igneous Complex

Distribution

The porphyritic granitoid is exposed in kidney to oval-shaped plutons in the Sierra de Chepes. The long dimension of the largest pluton is 17 km. The unit is not exposed in the Sierra de Las Minas and the southern part of the Sierra de Los Llanos.

Nomenclature, stratigraphic relations and age

Caminos (1979) and Ramos (1982) included this unit in the 'porphyritic granodiorite facies of the Chepes Formation'. In this report it is proposed to change the name 'Chepes Formation' to Chepes Igneous Complex and to subdivide this complex into twelve lithological units including the porphyritic granitoid (see section *Nomenclature* of Chepes Igneous Complex).

The porphyritic granitoid plutons intrude the Olta Metamorphic Complex, migmatite unit (€oOmg), and generally the boundary is well defined. The contact is mostly steep to vertical but in places it is gently dipping to subhorizontal with the porphyritic granitoid overlying the metasediments of the Olta Metamorphic Complex. Where present the contact aureole is very poorly developed. The contact with the migmatite unit (Omg) is also intrusive (Figure 16), but is difficult to trace from airphotos and Landsat TM images; aeromagnetic and radiometric images have been used to locate the boundary. The unit is intruded by the Asperezas Granite and by the biotite granite unit (Ogr).

The unit is thought to be comagmatic with the biotite granite, granodiorite, granitoid units and the Asperezas Granite of the Chepes Igneous Complex, and therefore the age is bracketed by 478-490 Ma.

Lithology

Although medium to coarse-grained, porphyritic biotite granodiorite is the most typical rock type, the unit covers a wide range in composition and texture. The granodiorite grades into monzogranite as well as tonalite, and in addition to porphyritic textures the rocks are also commonly seriate and equigranular. The phenocrysts consist of alkali-feldspar. The mineral assemblages are similar to those of the granodiorite, biotite granite and tonalite units except that the presence of hornblende is less common. The effects of deformation and regional greenschist metamorphism are the same as for the other units of the Chepes Igneous Complex.

Tuani Granite (Otu) of the Chepes Igneous Complex

Distribution

The muscovite-biotite granite of the Tuani Granite is a common rock type associated with the migmatite (Omg) unit and to a lesser degree with the Olta Metamorphic Complex migmatite unit, but only in a few places the outcrops reach a size that could be mapped at 1:100 000 scale. A prominent outcrop occurs on the eastern side of the wide valley that separates the western from the eastern mountain block of the Sierra de Los Llanos, and smaller exposures were mapped in the southernmost part of the Sierra de Las Minas and in the subdued hills east of the Sierra de Las Minas around latitude 30°49’ S. Outcrops of muscovite-biotite granite are also widespread along the southern margin of the Sierra de Chepes west of Chepes Viejo, and in the isolated hills southwest of Chepes Viejo.

Nomenclature, stratigraphic relations and age

The name Tuani Monzogranite was introduced by Dahlquist and Baldo (1996), and the name Tuani Granite by Pankhurst and others (1996). The unit is as yet not formally defined, and the usage of the name Tuani Granite is preferred in this report.

The unit has a well defined intrusive contact with the Olta Metamorphic Complex. The contact with the migmatite unit is complex and gradational.

Based on Rb-Sr ages Pankhurst and others (1996) concluded that the phase of Tuani

Granite magmatism and the magmatism producing the biotite (± hornblende) bearing granodiorite and granite phases of the Chepes Igneous Complex occurred contemporaneously over a time interval of 452-471 Ma. As U-Pb dating of zircons suggests that the Rb-Sr ages are consistently reset (Camacho and Ireland, 1997), the age of crystallization for the Tuani Granite probably falls into the U-Pb zircon age span of 478-495 Ma determined for the biotite (± hornblende) bearing granodiorite and granite phases of the Chepes Igneous Complex. A U-Pb zircon age of the Tuani Granite is not available.

Lithology

The typical lithologies of this unit are light pink, fine to medium-grained and equigranular to seriate muscovite-biotite (-cordierite) monzo- and syenogranite. The rocks consist of the following minerals: quartz (15-50%), K-feldspar (microcline) (15-30%), plagioclase (albite-oligoclase) (0-30%), muscovite (5-15%), biotite (0-15%), and cordierite (0-20%). Pankhurst and others (1996) reported the presence of sillimanite in some of the cordierite-bearing granites. Accessory minerals are zircon, opaques, and occasional tourmaline. Like the other units of the Chepes Igneous Complex, the granite has been subjected to deformation and regional greenschist metamorphism. A weakly to moderately well developed foliation is defined by subparallel alignment of biotite and muscovite, and by quartz ribbons and lenses. The feldspar is partly sericitized; the more calcic plagioclase shows alteration to fine or microcrystalline clinozoisite/epidote, and the biotite along the cleavage to chlorite and epidote. The quartz is mostly recrystallised to a fine, polygonal granoblastic matrix, and biotite and muscovite also are partly recrystallised.

The rocks are dominantly peraluminous, and generally have the characteristics consistent with S-type granites (Pankhurst and others, 1996; Rapela and others, 1996).

Asperezas Granite (Oa) of the Chepes Igneous Complex

Distribution

Leucogranite of the Asperezas Granite crops out in the Sierra de Las Minas, and occurs scattered in the Sierras de Chepes and de Los Llanos as commonly north-south elongate bodies ranging in size from up to 50 m thick dykes to stock-size bodies up to 8 km long and 2 km wide. The granite bodies stand out in the landscape as relatively resistant, light pink to white ridges which are almost bare of vegetation. The outcrops form rugged tors and irregular surfaces. On airphotos and Landsat images the unit is very conspicuous because of its light tones.

Nomenclature, stratigraphic relations and age

The name Asperezas Granite was formalised by Caminos (1968). The contacts with biotite granite (Ogr), granodiorite (Ogd), granitoid (Og) and porphyritic granitoid (Ogp) units vary from gradual to abrupt. In the southern part of the Sierra de Las Minas, where the Asperezas Granite grades westward into the biotite granite the boundary is poorly defined and the position is only approximate. On the other hand, the eastern contact with the granodiorite unit is sharp. The contacts with the rocks of the migmatite unit (Omg) are well-marked and intrusive. The U-Pb zircon analysis on one sample (A95PP159A; 66.2915°W/31.44962°S) yielded a crystallisation age of 495 ± 5 Ma (latest Cambrian).

Lithology

The leucogranite is light pink to white, fine to coarse-grained, seriate with relatively coarse K-feldspar, and homogeneous. Xenoliths are rare and very small (0.5-2cm across), and consist of biotite-rich microdiorite to quartz diorite. The unit is cut by pegmatite and aplite veins, and locally grades into pegmatitic granite and fine-grained granite or aplite. The pegmatite phase probably represents the final stage of differentiation by fractional crystallization of the magma which also produced the Asperezas Granite.

The typical rock type is leucocratic monzogranite composed of 30-60% K-feldspar (mostly microcline; rarely orthoclase), 10-30% Na-rich plagioclase, 20-50% quartz, <5% biotite and accessory zircon. The microcline is anhedral and perthitic, relatively fresh, and in places is deformed by kinking. The plagioclase is an- to subhedral and commonly more or less replaced by sericite and epidote/clinozoisite in the form of very fine crystals as well as microcrystalline aggregate. Most of the quartz is recrystallised to a fine polygonal granoblastic aggregate. Brown biotite occurs in single crystals and in small, subparallel oriented aggregates, and is altered to chlorite along the cleavage and margins. Fine muscovite is a minor (<2%) secondary mineral associated with feldspar and biotite.

The rocks are variably deformed and the assemblage of secondary minerals indicates that they have been subjected to greenschist facies metamorphism. The northerly trend of the elongate bodies parallels the trend of a commonly present discontinuous, spaced foliation, and the trend of brittle-ductile shear zones within and along contacts of the bodies. The foliation is steep to vertical, and defined by lenses of recrystallised quartz, biotite folia or streaks and platy K-feldspar.

The magnetic susceptibility of the unit is typically low and varies between 0 and 70 x 10^{-5} SI. On the other hand, the radiometric response is high compared to that of the other plutonic units of the Chepes Igneous Complex.

Remarks

The contact relationships, geochemistry and U-Pb zircon dating indicate that the Asperezas Granite forms a late crystallization phase genetically associated with the granite, granodiorite, granitoid and porphyritic granitoid units of the Chepes Igneous Complex.

Migmatite, granitoid, tonalite unit (Ox) of the Chepes Igneous Complex

Distribution

Exposures of this unit are confined to the central western part of the Sierra de Las Minas (Figures 18, 19).

Nomenclature, stratigraphic relations and age

This unit consists of various other units of the Chepes Igneous Complex which are not separable at 1:100 000 scale, because of the small outcrop areas and complex contact relationships.

The boundaries with the granitoid unit (Og) and granodiorite unit (Ogd) are gradational and poorly defined.

The plutonic rock types in this unit are thought to be comagmatic with the plutonic rocks of the other units of the Chepes igneous complex, and therefore their crystallisation age is early Ordovician.

Figure 18. Locality A95PP175 (66°21.78’W/31°44.17’S). Foliated granodiorite of unit Ox (Chepes Igneous Complex) containing northerly aligned and flattened microdiorite xenoliths. This outcrop is located in the peripheral part of a northerly trending shear zone which is interpreted from aeromagnetics about 2 km to the west and covered by alluvial sediments.

Figure 19. Locality A95PP244 (66°20.95’W/31°36.53’S). Discrete, narrow and subvertical D3 shear zones cutting granodiorite, pegmatite and flattened (D2) microdiorite xenoliths of the Ox unit (Chepes Igneous Complex).

Lithology

The rock types making up this unit are described in separate sections on the migmatite (Omg), granitoid (Og) and tonalite (Ot) units.

Migmatite and 2-mica granite unit (Omgg) of the Chepes Igneous Complex

Distribution

This unit is exposed in the small group of hills south of the southern margin of the Sierra de Chepes west of Chepes Viejo.

Nomenclature and age

This unit is a mixture of the migmatite unit and Tuani Granite of the Chepes Igneous Complex which could not be separated at 1:100 000 scale, because of the small outcrop areas and complex contact relationships.

The plutonic rock types in this unit are thought to be comagmatic with the plutonic rocks of the other units of the Chepes igneous complex, and therefore their crystallisation age is early Ordovician.

Lithology

The rock types making up this unit are described in separate sections on the migmatite (Omg) unit and the Tuani Granite (Ot).

Chepes Igneous Complex, undivided (Oc)

Distribution

The undivided Chepes Igneous Complex comprises a complex mixture of rock units, which could not be differentiated at 1:100 000 scale, in the southwest part of the Sierra de Chepes. The units, in decreasing order of significance, mapped in this area are: granodiorite (Ogd)/biotite granite (Ogr), migmatite (Omg), tonalite (Ot), 2-mica granite (Tuani Granite), and leucogranite (Asperezas Granite). The 2-mica granite is widely exposed along the eastern half of the southern fault margin bounding the southwest Sierra de Chepes; distinct bodies of porhyritic granitoid were not observed. Locally the various rock units are cut by pegmatite , aplite and microgranite dykes and veins.

Nomenclature, age, lithology

The nomenclature, age (geochronology) and geochemistry are described in the section **Chepes Igneous Complex**, and the lithology is described in the sections on the various rock units.

2.5 Ordovician pegmatite, aplite and microgranite dykes

Distribution

Dykes and veins of pegmatite, aplite and microgranite occur in swarms and also solitairy throughout the Sierras de Chepes and de Los Llanos. In the Sierra de Las Minas these rocks are much less common and they are commonly spatially associated with the Asperezas Granite. The dykes and veins are shown on the map with the standard dyke map symbol, except in the southeast part of the Sierra de Chepes, west of Ambil, where the dykes are up to 100 m wide and form mappable units (Op) at 1:100 000 scale.

Nomenclature and age

This unit is informal and unnamed as it comprises two and possibly three phases of felsic dykes and veins, which, at the present stage of mapping, only locally can be differentiated. The dykes and veins were emplaced in the early Ordovician during the magmatic cycle of the Chepes Igneous Complex, and possibly in the late Ordovician during regional compressive deformation.

Lithology

A distinct phase of pegmatite, aplite and microgranite emplacement is closely associated with the migmatite of the Chepes Igneous Complex. The rocks occur in discontinuous and irregular shaped veins and pods, most commonly 4-10 cm and up to 40 cm thick. Generally, the veins follow the northerly structural trend of the migmatite and associated Olta Metamorphic Complex lithologies; locally they are folded. The rocks consist of quartz, albite/oligoclase and K-feldspar with minor muscovite, and accessory biotite. In the pegmatite the feldspar forms the coarse phase. Because of the small size of the bodies this phase is not represented on the map. Like the associated lithologies of the Chepes Igneous Complex, the pegmatite, aplite and microgranite were deformed in late Ordovician time. The quartz is partly to completely recrystallized to aggregates and ribbons of fine granoblastic grains; a weakly developed, commonly anastomising foliation is defined by elongate aggregates and ribbons of granoblastic quartz and subparallel aligned muscovite and biotite wrapped around the feldspar. Boudinage structures occur at misroscopic to outcrop scale. The plagioclase is variably altered to sericite.

Another phase of dykes and veins is attributed to advanced differentiation by fractional crystallization of granitic magma which probably also produced the various granites, in particular the Asperezas Granite, of the Chepes Igneous Complex. The rocks intrude all lithologies of the Olta Metamorphic Complex and Chepes Igneous Complex, and also are incorporated in the Ulapes mylonite. Generally, the dykes and veins have a northerly to northwesterly trend, and are affected by shear deformation. In the central eastern part of the Sierra de Las Minas the bodies reach a thickness up to 50 m and a length of 2 km. Boudinageing and tight folding were observed in outcrops as well as on airphotos, and deformation at microscopic scale is similar to that of the pegmatite, aplite and microgranite associated with the migmatite. The rocks are composed of quartz, albite/oligoclase and K-feldspar with minor muscovite, accessory biotite, and locally contain tourmaline.

The origin of the remaining dykes and veins is uncertain. The orientations of the bodies vary greatly, although northerly and westerly trends are most common. The conjugate set of easterly and northerly trending, curved, and up to 4 km long and 100 m wide dykes west of Ambil probably fall into this category. The majority of dykes are up to 1.5 km long and up to 30 m wide. In addition to quartz, albite/oligoclase, K-feldspar, minor muscovite and accessory biotite the pegmatite also contains locally tourmaline and garnet. Many bodies show a more or less well defined zoning, particularly in texture. From the margins inward the texture has been observed to change from microgranitic or aplitic through graphic or heterogeneous to blocky and coarse-grained monomineralic. Except for minor macroscopic open folding, and locally shearing and faulting the rocks are relatively little deformed. The rocks may have been emplaced during the waning stages of the late Ordovician phase of east-west compressive deformation; however, no other felsic magmatism has been recorded from that time in the region. In other parts of the southern Sierras Pampeanas pegmatites are genetically related to the Devonian Achala Granite Complex (Morteani and others, 1995), but in the Sierras de Chepes, de Los Llanos and de Las Minas there is no field and aeromagnetic evidence that the Devonian granite plutons, concealed beneath the alluvial plains adjacent to the sierras, are accompanied by pegmatites and other highly differentiated rocks. On the other hand, these dykes and veins may also have been derived from the felsic magma which produced the granites of the Chepes Igneous Complex, but they were only slightly affected by deformation as they are located in zones of low strain.

2.6 ORDOVICIAN ULAPES MYLONITE

Distribution

The Ulapes mylonite was mapped as a lithological unit along almost the entire eastern margin of the Sierra de Las Minas where it is exposed in a 200-1000 m wide zone. The unit is also exposed in the north-northwest elongate sierra, 1-2 km east of the southeast flank of the Sierra de Los Llanos (Santa Rita de Catuna (3166-15) 1:100 000 sheet), and 10 km northwest of the Dique de Anzulón (Santa Rita de Catuna (3166-15) 1:100 000 sheet). Mylonite, although not mappable at 1:100 000 scale, is also associated with major, northerly trending and curved or sinuous shear zones traversing the basement rocks in the Sierras de Chepes and de Los Llanos.

Nomenclature and age

Caminos (1979) was the first author to report on the presence of mylonite along the eastern margin of the Sierra de Las Minas. The mylonite forms a distinct lithological unit which is mappable at 1:100 000 scale. In this report it is proposed to designate the unit as the Ulapes mylonite. The type area nominated is immediately west of Ulapes where the mylonite is well exposed and easily accessible.

Sample A95PP192B (66.33944°W/31.10252°S) consisting of mylonitised granite from a northerly trending high-strain shear zone about 3 km north of Ambil (Desiderio Tello (3166-21) 1:100 000 sheet) was submitted for ^{40}Ar-^{39}Ar isotopic age dating. The mapped shear zone straddles the contact between the Olta Metamorphic Complex and Chepes Igneous Complex, and aeromagnetics shows that it is continuous with shear zones concealed beneath the alluvial sediments of the plain to the north as well as the south. The secondary muscovite, interpreted to have grown in greenschist-facies conditions during shearing, is subparallel to the stretching lineation in the shear fabric. The muscovite gave a total fusion age of 454±1 Ma and a step heating age of 450-462 Ma, which are interpreted as the age range (late Ordovician) of the shearing deformation.

Lithology

The mylonite is typically associated with northerly trending, curved and sinuous, ductile shear zones which cut the basement rocks of the Olta Metamorphic and Chepes Igneous Complexes at intervals of 5-15 km (Figures 20, 21, 22). The shear zones are up to about 1 km wide, and aeromagnetics indicates that these structures are also present beneath the alluvial sediments of the plains east and west of the Sierras de Chepes, de Los Llanos and de Las Minas (Figure 18). The shear zones tend to follow the lithologies of the Olta

Metamorphic Complex where these form screens between granitoid bodies of the Chepes Igneous Complex. The mylonite in these shear zones is commonly a complex melange of sheared metasediment and granitoid. The mylonite passes gradually, at a high angle to the northerly trend of shear fabrics, into weakly to moderately deformed wall rock from which it was derived. The wall rock consists mostly of granite, granodiorite, tonalite and migmatite of the Chepes Igneous Complex, and lithologies of the Olta Metamorphic Complex. Towards the shear zone the strain gradient is accompanied by an increasing intensity of shear foliation (S2), and veins, layering and foliation in the wall rock are displaced and rotated into parallellism to the shear fabric in the zone.

Figure 20. Locality A95PP053 (66°39.60'W/30°38.86'S). Mylonite developed in granodiorite; shear surfaces dipping to the east.

Figure 21. Locality A95PP171 (66°14.96'W/31°34.63'S). Mylonite zone along the escarpment bounding the Sierra de Las Minas in the east. Mylonite developed in monzogranite; mylonitic fabric defined by aligned recystallised quartz, feldspar and biotite trails wrapping around K-feldspar porphyroclasts.

Figure 22. Locality A95PP203 (66°12.23’W/30°44.99’S). Ultramylonite developed in granitoid and cut by late-stage irregular quartz bodies at Dique El Cisco.

The mylonite is intercalated with protomylonite and ultramylonite indicating strongly variable strain conditions within the shear zones. The ultramylonite forms discontinuous and lenticular, up to 15 cm thick, dark grey layers of fine-grained homogeneous rock in which the original igneous and metamorphic fabrics are completely destroyed. The protomylonite is gradational with the mylonite and occurs in layers up to several metres thick; the proportion of protomylonite increases towards the margins of the shear zones. The protolith of the protomylonite is easily recognisable. The mylonite zones developed under greenschist-facies metamorphic conditions as indicated by the widespread occurrence of muscovite and biotite grown parallel to the mylonitic foliation, and the absence of high-grade metamorphic minerals such as garnet and sillimanite or pseudomorphs of these minerals.

2.7 DEVONIAN GRANITE

Devonian granite is not exposed in the Sierras de Chepes, de Los Llanos and de Las Minas. However, aeromagnetic domains of oval-shaped and zoned, stock to pluton-size structures suggest the presence of Devonian granite beneath the alluvial plains in the extreme northeast part of the map area and west of the central western margin of the Sierra de Las Minas. In other parts of the southern Sierras de Pampeanas, Devonian granites display similar aeromagnetic signatures (Sims and others, 1997; Stuart-Smith and others, 1997). Magnetic modelling indicates that the interpreted granite bodies occur at depths between 300 and 600 m below the alluvial plains (Hungerford and Pieters, 1996).

^{40}Ar-^{39}Ar isotopic dating of sericite associated with sericite – pyrite ± chlorite hydrothermal alteration and mesothermal Au (- Ag - Cu) bearing quartz veins in brittle-ductile shear zones gave an crystallization age range of 389-393 Ma. These results conform with the occurrence of an Early Devonian Au, Ag, Pb, Zn, W, Cu metallogenic event in the southern Sierras Pampeanas (see Skirrow; ECONOMIC GEOLOGY in this report). The concealed Devonian granite bodies in the map area may have provided the heat source that induced the convective circulation of hydrothermal fluids.

2.8 PERMO-CARBONIFEROUS SEDIMENTS

Malanzán Formation and La Colina Formation

Distribution

The distribution of the Carboniferous Malanzán Formation and Permian La Colina Formation is largely controlled by graben structures (Figures 23, 24) which cut the basement rocks at high angles and locally subparallel to the northerly to north-northwesterly regional structural trend. The valleys associated with the westerly oriented grabens separate the Sierras de Los Llanos, de Chepes and de Las Minas, and interrupt the Sierra de Las Minas in the extreme south. A northerly trending graben occurs in the northeast part of the Sierra de Las Minas, and aeromagnetics show that locally the axes of graben structures deviate considerably from the dominantly westerly trend. Because of their topographically low position in the fault-controlled valleys the sediments escaped complete erosion. However, a small outlier of sediments overlying basement rocks was interpreted from airphotos in the higher parts of the Sierra de

Chepes about 4 km south-southwest of Malanzán.

Nomenclature, stratigraphic relationships and age

The name Malanzán Formation was introduced by Furque (1968) although the sediments had been studied in detail by Bracaccini already in 1946 in the area of Malanzán. The La Colina Formation was named by Menéndez and Azcuy (1969). The formations belong to the Paganzo Group which was introduced by Azcuy and Morelli (1970).

The Malanzán Formation and La Colina Formation are separated by a paraconformity, and both units rest unconformably on the basement of the Olta Metamorphic and Chepes Igneous Complexes. Apparently the Malanzán Formation was locally eroded prior to the onset of deposition of the La Colina Formation. The units are unconformably overlain by Cainozoic terrestrial sediments.

Plant fossils indicate a Late Carboniferous age for the Malanzán Formation (Archangelsky and Leguizamón, 1971; Azcuy, 1975a, b; Frengüelli, 1946; Bracaccini, 1948), and an Early Permian age for the La Colina Formation (Azcuy, 1975a, b; Frengüelli, 1946, 1949).

Figure 23. Looking westward from locality A95PP005 (66°28.28'W/33°46.65'S). The Sierra de Los Llanos (Malanzán) to the north is separated from the Sierra de Chepes by a valley which conforms with a graben structure. Low hills in the foreground are underlain by Carboniferous and Permian sediments. The Sierra de Los Llanos is bounded by a southerly dipping alluvial fan.

Figure 24. Locality A95PP166 (66°16.96'W/31°32.30'S). Narrow, northerly trending graben structure in the Sierra de Las Minas in which Carboniferous sediments are preserved. The Carboniferous sediments are bounded by a normal fault.

Lithology

The Malanzán Formation and La Colina Formation were deposited in the Paganzo Basin, a large cratonic basin which covered the west and central areas of Argentina (Gonzále and Aceñolaza, 1972; Gamundi and others, 1990). Sedimentation in this basin started in the Early Carboniferous and continued up into the Triassic. The environment of deposition was dominantly continental, and a thin interval of shallow marine Carboniferous sediments was deposited during a short-lived transgression from the west. To the west the Paganzo Basin passes into basins with dominantly marine-facies sediments which are interpreted to have formed in a back-arc tectonic setting (Gamundi and others, 1990). Tuff beds have been recorded to occur in the Permian sequence of the continental sediments.

The Malanzán Formation consists of a basal polymictic conglomerate followed by grey, green and brown fine to coarse sandstone and mudstone with sparse intercalations of conglomerate. The mudstone and fine sandstone are commonly carbonaceous and contain plant remains. The sandstone is commonly feldspathic and in places arkosic. The sediments were deposited in a fluviatile channel and floodplain, and lacustrine environments. The maximum thickness of the unit is about 600 m.

The La Colina Formation is mostly made up of feldspathic, arkosic and micaceous fine to coarse sandstone with minor polymictic conglomerate and rare mudstone intercalations. The sandstone is characteristically pink, red, white and light grey, and the dominant sedimentary structure is decimetres to metres scale trough cross-bedding. The sequence includes a few beds of felsic tuff. The environment of deposition was alluvial fan to fluviatile channel and floodplain. The maximum thickness is about 250 m.

2.9 CAINOZOIC SEDIMENTS

Los Llanos Formation (Tpl)

Distribution

The Los Llanos Formation is exposed in isolated, low but steeply dissected hilly areas immediately west of the southern and northern parts of the Sierra de Las Minas, and in the northeastern part of the map area, east of the southeast margin of the Sierra de Los Llanos. The unit is covered by and in places difficult to differentiate from alluvial terrace and dissected alluvial fan deposits (Czd), and alluvial plain, palaeosoil and eolian deposits (Czu). In general, the Los Llanos Formation is slightly more deformed by gently tilting than the subhorizontal Czd and Czu units, and it is also more closely dissected. However, in many places (particularly in the northeast part of the map area), two or three units of alluvial fan and terrace deposits are juxtaposed and appear to have formed without easily recognisable sedimentary breaks.

Nomenclature, stratigraphic relationships and age

The unit was first described by Bodenbender (1911) as the Los Llanos Beds (Estratos de Los Llanos); Caminos (1979) revised this name to the Los Llanos Formation. The unit lies unconfomable on the basement of the Olta Metamorphic and Chepes Igneous Complexes, and is overlain conformably or with an erosive contact by the Czd and Czu units. Based on mammalian fossils the age of the unit is early Pliocene (Pascual and others, 1965).

Lithology

The unit consists of poorly sorted, polymictic sandstone and pebble to boulder conglomerate with rare discontinuous beds of sandy mudstone. The rocks are commonly white to light grey. The sandstone is quartz-rich and in places feldspathic. The subangular to subrounded pebbles of the conglomerate consist mostly of various quartz types and minor granitoid. Calcareous cement is present in places, and is partly replaced by silica. Large-scale trough cross-bedding occurs widespread. Based on drilling the maximum thickness is at least 290 m. The unit was deposited in an alluvial fan environment, and the fans probably flanked the sierras in the early stages of uplift.

Alluvial, eolian and paeosoil deposits in intermonane basins (Cza)

This unit is restricted to small intermontane basins in the higher parts of the Sierra de Chepes. The basins are thought to be remnants of an old erosion surface where partly preserved soils (age unknown) are overlain by fluviatile poorly to moderately consolidated silt and sand and fine eolian (possibly loess) deposits.

Eolian deposits (Cze)

Sandy to silty eolian sediments overlie the alluvial plain in the southeast corner of the map area. On the Landsat TM this unit is characterised by parallel discontinuous dunes.

Alluvial plain, paleosoil and eolian deposits (Czu)

This unit occurs widespread in the map area underlying the vast plain which surrounds the sierras. Only near the sierras the plain is eroded and dissected by streams debouching from the uplands forming escarpments up to 20-30 m high. The alluvial plain sediments consist mainly of poorly to moderately consolidated sand with minor gravel and silt, and paleosoils indicating periods of non-deposition. The sandy to silty eolian deposits are thin and locally overlie the plain.

Alluvial terrace and dissected alluvial fan deposits (Czd)

These deposits are located nearby or onlap the basement rocks and also the Permo-Carboniferous sediments exposed in the sierras. The poorly to moderately consolidated sand, gravel and silt were deposited in alluvial fans (Figure 23) which are younger than and locally overlie partly eroded Czu deposits.

Alluvial plain deposit (Qal)

The outcrop area of this unit is restricted to the extreme northeast part of the map area. The poorly to moderately sand, gravel and silt are deposited in a topographic low formed by the erosion of the Czu unit. However, remnants of the Czu unit are probably preserved as indicated by the shallowly dissected topography.

Alluvial deposits (Qa)

Sand, silt and minor gravel are deposited by intermittent streams flowing from the sierras onto the surrounding plains. The streams are mostly anastomising, have formed broad but very shallow valleys which become rapidly narrower away from the sierras, and eventually peter out on the sandy plain.

Alluvial fan and talus deposits (Qg)

Gravel, sand and silt are deposited in alluvial fan and talus deposits along the margins of the sierras. The deposits are most extensive where they flank fault-controlled escarpments, for example along the eastern margin of the Sierra de Las Minas.

3. TECTONICS

Three major deformation/metamorphic and magmatic events have affected the basement rocks:

- the Cambrian Pampean cycle,
- the Ordovician Famatinian cycle, and
- the Devonian Achalian cycle.

Faulting, tilting and uplift occurred during the Cainozoic associated with the Andean cycle.

3.1 PAMPEAN CYCLE

Within the map area only the Olta Metamorphic Complex has been affected by the deformation and metamorphism of the Pampean cycle. Except for bedding (S0) in a few places, the original sedimentary and igneous structures of the rocks are destroyed by the deformation and metamorphism. The main deformational/metamorphic fabric in the metasediments as well as meta-igneous rocks is defined by a characteristic parallel metamorphic segregation layering (S1) of felsic minerals (quartz, plagioclase and K-feldspar) and mica (biotite and muscovite). The layers range in thickness from a few mms to 2 cm, and are commonly lensoid and anastomising. A layer parallel foliation (S1) is defined by subparallel aligned micas. Where observed, the bedding is subparallel to the segregation layering and foliation.

The S1 foliation strikes between northeast and northwest with dips ranging from shallow to steep to the east as well as the west. The rare observation of remnants of intrafolial folds suggests deformation by layer parallel folding at the same time as the development of the S1 foliation (Figure 6). The S1 foliation is locally deformed by open to tight, microscopic to mesoscopic folds which are accompanied by a more or less well developed axial-plane or crenulation cleavage (S1'; Figure 4).

The mineral assemblages associated with the S1 fabric suggest that deformation was accompanied by greenschist-facies regional metamorphism.

3.2 FAMATINIAN CYCLE

During the Famatinian cycle the terrane of metasediments and meta-igneous rocks of the Olta Metamorphic Complex was intruded by granitoids and minor intermediate to mafic plutonic rocks. As result of the high heat flow the country rocks of the Olta Metamorphic Complex underwent low-pressure/high temperature thermal metamorphism and migmatisation (M2). Mineral assemblages indicating metamorphic conditions of the hornblende hornfels facies and pyroxene hornfels facies were recorded by this survey and by Dahlquist and Baldo (1996). Many rocks of the Olta Metamorphic Complex, particularly where they occur close to or are contained by migmatite of the Chepes Igneous Complex, contain an assemblage of metamorphic minerals which overprint the S1 fabric. The minerals making up this assemblage include randomly oriented and mimetic biotite, muscovite and cordierite which were formed during the phase of low-pressure/high-temperature metamorphism and anatexis accompanying the magmatic event which produced the Chepes Igneous Complex in the early Ordovician (see Famatinian cycle). A study by Dahlquist and Baldo (1996) of trains of opaque and mica inclusions in poikilitic cordierite porphyroblasts showed the presence of a pre-metamorphic deformational fabric which probably is temporally related to the S1 deformation.

There is no unequivocal field evidence of deformational structures which are associated with this phase of magmatism and thermal metamorphism.

Subsequent to the magmatism and low-pressure/high temperature thermal metamorphism the rocks of the Olta Metamorphic Complex and Chepes Igneous Complex were subjected to regional, east-west, non-coaxial compressional deformation (D2) at greenschist facies metamorphic conditions (M3). Throughout the sierras the D1 fabric elements in the rocks of the Olta Metamorphic Complex and igneous fabric in the rocks of the Chepes Igneous Complex are rotated and recrystallized into parallellism by a moderately to steeply easterly-dipping, weakly to strongly penetrative shear fabric associated with westerly-directed thrusting, development of mylonite in high-strain zones, and retrogressive greenschist facies metamorphism. A weakly to moderately well developed mineral lineation of biotite, muscovite and quartz aggregates occurs widespread, and plunges generally moderately to steeply to the east. Zones of high strain are focussed in northerly-trending, curved or sinuous, and up to 1 km wide and up to 80 km long mylonitic shear zones (Ulapes mylonite). Aeromagnetics indicates the presence of similar structures beneath the Cainozoic sediments of the plain, and on a regional scale the shear zones are spaced at intervals varying from a few kilometers to 15 km. Geophysical modeling suggests that most shear zones dip to the east (Hungerford and Pieters, 1996). The westerly-directed shear movement was determined from S-C fabric, extension of originally parallel veins, asymmetric feldspar porphyroclasts, and fragmented rigid grains with antithetic slip between the fragments.

^{40}Ar- ^{39}Ar isotopic dating of muscovite of mylonitised granite sample A95PP192B gave an age range of 450 to 462 Ma (late Ordovician) which is interpreted to represent the age of shearing (Camacho, 1997).

3.3 ACHALIAN CYCLE

During the early stage of the Achalian cycle, felsic magmatism, resulting in the emplacement of granite plutons, took place over a large part of the southern Sierras Pampeanas. Most of the plutons are exposed east of the map area in the Cordoba and San Luis Provinces, but aeromagnetics has shown that plutons belonging to this cycle may be present concealed beneath the Cainozoic sediments of the plain west of the Sierra de Las Minas. U-Pb zircon dating of the granites from the sierras of Cordoba and San Luis Provinces brackets the crystallization of the felsic magma over a 20 Ma period from 400 Ma to 380 Ma (Camacho and Ireland, 1997).

During the late stage of the Achalian cycle, east-west compression produced a regionally widespread conjugate system of rectilinear brittle-ductile, vertical, northwest- and northeast-trending strike-slip faults (Figures 25, 19). In the Sierra de Las Minas this fault system is particularly well developed, and is accompanied by easterly trending extensional faults. Some north-south trending reverse faults possibly also belong to the system. Kinematic indicators (such as the displacement and deflection of veins, dykes, xenoliths and older (S2) foliation, and S-C fabric) show that the northwest structures are sinistral strike-slip faults, and the northeast structures dextral faults. In the Sierra de Las Minas the northwest-trending and to a lesser degree the northeast-trending shear faults are clearly marked as linear valleys on air photos and Landsat TM, and as demagnetized lineaments on aeromagnetic images. The structures are topographically recessive and supergene alteration has oxidized the magnetite to hematite/limonite. From fieldwork it is known that the shear zones are commonly 1-3 m and at the most 6 m wide; a maximum width of 10 m was recorded by the Metal Mining Agency of Japan (JICA, 1993). The dominance of the northwest-trending structures, in number as well as extent, suggests that the conjugate fault system (and east-west compression) is associated with a northwest-oriented sinistral wrench zone in which movement was mostly concentrated on the synthetic northwest shear faults. The brittle-ductile shear zones were progressively deformed by at least two phases of brittle deformation resulting in fracturing and brecciation of the shear fabric and quartz veins enclosed by the shear zones.

In the Sierra de Las Minas the shear faults, in particular the northwest-trensing set, arecommonly associated with sericite - pyrite ± chlorite alteration and quartz vein-type Au ± Cu mineralisation, the result of mesothermal hydrothermal activity. ^{40}Ar-^{39}Ar

Figure 25. Locality A95PP108 (66°32.97'W/31°03.16'S). Brittle-ductile shear zone (D3) in metasediments of the Olta Metamorphic Complex showing en-echelon quartz tension gashes.

Figure 26. Locality A95PP203 (66°12.23'W/30°44.99'S). Immediately downstream of the Dique El Cisco where the river has cut a steep and deep valley across the north-northwest trending range.

isotopic dating of sericite associated with the hydrothermal alteration gave an crystallization age range of 389-393 Ma (Camacho, 1997). Granites emplaced during the late stages of the Achalian cycle of felsic magmatism possibly provided the heat source for the convective circulation of hydrothermal fluids.

3.4 ANDEAN CYCLE

During the Cainozoic the peneplained Paleozoic basement was uplifted in north-south oriented, elongate fault blocks forming the present-day characteristic topography of rugged sierras separated by flat intermontane basins. It is generally thought that the sierras were uplifted and tilted by late Cainozoic listric reverse faults (Jordan and Allmendinger, 1986). However, during this survey no unequivocal field evidence was found to ascertain the nature of faulting. Along many escarpments bounding the sierras occur regular, moderately to steeply-dipping triangular facets which appear to have formed on east-dipping planar fault scarps dissected by erosion. If so, the escarpments would represent normal faults. Another argument for uplift by young extensional faulting is the presence of westerly and/or northerly trending graben structures, which are bounded by escarpments with similar geomorphic expression as the border escarpment (Figures 23, 24). The graben structures are up to a few kilometers wide, and also cut the basement beneath the Cainozoic sediments of the plain, as indicated by the aeromagnetics. On the other hand, in a compressional tectonic regime the east-west oriented grabens may have formed at a high angle to the north-south oriented minimum principal stress, and the narrow, north-south oriented graben structures (for example in northeast Sierra de Las Minas) may have developed on tension fractures associated with arching of the basement rocks during east-west compression. Jordan and Allmendinger (1986) discussed the occurrence of two broad and northerly plunging arched structures developed in crystalline basement underlying the two northern conical projections of the Sierra de Los Llanos (north of the map area).

In other parts of the southern Sierras Pampeanas is outcrop evidence of young (Quaternary) reverse faulting (for example Sims and others, 1997), and focal mechanism solutions of earth quakes in the Sierras Pampeanas indicate moderate-angle reverse faulting at mid to lower crustal depths (Jordan and Allmendinger (1986).

4. GEOMORPHOLOGY

The two main geomorphological units in the map area are the mountain ranges of the Sierras de Chepes, de Las Minas and de Los Llanos, and the plains. The mountain ranges or sierras are elongate in northerly to north-northwesterly directions and are separated by fault-controlled valleys which trend roughly about an east-west trend. In longitudinal direction the sierras are interrupted by northerly to north-northwesterly aligned valleys which, at least partly, are controlled by faulting; for example the Sierra de Los Llanos is divided in two north-northwest trending mountain blocks by a valley up to 4 km wide and because of this distinct topographic break the western block is also known as the Sierra de Malanzán. The average height of the mountains decreases gradually in southward direction from the Sierra de Los Llanos to the Sierra de Chepes; on the other hand, the average height in the Sierra de Las Minas is markedly lower than in the Sierra de Chepes. The highest elevations in the Sierra de Los Llanos are about 1900 m, in the Sierra de Chepes about 1550 m and in the Sierra de Las Minas about 1000 m. The two mountain blocks of the Sierra de Los Llanos taper in northward direction to form well defined conical projections with topographically remarkably smooth surfaces (outside the map area).

On a regional scale the sierras form in many parts sloping plateaux as their summit surface forms a distinct plane of accordance that slopes consistently in one direction. The plateau surface is interpreted to represent a peneplain of late Paleozoic age which was uplifted and arched in Cainozoic time.

All streams in the map area are intermittent, and in the sierras the streams are generally poorly adjusted as result of subrecent tectonic movements. The drainage in the sierras is partly subsequent, partly consequent and locally antecedent or superposed. The Quebrada Baigorria, where it cuts across a small northerly aligned range east of Dique El Cisco (Santa Rita de Catuna 1:100 000 sheet; 3166-15) is an example of an antecedent or superposed river (Figure 26). The drainage pattern is commonly rectangular to angulate where it is controlled by faults and fractures, and in places the stream courses are marked by abrupt changes in gradient (waterfalls and rapids) and are anomalous as result of stream piracy.

The plains surrounding the sierras dip away very gently and gradually from the uplands, and in the topographic lows between the main north-south elongate sierras in the Sierras de Pampeanas occur in places large salt lakes, for example the Pampa de Las Salinas between the southern end of the Sierra de Las Minas and the Sierra de La Huerta (outside the map area). However, surrounding the sierras the plain is eroded and dissected by streams debouching from the uplands which has resulted in an up to 6 km wide, gently dipping and low-relief topographic depression. In many places the margin of the plain is expressed by an up to 20 m high scarp, but in other places headward erosion is gradual. A minor, secondary consequent drainage has developed from the margin of the plain towards the trunk rivers in the depressions. The main (trunk) rivers have incised wedge-shaped indentations in the plain and eventually peter out on the plain.

5. GEOLOGICAL HISTORY

5.1 CAMBRIAN

The oldest rocks in the map area are metasediments and meta-igneous rocks of the Olta Metamorphic Complex, which are exposed in the Sierras de Chepes and de Los Llanos. These lithologies also occur as paleosomes associated with the migmatite units (Ox, Omgg, Oc) of the Chepes Igneous Complex, extending the distribution to the Sierra de Las Minas. The metasediments are interpreted as being deposited on the passive margin of western Gondwana, developed during intracontinental rifting and break-up of Laurentia from Gondwana and opening of the Iapetus ocean in Early Cambrian time at about 540 Ma (Dalziel and others, 1994).

The age of sedimentation of the Olta Metamorphic Complex metasediments is based on indirect isotopic age control. A U-Pb age analysis on single-crystal zircon grains yielded a minimum provenance age of around 540 Ma (Camacho and Ireland, 1997), and is interpreted to represent the maximum age of sedimentation. The metasediments of the Olta Metamorphic Complex are tentatively correlated with the Tuclame Formation (Stuart-Smith and others, 1997) exposed in the 3166-17 1:100 000 sheet area (Cordoba Province). Zircon and monazite U-Pb metamorphic ages of around 530 Ma for a migmatitic rock of the Tuclame Formation (Camacho and Ireland, 1997) provide the minimum age limit of sedimentation.

Following sedimentation and minor magmatic activity the newly formed western margin of the Gondwana continent was subjected to compressive deformation and regional metamorphism of the Pampean cycle. The sediments, together with felsic to mafic volcanic and plutonic rocks were deformed by a roughly east-west oriented compressive event (D1) and regionally metamorphosed at greenschist facies conditions (M1) to form phyllite, schist and locally gneiss. Based on the U-Pb ages of the Tuclame Formation (see above), the age of the Pampean cycle is about 530 Ma (Early Cambrian).

5.2 EARLY ORDOVICIAN

In the early Ordovician, closure of the Iapetus Ocean (Niocaill and others, 1997) and eastward subduction beneath the western margin of Gondwana (Pampean terrane) were accompanied by the formation of a large continental margin magmatic arc. During this early phase of the Famatinian cycle the dominantly calc-alkaline granitoids and minor intermediate and mafic plutonic rocks of the Chepes Igneous Complex were emplaced in the area of the Sierras de Las Minas, de Chepes and de Los Llanos. These rocks represent the infrastructure of the magmatic arc, and because of the high heatflow the country rock of the Olta Metamorphic Complex (Pampean terrane) was subjected to low pressure/high temperature metamorphism and migmatisation (M2) overprinting the earlier phase of regional metamorphism (M1). U-Pb dating of zircons of the granitoids of the Chepes Igneous Complex yielded crystallizaton ages ranging from 491 to 477 Ma (early Ordovician).

5.3 LATE ORDOVICIAN

During this time the Pampean terrane and continental margin magmatic arc underwent east-west, non-coaxial compressive deformation (D2) at greenschist facies regional metamorphic conditions (M3). A weakly to strongly penetrative north to north-northwest trending foliation has affected the rocks of both the Olta Metamorphic and Chepes Igneous Complexes, and retrogressive metamorphism occurred widespread. In zones of high strain, up to 1 km wide, mylonitic shear zones were formed within and bounding the sierras, but also, as indicated by airborne geophysics, in the basement rocks underlying the plains. The ductile shear zones are mostly east dipping and kinematic indicators show orthogonal, westerly directed thrust movement.

^{40}Ar-^{39}Ar dating of muscovite from mylonitised granite exposed in the southeast part of the Sierra de Chepes gave a total fusion age of 454±1 Ma and a step heating age of 450-462 Ma (Camacho, 1997), which are interpreted as the age range (late Ordovician) of the shearing deformation. In the area of the Sierras de Las Minas, de Chepes and de Los Llanos there is no evidence of deformation, magmatism and metamorphism during the time interval of about 30 Ma separating the formation of the continental margin magmatic arc and the regional east-west compressive deformation.

In a number of tectonic interpretations of the Sierras Pampeanas it was suggested that in the final stage of the Famatinian cycle (orogeny), at about 450 Ma and contemporaneously with the Taconic orogeny in North America, the Precordilleran terrane amalgamated with western Gondwana (for example, Martino and others, 1994; Astini and others, 1996; Toselli and others, 1996; Dalla Salda and others, 1992; Van der Voo, 1993). The age of the regional east-west compressive deformation in the Sierras de Las Minas, de Chepes and de Los Llanos is in agreement with this major collision event.

5.4 DEVONIAN

Peraluminous to slightly peralkaline and zoned granite plutons occur widespread east of the map area in the sierras of Córdoba and San Luis Provinces. The granite bodies were emplaced in country rock of the Pampean and Famatinian terranes during and after compressive deformation dominated by orthogonal westerly-directed thrusting and the development of regional ductile shear zones at greenschist facies metamorphic conditions. This phase of felsic magmatism and deformation belongs to the Achalian cycle. In the map area is no outcrop evidence of felsic magmatism and deformation, but airborne magnetics suggests the presence of zoned granite bodies concealed beneath Cainozoic sediments in the plain west of the Sierra de las Minas and east of the southeast part of the Sierra de Los Llanos. U-Pb zircon dating of the granites from the sierras of Córdoba and San Luis Provinces brackets the crystallization of the felsic magma over a 20 Ma period from 400 Ma to 380 Ma (Camacho and Ireland, 1997).

During the later stage of the Achalian cycle east-west compression produced a regionally widespread conjugate system of rectilinear brittle-ductile, vertical, northwest- and northeast-trending strike-slip faults and fractures. The orientation and conjugate relationship of the faults indicate a continuation of the east-west compressive tectonic regime. In the Sierra de Las Minas this fault system is particularly well developed, and is associated with sericite - pyrite ± chlorite alteration and quartz vein-type Au ± Cu mineralisation, the result of mesothermal hydrothermal activity. ^{40}Ar-^{39}Ar isotopic dating of sericite associated with the hydrothermal alteration gave an crystallization age range of 389-393 Ma (Camacho, 1997). These results conform with the occurrence of a regional Early Devonian Au, Ag, Pb, Zn, W, Cu metallogenic event in the southern Sierras Pampeanas (see Skirrow; ECONOMIC GEOLOGY in this report). Granites emplaced during the Achalian felsic magmatic phase possibly provided the heat source for the convective circulation of hydrothermal fluids.

5.5 PERMO-CARBONIFEROUS

Following peneplanation of the Cambrian to Devonian basement, continental sediments with rare marine incursions (from the west) were deposited in the Paganzo Basin, a large cratonic basin which covered the west and central areas of Argentina (Gonzále and Aceñolaza, 1972; Gamundi and others, 1990). Sedimentation in this basin started in the early Carboniferous and continued up into the Triassic. To the west the Paganzo Basin passes into basins with dominantly marine-facies sediments which are interpreted to have formed in a back-arc tectonic setting (Gamundi and others, 1990). Tuff beds have been recorded to occur in the Permian sequence of continental sediments. In the area of the Sierras de Las Minas, de Chepes and de Los Llanos only remnants of late

Carboniferous and Early Permian sediments of the Paganzo Group are preserved in graben structures.

5.6 CAINOZOIC

During the Cainozoic the peneplained Paleozoic basement and preserved overlying sediments of the Sierras Pampeanas were deformed into north-south oriented, elongate fault blocks forming the present characteristic topography of rugged sierras separated by broad intermontane basins.

The Sierras de Las Minas, de Chepes and de Los Llanos were uplifted and tilted by reverse faults which in places have reactivated Paleozoic mylonitic shear zones. Locally these Sierras are traversed by graben structures parallel as well as transverse to the regional north-south structural grain. The Pliocene Los Llanos Formation is the oldest exposed alluvial fan deposit possibly related to the uplift, and Jordan and Allmendinger (1986) reasoned that the faulting is not older than 10 Ma.

SECTION II: ECONOMIC GEOLOGY

By Roger G. Skirrow

1. INTRODUCTION

The La Rioja map area contains significant occurrences of Au with associated Cu and Ag mineralisation in Ordovician metamorphic and igneous rocks, and minor U occurrences are present within Carboniferous and/or Permian sedimentary rocks. The northeast of the region is also known for its production of granite building stone and *piedras lajas*.

In the Geoscientific Mapping of Sierras Pampeanas Cooperative Project the principal metallic deposits in all main mining districts of the map area were investigated in the field, and geological observations were entered into the ARGROC and ARGMIN databases (Skirrow & Trudu, 1997). ARGMIN is a Microsoft Access database that was initially developed jointly by AGSO and the Secretaría de Minería in ORACLE, based on OZMIN (Ewers & Ryburn, 1993). Additional geological and resource data from the literature on mineral occurrences have been compiled in ARGMIN. Petrography of ore and host rock samples (thin sections and polished thin sections) was recorded in a petrographic database (Sims and others, 1996), and selected samples for ore genesis studies were analysed for whole rock geochemistry (Lyons and others, 1996; Lyons & Skirrow, 1996), stable isotopes of oxygen, hydrogen and sulfur (Lyons & Skirrow, 1986), as well as $^{40}Ar/^{39}Ar$ radiometric age dating (Camacho, 1997). Geographic coordinates of mineral occurrences were obtained by GPS in this and a previous study of the Sierra de las Minas (accuracy ± 50 m). The locations of remaining occurrences are taken from various published sources, which in some cases allow only very approximate geographic coordinates to be estimated (e.g . ± 3 km for U deposits).

Mineral occcurrence data as well as non-metallic mineral and dimension stone occurrences are shown on the 1:100 000 scale metallogenic map series and accompanying reports. Output data sheets from the ARGMIN database are appended to the reports. Details of the geology and grade-tonnage data, where available, for individual metallic mineral occurrences may be found in the database. The 1:250 000 scale Metallogenic Map for the Sierras de Chepes, Las Minas and Los Llanos shows the mineral occurrences in relation to 'prospectivity domains' or areas of mineral potential. These domains are defined on the basis of 'metallogenic models' for each mineral deposit style, which were developed from the observations and interpretations presented in the following sections. For further datasets of mineral potential, the reader is referred to the *Atlas Metalogenético* (1:400 000 scale) for the Sierras Pampeanas mapping project (Skirrow and Johnston, 1997), and project GIS (Butrovski, 1997) in which metallogenetic models for the principal styles of metallic mineralisation are presented as separate coverages.

2. METALLIC MINERAL OCCURRENCES

2.1 AU (-CU-AG) DEPOSITS

2.1.1 Previous work and exploration

Quartz vein systems hosting Au, Cu and Ag mineralisation occur widely throughout the sierras de Las Minas and Ulapes and to a lesser extent in the Sierra de Chepes. The deposits were initially worked towards the end of the last century, and small scale mining activity continued intermittently until ~1990 (El Espinillo II). Previous work on the regional geology is discussed by Pieters and Lyons (this Report). The geology of the Au, Ag and Cu mineral deposits and their workings were briefly described by Caminos (1979), Ramos (1982) and Angelelli (1984). Economic and geological evaluations of the occurrences were carried out by Mastandrea (1961), Sarudiansky (1988, 1990), Marcos (1987, 1988, 1989) and Cravero and Ríos (1988). Mapping of several occurrences in the Sierra de Chepes was carried out by the Secretaría de Minería de la Nación in 1988-89. A synthesis of the geology and mineralogy of the Au deposits was presented by Ríos and others (1992), while fluid inclusion and multi-element geochemical data were given by Cravero and others (1995). A program of regional stream sediment geochemistry (Cu, Pb, Zn) was undertaken by the Secretaría de Minería de la Nación in the 1980's (?), and the results are currently being recompiled at the Subsecretaría de Minería.

Most recently a project carried out over three years by the Metal Mining Agency of Japan and the Secretaría de Estado de Minería was completed on Au-Ag exploration in the sierras de Las Minas and Ulapes (JICA/MMAJ, 1993, 1994, 1995). The first phase of the project involved three Japanese and three Argentinian geoscientists in the following activities: reconnaissance geology of the region, detailed mapping of veins and GPS location of workings, geochemical analysis of 300 vein and host rock samples for Au and Ag, whole rock (major element) analysis of 20 samples, three Rb-Sr age determinations on host rocks, fluid inclusions studies, XRD and EPMA analysis (JICA/MMAJ, 1993). Phase II activities included six diamond drill holes in the Las Callanas district and geochemical analysis of limited intervals for Au and Ag (JICA/MMAJ, 1994). Four additional diamond drill holes were completed and analysed for Au and Ag: MJAL7 at La Callana V, and MJAL8, 9 and 10 at La Pirca

Au (-Cu-Ag) mineralised quartz vein systems of the sierras de Las Minas, Ulapes and

Chepes have previously been interpreted as 'epi-hydrothermal' (Sarudiansky, 1988, 1988; Cangialosi & Baldis, 1995); epithermal (JICA/MMAJ, 1993); and shear zone hosted deposits related to regional tectonic processes (Cravero & Ríos, 1988; Ríos and others, 1992; Cravero and others, 1995). An association of Au-Cu-Ag with granites of the Asperezas Formation was suggested by JICA/MMAJ (1993), who proposed that mineralisation formed between the Ordovician and Carboniferous. Cangialosi and Baldis (1995) suggested formation during the Pampean cycle.

Results of the present study corroborate the model of Au-Cu-Ag quartz vein formation in shear zones related to regional deformation, and additionally point to a possible genetic relationship with Devonian granitoids. Structural measurements of kinematic indicators place new constraints on the geometry and timing of regional tectonic processes during mineralisation. Argon-argon dating of white mica hydrothermal alteration associated with Au-Cu-Ag mineralisation, together with the field observations, regional geological studies (Pieters and others, 1997), stable isotope geochemistry and paragenetic studies, have been used to develop a new ore genetic and exploration model (see sections 2.1.7 & 5.2). These models have been used in an attempt to evaluate the prospectivity of the region.

2.1.2 Regional geological setting

Most Au-Cu-Ag deposits of the sierras de Las Minas, Ulapes and Chepes are hosted by granodioritic to granitic plutonic rocks of the Chepes Igneous Complex which were emplaced, metamorphosed to amphibolite facies, and deformed in a compressive tectonic setting in the early Ordovician (Pieters, this Report). Granitoids are mostly calc-alkaline metaluminous I-types, and may represent the mid-crustal levels of a continental margin subduction-related magmatic arc (Pieters, this Report). Older, possibly early Cambrian, pelitic and psammitic metasediments and metamorphosed feldspathic (volcanic?) rocks of the Olta Metamorphic Complex host a small number of Au-Cu-Ag occurrences in the Sierra de Chepes (e.g. Porongo). Rocks of the Olta Metamorphic Complex occur as generally irregularly shaped bodies and enclaves of phyllite, schist, gneiss and migmatite, and contain varying proportions of quartz, muscovite, biotite, feldspar and cordierite. Contacts with the Chepes Igneous Complex range from sharp to gradational or tectonic. Small bodies of fine-grained plagioclase-hornblende schists within the Olta Metamorphic Complex are relatively common throughout the sierras. A large, strongly magnetic, metagabbroic to metadioritic intrusion, the Quemado norite (part of the Chepes Igneous Complex) occurs in the southern part of the Sierra de Las Minas, and smaller bodies of amphibole-feldspar metagabbroid are present in the Las Callanas district.

Major mylonite zones of up to several kilometres width developed during the late Ordovician deformation, and in part controlled the emplacement of leucogranitic bodies of the Asperezas Formation, which in places are mylonitised. Many of these mylonite zones now trend north-south (e.g. Ulapes mylonite) and developed biotite-muscovite fabrics at greenshist facies conditions. The mylonite zones and Asperezas Formation typically show very low aeromagnetic responses. Kinematic indicators suggest that the biotite-muscovite shear fabric was associated with westerly-directed movement on moderately to steeply easterly-dipping surfaces.

Several inferred granitoids with similar aeromagnetic signatures to Devonian granites in the San Luis map area occur under shallow cover in the extreme northeast of the La Rioja area, and also to the west of the Sierras de Las Minas (Hungerford and others, 1996).

A striking feature of the aeromagnetic imagery in particularly the sierras de Las Minas and Ulapes is the pattern of NW and NE trending lineaments and zones of very low magnetic response. In outcropping areas some magnetic low lineaments correspond to mineralised shear and fracture zones, and have been traced under cover to the east and west of the exposed basement (Hungerford and others, 1996). The magnetic lineaments cross cut all basement metamorphic rock types including the Asperezas Formation. Their temporal relationship to N-S mylonite zones is not clear because these zones are also magnetic lows. However, the NW and NE lineaments do not appear to be offset at the N-S mylonites, and most likely postdate the N-S mylonites. Dating by the $^{40}Ar/^{39}Ar$ method of white mica hydrothermal alteration associated with Au-Cu-Ag mineralisation within the NW trending structures suggests that both alteration and shearing in conjugate NW and NE structures occurred in the early Devonian (see below).

Regional aeromagnetics of the Sierra de Las Minas also exhibit a broad zone of apparently low response, bounded to the west and east by inferred mylonite zones and centred on an area between the Las Callanas and El Espinillo districts. It is interesting to note that most of the larger exploited deposits of Au-Cu-Ag occur within this regional low magnetic domain. Granodioritic gneiss and migmatite in this domain appear to be compositionally and mineralogically similar to Chepes Igneous Complex in the Sierra de Chepes, and their measured magnetic susceptibilities in both areas are relatively high, except within intensely altered shear zones. The existence of the broad zone of apparently low response therefore is enigmatic. Three alternative origins for this aeromagnetic response are: (i) the rocks of the Sierra de Las Minas are reverse polarised, (ii) magnetite in rocks of this zone is partially altered to hematite or other minerals of low magnetic susceptibility, or (iii) a large deep-seated intrusion of low magnetic susceptibility is masking the ‘normal’ aeromagnetic signature of the Chepes Igneous Complex.

2.1.3 Structure of the deposits

Quartz veins containing Au, Cu and Ag occur in two principal orientations: NW- and NE-striking with steep dips, with a small proportion oriented roughly E-W. The veins form linear to sinuous and sigmoidal gash-like sets, and in some deposits show *en echelon* distributions. Pinch-and-swell is common, resulting in subvertically extensive vein ‘shoots’. The host rocks within a few metres of veins are commonly (but not in all deposits) intensely foliated and hydrothermally altered to sericite±pyrite±chlorite. Mylonite and S-C shear fabrics are well developed in places, and show consistent geometrical relationships to quartz vein orientations, as presented in Table 1. In many cases the S-foliation appears to be oriented similarly to the pre-existing regional Ordovician foliation, and may represent an intensified, more closely spaced, and variably reoriented modification of this foliation.

Table 1. Summary of structural data in mineralised shear zones, La Rioja

Locality	Field ID	Structure	Orientation* (S, C surfaces or	Kinematics	Shear trend

			lineation)		
Callana V	A95RS038	S-C	078/85, 055/90	sinistral	NW
Callana V	A95RS038	stretching lineation	325/00	horizontal	NW
Callana V	A95RS038	qz vein	NW strike		
Callana IV	A95RS036	S-C		sinistral	NW
Callana IV	A95RS036	mineral (qz) elongation	000/12	subhorizon-tal	NW
Callana IV	A95RS036	qz vein	060/90		
Espinillo I	A95RS057	S-C	248/76, 212/70	sinistral	NW
Espinillo I	A95RS057	qz vein	219/75		
La Chilca	A95RS046	shear foliation	070/90	sinistral	NW
La Chilca	A95RS046	sigmoidal, *en echelon* qz veins	350/90 (vein tips)	sinistral	NW
Vallecito	A95RS047	S-C	065/90 (C)	sinistral	NW
Vallecito	A95RS047	qz vein	035/90		
La Pirca	A95RS048	S-C	115/90, 133/87	dextral	NE
La Pirca	A95RS048	mineral (qz) elongation	234/10	subhorizon-tal	NE
La Pirca	A95RS048	qz vein	148/88 to 000/90		
La Pirca	A95RS049	S-C	312/90, 320/84	dextral	NE
La Pirca	A95RS049	stretching lineation	212/18	subhorizon-tal	NE
La Pirca	A95RS050	S-C	290/85, 310/82	dextral	NE
La Pirca	A95RS050	mineral (qz) elongation	208/11	subhorizon-tal	NE
Dos Buhos	A95RS054	S-C	292/85, 322/87	dextral	NE
Dos Buhos	A95RS054	stretching lineation	209/14	subhorizon-tal	NE
Dos Buhos	A95RS054	qz vein	325/83		
El Abra	A95RS058A	S-C	089/88, 100/82	dextral	NE
El Abra	A95RS058A	stretching lineation	193/08	subhorizon-tal	NE
El Abra	A95RS058A	qz vein	120/90		
El Abra	A95RS058B	S-C	125/90 (C)		NE
El Abra	A95RS058B	stretching lineation	215/00	horizontal	NE
Ñoquebe	A95RS062	S-C	115/70, 134/75	dextral	NE
Ñoquebe	A95RS062	qz vein	145/45		

* Surface orientations are presented as dip azimuth/dip angle

These results indicate consistent region-wide kinematic and geometrical relationships in shear zones hosting mineralised quartz veins. Movement on NW trending shear zones was sinistral with subhorizontal (strike-slip) displacements, whereas movement on NE trending shears was dextral, again with strike-slip displacements (Figure 1). There is a tendency for NW trending systems to occur in the western part of the sierras de Las Minas and Ulapes, and NE trending systems to occur in the eastern and southern parts of the region. The orientations and morphologies of quartz veins are consistent with their formation syntectonically in extensional domains within the shear zones. Similar structural relationships in the formation of Au-bearing quartz veins have been widely documented elsewhere (e.g. Robert & Brown, 1986; Robert, 1990; Hodgson, 1993). Progressive deformation in the shear zones resulted in 'shear vein' formation (subparallel to shear foliation) and rotation of veins into subparallelism with the shear foliation, as well as boudinage of veins in some deposits. Recrystallisation and later cataclastic deformation of the veins is viewed as part of this progressive deformation, although a separate and later brittle event also has been identified (see below).

The NW and NE trending shear zones and contained quartz veins are proposed to have formed as a conjugate set within a region of E-W compression and N-S extension (Figure 1). Similarly oriented shear zones, faults and aeromagnetic lineaments occur throughout the southern Sierras Pampeanas. The E-W directed σ_1 component may reflect wrench tectonics - the sierras de Las Minas, Ulapes and Chepes representing a domain of N-S extension between bounding strike-slip structures (at present unidentified). The same E-W σ_1 component may have resulted in reverse faulting in the Candelaria Au district in Provincia de Córdoba (Skirrow, 1997).

2.1.4 Mineralisation, alteration and paragenetic sequence

Similarities in structural setting, vein mineralogy, alteration, textures, geochemistry and paragenetic sequences in more than 15 observed Au-Cu-Ag occurrences in the sierras de Las Minas, Ulapes and Chepes allow the deposits to be discussed as a group. Based on observations of surface exposures and diamond drill core, together with petrographic examination of polished thin sections and previous work, a generalised paragenetic sequence for the Au-Cu-Ag deposits is proposed in Table 2. It should be noted that not all stages are represented in all deposits. Vein textures and parageneses are illustrated in Figures 2, 3 and 4.

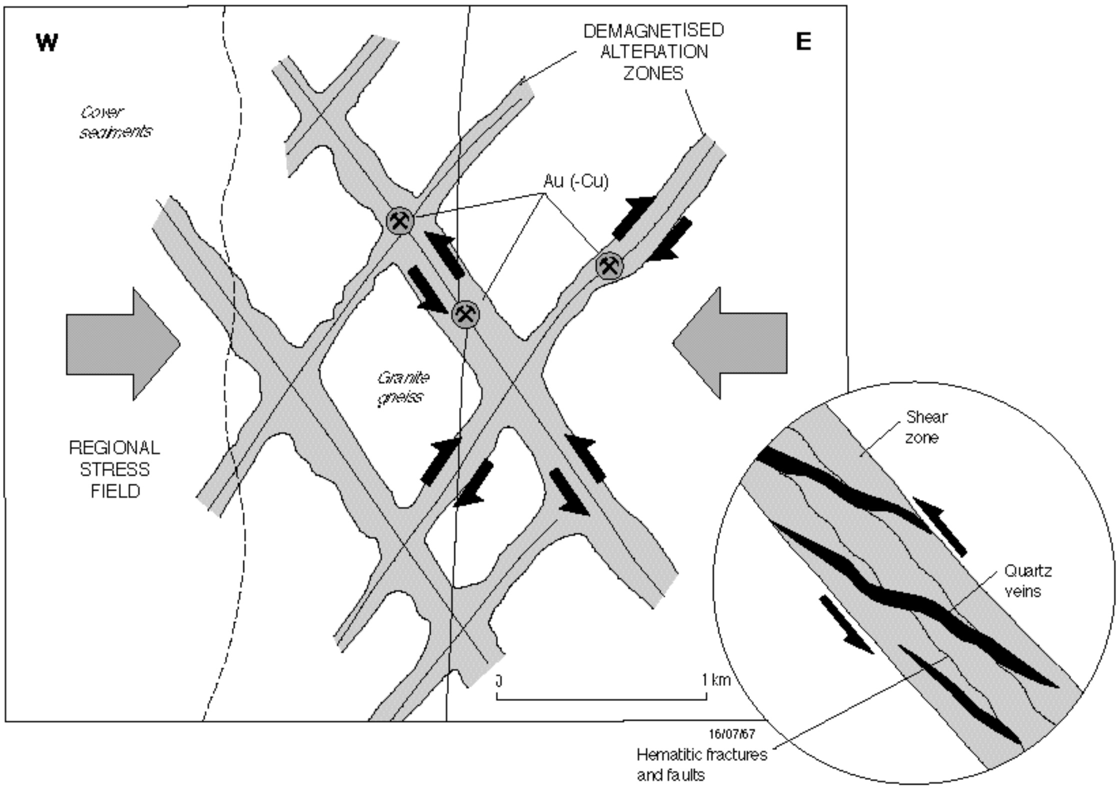


Figure 1. Schematic plan of regional- to local-scale structural relationships for shear-hosted Au±Cu±Ag quartz vein deposits, Sierra de Las Minas and Ulapes, La Rioja. Demagnetised alteration zones, represented by areas of low magnetic response in aeromagnetic imagery, consist of hematite and sericite-pyrite altered granitic and granodioritic gneiss.

This paragenetic scheme may be corrrelated with the quartz paragenetic types described by Cravero and others (1995): Stages 1 and 2 probably correspond to their quartz types I and II, and Stages 3 may incorporate their quartz types III and IV. It is suggested that pyrite, chalcopyrite and galena formed mainly during Stage 1 rather than with later quartz (cf. Cravero and others, 1995), and that a hypogene to deep-supergene stage of hematite±carbonate veining and alteration postdated Stage 1 but preceded weathering of the deposits (Stage 3).

Figure 2. Gold mineralised quartz-hematite-goethite vein, Callana VI (Veta I), Sierra de Las Minas, Site A95RS033. Paragenetically early, relatively coarse, milky white quartz (Stage 1) with intergrown bands of fine grained quartz, goethite and hematite (some secondary, after sulfide), which are cut by anastomosing fractures filled with hematite and goethite (upper right of specimen; Stage 2a). Vughs in centre of sample are partly infilled with secondary quartz, microcystalline silica, and in places chrysocolla, malachite and secondary gold (Stage 3). Scale bar 10cm total length.

Figure 3. Early quartz (Stage 1) cut by fractures filled with microcrystalline hematite (red patches and bands; Stage 2a), which are in turn cross cut by a network of chalcedony-goethite-filled veinlets (Stage 2b). Minor fine grained galena and pyrite are intergrown with the early quartz. Site A95RS047, Vallecito, Sierra del Las Minas. Smaller scale divisions are 1cm.

Figure 4. Banded quartz-goethite-hematite vein, Veta Ortiz, east of Sierra de Las Minas. Banding may represent relict crack-seal vein structure, deformed and recrystallised. Visible gold occurs within Fe-oxide bands. Site A95RS051. Scale bar 10cm total length.

Figure 5. Quartz±goethite-hematite veins (white, at upper right, ~149.5m; and dark reddish, lower half of core tray) with weakly foliated sericitic alteration envelopes (pale greenish zones), developed in granodioritic host rock. Las Callanas, Sierra del Las Minas, drill hole MJAL1, Callana VI.

Two textural and compositional types of gold are present: early fine grained electrum closely associated with pyrite, with fineness as low as 640 (JICA/MMAJ, 1993; Cravero and others, 1995), and later coarse gold associated with hematite, goethite, chalcedony, opal, chrysocolla, malachite, and other supergene phases with fineness of greater than 950 (Cravero and others, 1995). Coarse late gold is readily observed in hand specimen and is interpreted to have formed during oxidation in Stages 2 and 3 from remobilisation of Stage 1 Au (Ríos and others, 1992; Cravero and others, 1995).

Relatively narrow zones (<3 m) of sericite-pyrite and hematitic hydrothermal alteration are well developed around some vein systems (Figure 5), whereas distal chlorite±epidote±carbonate alteration is generally weak (Las Callanas district; La Pirca) or absent. Pervasive silicification and development of quartz vein stockworks are uncommon (e.g. San Isidro - Grupo Sur). Sericite-pyrite and hematitic alteration and quartz veins show uniformly very low magnetic susceptibility, matching the low aeromagnetic responses for the linear shear zones hosting mineralisation. However, the aeromagnetic lows appear to be significantly broader than the zones measured at surface.

Several authors have described an association of aplitic dykes of the Asperezas Formation and K-feldspar alteration with quartz veins and the NW and NE trending shear zones (Caminos, 1979; Cravero & Ríos, 1988; Ríos and others, 1992; Cravero and others, 1995). In the present work, light pinkish grey to deep pink aplite dykes were observed in the vicinity of many of the quartz vein deposits, trending in a wide range of orientations and in places containing the regional deformational as well as the later NW or NE trending shear foliations. In drill core from the Las Callanas area pink K-feldspar-quartz±amphibole dyklets are cut by quartz-carbonate-pyrite veins and are sericitised. Near the San Isidro - Grupo Sur deposits granodiorite is cut by numerous pink K-feldspar-quartz dyklets and new K-feldspar appears to have formed as an alteration

Table 2. Generalised paragenetic stages, alteration and textures for Au-Cu-Ag deposits, La Rioja

Stage	Vein mineral assemblage	Wall rock alteration relative to vein	Vein textures	Deformation
1.	milky white	proximal (<3m):	massive, deformed,	S-C fabrics in

hypogene, (~300°C)	quartz, carbonate, pyrite, chalcopyrite, galena, sphalerite, Au (electrum)	sericite-pyrite (sericitisation of feldspar) distal: chlorite±epidote (chloritisation of biotite)	anhedral to subhedral milky quartz; disseminated fine grained pyrite; cavity-filling chalcopyrite & other sulfides; disseminated anhedral white±brown carbonate; Au-Ag with/in pyrite?	altered wall rocks; extensional quartz veins
2a. hypogene to deep-supergene, low temp., oxidised	hematite, carbonate, clear grey quartz and recystallised quartz, Au	proximal and distal: hematite (extremely fine grained, disseminated)	anastomosing seams/fractures of fine hematite & thin veins of fine grained hematite-carbonate (brown); networks of fine clear grey quartz in older quartz; coarse Au with Fe-oxide	fracturing, brecciation of stage 1 quartz
2b. supergene oxidation	chalcedony-hematite (jasper), goethite, clear quartz, Au, malachite, chrysocolla, covellite, tenorite, cuprite, anglesite, cerrusite	proximal: hematite, goethite	finely banded chalcedony; microbreccia veinlets of jasper cutting earlier quartz; cavity infilling by goethite, fine specular hematite; clear euhedral quartz; coarse Au	brittle fracturing along vein structures
3. weather-ing	clay, limonite, goethite, malachite, chrysocolla, covellite, tenorite, cuprite, anglesite, cerrusite		fine grained replacement of silicates, sulfides, carbonates, oxides; coarse Au with Cu phases	no deformation

phase in the granodiorite near the dyklets (Figure 6). Both the dyklets and K-feldspar alteration are clearly cross cut by quartz veinlets and fractures subparallel to the NW trending main Au mineralised quartz veins (Figure 7). Deep red hematisation of the K-feldspar altered granodiorite and felsic dyklets is spatially associated with the quartz veining and is superimposed on the K-feldspar alteration. If the K-feldspar-quartz dyklets at Grupo Sur and Las Callanas areas are part of the Las Asperezas Formation, then based on isotopic age dating (Camacho, 1997; Camacho & Ireland, 1997) the quartz veining and associated alteration postdated formation of the dyklets and K-feldspar alteration by roughly 80 Ma. Nevertheless, a spatial association of quartz vein hosted Au mineralisation with K-feldspar-rich rocks may exist. This is likely to have resulted from the capacity of the the feldspathic rocks as structural and/or chemical traps.

Other minerals noted by JICA/MMAJ (1993) are native Cu (El Arbolito), and an unidentified Bi-Cu mineral (La Pirca). Arsenopyrite and berthierite were reported at El Abra by Sarudiansky (1988).

2.1.5 Geochemistry

300 rock samples across exposed veins and mullock and 35 drill core samples (0.4-3.3 m intervals) were analysed for Au (detection limit 10 ppb) and Ag (detection limit 0.01 ppm) in the work of JICA/MMAJ (1993, 1994); sampling and analytical methods were not reported. In 1988-89 YAMIRI and the Secretaría de Estado de Minería (SEM) undertook surface and underground geochemical sampling at El Arbolito, El Espinillo I and II (results reported in JICA/MMAJ, 1993). The SEM also commissioned geochemical analysis of 38 rock samples for Au, Ag and Cu (O. Marcos, pers. comm., 1995), and 76 rock samples for Au, Ag, Cu, Pb, Zn and Sb (J. Ríos Gómez, pers. comm., 1995). Other unpublished data include those of Sarudiansky (1988), Marcos (1987, 1988; reported in JICA/MMAJ, 1993). Cravero and others (1995) reported analyses for 18 trace elements and 8 major elements (by ICP) and Au (by HF/Aqua Regia & AAS) for 9 rock samples from the Au-Cu-Ag deposits. An additional 12 rock samples analysed for 23 elements including Au were analysed by the Secretaría de Minería (J. Ríos Gómez, pers. comm., 1995). Major and trace elements have been analysed in a number of regional rock samples and in four mineralised rock samples in the current project (Lyons and others, 1996).

Figure 6. Intense sericite-pyrite alteration of granodiorite (pale greenish patches) associated with thin quartz-pyrite-galena veins (white, trending from lower left to upper right across lower piece of drill core, parallel to foliation). This Stage 1 veining and alteration is cut by thin carbonate-hematite veins with hematitic alteration selvages (deep red band trending from lower right to upper left). MMAJ1, 122.3m, Callana VI.

Figure 7. Narrow, planar quartz-goethite veins cutting a pink dyklet of K-feldspar–quartz (lower right to upper left). Note sinistral displacement of dyklet on the quartz-goethite veins, whose NW strike (263°) and steep dip are similar to those of the main quartz vein system nearby. San Isidro, Grupo Sur, Sierra de Las Minas. Site A95RS043. Scale bar 10cm total length.

Strong correlation coefficients were found between Au, Ag, Cu, Pb and As, and between Zn, Ag and Ni (Cravero and others, 1995). Although the maximum reported Au values for some deposits are relatively high, Au grades are extremely variable in both surficial and diamond drill core samples (Table 3). The variability is indicated by very high standard deviations for some deposits and very low mode values. The overall average for 525 samples is 5.7 g/t Au, with standard deviation of 16.5 g/t and skewness of 6.1.

The predominance of oxidised, supergene, assemblages at surface suggests that most analyses of Au from outcrop and shallow workings (e.g. JICA/MMAJ, 1993) represent supergene rather than primary/hypogene Au. This may account for the extremely variable assay results from surface sampling. Diamond drill hole and underground sampling reveals that this variability extends to depths of at least 60-100 m (JICA/MMAJ, 1993, 1994), although primary sulfide mineralisation is also present at these depths.

Ag grades in higher grade Au zones are generally up to 10-30 ppm; rare values up to 553 ppm were reported by JICA/MMAJ (1993). Cu is commonly in the range 0.1-3%, whereas Pb is generally in the range 200-3000 ppm in higher grade Au-Cu-Ag zones. Given the relatively thin and sparse veins (<1.5m wide generally), the known deposits are not indicative of large Cu or Pb resources. Clearly the potential of the sierras de Las Minas, Ulapes and Chepes is for dominantly Au and to a lesser extent Ag.

2.1.6 Fluid inclusion studies

Fluid inclusion studies have been undertaken by JICA/MMAJ (1993) and by Cravero and others (1995). In the former study 20 samples from 20 deposits were investigated and homogenisation temperatures determined. Unfortunately no documentation of host

Table 3. Au geochemistry - statistics for sierras de Las Minas, Ulapes and Chepes

Deposit	Average g/t	Maximum g/t	Standard deviation	Number of samples	Data source

Brava	1.0	5.3	1.9	13	1
Callana III	6.0	40.4	10.5	15	1
SE Callana IV	0.6	4.2	1.2	22	1
SE Callana V	4.6	87.3	16.8	27	1
Callana VII	0.0	0.3	0.1	25	1
Cerco Quemada	0.4	1.0	0.4	5	1
Chilca	1.8	7.1	3.6	4	1
El Abra	0.6	2.6	1.1	5	1; 5
El Arbolito	2.6	19.7	3.5	95	1; 2
El Espinillo I	14.3	110.0	28.0	31	1; 2
El Espinillo II	17.1	177.0	29.0	54	1; 2
El Puerto	12.7	34.8	14.9	8	3; 6; 5
Grupo Norte	7.5	25.7	9.9	14	1; 4
Grupo Sur	3.3	13.6	4.4	20	1
La Brava	2.5	8.6	3.5	9	3; 6; 5
La Florida	28.1	82.2	32.2	5	1
La Marta	1.4	4.2	2.4	3	1
La Negra	0.1	0.2	0.1	3	1
La Pirca	23.0	142.5	46.1	9	1
Leon	2.6	5.5	2.4	8	3; 6; 5
Ñoquebe	0.4	1.0	0.3	9	3
P. los Arces	0.1	0.1	0.0	5	1
Porongo	6.7	28.6	9.6	15	3; 6; 5
Rio Noquis	0.3	3.5	1.0	11	1
San Antonio	0.0	0.2	0.1	5	1
San Rafael	0.0	0.1	0.0	5	1
Santa María	9.0	17.4	9.8	4	3; 6; 5
Santa Rita	1.0	4.1	1.7	5	3; 5
Senda Compuesta	1.4	6.5	2.2	9	1
V. Ortiz	3.9	16.1	6.2	6	1
Vallecito	5.7	131.0	26.2	25	1
W El Retarmo	0.4	1.3	0.6	4	1

Data sources:
1. JICA/MMAJ (1993)
2. YAMIRI - Secretaría de Estado de Minería
3. Secretaría de Estado de Minería, 1989 (J. Ríos Gómez)
4. Marcos (1988)
5. Cravero and others (1995)
6. J. Ríos Gómez, pers. comm. (1995)

quartz types or fluid inclusion types and heating-cooling behaviour was given. Median homogenisation temperatures ranged from 168°C to 317°C. Liquid CO_2 was noted in most samples, and was confirmed by Cravero and others (1995).

Cravero and others (1995) described the following three types of fluid inclusions, based on phase ratios at room temperature (see also Table 4):
Type I, aqueous liquid-vapour,
Type II, CO_2 - rich inclusions, with H_2O (liquid) + CO_2 (liquid and/or vapour),
Type III (rare), hypersaline, with aqueous liquid+vapour phases and a halite daughter crystal.

Table 4. Summary of fluid inclusion results from Cravero and others (1995).

Quartz type: Cravero and others; this study	Fluid inclusion types	Homogenisation temp., °C	Salinity, eq.wt.% NaCl
I; Stage 1	none suitable		
II; Stage 2	I, II	average 330° (homog. to liquid)	average 12%
		320-360° (homog. to vapour)	
III; Stage 2 or 3?	I?	270°	8-10%
IV; Stage 3	I	190-250°	average 8%

Slightly depressed melting temperatures for CO_2 were interpreted to be due to the presence of minor CH_4; alternatively, N_2 would have the same effect. Cravero and others (1995) suggested that the textures and heating-cooling behaviour of Type II inclusions is consistent with phase separation in the H_2O - CO_2 system. Ore deposition was interpreted to be related to phase separation, progressive cooling, and decreasing salinity and f_{CO2} in the hydrothermal fluids. However, fluids from which the Stage 1 early milky quartz and sulfides (+Au?) are interpreted to have been deposited remain of unknown temperature and salinity.

2.1.7 Genesis

Stable isotopes: Oxygen, hydrogen and sulfur isotope analyses of hydrothermal minerals in the sierras de Las Minas, Ulapes and Chepes Au-Cu-Ag deposits were carried out in the present study, aimed at constraining the sources of hydrothermal fluid components. The data for the three study areas (La Rioja, San Luis and Córdoba) were given by Lyons and Skirrow (1996), and the results are summarised in Figures 8, 9 and 10.

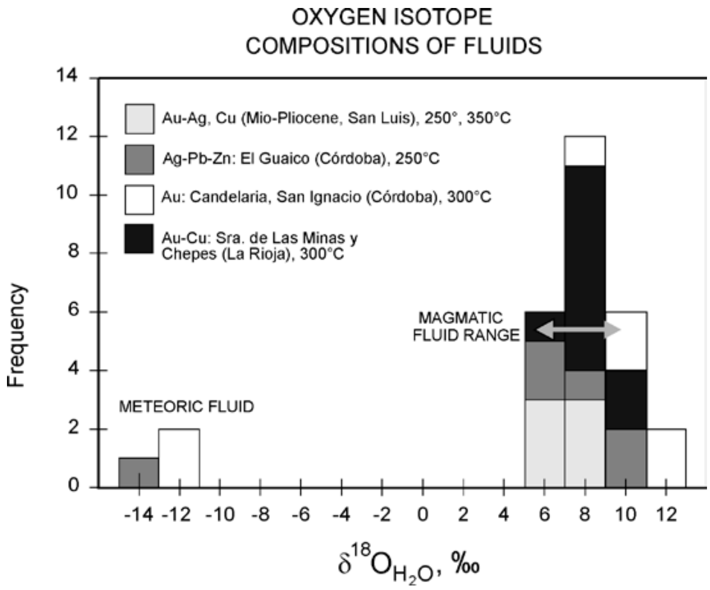


Figure 8. Calculated oxygen isotope compositions of hydrothermal fluids in Au±Cu, Ag-Pb-Zn and W deposits of the southern Sierras Pampeanas, derived from $\delta^{18}O$ values of quartz and chalcedony (Lyons & Skirrow, 1996) at the assumed temperatures given in the figure (see text for discussion). Quartz-water fractionation factor from Matsuhisa et al. (1979).

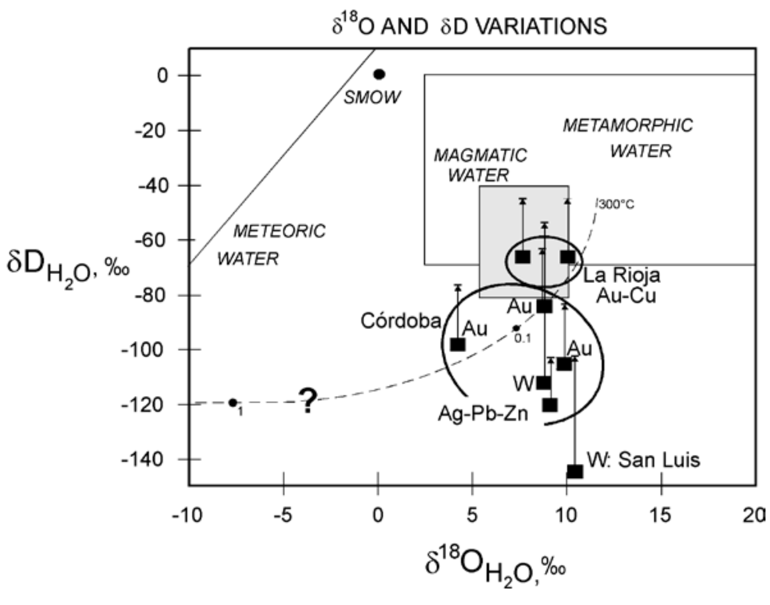


Figure 9. Calculated oxygen and hydrogen isotope compositions of hydrothermal fluids in Au±Cu, Ag-Pb-Zn and W deposits of the southern Sierras Pampeanas, derived from $\delta^{18}O$ and δD values of hydrothermal white mica at the assumed temperatures given in the figure (see text for discussion). SMOW = standard mean ocean water; magmatic water field from Taylor (1979); meteoric water line after Craig (1961); metamorphic water field from Sheppard (1986). Dashed line: trend of possible reaction of

deuterium-depleted meteoric water with sedimentary (or metasedimentary) rocks at low water-rock ratios (labelled points at w/r=1, 0.1) at 300°C, from Field and Fifarek (1985). Muscovite-water $\delta^{18}O$ fractionation factor from O'Neil & Taylor (1969); muscovite-water δD fractionation factor from Suzuoki & Epstein (1976; lower limit of bars) compared to that of Vennemann & O'Neil (1996; upper limit of bars).

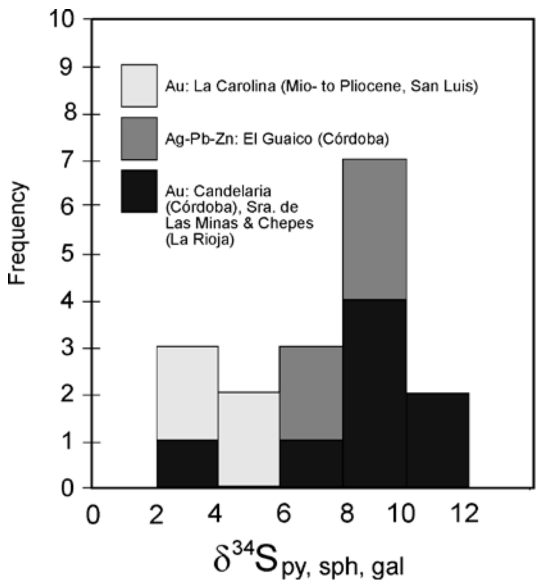


Figure 10. Sulfur isotope compositions of sulfides in Au±Cu, Ag-Pb-Zn and W deposits of the southern Sierras Pampeanas.

Quartz selected from nine Au-Cu-Ag deposits was primarily the milky white, coarse, anhedral type associated with sulfide deposition in paragenetic Stage 1 (Table 1). Minor amounts of clear grey quartz veinlets of Stage 2 may have been present in some samples. Sericite samples are from hydrothermally altered wall rock fragments within quartz veins and adjacent to veins. A temperature of 300°C has been assumed for calculation of $\delta^{18}O$ and δD fluid compositions, based on the fluid inclusion homogenisation temperatures of quartz types II (average T_h =330°C) and III (average T_h =270°C) of Cravero and others (1995). This may be a minimum temperature because no 'pressure correction' has been applied to the fluid inclusion homogenisation data, and the quartz analysed for $\delta^{18}O$ may have formed earlier than the quartz types II and III of Cravero and others (1995).

The calculated $\delta^{18}O_{fluid}$ and δD_{fluid} results are plotted in Figures 8 and 9, and indicate that fluids forming Stage 1 quartz and sericite were similar to magmatic waters. However, these isotopic compositions are not unique to magmatic fluids, and alternatively could be derived through extensive reaction at high temperature of meteoric waters with wall rock at low water/rock ratios, or could be metamorphic in origin.

The $\delta^{34}S$ compositions of five sulfide separates lie in the range 6.2-8.4‰, while pyrite from Santa María is lower at 1.5‰ (Figure 10) Given the likelihood of significant aqueous sulfate as well as dissolved sulfide in the hydrothermal fluids, it is not possible to unambiguously define the origin of the sulfur. However, the results are consistent with a significant input of metasedimentary-sourced sulfur in the hydrothermal fluids.

Isotopic dating of alteration: Dating of white mica hydrothermal alteration by the $^{40}Ar/^{39}Ar$ method (Camacho, 1997) has been used to constrain the age of sericite-pyrite alteration in paragenetic Stage 1. Although only two mineralisation-related samples from La Rioja have been dated by $^{40}Ar/^{39}Ar$, and the age spectra do not exhibit 'ideal' plateaux, the results can be interpreted to represent initial white mica alteration at ~390 Ma, with subsequent cooling resulting in the finer grained sericite crystals reaching their Ar closure temperatures over the next ~5-10 Ma (Camacho, 1997). The results are remarkably similar to those for sericite associated with Ag-Pb-Zn veins from Córdoba (386±4 Ma), and indicate marginally earlier Au introduction in La Rioja compared to that in mesothermal Au deposits of Córdoba (~370-378 Ma). Tungsten mineralisation in two vein deposits from San Luis and Córdoba (363±1, 366±1 Ma) appears to have formed coevally with or slightly later than Au in Córdoba.

Based on U-Pb and $^{40}Ar/^{39}Ar$ dating (Camacho & Ireland, 1997; Camacho, 1997) the results are consistent with introduction of Au, Cu, Ag, Pb, Zn and W broadly synchronous with early Devonian granite emplacement in the southern Sierras Pampeanas.

Table 5. Summary of $^{40}Ar/^{39}Ar$ step heating results for hydrothermal sericite, La Rioja

Deposit	Sample No.	Mineral	Texture	Age range (Ma)
Callana VI	A95RS033B	sericite	alteration of granite	~390
Vallecito	A95RS047A	sericite	in quartz vein	382-393

Model of Au ore formation: Hydrothermal fluids responsible for transporting Au, Cu, Ag, Pb and other metals in the La Rioja deposits are interpreted to have been slightly acidic or near-neutral pH, as indicated by the presence of sericite alteration and vein carbonate. The lack of pyrrhotite and other phases typical of reduced conditions, and presence of pyrite, suggests the Stage 1 fluids were of intermediate to oxidising redox potential; no fluid inclusion constraints on temperature or salinity are available for this Stage, although the quartz II of Cravero and others (1995) could have formed late in Stage 1. Given the coexistence of carbonate with sulfides in Stage 1 assemblages it is possible the Au-Cu-Ag-Pb transport fluids were both saline and CO_2-rich, or, more likely, two fluids were involved. The presence of liquid CO_2 in fluid inclusions, and brittle-ductile style of deformation during Stage 1 suggest vein formation at moderately elevated PT conditions, as in a mesothermal environment (Figure 1).

Stage 2 fluids were lower temperature, oxidised (hematite-stable), CO_2-rich (coexistence of carbonate with hematite) and probably of near-neutral pH. These fluids may have remobilised Au to form secondary grains of high fineness. Based on similarities in fluid chemistry it is probable that Stage 2 was more or less continuous with Stage 1, occurring during progressive deformation within the shear zones. The decrease in temperature and increase in oxidation conditions is speculated to reflect influx of meteoric water.

Stage 3 deformation style and mineral assemblages indicate low temperature, supergene, oxidising conditions at very high crustal levels, as may be expected during Andean tectonics and exhumation of the deposits to near-surface levels where meteoric waters are dominant. Weathering and oxidation at surface constitute Stage 4, and combined with earlier oxidation have resulted in possibly several Au remobilisation events.

The structural and tectonic setting of vein formation (Figure 1), vein textures and geometries, hydrothermal alteration and stable isotope geochemistry bear similarities to mesothermal lode Au deposits of the North American cordillera (Nesbitt & Muehlenbachs, 1989; Goldfarb and others, 1997). As such, we consider the Au (Cu, Ag) deposits of the sierras de Las Minas, Ulapes and Chepes to be members of the broad class of structurally-controlled mesothermal lode Au deposits found in orogenic terranes (including 'low-sulfide Au-quartz veins of Cox & Singer, 1986). However, the La Rioja deposits are relatively Cu±Pb-rich variants compared to 'typical' mesothermal lode Au deposits of the North American cordillera. The elevated Cu±Pb contents, moderate to high salinities of some fluids involved in vein formation, and similarity of calculated fluid oxygen-hydrogen isotopic compositions with magmatic waters, collectively point to a contribution of fluids and/or metals from igneous rocks. Early Devonian granitoids, such as that inferred from aeromagnetic imagery under cover rocks to the west of the Sierra de La Minas, are possible candidates for sources of fluid and/or metals and/or heat energy.

2.2 U OCCURRENCES

A number of U occurrences are shown on previous maps of the sierras de Chepes, Las Minas and Ulapes. These were not investigated in the field due to lack of precise locational data from the literature (±3000m). The descriptions of the U occurrences given by Belluco et al (1974) indicate they occur within Carboniferous or Permian sedimentary rocks that occur in narrow basins traversing the sierras de Chepes, Las Minas and Ulapes. However, the imprecise locations available for the U occurrences plot generally in Paleozoic basement or in Cainozoic cover sediments. It appears likely the U occurrences are small examples of 'sandstone uranium' or 'roll-front uranium' style deposits (e.g. Ruznicka & Bell, 1984).

In addition, several data sources list the occurrence of U with Au-Cu deposits in the Sierras de Las Minas. As U is effectively transported in oxidising fluids (Wilde and others, 1989), U mineralisation may be associated with hematitic alteration in the Au-Cu deposits. As such, U may prove to be a useful pathfinder element in exploration for the Au deposits.

3. NON-METALLIC DEPOSITS AND ROCAS DE APLICACIÓN

3.1 GRANITE ORNAMENTAL STONE AND PIEDRAS LAJAS

The La Rioja region contains several quarries for granite, and a number of occurrences of piedras lajas in the northeast of the region. Non-metallic deposits and rocas de aplicación were not investigated in the current project.

The coarse grained, relatively unlaltered, Quemado norite has significant potential as a building stone.

4. METALLOGENIC EVOLUTION OF THE REGION

The southern Sierras Pampeanas comprise a basement terrane dominated by Paleozoic tectonics (Stuart-Smith and others, 1996). The eastern part of the region, which includes part of the San Luis map area and all of the Córdoba map area, was metamorphosed at medium-high grade, intruded by I- and S-type granitoids and deformed during the Cambrian (Pampean cycle). Low to high grade metamorphism and compressive deformation of the western part of the region peaked in the early Ordovician. I-type granites were emplaced throughout the La Rioja map area and in parts of the Sierra de San Luis during this early part of the Famatinian cycle. This was closely followed by extensional tectonism, retrograde metamorphism and emplacement of mainly S-type granitoids and pegmatites late in the Famatinian cycle. The extensional tectonism was evidently confined to belts to the east of the La Rioja area. The post-Ordovician history was dominated by the emplacement of fractionated granites in a compressive tectonic setting synchronous with folding and shearing of the terrane during the early Devonian (Achalian cycle). These shallow intrusions crystallised from relatively oxidised magmas and have ASI values ranging from those typical of S-type granites to values transitional between I- and S-type granites. Sedimentation in the Carboniferous and early Mesozoic were followed by graben formation in the Cretaceous and basaltic volcanism in the Sierras de Córdoba. Finally, intermediate to felsic high-K calcalkaline volcanic rocks were erupted in the Neogene and were associated with Andean tectonics.

Determination of relative and absolute timing relationships in conjunction with regional geological and stable isotope studies has led to significant improvement in the resolution of Paleozoic metallogenic phases in the southern Sierras Pampeanas. The three principal Paleozoic stages and one Neogene stage recognised in the project areas each exhibit distinctive metal associations and deposit styles. The earliest metallogenic stage investigated includes magmatic Ni-Cu-Co sulfide deposits with anomalous PGE-Au hosted by mafic-ultramafic intrusions, in the Sierras de San Luis. Differentiates of the mafic parent magma crystallised during the early Ordovician, approximately coeval with Famatinian high grade metamorphism and compressive deformation. The whole rock geochemistry of the mafic-ultramafic rocks and metasediments from the Sierras de San Luis is similar to those of rocks emplaced in back-arc basin tectonic settings (Brogioni & Ribot, 1994; Sims and others, 1997). It is proposed that the mafic-ultramafic rocks were emplaced within a back-arc basin as it underwent compression in a collisional tectonic setting.

No metallic manifestations of the Pampean cycle have been recognised in the present study in the Córdoba, La Rioja or San Luis map areas, although such mineralisation has been suggested by many authors as discussed above.

The second metallogenic phase in the map areas is spatially and temporally related to extensional deformation in the final stages of Famatinian tectonism in the early Ordovician. This tectonism is well developed in the San Luis map area, during which granites and voluminous pegmatites were emplaced that contain important deposits of Li, Be, Nb, Ta, Sn, and industrial minerals. Although subordinate W mineralisation may have formed as early as the Ordovician in the Sierras de San Luis, the majority of the W deposits in the map areas are proposed to have formed during the Devonian (below).

The third phase of metallogenic evolution in the southern Sierras Pampeanas occurred in the Devonian and is characterised by diverse deposits of Au, W, Ag, Pb, Zn, Cu, and a second period of pegmatite-related mineralisation including Be, Li, Nb, Ta, U, REE, Th and F. New $^{40}Ar/^{39}Ar$ dating of white mica hydrothermal alteration associated with Au±Cu, W and Ag-Pb-Zn veins suggests mineralisation occurred from ~390 to ~360 Ma in the southern Sierras Pampeanas including some W deposits of the San Luis map area (Figure 11). Based on this and U-Pb zircon dating this metallogenic phase commenced during the period of Devonian magmatism (~403 to ~382 Ma, Camacho & Ireland, 1997), and may have continued for at least 25 Ma after granite emplacement (Figure 11). However, Rb-Sr and K-Ar age data for these granites extend to as young as 300 Ma (Rapela and others, 1990). Malvicini and others (1991) proposed that some deposits of W, Pb, Zn Cu and Bi in the Sierras de San Luis formed in association with Carboniferous granites. A clearer understanding of the significance of this Rb-Sr and K-Ar data in the magmatic and thermal history of the region is required before it is possible to define the full extent of temporal overlap of mineralisation with the period of Achalian granite emplacement. Mesothermal shear-hosted Au±Cu quartz vein deposits in the Sierra de las Minas (Prov. de La Rioja), shear-related Au in the Candelaria district and high-level Ag-Pb-Zn quartz veins in the El Guaico district (both Prov. de Córdoba) are now recognised to have formed during the Devonian metallogenic phase from fluids of similar stable isotopic composition. It is probable that Pb-Zn-Cu quartz veins of the Las Aguadas district in the

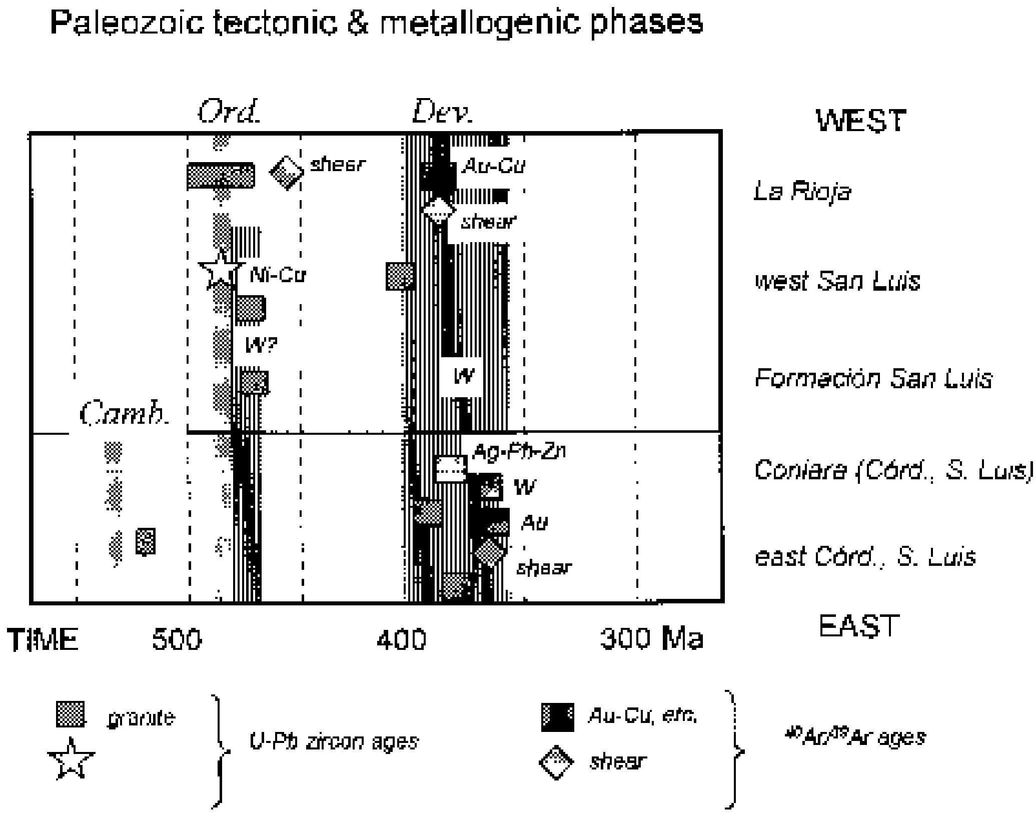


Figure 11. Summary of argon-argon dating of white mica alteration associated with metallic mineralisation, and U-Pb (zircon) age dating, in relation to the Pampean (early Cambrian), Famatinian (Ordovician) and Achalian (Devonian) tectonic cycles in the southern Sierras Pampeanas. Shaded vertical bars represent main periods of medium-high grade metamorphism, and ruled vertical pattern represents main periods of low grade metamorphism. Geochronology data from Camacho and Ireland (1997) and Camacho (1997).

northern Sierras de San Luis also formed during the Achalian cycle (Malvicini and others, 1991). Our oxygen and hydrogen isotope results are compatible with input of evolved meteoric fluids with or without a minor component of magmatic or metamorphic waters in the formation of these Au±Cu and Ag-Pb-Zn deposits (Figs. 8, 9). Sulfur was probably derived from the host metasedimentary rocks. Hydrothermal muscovite from the Loma Blanca W deposit in the Sierra del Morro has oxygen and hydrogen isotopic compositions and a $^{40}Ar/^{39}Ar$ age broadly similar to those of the other Devonian deposits investigated. Epigenetic tungsten deposits hosted mainly by calcsilicate rocks in the Sierras del Morro, Yulto and Estanzuela (Prov. de San Luis) and W±Cu in the Punilla region of the Sierras de Córdoba are proposed to have formed during the Devonian metallogenic phase. Localisation of quartz-scheelite vein deposits and possibly some Au±W quartz vein deposits in the Sierras de San Luis in structures characteristic of the Achalian tectonism suggests these deposits also formed during the Devonian metallogenic stage.

In the final main metallogenic stage, Au (-Ag-Pb-Zn) mineralisation in the La Carolina district of the Sierra de San Luis formed in association with Miocene-Pliocene volcanism. Alteration, geochemical and geological characteristics indicate metal deposition in the upper levels of low sulfidation epithermal systems. Andesitic volcanics in the Pocho district of Provincia de Córdoba also were erupted in the Miocene (Gordillo & Linares, 1981).

The significance of a possible Cretaceous metallogenic event associated with basaltic volcanism (e.g. fluorite deposits in the Cerro Aspero batholith, Sierra de Comechingones, Galindo and others, 1996) and a Tertiary U event (e.g. in Valle de Punilla, Provincia de Córdoba) has yet to be determined.

5. PROSPECTIVITY AND METALLOGENIC MODELS

5.1 METHODOLOGY

A qualitative appraisal of metallic mineral prospectivity for the map area has been carried out using the 'Mineral Systems' approach and the concepts of 'essential ingredients' and 'mappable criteria' developed in AGSO (Wyborn and others, 1994). In this methodology a number of 'essential ingredients' in a genetic model for a particular style of mineralisation in an ore-forming hydrothermal system are chosen. These geological factors have been selected on the basis of multi-disciplinary ore deposit and regional geological studies, as discussed in preceding sections for specific deposit styles. In general, an ore-forming system requires: (1) a source of hydrothermal fluid components and metals, (2) energy to drive fluid flow, (3) fluid transport pathways linking the source regions with depositional sites, and (4) depositional 'traps' for ore deposition. An outflow pathway must also exist.

The ‘essential ingredients’ are manifested in some cases by observable features, or ‘mappable criteria’, which may be represented as domains in geoscientific maps and in a GIS. By combining the domains of ‘mappable criteria’ a map representation of a metallogenic model can be constructed for particular ore-forming systems and deposit styles. The final results of this procedure are metallogenic or prospectivity maps showing areas where critical geological factors in ore formation are similar to those existing at the known deposits (1:250 000 Metallogenic Map, La Rioja). In theory the methodology also allows prediction of areas for mineralisation styles not previously known to exist in a region.

Set out below are proposed metallogenic models for the principal mineral deposit styles recognised in the La Rioja map area, based on the methodology described above. These models were used in production of the 1:250 000 Metallogenic Map for the La Rioja area. Also shown are several hypothetical mineralisation styles not known in the map area but which are considered to have potential within and close to the area investigated. The model ingredients and criteria are based on deposit models described in the literature together with local geological constraints in the map area.

It should be noted that the methodology is qualitative and interpretive in nature, and should be considered a preliminary stage in assessment of prospectivity. Further work (research and exploration) is required to validate the proposed 'essential ingredients' in the models, and test their related 'mappable criteria', so that the prospectivity evaluations can be refined.

5.2 METALLOGENIC MODELS

5.2.1 Shear-related lode Au±Cu±Ag

Essential ingredients	**Mappable criteria**
Source of energy for hydrothermal system and/or source of fluid components and/or metals; related to Devonian magmatism	Devonian granites - 10 km buffer on outcrops and magnetic lows interpreted as Devonian granite
Extensive fluid flow paths that were active in the Devonian	Devonian shear/mylonite zones trending NW and NE; also older NS mylonites reactivated in Devonian; magnetic low lineaments
Hydrothermal fluids out of equilibrium with feldspathic host rocks; changing physico-chemical conditions for ore deposition	quartz veins; sericite-pyrite alteration & later hematitic alteration represented by magnetic lows; geochemical anomalies of Fe, Au, Cu, Ag, Pb, As, U, Zn, Bi
Structural 'traps' for ore deposition - dilational zones	intersections of NW-, NE- & NS-trending lineaments; flexures/jogs in shears, lineaments; contacts between rocks of differing competancy, e.g. granite and schist
Chemical 'traps' for ore deposition: reductants, desulfidants, acid neutralisers	abundant magnetite (magnetic highs) or other Fe^{2+}-rich phases, e.g. amphibole/pyroxene (metabasic rocks); abundant K-feldspar (leucogranite, aplite-pegmatite)

5.2.2 Sediment-hosted U

Essential ingredients	Mappable criteria
Source of metals (U, Cu?, Au?)	granites, pegmatites(?) - 10 km buffer on outcrops older than Carboniferous
Metal transport: oxidised fluids (meteoric water) in equilibrium with Carboniferous or younger aquifer rocks	red beds (e.g. Permian - Formación La Colina, once very widespread), overlying or lateral to trap rocks
Physiography suitable for fluid flow from source regions to host rock environments	regions of pre-Carboniferous granite-pegmatite, upthrown relative to adjacent basins/grabens containing aquifer and trap rocks
Focussed fluid flow	Carboniferous or younger faults - 1 km buffer
Chemical trap rocks: reduced rocks	Below contacts of red beds with carbonaceous (e.g. Carboniferous Formación Malanzan), pyritic- or magnetic-rich units; geochemical anomalies of U, Cu, Au, Pt, Pd, REE, Th

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