Report on

1:100 000 Scale Geological and Metallogenic Maps
Sheet 3166-24

Province of Córdoba

Patrick Lyons and Roger G. Skirrow

GEOSCIENTIFIC MAPPING OF THE SIERRAS PAMPEANAS ARGENTINA-AUSTRALIA COOPERATIVE PROJECT

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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by Patrick Lyons

1. INTRODUCTION

1.1 LOCATION AND ACCESS

The 3166-24 1:100 000 Sheet area lies within Córdoba Province, between 31°40’-31°20’S and 64°30’-65°00’W. The area is part of the 3163-IV (Villa Dolores)1:250 000 sheet area.

The region includes the central northern Sierra Grande which is drained by the north flowing Ríos Pintos, de La Candelaria, and Soto.

Access to the region, from Córdoba city, is via Ruta Nacional 38 which connects the main population centres of La Cumbre, Capilla del Monte, Cruz del Eje, and Villa de Soto. A number of secondary roads, generally unsealed, connecting the centres of Paso del Carmen and Candelaria to the main centres afford good access to most of the rock types in the sheet area.

1.2 NATURE OF WORK AND PREVIOUS INVESTIGATIONS

Mapping of the 3166-24 Sheet was carried out in 1995 and 1996 under the Geoscientific Mapping of the Sierras Pampeanas Argentina - Australia Cooperative Project by geologists from the Australian Geological Survey Organisation (AGSO) and the Subsecretaria de Mineria (DNSG) (Figure 1.1). The mapping employed a multidisciplinary approach using the newly acquired high-resolution airborne magnetic

Figure 1.1. Location and simplified geology of the Sierras septentrionales de Córdoba and location of 1:100 000 sheets.

and gamma-ray spectrometric data, Landsat TM imagery, and 1:20 000 scale (approximate) black and white air photography. The geological map was compiled on topographic bases produced at photo-scale from rectified Landsat images controlled by field GPS sites. Geologists involved in the fieldwork were P. Lyons, and P.G. Stuart-Smith (AGSO), and J.C. Canadiani, H. Lopez, and R. Miro (DNSG). P. Espejo, M. Viruel, D. Martos (DNSG) and B. Torres (Secretaría de Minería de la Provincia de Córdoba) assisted with the fieldwork.

The area was first mapped as undifferentiated metamorphic basement by early workers (e.g. Pastore, 1932). Much of the Sierra Grande was mapped by Olsacher between 1961 and 1964 (Lucero Michaut and Olsacher, 1981). More detailed work has been carried out by Caminos and Cucchi (1990) and Martino (1993) who studied part of the Guamanes Shear Zone to the south of the sheet.

2. STRATIGRAPHY

2.1 GENERAL RELATIONS

The 3166-24 Sheet area is part of the southern Sierras Pampeanas, a distinct morphotectonic province of early to mid Palaeozoic metamorphic, felsic and mafic rocks, forming a series of block-tilted, north-south oriented ranges separated by intermontane basins (Figure 2.1). The ranges are bounded by escarpments developed on moderate to steeply dipping reverse faults developed during the Cainozoic Andean uplift (Jordan and Allmendinger, 1986).

Basement consists of Early Cambrian metamorphic and igneous complexes intruded by Cambrian, Ordovician, and Devonian granitoids. Mesozoic and Cainozoic cover units occupy major valleys and intramontane areas to the north and east.

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Figure 2.1. Location of the three project areas of the Argentina-Australia Cooperative Project and simplified regional geology of the southern Sierras Pampeanas.

Recent geological and geophysical surveys conducted as part of the Cooperative Argentine-Australia project in the Sierras Pampeanas show that the Paleozoic basement of the southern Sierras Pampeanas contains of a number of distinct lithological and structural domains separated by major tectonic zones. There are two principal domains: a Cambrian Pampean domain, and the Ordovician Famatinian domain to the west. Both domains have shared a common geological history since early Ordovician times. The boundary between the domains is broadly coincident with a regional change in the gravity near the western flank of the Sierras de Córdoba (Miranda and Introcaso, 1996) and is marked by the Guzman Fault further south in the Province of San Luis. Only the Pampean domain is exposed in the Sierras septentrionales de Córdoba. However, the younger Famatinian domain is inferred to be present in the subsurface west of the Sierra Grande. A summary of stratigraphy and relations is given in Table 2.1.

2.2 EARLY PALAEOZOIC METAMORPHIC BASEMENT

Marble (∈m)

Minor marble units are found throughout the sheet area but mappable outcrop is found in the Quilpo Formation and the Cruz del Eje Metamorphic Complex. Details are given under the respective sections.

Quilpo Formation (∈lq)

Pelitic gneiss, marble, calc-silicate rock

A zone of mostly low gamma-ray spectrometric responses corresponds to a distinct belt of Cambrian metasedimentary and metamafic rocks, extending south-south east from the from the Canteras Quilpo area (about 20 km south east of Cruz del Eje on

Table 2.1. Summary of stratigraphy and relationships in the 3166-24 1:100 000 Sheet.

Age (Ma)	Unit	Description	Relations

QUATERNARY	Alluvium	Unconsolidated clay, sand and gravel	Deposits along active river courses
	Fluvial fans	Unconsolidated bouldery gravels	Interfinger with alluvial deposits
TERTIARY TO QUATERNARY	Calcrete	Paleosol	Mantles older units.
DEVONIAN	Unassigned granite	Granite	Intrudes Cruz del Eje Complex.
CAMBRIAN	La Falda Complex	Banded pelitic gneiss, leuco-tonalitic ortho-gneiss, marble, and calc-silicate rocks	Faulted against El Manzano Formation. Intruded by Guiraldes Tonalite and Capilla del Monte Granite
	Quilpo Formation	Marble, calc-silicate rocks, pelitic gneiss, amphibolite.	Concordant with La Falda Complex, structurally overlies Cruz del Eje Complex.
	Cruz del Eje Complex	Pelitic gneiss, minor quartzite, marble, amphibolite, calc silicate rocks.	Structurally beneath La Falda Complex(?).
	Guamanes Shear Zone	Sheared and mylonitised pelitic gneiss; boudinaged phyric granite.	Forms a division between Cruz del Eje and Pichanas Complexes and affected rocks of both.
	Pichanas Complex	Pelitic gneiss, quartzite, migmatite, S-type granite, minor marble and amphibolite.	Concordant(?) with Cruz del Eje Complex.
	Paso del Carmen Granodiorite	Granodiorite	Intrudes Pichanas Complex.

Sheet 3166-18) to south of Pampa de Olaen is defined here as the Quilpo Formation. The area was mapped in detail by Massabie (1982) and Caffe (1993). Outcrop is generally excellent but mostly covered by low and dense vegetation.

The Quilpo Formation structurally overlies the adjacent Cruz del Eje Metamorphic Complex to the west and is possibly concordant. South of the Pampa de Olaen, converging structural trends indicate that the contact here is probably faulted in part, and to the east, the contact with the La Falda Metamorphic Complex is concordant.

Zircons from a sample of gneiss taken from the eastern edge of the formation, on the 3166-18 Sheet to the north, gave a U-PB age for peak metamorphism of about 529±8 Ma (Camacho and Ireland, 1997).

The formation is one of a number of fault-bounded, or partially fault bounded, semi-continuos carbonate-rich metasedimentary belts which traverse the southern Sierras Pampeanas. Like the El Manzano Formation in the Sierra Chica to the east, the Quilpo Formation comprises interlayered pelitic gneiss, marble, calc-silicate rocks, and amphibolite.

More than half the formation is composed of muscovite-biotite-K-feldspar-plagioclase-garnet ± sillimanite gneiss which shows well developed layering and locally grades into migmatite. Mineral lineations are absent or poorly developed and myrmekitic textures are common.

South of the Pampa de Olaen *marble* (∈l) is a minor component of the Quilpo Formation.

Calc-silicate rocks have a granoblastic texture and contain minor tremolite, K-feldspar, clinozoisite, muscovite, biotite, quartz, and diopside.

Cruz del Eje Metamorphic Complex (∈rgn)
Quartz feldspar biotite garnet gneiss, migmatite, marble, amphibolite

The Cruz del Eje Metamorphic Complex, is the major unit on the map sheet. The formation is principally composed of quartz-feldspar-biotite ± garnet gneiss with locally developed migmatite, and minor carbonate rocks and amphibolite. Marble, calc-silicate and amphibolite rich portions of the complex have been distinguished on the map and possibly represent equivalents of the Quilpo Formation.

There are no isotopic age determinations for the unit. However, an Early Cambrian age is interpreted as the unit shares the same regional deformational and metamorphic history as the Quilpo Formation.

Gneiss and *migmatite* are composed of quartz (30% - 70%), plagioclase (10% to 40%), K-feldspar (<25%), biotite (<10%), and up to 5 % garnet. Minor cordierite and chlorite are also present, and zircon, apatite, titanite, epidote, sericite, haematite, and carbonate are common accessory minerals. Sillimanite (and retrograde muscovite) may also be present where gneiss is interlayered with marble. Mineralogically and geochemically, the gneiss is similar to that within the Pichanas Metamorphic Complex but overall, has lower mica and K-feldspar contents. Geophysically, the Cruz del Eje Metamorphic Complex is distinguished from the Pichanas Metamorphic Complex by its relatively higher thorium gamma-ray spectrometric response and moderately stronger magnetic anomalies.

Interlayered *marble, calc-silicate* rock and *amphibolite* are found in the Los Callejones area about 6 km north east of Candelaria. Marble units are mostly composed of calcite with lesser dolomite and calc-silicate minerals where protoliths were impure limestones. Marble from the principal quarries in the area, at Canteras Iguazú, contain nearly 50% dolomite (Di Fini, 1970). Calc-silicate rocks are typified by the presence of carbonate, quartz, tremolite, diopside, K-feldspar, clinozoisite, biotite, and muscovite assemblages. Individual marble and calc-silicate lenses vary from a few metres to tens of metres thick but (along with amphibolite) form tectonically thickened and transposed lenses some hundreds of metres across.

La Falda Metamorphic Complex (∈gfn)
Paragneiss intercalated with orthogneiss

The La Falda Metamorphic Complex lies between two separate north to northwest-trending largely fault-bounded carbonate-rich metamorphic units of the El Manzano Formation in the Sierra Chica and the Quilpo Formation. In the Punilla Valley, the unit is covered by unconsolidated Quaternary coarse clastic deposits and only crops out west of the valley.

The La Falda Metamorphic Complex is distinguished from the and Quilpo Formation by the presence of tonalite and a smaller proportion carbonate rocks (generally confined to the north on Sheet 3166-18) but shared a common structural and metamorphic history and is, thus, Early Cambrian. Numerous aplite and muscovite - quartz - K-feldspar pegmatite dykes, up to 10 m wide, intrude the unit and are probably associated with numerous unnamed granitic intrusive bodies which crop out north of Pampa de Olaen and probably exist close to the surface in the map area. Magnetic anomalies indicate that these small granite bodies may apophyses of a single body at shallow depth.

The complex consists mostly of pelitic gneiss with about 20% interlayered leucotonalitic ortho-gneiss and very minor marble and calc-silicate rocks. Rare amphibolite boudins probably represent meta-mafic dyke rocks. The complex is subdivided into two subunits based on the predominance of either pelitic gneiss or ortho-gneiss. The orthogneiss dominant unit was mapped and named the San Marcos Formation by Massabie (1982).

The La Falda Metamorphic Complex in the sheet area is largely grey *banded muscovite-biotite-feldspar-quartz-garnet ±sillimanite gneiss* (∈fgn). Feldspar contents range from 10% to 20% with plagioclase predominating over K-feldspar. It is typically gneissic and is migmatitic in places with leucosome bands of quartz-feldspar. A vestige of the second unit (∈sgn) crops out on the northwest side of the Pampa de Olaen. This unit is dominated by grey *medium-grained equigranular muscovite-biotite leuco-tonalitic ortho-gneiss* lenses within pelitic gneiss, ranging from less than a metre to several metres wide. Quartz contents are uniformly high (40%-45%) with some variation in proportional feldspar content. Zircon is the only common accessory phase. Locally, their composition is a leuco-monzogranite. In places, the ortho-gneiss truncates the main S1 metamorphic differentiated fabric, enclosing rotated enclaves of pelitic gneiss. Both the pelitic and ortho- gneisses are isoclinally folded by F2 with the ortho-gneiss extended within the S2 foliation plane. Biotite folia within the ortho-gneiss are continuos with S2 and S1 foliations in the pelitic gneiss. These relationships indicate that the ortho-gneiss originally intruded the pelitic gneiss at the close of the Early Cambrian Pampean deformation (D1) prior to the Early Ordovician Famantinian deformation (D2).

Pichanas Metamorphic Complex and associated S-type granites (∈gnp, ∈gi1, ∈g)

Paragneiss, migmatite, associated S-type granite

The Pichanas Metamorphic Complex is an extensive unit cropping out over a wide area between the Río Soto and the Sierra de Guasapampa, the western most part of the Sierra Grande. Its name derives from the Río Pichanas. It is primarily composed of cordierite and garnet paragneiss and migmatite with minor marble and amphibolite units. In places, high T metamorphism resulted in local melting which produced a number S-type granite bodies, the most well known being the ‘El Pilón’ body.

The Pichanas Metamorphic Complex shares a common deformational and metamorphic history with the Cruz del Eje Metamorphic Complex and a Th-Pb age determined from monazite gave 526±11 Ma as the age for peak metamorphism which attained amphibolite grade (Camacho and Ireland, 1997).

Metapelite with minor marble and amphibolite (∈gnp) forms the dominant unit in the complex. It grades into migmatite in places. It contains medium- to high-grade assemblages of quartz (25% to 40%), K-feldspar (25% to 35%), biotite (10% to 30%), plagioclase (5% to 10%), muscovite (5% to 10%) and minor garnet, cordierite, and sillimanite. Retrograde effects are evident by muscovite replacement of sillimanite and K-feldspar and chlorite replacement of cordierite and garnet.

Bodies of S-type granite associated with Early Cambrian high grade metamorphism occur throughout the Pichanas Metamorphic Complex. Two units occur on the sheet, a

K-feldspar phyric granite(∈gi1) and unassigned granite (∈g) interpreted from aerial photos.

Concordant and discordant contacts with the surrounding meta-pelites, and numerous enclaves of the same, provide field evidence that these granite bodies are accumulations of partial melt products generated during high-T metamorphism of the pelites. Analyses of Rb-Sr and Sm-Nd isotopes from the largest of these bodies (not in this sheet area) indicate they are products of ultra metamorphism (Rapela and others, 1995).

The dominant granite unit (∈gi1) in the Pichanas Metamorphic Complex, although minor in this sheet area, is a pink to deep pink, *phyric to megaphyric, K-feldspar biotite granite* with minor muscovite, sillimanite, chlorite, after biotite, and cordierite and trace amounts of plagioclase and zircon. K-feldspar laths often display a local flow alignment, and make up about 40% to 45% of the granite. Biotite contents are about 15% to 20%. The radiometric response is high with total counts around 90 cps to 95 cps and potassium around 6.5 cps which gives a clearly identifiable response on radiometric images. Magnetic susceptibility is low, generally about 10×10-5 SI.

Recent isotopic age data from the S-type granite of the Pichanas Metamorphic Complex are summarised in Table 2.2. Although recent U-Pb zircon data (Camacho and Ireland, 1997) are approximate, due to some Pb loss, there is broad agreement with Rb-Sr ages obtained by Rapela and others (1995).

Table 2.2. Isotopic ages of S-type granite from the Pichanas Metamorphic Complex. 1. Rapela and others (1995) 2. Camacho and Ireland (1997).

Rock type	Age (Ma)	Method	Ref.	Comment
Granite	520±5	Rb-Sr	1	Leucogranite (and cordierite rock)
Granite	ca 527	U-Pb	2	Phyric granite
Granite	ca 514	U-Pb	2	Leucogranite

Some lead loss at about 480 Ma (Camacho and Ireland, 1997) may be due to the Ordovician Famatinian event.

Small bodies of unassigned granite (∈g)are interpreted from aerial photographs.

Limited field evidence suggests they are porphyritic to equigranular, ranging in composition from granite to granodiorite. They contain numerous enclaves of schist and gneiss derived from meta-pelites and typically form intrusive, elongate to equidimensional, bodies which are concordant to sub-cordant with the regional fabric of the enclosing metamorphic rocks. They probably originated as melt products derived during high-T regional metamorphism of the metasediments. There are no isotopic age determinations, however, an Early Cambrian age is interpreted as the age of the peak regional metamorphism in the area is about 530 Ma (Camacho and Ireland, 1997

Guamanes Shear Zone (Dmg, Og)

Quartz, feldspar, biotite,±garnet,±sillimanite gneiss, amphibolite, phyric granite, mylonite

The north to north-west trending Guamanes Shear Zone, Dmg, dips moderately to steeply east and comprises a belt of mylonitised Early Cambrian rocks of the Pichanas and Cruz del Eje Metamorphic Complexes, and Palaeozoic phyric granite and pegmatite. The belt here is the northern continuation of the Guamanes Shear Zone, named and described by Martino (1993). Previous authors (e.g. Bodenbender, 1905; Olsacher, 1960; Bonalumi and Gigena, 1982; Caminos and Cucchi, 1990) described the mylonitic rocks within the belt as phyllites, micaceous quartzites, “metaquartzites” or laminated schists. Bonalumi and Gigena (1984) identified it as a belt of “tectonised schists”.

In addition, bodies of phyric granite(Og) mapped as granodiorite by Caminos and Cucchi (1990), form boudinaged and dismembered bodies.

The Guamanes Shear Zone preserves a long history of repeated episodes of ductile shearing producing a range of mylonitic rocks, including ultramylonite. Although shearing may have initiated during the Early Cambrian Pampean deformation, Ar-Ar isotopic age determinations of biotite and muscovites which grew during the last event yield Devonian ages of about 360 Ma with indicated temperature conditions of about

300° (Camacho, 1997). Movement during the Devonian, clearly shown by kinematic indicators in mylonites was east over west thrusting. This movement largely overprints previous fabrics. Therefore, the Guamanes Shear Zone has been accorded a Devonian age.

There are no age data for the phyric granite bodies. However, they intruded prior to Devonian thrusting and strain was largely localised around their margins, although they were dismembered and stretched in the direction of movement. They were possibly emplaced during the Ordovician Famatinian extensional event around 470 Ma (Sims and others, 1997) prior to tourmaline-bearing pegmatite intrusion and have, thus, been given and Ordovician age.

2.3 PLUTONIC ROCKS

Paso del Carmen Granodiorite (∈gp)

The Paso del Carmen Granodiorite is a small exposure, about 5 km^2, located between Cruz de Caña and Paso del Carmen (from which it derives its name) just east of the Río Soto. It intruded rocks of the Pichanas Complex. It contains about 70% feldspar, now totally saussuritised, 15% to 20% quartz, 5% to 10% chlorite after biotite, and 5% epidote with minor clinozoisite but has some geochemical tonalitic affinities. Magnetic susceptibility is near zero and it has a very low radiometric response. There are no age data for the Paso del Carmen Granodiorite but the degree of metamorphism suggests it is pre-Famatinian and has been assigned here to the Cambrian.

Granite, unassigned (Dg)

Unassigned Devonian granite are common through out the Sierra de Cuniputo to the north of the Pampa de Olaen and part of a small out crop occurs in the north est corner of the sheet area. magnetic anomalies indicate that they are probably apophyses to much larger plutons at shallow depths. The proximity of these granite to the Capilla del Monte Granite and their similar magnetic and gamma-ray spectrometric signatures suggests they are part of a Devonian suite which may also be genetically related to pegmatite dyke swarms present in the area

Minor dyke rocks

Pegmatite

Several generations of pegmatite dykes intrude basement metamorphics and granitic rocks. The oldest are form small deformed pods, less than a metre wide. These pegmatites are probably the product of partial melting during Cambrian M1 metamorphism (Pampean).

Swarms of (?)Ordovician tourmaline pegmatite occur around Oro Grueso and Chacra Vieja within the Guamanes Shear Zone. Individual dykes may attain ten metres or more in width and were deformed during Devonian thrusting. The largest swarm was previously mapped as the Chacra Vieja Granite (e.g. Caminos and Cucchi, 1990).

North-trending pegmatite dykes in the east if the sheet area are associated with numerous unnamed, possibly Devonian, granitic intrusive bodies. Magnetic anomalies indicate that these small granite bodies may be joined at shallow depth and underlie much of the La Falda Metamorphic Complex in the vicinity.

Andesite

Numerous thin andesite dykes are found in the southern part of the Guamanes Shear Zone. They are undeformed, about a metre wide, and intrude granitoid and metamorphic rocks, post-dating Devonian mylonitic fabrics. Contacts are both concordant and discordant to the regional foliation. They consist of fine- to medium-grained hornblende phenocrysts in a microcrystalline groundmass of plagioclase and minor quartz. Accessory pyrite is visible in hand specimen. Magnetic susceptibility varies from about 20×10-5 to 700×10-5 SI despite little variation in major and trace element geochemistry. The variation may be due to magnetite destruction during Neogene faulting. There are no age data available for these rocks. Their similar composition to some of the San Luis Volcanic Group (Sims and others, 1997) and their spatial distribution northeast of the Miocene volcanics at Cerro Pocho indicate a probable Miocene age.

2.4 CAINOZOIC

2.4.1 Tertiary to Quaternary

Paleosol (Czc)

Along the Punilla Valley and in the Sierra Grande, *paleosols* (Czc), commonly with a hardpan of calcrete, form thin (a few metres thick) remnant cappings over basement rocks. They are best exposed along the gently sloping eastern flanks of the ranges where they are overlain by intercalated Tertiary to Quaternary fan deposits bordering the Punilla Fault scarp. The most extensive palaeosol development occurs on the Pampa de Olaen west of the Punilla Valley. The age of the deposits is not known. Their formation predates the last significant uplift which probably took place during the Late Pliocene-Pleistocene (Costa, 1996).

2.5 QUATERNARY

Holocene (Santa Cruz, 1978) to Recent *fluvial fan deposits of unconsolidated bouldery gravels* (Qg) interfinger downslope with finer-grained Qa alluvial deposits. The fan deposits occur along the base of the Punilla Fault scarp filling the Punilla Valley.

Holocene (Santa Cruz, 1978) to Recent *alluvial deposits of clay, sand and gravel* (Qa) occur along active river courses and adjacent terraces. The unit includes the Level III Quaternary unit of Massabie (1982) in the Capilla del Monte area north of the sheet area.

3. TECTONICS

Three major deformation/metamorphic and magmatic events have affected basement rocks: the Early Cambrian Pampean Cycle, the Early Ordovician Famatinian Cycle and the Devonian Achalian Cycle. Faulting and block-tilting occurred during the Mesozoic and later Cainozoic Andean Cycle.

3.1 PAMPEAN CYCLE: EARLY CAMBRIAN DEFORMATION AND METAMORPHISM

No original sedimentary structures, such as bedding, are unequivocally recognised in the metamorphic rocks. Regionally, the oldest preserved structure is a medium-grade metamorphic differentiated foliation which is well-preserved in pelitic gneiss of the La Falda Metamorphic Complex. This foliation (S1), is a penetrative gneissic foliation in pelitic gneiss, defined by leucosome lenses and bands and foliated muscovite-biotite-rich bands. In amphibolite and calc-silicate rocks the foliation forms strongly differentiated mineralogical bands with aligned hornblende. Throughout most of the region the S1 foliation forms the dominant trends on aerial photographs and satellite imagery.

Quartzite units in the La Falda Metamorphic Complex preserve an earlier differentiated cleavage of spaced biotite-rich folia which are truncated by leucosome veinlets and the differentiated S1 gneissic foliation. This cleavage may either represent an earlier surface, obliterated by the S1 foliation during peak metamorphic conditions, or it may have formed early during progressive deformation and S1 development.

Sillimanite-garnet assemblages in pelitic gneiss indicate M1 metamorphism was at least upper amphibolite facies and abundant muscovite-pegmatites and leucosome (forming subconcordant lenses with S1), suggest limited partial melting took place. Estimates of peak metamorphic conditions for the Sierra Chica are mostly about 6 Kb, and 700°C to 800°C (see Table 3.1). Uranium-lead dating of zircon rims and monazite grains which grew during the peak metamorphic event (M1) in both the Pichanas and Cruz del Eje Metamorphic Complexes, give an age of about 530 Ma, interpreted here as the age of the M1/D1 event of the Pampean Cycle (Camacho and Ireland, 1997).

3.2 FAMATINIAN CYCLE: ORDOVICIAN DEFORMATION AND METAMORPHISM

Widespread isoclinal folding and thrusting, at lower amphibolite/upper greenschist facies conditions, throughout the region is attributed to the Early Ordovician Famatinian Cycle.

In areas of penetrative S2 development all planar D1 fabric elements are rotated into parallelism with the S2 foliation with a pronounced mineral lineation (L2) of biotite, muscovite and quartz, which plunges shallowly to the east (~ 100°). This lineation is perpendicular to long axes of boudinaged tonalitic layers, indicating a broadly coaxial deformation. Lower amphibolite/upper greenschist facies metamorphism (M2) is indicated.

Table 3.1. M1 Metamorphism - estimated peak conditions in the southern Sierras Pampeanas

Location	Temperature (°C)	Pressure (Kb)	Reference
Sierras de Córdoba	700 - 750	6.1 - 6.4	Toselli & others, 1992
Sierra Chica	500 - 700	4 - 6	Pérez & others, 1996
Sierra del Cuniputo-Totoralejo	700 - 800	6 - 8	Murra & Baldo, 1996
Sierras Comechingones	700 - 750	6.1 - 6.4	Cordillo, 1984
Sierra Chica de Córdoba	820	5.7	Baldo & Casquet, 1996
Sierras Comechingones	760-800	8.5-9.5	Cerredo, 1996
San Carlos	650-700	4.5-5	Demange & others, 1993
Sierras Comechingones/ Chicas	800	8	Martino & others, 1994
Guamanes Belt	700	6	Martino & Simpson, 1993

The age of this deformation is poorly constrained in the Sierra Septentrionales de Córdoba. K-Ar and Rb-Sr dating of muscovite from a pegmatite which was emplaced syn D2 yields a minimum age of about 428 Ma (Camacho,1997). The deformation (D2) is interpreted here as part of the Early Ordovician Famatinian Cycle which is dated in the Sierras de San Luis at 490 Ma (Camacho, 1997)

Sims and others (1997) have identified a *compressional* and an *extensional* phase of the Famatinian event in Sierras de San Luis. However, no evidence for a widespread extensional regime has been found in the sierras septentrionales de Córdoba. Boudinaged phyric granites in the Guamanes Shear Zone predate the final Devonian compression and may have intruded during the Famatinian extensional regime.

3.3 ACHALIAN CYCLE: DEVONIAN DEFORMATION AND METAMORPHISM

Throughout much of the region, medium-grade D1 and D2 fabric elements are locally rotated into parallelism by a shallow- to moderately- ENE-dipping penetrative D3 shear fabric associated with westerly-directed thrusting, development of mylonite in high-strain zones and retrogressive greenschist facies metamorphism (M3). To varying degrees, this deformation affects all basement rocks in the region, including Early Devonian granites. Zones of high-strain were focussed in two mylonite zones, one west of the Sierras San Marcos passing west of La Falda within the western margin of the La Falda Metamorphic Complex and parts of the Quilpo Formation, and the other, in the north trending Guamanes Shear Zone, which separates the Pichanas and Cruz del Eje Metamorphic Complexes. Within the zones, an S3 mylonitic foliation is well defined. The foliation is axial planar to tight F3 folds which become open in areas of low-strain. In these areas the S3 foliation is a crenulation cleavage and folds have wavelengths up to 1 km.

A complex system of rectilinear brittle subvertical sinistral NW- and dextral NE-trending strike-slip faults, breccia zones, fractures and kink zones (S4) affect all the basement units in the Sierras Septentrionales de Córdoba, crosscutting the S3 foliation where present. Regional faults are rarely exposed, but are prominent on aerial photographs and Landsat images. Some of the faults are also delineated on magnetic images as zones of demagnetisation.

The orientation and conjugate relationship of the WNW- and NE-trending strike-slip faults, breccia zones and fractures indicates a possible continuation of the east-west compressive regime that accompanied S3 and S4 development. This fracture system is developed throughout the Sierras Pampeanas, and in Córdoba and La Rioja Provinces where muscovite Ar-Ar ages of micas from quartz veins indicate that this stage began about 385 Ma, peaked at 370 Ma and continued until 355 Ma (Camacho, 1997). These faults zones therefore represent the final stage of the Achalian Cycle.

3.4 ANDIAN CYCLE: REVERSE FAULTING

The Sierras Chica and Grande are examples of basement tilt blocks formed by east-west compression during the Cainozoic Andean uplift (Jordan and Allmendinger, 1986). The ranges slope gently to the east and are bounded to the west by escarpments developed on moderate to steep east-dipping reverse faults such as the Punilla Fault, which extends along the full length of the Sierra Chica. Many of the faults are reactivated Palaeozoic or Mesozoic structures. Quaternary faulting effects are limited to characteristic haematitic zones of fault gouge up to 5 m wide which dip 30-55° to the east, crosscutting older and mostly steeper fault fabrics.

4. GEOLOGICAL HISTORY

The Sierras Septentrionales de Córdoba area forms part of the southern Sierras Pampeanas, comprising basement ranges of early Palaeozoic metamorphic rocks and Palaeozoic granitoids, separated by intermontane Mesozoic and Cainozoic sediments.

The basement rocks form a series of north-trending lithological and structural domains separated by major mid-crustal shear zones. These domains have been variously interpreted to form (originally) part of an ensialic mobile belt (e.g. Dalla Salda, 1987) or as terranes which either accreted or developed on a western convergent margin of the Río Plata craton (e.g. Ramos, 1988; Demange and others, 1993; Escayola and others, 1996, Kraemer and others, 1995, 1996). Recent geochronological indicate that their are two principal domains in the southern Sierras Pampeanas: an older Cambrian Pampean domain, and a younger Ordovician Famatinian domain to the west, not exposed in the map area. Both domains share a common geological history since early Ordovician times. The boundary between the domains is broadly coincident with a regional change in the gravity on western flank of the Sierras de Córdoba (Miranda and Introcaso, 1996) and is marked by the Guzman Fault in San Luis.

4.1 EARLY CAMBRIAN SEDIMENTATION

The oldest rocks in the region form a structurally thick sequence paragneisses which comprise parts of the La Falda, Cruz del Eje, and Pinchanas Metamorphic Complexes. Carbonate-rich metasediments also occur within the complexes and in the Quilpo Formation. These metasediments are interpreted as being deposited on a passive margin, developed during intracontinental rifting and break up of Laurentia from Gondwana in Eocambrian times at about 540Ma (Dalziel and others 1994) in a tectonic environment similar to that envisaged by Dalla Salda and others (1994). Lithological similarities and comparable ages indicate that the metasediments may be correlatives of the Early Cambrian (Aceñolaza and Toselli, 1981) Puncoviscana Formation in the northern Sierras Pampeanas as postulated by Willner and Miller (1986).

4.2 PAMPEAN CYCLE

Early Cambrian deformation, metamorphism, mafic and felsic intrusion

Following intrusion of rare tholeiitic mafic dykes, the sediments were deformed at mid-crustal levels by a compressive event (D1) and metamorphosed at mostly upper amphibolite facies and locally, granulite-facies to form banded gneiss and locally migmatites. Mafic dykes were converted to amphibolite and extensively boudinaged. Muscovite-pegmatites formed subconcordant lenses. Estimates of peak metamorphic conditions for the area are mostly about 6 Kb, and 700°C to 800°C. A penetrative differentiated foliation formed as the last, and possibly second or even third fabric, in a progressive westerly-directed thrusting event, which is evident in the rocks by the presence of mylonite and a ubiquitous east-plunging mineral lineation, commonly sillimanite. Uranium-lead dating of zircon rims formed during this metamorphic event (M1) in Córdoba give an age of about 530 Ma (Camacho and Ireland, 1997). In the map region this event includes both the D1 and D2 domains of Dalla Salda (1987) and has been previously termed the “Ciclo orogénico Pampeano” (Aceñolaza and Toselli, 1976) or “Ciclo Pampeano” (Dalla Salda, 1987, Toselli and others, 1992). The deformation is interpreted as the first in a series of deformation events associated with convergence on the newly created Pacific Gondwana margin formed after final amalgamation of the supercontinent (e.g. Dalzeil and others, 1994).

At the closing stages of the Pampean Cycle, an extensive phase of felsic magmatism is evident by widespread subconcordant intrusion of granodiorite. There are no radiometric dates on these intrusions, however, in the Sierra Norte, similar intrusions in a northern extension of the Ascoghinga Igneous Complex are dated at about 514 Ma.

4.3 FAMATINIAN CYCLE

Early Ordovician Deformation, metamorphism, mafic and felsic intrusion

Dalla Salda (1987) and Toselli and others (1992) ascribed this deformation to the D2 domain. Zircons which grew during this event yield an age of about 480 Ma dating the timing of peak metamorphism in the Famatinian Terrane in San Luis.

Compression was followed closely, possibly in the one continuos event, by extensional deformation (D2 in the Famatinian domain) at amphibolite- to greenschist-facies. This deformation was mostly confined to the already established ductile shear-zones and was accompanied by retrogression of higher grade metamorphic assemblages and by intrusion of numerous granitic to tonalitic bodies and tourmaline-bearing pegmatites. This phase of magmatism corresponds to the G2 granites of Rapela and others (1992). U-Pb dating of zircons from granites in both the Sierras de San Luis and the Sierras de Chepes (to the north in La Rioja) indicate crystallisation ages of about 470 Ma (Camacho and Ireland, 1997). Apart from the presence of minor amphibolite facies extensional shear bands, granitic intrusives and pegmatites veins in the Guamanes Shear Zone there is little evidence for extensional structures or magmatism associated with this event in the map region.

4.4 ACHALIAN CYCLE

Early Devonian granite intrusion and deformation

Mid Palaeozoic resumption of convergence on the western margin of Gondwanaland is evidenced by a widespread compressive deformation in the Famatinian (D2) and Pampean domains (D3), and the development of an Early Devonian magmatic arc. The deformation was dominated by orthogonal westerly-directed thrusting and the development of regionally extensive ductile shear zones with intensive greenschist facies retrogressive fabrics. Locally, outside the principal shear zones, the metamorphic rocks were open to isoclinally folded with an axial crenulation developed in places.

Dalla Salda (1987) defined this deformation as D3, placing it in the "Ciclo Famatiniano".

Peraluminous to slightly peralkaline felsic melts, generated from partial melting of MgO depleted crustal rocks (Dalla Salda and others, 1995) intruded the metamorphics discontinuously during and after shear zone development.). U-Pb zircon dating of these granites in the southern Sierras Pampeanas brackets crystallisation of the felsic magmas and shear zone formation over a 20 Ma period between 404 Ma and 384 Ma. The Achalian Cycle derives its name from the Achala Batholith, the largest of the Devonian batholiths in the southern Sierras Pampeanas, which is exposed south of the map area in the Sierra Grande. The cycle probably corresponds to the "Fase Precordilleránica" (Astini, 1996) in the precordillera west of the Sierras Pampeanas where it is related to the amalgamation of the Chilena domain.

The final stages of the Achalian Cycle were the province-wide development of a complex system of rectilinear brittle-ductile vertical NW- and NE-trending strike-slip faults and fractures. The orientation and conjugate relationship of the fractures indicates a continuation of the east-west compressive regime. Locally, the structures are associated with vein-type Au±Cu mineralisation, the result of mesothermal activity interpreted to be associated with the waning stages of magmatic arc activity as the centre of magmatic activity migrated westward (Ramos and others, 1986). Muscovite Ar-Ar ages indicate that this stage began about 385 Ma, peaked at 370 Ma and continued until 355 Ma (Camacho, 1997). Toselli and others (1996) attribute development of the fracture system to a 355 Ma old "Chánica Orogeny".

4.5 CARBONIFEROUS - PERMIAN SEDIMENTATION

Following peneplanation, and later marine transgression, fluvio-lacustrine and shallow-marine sediments of the Paganzo Group (Gonzále and Aceñolaza, 1972) were deposited during the Carboniferous and Permian. The sediments may have covered much of the crystalline basement, however, no remnant outcrops of the group are now preserved in the sheet area.

4.6 ANDEAN CYCLE

East-west compression during the Cainozoic Andean uplift resulted in Neogene inversion of the Cretaceous basins (Schmidt, 1993) and block tilting of basement rocks, forming north-south oriented ranges separated by intermontane basins. The ranges are bounded by escarpments developed on moderate to steeply-dipping reverse faults (Jordan and Allmendinger, 1986; Martino and others, 1995; Costa, 1996), many of which show repeated reactivation. Costa interpreted the last and most significant movement in the region took place during the Late Pliocene-Pleistocene with some movement continuing during the Quaternary.

SECTION 2: ECONOMIC GEOLOGY

By Roger G. Skirrow

1. INTRODUCTION

The northern 0°5’ portion of Sheet 3166-24 covered in this report contains an important segment of the Candelaria Au district including the Puigari-Monserrat deposit, and minor Cu and Fe occurrences. The region also contains numerous marble and limestone quarries near Oro Grueso.

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 and Trudu, 1997). ARGMIN is a Microsoft Access database that was initially developed jointly by AGSO and the Subsecretaría de Minería in ORACLE, based on OZMIN (Ewers and 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 and Skirrow, 1996), stable isotopes of oxygen, hydrogen and sulfur (Lyons and Skirrow, 1986), as well as $^{40}Ar/^{39}Ar$ radiometric age dating (Camacho, 1997). Geographic coordinates were measured by GPS (locational accuracy 50 m), whereas those occurrences not visited in the field were generally located on aerial photographs and their geographic coordinates digitised. The locational accuracy for photo-located occurrences is 200 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 occurrence data as well as non-metallic mineral and dimension stone occurrences are shown on the 1:100 000 scale metallogenic map accompanying this report. Output data sheets from the ARGMIN database are appended to the report. 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 Septentrionales de Córdoba (Skirrow, 1997) 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, as discussed by Skirrow (1997) and 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 CANDELARIA AU DISTRICT

The central-south portion of the Candelaria Au district is situated on Sheet 3166-18, including the Puigari-Monserrat, La Bragada, Oro Grueso and Paso de La Quinta deposits. The northern sector of the Candelaria district is situated on Sheet 3166-24. A summary of the general characteristics of the mineralisation in the Candelaria district is presented below.

Regional setting: The Candelaria district is located about 20 km southeast of Villa de Soto. The district comprises more than 25 identified small Au-quartz vein deposits and occurrences, and numerous un-named workings that were operated mainly up to the 1930s. They lie within a belt that trends north-south for about 16 km in the vicinity of the Río Candelaria and extends a further about 5 km south of the map area (Caminos and Cucchi, 1990).

Regional and district geology was discussed by Lucero Michaut and Olascher (1981), Bonalumi and Gigena (1984) and Caminos and Cucchi (1990). Economic assessments of resources have been carried out by Zolezzi and others (1988), Anonymous (1987), Torres and Miró (1986), Anonymous (1989) and Deantonio (1994). Martos and others(1994) briefly described the occurrences.

The Au mineralisation is located principally within a 4-7 km wide north-south striking Guamanes Shear Zone, a zone of sheared gneiss that contains numerous zones of mylonite and ultra-mylonite. Several deposits occur in quartz-biotite-feldspar±garnet gneiss (Cruz del Eje Metamorphic Complex) to the east of the shear zone, including some of the larger deposits in the district such as Puigari-Monserrat. Elongate Ordovician(?) granite stocks up to 1 km wide and 4 km long, and numerous associated tourmaline-bearing pegmatites, occur within the shear zone, and contain the shear fabric. Mylonite zones are characteristically chlorite-haematite altered and overprint a biotite shear fabric in the gneiss. Movement on the steeply east-dipping mylonite zones was generally east side up, and represents reactivation of the shear zone.

A swarm of undeformed porphyritic hornblende andesite dykes occurs within the Guamanes Shear Zone west of Paso de La Quinta and Oro Grueso. The dykes are inferred to be post-Devonian to Tertiary in age.

Geology of Au mineralisation, Candelaria district: Gold occurs in single and multiple quartz veins striking 330°-030° and dipping 20°-45° to the east. Vein thicknesses range up to 1m, or so, and typically show pinch-and-swell morphology. *En echelon* arrays of gash-shaped, gently sigmoidal, veins are present in places. Although the host gneisses contain well-developed foliations, intense shearing adjacent to veins is generally not present (cf. Au deposits of Sierra de las Minas, La Rioja). The high angle between quartz veins and the gneissic foliation, and the vein morphology and orientation, indicate that the veins probably formed in zones of subvertical extension within the

Guamanes Shear Zone (Fig. 1). An exception to this style of Au deposit occurs at Paso de La Quinta (see below).

Most quartz veins consist of massive, milky white, recrystallised quartz with uncommon cavities lined with subhedral quartz. Minor pyrite and trace amounts of sphalerite, galena, chalcopyrite, and arsenopyrite (Anonymous, 1989) occur in association with this subhedral quartz. The margins of some quartz veins are brecciated in brittle faults. Hematitic-goethitic fracturing of the early quartz is widespread and appears to be associated with the brecciation. Hydrothermal alteration consists of intense sericitisation of host rocks within about 1m of major veins, and of wall rock remnants within veins. Localised haematisation of wall rocks and haematitic fracturing of vein quartz may be synchronous with the regional mylonitisation with which chlorite-haematite alteration is associated.

Gold mineralisation occurs in two principal textural styles with sulfides in the primary ore zones and as coarser free Au in near-surface secondary ore zones (<40m depth; Anonymous, 1989). Grain sizes of up to 200 microns were reported by Anonymous (1989). Gold grades appear to be highly variable. For example at Puigari-Monserrat, 0.3-1.8 m wide channel samples across veins indicated that grades of 0.2-2 g/t Au are common but sporadic samples contained 15-70 g/t Au (Zolezzi and others, 1988).

Hydrothermal altered zones associated with Au mineralisation exhibit a pronounced depletion in magnetic susceptibility compared with gneissic host units. This relatively local, deposit-scale, signature is clearly related to haematisation which occurred late in the paragenetic sequence. The Guamanes Shear Zone that hosts most of the Au deposits of the Candelaria district displays a low aeromagnetic response, particularly in its eastern parts, with higher response along the eastern contact (Fig. 1). Some of the Au deposits are located close to NW and NE trending magnetic lineaments where they intersect the eastern margin of the N-S trending Guamanes Shear Zone.

At the Paso de La Quinta prospect, a contrasting style of Au mineralisation is present. Cropping out as a prominent N-S trending ridge, the 3-7m wide and >1600m strike length siliceous zone consists of crystalline quartz and chalcedony vein networks, silicified mylonite and breccia. The siliceous zone appears to dip subvertically, in contrast to the shallow dips of other vein Au deposits of the district. Vein textures include fine-grained cockade and crustiform quartz infilling cavities in silicified-sericitised breccia, and fine-grained drusy quartz vein stockworks. Uncommon fine-grained specularite also infills cavities, and abundant goethite is associated with coarser quartz. Pale greenish, botryoidal, chalcedonic quartz is one of the latest minerals in the paragenetic sequence. In contrast to other deposits in the Candelaria district, there is no evidence of extensive recrystallisation of silica minerals. Alteration of fine-grained mylonite host rocks consists of intense chlorite-sericite-pyrite. Reported maximum grades are 160 g/t Au and 460 g/t Ag, and a resource of 1 000 000 tonnes of ore was estimated by Deantonio (1994), although no average grade was quoted.

Genesis: Hydrothermal sericite from the Puigari-Monserrat and La Bragada deposits give $^{40}Ar/^{39}Ar$ ages of about 376-378 Ma (Camacho, 1997). This age represents initial white mica alteration, with subsequent cooling over the next 12-20 Ma (Skirrow, 1997). Alteration and, by implication, Au mineralisation in the Candelaria district either postdated Achalian magmatism by at least around 7 Ma (Camacho, 1997), or temporally overlapped emplacement of Achalian granite. Stable isotopic studies suggest that the hydrothermal ore fluids could have evolved from meteoric waters reacting with metasedimentary rocks, although small magmatic or metamorphic water input to the ore fluids cannot be excluded (Skirrow, 1997)

The quartz-Au veins formed initially in a brittle-ductile deformational regime, possibly synchronous with reverse movement on mylonite structures within the Guamanes Shear Zone. Later fracturing, faulting and brecciation of the vein systems and associated hematite±chlorite alteration suggest a change in pressure, temperature and/or strain rate conditions. Some remobilisation of Au may have occurred at this time.

The Au deposits of the Candelaria district are interpreted here to be members of the broad class of structurally-controlled mesothermal lode Au deposits found in regionally metamorphosed orogenic terranes. Martos and others (1994) grouped the Candelaria Au deposits with the ‘low-sulfide Au-quartz veins’ model of Cox and Singer (1986).

At the Paso de La Quinta prospect, the geological, textural, mineralogical and stable isotopic characteristics are notably different to those of other deposits of the Candelaria district. The features are consistent with vein formation in the uppermost few kilometres of the crust, sometime between the early Devonian and the Tertiary (Skirrow, 1997). It is interesting to note that undeformed fine-grained andesite dykes nearby Paso de La Quinta have porphyritic textures suggestive of emplacement in a subvolcanic environment.

2.2 CU OCCURRENCES

One occurrences of Cu mineralisation is known in the northern portion of Sheet 3166-24 (Ricci, 1974).

2.3 FE MINERALISATION

One occurrences of Fe mineralisation is known in the northern portion of Sheet 3166-24 (Ricci, 1974).

3. NON-METALLIC MINERALS

3.1 LIMESTONE, MARBLE

Several deposits of limestone, dolomite and marble are present in the northern portion of Sheet 3166-24, in the Oro Grueso area. The carbonate bodies form part of a sequence of intensely deformed early Cambrian metacarbonate-amphibolite rocks within medium to high grade gneiss of the Cruz del Eje Metamorphic Complex.

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