High resolution conodont-graptolite biostratigraphy in the Middle-Upper Ordovician of the Sierra de La Invernada Formation (Central Precordillera, Argentina)

G. ORTEGA¹ | G.L. ALBANESI² | A.L. BANCHIG³ and G.L. PERALTA³

¹ CONICET - Museo de Paleontología, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba
CC 1598, 5000 Córdoba, Argentina. Ortega E-mail: gcortega@arnet.com.ar

² IANIGLA-CRICYT-CONICET, Departamento de Geología y Paleontología
Av. Adrián Ruiz Leal s/n, Parque General San Martín, 5500 Mendoza, Argentina

³ Departamento de Geología, Universidad Nacional de San Juan
Ignacio de La Rosa y Meglioli s/n, 5400 Rivadavia, San Juan, Argentina

ABSTRACT

Outcrops on the western slope of the La Invernada Range, San Juan Precordillera (W Argentina), were surveyed for lithofacial analysis and graptolite-conodont high resolution biostratigraphy. The study profile for the upper Sierra de La Invernada Formation is approximately 500 m thick and is located in the northern part of the La Invernada Range. Successive shallowing-deepening sedimentary cycles crop out throughout the upper part of the formation. The dominantly lower turbiditic sandy deposits alternate with shaly pelagic sedimentation, and occasional coarser intervals that record gravitational flows. Hummocky structures occur in the uppermost part of the formation, indicating sedimentation under storm weather conditions. Rich graptolite faunas representing six upper Middle to lower Upper Ordovician biozones have been recorded from this section: Pterograptus elegans (tentative assignment), Hustedograptus teretiusculus, Nemagraptus gracilis, Climacograptus bicornis, Diplacanthograptus caudatus, and Climacograptus tubuliferus biozones. This graptolite biostratigraphy is complemented by the conodont records from successive productive levels, which yielded conodonts that represent the Pygodus serra, P. anserinus, Amorphognathus tvaerensis, and A. superbus biozones. The recorded conodont-graptolite assemblages allow for a correlation with the upper Darriwilian, Sandbian and lower Katian global stages, and provide preliminary biofacies records for the upper Sierra de La Invernada Formation.


INTRODUCTION

A new stratigraphic profile through the upper part of the Sierra de La Invernada Formation (Fm) (Precordillera Argentina), which is exposed ca. 3 km to the south of the La Puerta Creek in the northern La Invernada Range and covers the Mid-Late Ordovician time span, is investigated in the present contribution (Fig. 1). Graptolites are the...
most frequent fossils in this section that also yielded a variety of conodonts, chitinophosphatic brachiopods, chitinozoans, and scarce crinoid remains. This rich fossil record has enabled the authors to carry out a detailed biostratigraphic study.

This paper deals with integrating the previously available information on these Ordovician fossil assemblages (Ortega et al., 2004, 2006, 2007; Banchig et al., 2007) together with new additional stratigraphic and paleontological data that resulted from the study of the above mentioned section. As a result, an improved, high resolution conodont-graptolite biostratigraphic scheme is provided for the Mid-Late Ordovician of the upper part of the Sierra de La Invernada Fm.

PREVIOUS BIOSTRATIGRAPHIC WORK

This unit was subject of several studies since the pioneering works by Furque (1983) and Furque and Caballé (1985, 1988). Furque (1983) originally defined the La Invernada Fm as a siliciclastic sedimentary succession, with basaltic intercalations, and interpreted it as the flysch stage in a geosyncline development. Afterwards, the unit was redefined as the Sierra de La Invernada Fm by Furque and Caballé (1985).

The first studies on graptolites from the La Invernada Range were by Furque et al. (1990), who recorded the following taxa: Cryptograptus cf. C. tricornis (CARRUTHERS), Dicranograptus ramosus (HALL), Climacograptus invernadensis FURQUE, CUERDA, CABALLÉ and ALFARO, Climacograptus aff. C. brevis ELLES and WOOD, Pseudoclimacograptus scharenbergi (LAPWORTH), Amplexograptus aff. A. arctus (ELLES and WOOD), Amplexograptus minutus CUERDA, CINGOLANI, SCHAUER and VARELA, Orthograptus aff. O. calcarius var. vulgaris LAPWORTH, Hallograptus aff. H. mucronatus (HALL) and ?Neurograptus sp., among others. These authors suggested a Llanvirn-Caradoc age for the Sierra de La Invernada Fm in accordance with reported fauna. Later, Caballé et al. (1992) described a graptolite association recovered from the Vallecito Creek, in the southern sector of the La Invernada Range, and referred it to the Nemagraptus gracilis Zone. That fossil assemblage included Glossograptus hincksii (HOPKINSON), Cryptograptus tricornis (CARRUTHERS), N. gracilis (HALL), Hustedograptus cf. H. teretiusculus (HISINGER), “Climacograptus” cf. “C”. antiquus LAPWORTH, Retiograptus aff. R. geinitzianus HALL, and Dicellograptus spp. as the most common forms.

Banchig (1995, 1996) analized the lithofacial characteristics of Ordovician rocks in the range, and reconsidered the concept of the Vallecito Group, which includes the Corralito, Sierra de La Invernada and Cántaro de Oro Fms (Furque and Caballé, 1988; Furque et al., 1990). The author considered the Cántaro de Oro Fm as a lateral variation of the Sierra de La Invernada Fm and new aspects about sedimentation and coeval volcanism that demonstrate important geotectonic features of the Eopaleozoic continental margin were later published by Banchig et al. (2004, 2007).

Brussa (1997a, 1997b, 1997c) described a Darriwilian graptolite fauna from newly measured outcrops of the Sierra de La Invernada Fm in the section of the provincial road n° 436 (Fig. 1, B-B”). The lower association of this fauna consists of Undulograptus austrodentatus (HARRIS and KEBLE), U. sinicus (MU and LEE), Isograptus horridus HARRIS, Isograptus caduceus (SALTER), Xiphograptus svalbardensis (ARCHER and FORTEY), Tetragraptus spp., Pseudotrigonograptus ensiformis (HALL), Cryptograptus antennarius (HALL) and P. tentaculatus (HALL), among most conspicuous forms. The higher association includes Holmograptus spinosus, C. antennarius, and P. tentaculatus (Da2-Da3 in age) (Brussa, 1999).
Outcrops of the Cántaro de Oro Fm (= Sierra de La Invernada Fm in the present paper) placed ca. 19 km to the south of road 436 were described by Caballé et al. (1997) and Cuerda et al. (1999). The authors recorded a graptolite assemblage referred to the Climacograptus bicornis Zone, which is composed of Dicranograptus ramosus cf. D. r. spinifer ELLES and WOOD, D. nicholsoni nicholsoni HOPKINSON, D. kirki RUEDEMANN, O. cf. O. spinigerus (ELLES and WOOD), Cryptograptus tricornis (CARRUTHERS), Climacograptus bicornis bicornis (HALL), Leptograptus sp., Neurograptus cf. N. margaritatus (LAP-WORTH), Orthoretiolites cf. O. hami Wittington, and O. cf. O. tigris BRUSSA.

Astini (2003) and Basilici et al. (2005) correlated Sierra de La Invernada, Yerba Loca, and Portezuelo del Tontal Fms. The first paper provides an updated correlation chart for the formations from the Argentine Precordillera.

The occurrence of late Darriwilian and younger assemblages of the Nemagraptus gracilis (early Sandbian), Climacograptus bicornis (late Sandbian), Diplacanthograptus caudatus and Climacograptus tubiformis zones (early Katian) from the Sierra de La Invernada Fm were noted by Ortega et al. (2004, 2006, 2007) and Banchig et al. (2007) in a section located 300 m to the north of the profile studied here (the reader should take into account the graphic scale of text-fig. 2 in the paper by Ortega et al. (2007) is mistaken: it should say 30 m instead of 10 m in the scale bar).

GEOLOGICAL SETTING

The La Invernada Range is the westernmost morphostructural unit of the Central Precordillera (San Juan Province, Argentina). It stretches for about 60 km with north-south orientation, and is bounded by two longitudinal valleys, the Bolsón de Gualilán – La Cantera River to the east and the La Invernada creek – Seco de La Invernada River to the west. The western boundary is a defined lineament that obliquely cuts the northern outcrops. This structure extends through the whole range. The eastern boundary, where some greenish Siluro-Devonian exposures occasionally appear, is more irregular due to the development of coalescent alluvial fans.

The La Invernada Range includes the outcrops of Ordovician siliciclastic rocks of the Sierra de La Invernada Fm (Middle-Upper Ordovician, i.e. Darriwilian-Katian) that crop out in its western flank, and the rocks of the Corralito Fm (Siluro-Devonian) in the eastern exposures. The Sierra de La Invernada Fm is a heterolithic succession with scarce calcarenites and interbedded conglomerates. This unit is about 2,000 m thick on average, although maximum and minimum thicknesses of 4,000 m and 1,000 m, respectively, are measured due to partial wedging of the succession to the north and frequent fault repetition to the south. In the eastern range flank, large Ordovician carbonate blocks resedimented in a greenish sandstone matrix of the Siluro-Devonian Corralito Fm crop out (Furque and Caballé, 1988; Furque et al., 1990; Banchig, 1995).

Sedimentological facies

The Sierra de La Invernada Fm includes five main depositional lithofacies (conglomerates, sandstones, carbonates, shales, and calcareous breccias) that make up coarsening and thinning upwards submarine fan sequences developed over gentle paleoreliefs and ranging from platform margin to slope (Banchig et al., 2004).

The selected profile for this study is located ca. 18 km south of provincial road n° 436 between Rodeo and Talacasto localities, San Juan Province. This section includes approximately 500 m of the upper Sierra de La Invernada Fm, the base of which is a conspicuous basalt body, 50 to 70 m thick on average, which lies parallel to the stratification strike and extends regionally (Fig. 1). Although this new selected profile is located ca. 300 m to the south of the section described by Banchig et al. (2007) and Ortega et al. (2007), it is possible to correlate most of the samples of these previous contributions with the new graptolite and conodont records from the new profile. It is important to emphasize that this correlation is feasible, despite of the significant lateral facies variations between neighbouring sections within the Sierra de La Invernada Fm, resulting from the occurrence of interbedding conglomerate lenses.

The lower part of the sedimentary succession overlies a sharp contact between the basalt body and immature coarse grained graded wackes (Fig. 2). They consist of thick bedded (0.5-1 m) accumulations with sedimentary structures that characterize the Ta-b, Ta-c Bouma sets and correspond to turbidite deposits. Amalgamation surfaces on thick beds are widespread, and sandy intervals no more than 10 cm thick, which could record dense grain flows associated to submarine extrusions, appear occasionally.

A sharp sandstone-basalt contact that seldom shows pillow structures with vesicles on the basaltic surface was observed. Moreover, there appear spherical and subspherical basaltic bodies, partly amalgamated with development of peripheral contact aureoles (probable fragments of pillow lavas that were detached during subaqueous extrusions), which are incorporated in the sandy pack-
ages. This feature is indicative of a contemporaneous process of intrusion-extrusion of lavas with turbidite sedimentation.

The sedimentary succession exhibits prograding and retrograding cycles. The alternate sequences result in gradual and sustained changes for a thickness around 154 m. Massive sandy beds at the base allow for identification of Ta-c and Tb-c type turbidite sequences, and levels of fine to very fine sandy beds, which typifies the Tb-e, Td-e turbidites.

Overlying these sedimentary cycles (between LIC1 and LIC4, Fig. 2), ca. 105 m of fine-grained and monotonous sediments that show a gradual upward change from light green to black colour (reflecting a gradual increase in organic matter and sulphide content) were deposited. Several horizons that contain graptolites are located in this part of the succession.

The upper part of the Sierra de La Invernada Fm, between LIC4 and LIC11 (Fig. 2), consists of a sandy and coarser succession, whose exposed thickness (ca. 230 m) is controlled by the presence of a reverse fault of regional magnitude that cut obliquely the western border of the outcrops. The conglomerate beds present channelized erosive bottoms and planar tops with frequent erosion and amalgamation. These intervals are normally graded and the internal arrangement is grain and matrix supported. Laminate carbonate intervals frequently appear at the top of the channelized beds. This part presents a general prograding arrangement, which is frequently associated with coarse sandy bodies and bulbiclastic lenses of erosive bases and normal or transitional top, with high flow regime planar laminations, vertical aggradation, and lateral wedging. In this part of the column, medium-coarse grain sandy intervals are frequent with dome laminations and tangent wedging that define hummocky structures, and truncated waving lamination. The thinner sandy intervals with fine and very fine grain often present wave structures and coeval plastic sedimentary deformation to the top. Interbedded shales alternate with massive sandy levels or tabular levels in relation to the sharp contacts.

Present study and earlier contributions by Banchig et al. (2007) and Ortega et al. (2007) regarding northern sections of the La Invernada Range, demonstrate that the basal part of the Sierra de La Invernada Fm is placed to the east, in tectonic contact with the Corralito Fm. This real polarity of the formation was misunderstood in previous works (e.g., Caballé et al., 1997; Cuerda et al., 1999). Actually, the polarity is inverted in the southern sections of the La Invernada Range; for example, in the Vallecito creek, where the top levels of the Sierra de La Invernada Fm contact tectonically with the Corralito Fm.

The homotaxial faunal succession in the described profile indicates that the correlative early Darriwilian strata described by Brussa (1997a, 1997b, 1997c) in the section of road 436 (see Fig. 1) are dislocated from the main structure of the La Invernada Range.

The inversions of bed polarity and dislocations in certain parts of the Sierra de La Invernada Fm reveal a complex structure along the La Invernada Range, as significant effects of the recent Andean Orogeny.

**Paleoenvironments**

In a recent paper (Basilici et al., 2005), the Sierra de La Invernada Fm together with the Portezuelo del Tontal and the Yerba Loca Fms are considered as corresponding to the same depositional system, which is dominated by storm activity. The authors noted the prevalence of the sandy over the shaly fraction for the Portezuelo del Tontal and Yerba Loca Fms, which are characterized by the combination of gravitational deposits and turbiditic flows of very low density that would reflect deeper and anoxic conditions. In the Sierra de La Invernada Fm, however, the coarser and more bioturbated intervals record sedimentation under shallower and more oxygenated conditions. The presence of hummocky structures in the upper parts of the referred units indicates that the sedimentation occurred within the interval of storm weather waves, and gravitational flows would have developed at the same time of storm action.

We divide the upper Sierra de La Invernada Fm into two parts based on the sedimentary architecture and the nature of involved deposits. In the lower part, the identification of thinning upwards strata is interpreted as corresponding to the development of a sedimentary prism of turbiditic character. The stacking of proximal to distal turbidites would correspond to the development of the depositional space, a stage of eustatic rise that evolves towards conditions of pelagic deposition under anoxic environments as indicated by black shales of high organic content. This stratigraphic interval spans the upper Darriwilian - lower Sandbian (P. elegans, H. teretiusculus, and N. gracilis zones).

The second interval is characterized by a similar thinning upwards arrangement. The irregular lithofacies (e.g., carbonate/conglomerate alternations), the lensoidal geometry of the sandy-shaly deposits, as well as the presence of sedimentary structures of oscillatory flows (HCS), reveal conditions of deposition under shallow waters within storm wave base. This interval evidences the sudden appearance of paleoenvironmental conditions that
Ordovician graptolites and conodonts from Central Precordillera, Argentina

G. ORTEGA et al.


DOI: 10.1344/105.000000249

Stratigraphic column of the study section and ranges of conodont and graptolite species (white dots indicate reworked conodont species). Abbreviations: Se: Global Ordovician Series, St: Global Ordovician Stages, GZ: Graptolite Zones, CZ: Conodont Zones.

FIGURE 2

Stratigraphic column of the study section and ranges of conodont and graptolite species (white dots indicate reworked conodont species). Abbreviations: Se: Global Ordovician Series, St: Global Ordovician Stages, GZ: Graptolite Zones, CZ: Conodont Zones.

LEGEND
- Limestone
- Calcarenite
- Shale
- Fine sandstone
- Middle sandstone
- Coarse sandstone
- Conglomerate
- Basalt
- Pillow lavas
- LG6 Graptolite sample
- LIC7 Conodont sample
favour the development of a low sea-level sedimentary sequence. It is mainly associated with tractive deposits within regimes of high energy and progradation of a depositional system, and the development of channels and sandy bars in a siliciclastic platform. This interval represents a shallowing event that gradually evolves again to deepening conditions. The changing depositional conditions are indicated by intervals of black shales punctuated by sandy tabular levels that correspond to more defined tractive intervals and are followed, in turn, by background suspension fallout sedimentation. This upper interval is constrained to the upper Sandbian – lower Katian stages.

**BIOSTRATIGRAPHY AND CORRELATION**

The fossil collections used in this study are housed in the Museo de Paleontología, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, under repository codes CORD-PZ (graptolites) and CORD-MP (conodonts).

**Graptolites**

The study profile contains at least six different graptolite assemblages localized in the upper part of the Sierra de La Invernada Fm, above the upper basic dike: the “Pterograptus elegans”, Hustedograptus teretiusculus, Nemagraptus gracilis, Climacograptus bicornis, Diplacanthograptus caudatus, and Climacograptus tubuliferus zones. Recorded species ranges through these units are depicted in Fig. 2, spanning the upper Darriwilian to the lower Katian stages, and the correlation chart for the mentioned zones is presented in Fig. 3. Characteristic species of the faunas represented in the study section are illustrated in Figs. 4 and 5. Unfortunately, the preservation of rhabdosome collected from sandstones is frequently poor, making their study difficult. The poorly preserved material is most prevalent in the “P. elegans” and C. bicornis zones.

**Ordovician graptolites and conodonts from Central Precordillera, Argentina**

G. ORTEGA et al.


DOI: 10.1344/105.000000249

FIGURE 3

Correlation chart of graptolite and conodont zones. Modified from Albanesi and Ortega (2002), Webby et al. (2004), and updated after the ISOS-ICS-IUGS web site: www.ordovician.cn

FIGURE 4

Late Darriwilian to early Katian Darriwilian graptolite faunas from the Sierra de La Invernada Formation at study section. Graptolite samples (LIG) are indicated in Figure 2. 1) Corynoides ultimus RUEDEMANN, LIG17, CORD-PZ 24696. 2) Corynoides sp. 1, LIG20, CORD-PZ 24728. 3) Retegograptus cf. R. speciosus HARRIS, LIG2, CORD-PZ 24670. 4) Thamnograptus sp., LIG1, CORD-PZ 24690-B. 5) Dicranograptus cf. D. intortus LAPWORTH, LIG4, CORD-PZ 24975. 6) Nemagraptus cf. N. subtilis HADDING, LIG4, CORD-PZ 24967, b, CORD-PZ 24957, c, CORD-PZ 25041. 7) Pseudazygograptus incurvus (Ekström), LIG17, CORD-PZ 24654-A. 8) Haddingograptus cf. H. oliveri (BOUˇCEK), LIG2, CORD-PZ 24669. 10) Nemagraptus gracilis (HALL), LIG8, CORD-PZ 25042. 11) Orthoretiolites hami WHITTINGTON, LIG4, CORD-PZ 24811. 12) Dicellograptus salopiensis ELLES and WOOD, LIG17, CORD-PZ 24739. 13) Archiclimacograptus modestus (RUEDEMANN), LIG15, CORD-PZ 24728. 14) Diplacanthograptus spiniferus (RUEDEMANN), LIG15, CORD-PZ 25260.
Ordovician graptolites and conodonts from Central Precordillera, Argentina

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29

1 mm
Compared with the rich faunas of the *D. caudatus* Zone, the monotonous overlying *C. tubuliferus* fauna, which is almost exclusively composed of the eponymous taxon, reveals a strong biodiversity loss in the graptolite assemblages of the Sierra de La Invernada Fm.

**“Pterograptus elegans” Zone**

A graptolite assemblage composed by biserial rhabdosomes and scarce branches, probably referable to *Acrograptus*, were collected in greenish gray fine sandstones, ca. 27 m above the basalt body (LIG1, LIG2). It contains poorly preserved early astogenetic stages, juveniles and fragmentary mature rhabdosomes, usually flattened with distinct orientations. It is composed of *Archiclimacograptus* cf. *A. riddellensis* (HARRIS), *Archiclimacograptus* cf. *A. caelatus* (LAPWORTH), *Haddingograptus* cf. *H. oliveri* (BOUČEK), *Haddingograptus* cf. *H. euryxoma* (JAAJUNSSON), *Hustedograptus* sp., and *Reteograptus* cf. *R. speciosus* HARRIS. The presence of *Archiclimacograptus* and *Haddingograptus* as the dominant elements of the fauna suggests a tentative correlation with the *Pterograptus elegans* Zone of the Baltic area (Maletz, 1997). Considering the absence of the guide taxon for the biozone we refer this interval as the “*Pterograptus elegans* Zone”, mid-late Darriwilian in age.

Similar graptolite faunas were described for the lower member of the Los Azules Fm at Viejo Hill of Huaco, San Juan Precordillera (Ortega, 1987; Ottone et al., 1999; Brussa et al., 2003b) and in the Estancia San Isidro Fm (ex lower member of the Empozada Fm), Mendoza Precordillera (Ortega et al., 2007). The former is a rich graptolite fauna composed of diplograptids, dichograptids, glossograptids, and sigmagraptines. The latter, present at Estancia San Isidro Fm, is a low diversity, poorly preserved graptolite fauna distinguished principally by biserial rhabdosomes, with abundant *Archiclimacograptus* and *Haddingograptus* specimens.

**Hustedograptus teretiusculus Zone**

Above the greenish gray sandstones a facies change marked by the appearance of gray siltstones is observed. A graptolite fauna dominated by biserial graptolites is present in samples LIG3 and LIG4. It is composed of *Thannograptus* sp., *Cryptograptus schaeferi* LAPWORTH, *Glossograptus* cf. *G. hincksi* (HOPKINSON), *Nemagraptus* cf. *N. subsiliis* HADING, *Dicellograptus* spp., *Hustedograptus teretiusculus* (HISINGER), *H. vikarbyiensis* (JAAJUNSSON), *Hustedograptus* sp., *Archiclimacograptus* cf. *A. riddellensis* (HARRIS), A. cf. *A. angulatus* (BULMAN), *Archiclimacograptus* A. cf. *A. caelatus* (LAPWORTH), *Proclimacograptus* angustatus? (EKSTRÖM), *Retegraptus* geinitzianus HALL, *R. cf. R. speciosus* HARRIS, and *Acrograptus?* sp. *Pseudazygograptus incurvus* (EKSTRÖM), a form comparatively scarce at these levels, is recorded for the first time in the Argentine Precordillera (Fig. 4.7).

Nemagraptid records include growth stages, juvenile rhabdosomes and several stipe fragments without cladiol branches, suggesting the presence of a form comparable to *N. subsiliis* HADDING. At least three different forms of *Dicellograptus* were collected in this interval, resembling *Dicellograptus* tortuosus LAPWORTH, *D. salopiensis* ELLES and *D. alabamensis* RUEDEMANN. Conodont elements of *Pygodus anserinus* (LAMONT and LINDSTRÖM) are present in the same strata ranging to the next *N. gracilis* assemblage.

*N. subsiliis* precedes the appearance of *N. gracilis* (see Nőlvak and Goldman, 2007) in the Baltic area, ranging to the lowest Sandbian. Based on the presence of forms similar to *N. subsiliis* and the absence of the guide taxon *N. gracilis*, the assemblage from samples LIG3 and LIG4 of the Sierra de La Invernada Fm seems to be older than the *N. gracilis* Zone. Accordingly, these samples are referred to the upper *H. teretiusculus* Zone, which is late Darriwilian in age. Similar assemblages do not seem to be present in other parts of the Precordillera. In some sections of the cerro Viejo area, nemagraptids of the *N. subsiliis* type were recorded together with *H. teretiusculus* and the conodont *Pygodus serra* in a slightly older assemblage of the *H. teretiusculus* Zone (Ortega, 1987, 1995). Both faunas represent the only records of the entrance of nemagraptids and dicellograptids in the Argentine Precordillera.

**Nemagraptus gracilis Zone**

True specimens of *N. gracilis* (HALL) were found in the sample LIG8, ca. 223 m above the basalt body. The specimens are preserved in dark gray shales, which comprise the dominant lithology in the next 40 m of the succession. Samples LIG8-LIG13 yielded *Pseudazygograptus incurvus*, *Cryptograptus schaeferi*, *Glossograptus* sp., *Dicellograptus* cf. *D. alabamensis* RUEDEMANN, *Dicellograptus* cf. *D. sextans* (HALL), *Dicnograptus* cf. *D. furcatus* (HALL), *Nemagraptus gracilis* (HALL), *Nemagraptus* sp., *Dicladotheca* sp., *N. angulatus* (HARRIS), *Archiclimacograptus* cf. *A. caelatus* (LAPWORTH), *Archiclimacograptus* angustatus? (EKSTRÖM), *Reteograptus* geinitzianus HALL, *R. cf. R. speciosus* HARRIS, and *Acrograptus?* sp. *Pseudazygograptus incurvus* (EKSTRÖM), a form comparatively scarce at these levels, is recorded for the first time in the Argentine Precordillera (Fig. 4.7).

The first appearance of *N. gracilis*, which is considered synchronous worldwide, marks the base of the global Sandbian Stage of the Upper Ordovician Global Series (Finney and Bergström, 1986; Bergström et al., 2000,
The presence of the guide taxon indicates a correlation with the *N. gracilis* Zone of the Baltic region, Great Britain, North America, Australia, and China.

In the Argentine Precordillera, the *N. gracilis* Zone is documented from diverse lithologies and paleoenvironments in several localities of the San Juan Precordillera. It has been identified at the Portezuelo del Tontal Fm, El Tontal Range (Cuerda et al., 1986; Peralta et al., 2003), Las Aguaditas Fm (Los Blanquis and Las Charcitas sections) (Brussa, 1996), Los Azules Fm (La Chilca Hill) (Blasco and Ramos, 1976), and Sierra de La Invernada Fm (Peralta and Finney, 2002), Central Precordillera. It was also reported from the Yerba Loca Fm, Jáchal River section (Blasco and Ramos, 1976) in the Western Precordillera, and in the La Cantera Fm, Villicum Range, Eastern Precordillera (Peralta, 1990). According to Peralta and Finney (2002) the aforementioned graptolite assemblages comprise different taxonomic compositions, which suggest slightly different ages, and they consider that the fauna present in the La Invernada Range is younger. However, since our graptolite collections are associated with the conodont *P. anserinus*, we think that the basal part of the *N. gracilis* Zone is present in this locality.

**Climacograptus bicornis Zone**

Graptolites of this zone are recorded from level LIG14, where the succession becomes dominantly sandy, ranging several meters up to LIG15 just below the conglomerate. Rhabdosomes are frequently orientated, partially piritized or limonitized, and poorly preserved, making their identification difficult. In all cases the fossils were collected in fine to coarse sandstones. In addition to graptolites, a few crinoid remains were found.

The graptolite assemblage contains *Glossograptus* sp., remains of *Dicellograptus* sp., *Archiclimacograptus modestus* (Rueckemann), *Climacograptus bicornis* (Hall), *Orthograptus ex. gr. calcaratus* (Lapworth), and scarce stipes of probable dichograptids or sigmagnostines. Although this low diversity graptolite fauna is poorly preserved, the presence of *C. bicornis* allows identifying the homonymous zone, late Sandbian in age. A fauna composed by *O. calcaratus*, *C. bicornis*, dicellograptids and dicerographtids, characterizes the interval overlying the *N. gracilis* Zone in many sections of the world (Finney and Bergström, 1986) and precedes the entrance of the *Diplacanthograptus caudatus* fauna (Goldman, 2003; Goldman et al., 2007). The assemblage present in the La Invernada Range can be correlated with the *O. calcaratus* Zone of Australasia (VandenBerg and Cooper, 1992), *C. bicornis* Zone of North America (e.g., Berry, 1960; Finney, 1986), *C. bicornis* Subzone (C. wilsoni Zone) of China (Webby et al., 2004), and *D. foliaceus* (= *D. multdens*) Zone of Britain and Scania (Williams, 1994; Webby et al., 2004).

Graptolites of the *C. bicornis* Zone are distributed throughout the Central Precordillera, an interval usually assigned to the *N. gracilis* Zone in the past (see Ortega, 1987; Ortega and Brussa, 1990; Ortega and Albanesi, 1998). Fossils of this age were recorded in the Las Plantas Member (Las Vacas Fm) at Guadacol area, La Rioja Province (Astini and Brussa, 1997), and in the Potrerillo Mountain section (Benedetto et al., 1991; Ortega and Albanesi, 1998), northern San Juan Province. In the Viejo Hill, west of Huaco, a rich graptolite assemblage of this biozone is present in the upper member of the Los Azules Fm, where a hiatus that involve the upper Darrwilian and lower Sandbian was recognized between the *H. teretiusculus* and *C. bicornis* zones (Ortega, 1987; Ortega and Albanesi, 1998). Other records of the *C. bicornis* Zone correspond to the Sierra de La Invernada Fm in the eponymous locality (Furque et al., 1990), San Juan Precordillera.

Records of this biozone were also documented for the siliciclastic succession of the Cántaro de Oro Fm at El Tigre Range (Caballé et al., 1993), Western Precordillera. In the La Pola Fm, Villicum range, Eastern Precordillera, specimens of *D. ramosus ramosus* (Hall) and *D. nicholsoni Hopkinson* suggesting the *C. bicornis* Zone were mentioned by Brussa et al. (2003a). Two other units containing *C. bicornis* Zone graptolites crop out in the Mendoza Province. One of them is the Empoza Fm, west of Mendoza city (Alfaro, 1988; Cuerda and Alfaro, 1993; Mitchell et al., 1998; Ortega and Albanesi, 1998; Ortega et al., 2007) in the Precordillera, and the other one is the Arroyo Pavón Fm at San Rafael Block, southern Mendoza Province (Cuerda et al., 1998).

**Diplacanthograptus caudatus Zone**

Strata between LIG16 and LIG20 yielded a younger graptolite assemblage preserved in shales and sandstones. In the lower part of this interval there were recorded *Corynoides* cf. *C. ultimus* Rueckemann, *Corynoides* cf. *C. americanus* Rueckemann, *Cryptograptus* cf. *C. insectiformis* Rueckemann, *Dicranograptus spinifer* Elles et Wood, *Dicranograptus* cf. *D. hians* T.S. Hall, *Neurograptus margaritatus* (Lapworth), *Orthograptus spinigerus* (Elles et Wood), *Orthoretiolites hami Whitington*, *Diplacanthograptus spiniferus* (Rueckemann), and *Diplacanthograptus caudatus* (Lapworth). Specimens of *Dicranograptus spinifer* and *Diplacanthograptus spiniferus* are particularly abundant in these levels. At LIG20, *D. caudatus* is associated with *Corynoides* sp. 1, *Dicellograptus* sp., *Leptograptus* sp., *Rectograptus*...
amplexicaulis (HALL), and Rectograptus sp. Elements of Amorphogonatus superbus Rhodes are present on the same black shale bedding surfaces.

The mentioned graptolite assemblage was recently referred to the D. caudatus Zone by Ortega et al. (2007) following the scheme by Goldman (2003) and Goldman et al. (2007), as a distinguishable interval ranging between the C. bicornis Zone and the first appearance of the Climacograptus tubuliferus LWPWORTH. The first appearance datum (FAD) of D. caudatus marks the base of the Katian global Stage for the Upper Ordovician Series (Goldman et al., 2007), a level that can also be identified by the entrance of C. americanus, D. hians, O. quadriramus, O. pageanus, and N. margaritatus (Goldman, 2003; Goldman et al., 2007). In the La Invernada Range, conglomerate and sandstone deposits make up a barren interval present between the C. bicornis assemblage and the entrance of the D. caudatus fauna. The record of D. spiniferus at LIG16 may indicate that the basal part of the D. caudatus Zone is not present in the studied section.

The D. caudatus Zone is nearly equivalent to the Diplacanthograptus lanceolatus and D. spiniferus zones of Australasia (VandenBerg and Cooper, 1992), and the Dicranograptus clingani Zone from Scotland (Zalasiewicz et al., 1995) and Newfoundland (Williams, 1995). It also corresponds with the Corynoides americanus and Diplacanthograptus spiniferus zones of the south central USA (Finney, 1986; Goldman et al., 1999) and the C. americanus, Orthograptus ruedemannii and D. spiniferus zones of eastern North America (Riva, 1969, 1974). The studied interval is also coeval with the Diplacanthograptus lanceolatus and Diplacanthograptus spiniferus from the Kalpin area, Tarim region, China (Chen et al., 2000).

In the Argentine Precordillera a graptolite fauna probably equivalent to the D. caudatus Zone was mentioned by Ortega et al. (1991) in the Yerba Loca Fm (lately the Cánaro de Oro Fm sensu Caballé et al., 1993) on the profile of road n° 425 at El Tigre Range. This fauna, composed by Diplacanthograptus sp., Orthograptus spp. and Orthoretiolites sp., was identified as the “Cádoco post-gracilis assemblage” by the authors and correspond to the “not nominated interval” of the graptolite zonal scheme proposed by Albanesi and Ortega (2002). A similar assemblage comprising Cryptograptus insectiformis RUDDEMAN, Corynoides calicularis NICHOLSON, Diplacanthograptus flexuosus LWPWORTH, Phorograptus sooneri WHITTINGTON, Orthoretiolites cf. hami robustus KEVEY, Rectograptus cf. R. amplexicaulis (HALL), Orthograptus quadriramus (HALL), and D. caudatus (present only at the base of the succes- sion) among others, was mentioned for the Yerba Loca Fm at El Tigre Range by Brussa (1995) and Brussa et al. (1999). The authors correlated that assemblage with the Dicranograptus clingani Zone and equivalents. Speci mens of Neurograptus cf. N. margaritatus from the Cán taro de Oro Fm (= Sierra de La Invernada Fm in this paper) crops out ca. 19 km south of provincial road n° 436 were reported by Cuerda et al. (1999). These fossils were referred to the C. bicornis Zone by the authors, although they seem to correspond to the younger D. caudatus Zone.

**Climacograptus tubuliferus Zone**

The entrance of C. tubuliferus was recorded at LIG21 in the uppermost part of the Sierra de La Invernada Fm, where most of the graptolites from the C. caudatus Zone have already disappeared (Ortega et al., 2007). The assemblage is composed of C. tubuliferus, which is the dominant taxon, and scarce rhabdosomes of Corynoides sp. 2, R. amplexicaulis, Rectograptus sp., Orthograptus sp., as well as probable rhabdosome fragments. Graptolites are associated with conodonts of the A. superbus Zone, Obolus sp., particularly abundant in some layers, chitinozoans and scolecodonts. The monot onous C. tubuliferus fauna reveals a strong impoverishment in the diversity of the graptolite assemblages of the studied unit.

As pointed out by Goldman (2003) and Goldman et al. (2007), C. tubuliferus has a world-wide distribution (e.g., USA, Yukon Territory, Alaska, Newfoundland, Australasia, Scotia) appearing just above the D. caudatus assemblage. In the Argentine Precordillera it was recorded in the upper part of the Empozada Fm (Mendoza Province) in strata of the D. complanatus and D. ornatus zones (Mitchell et al., 1998). Other findings of this taxon correspond to the Puvón Fm, at San Rafael Block (Cuerda et al., 1998), and to the Alcaparrosa Fm, in the Western Precordillera (Brussa et al., 1999). The lowest C. tubuliferus record in the Sierra de La Invernada Fm, seems to correspond well with the FAD of this species in other parts of the world.
C. tubuliferus is part of the cosmopolitan mesopelagic biotope of the tropical Province during the Upper Ordovician (Goldman et al., 1995). Its presence represents the Oceanic biofacies in the upper part of the Sierra de La Invernada Fm, where it is associated with cosmopolitan epipelagic elements, such as R. amplexicaulis.

Conodonts

In the studied section, the Sierra de La Invernada Fm was sampled at levels LIC 0, 1, 2, 3, 4, 5, 8, and 11 for conodont biostratigraphy (Fig. 2). About 12 kg of calcarenite rocks, which are interbedded with fine sandstones and siltstones, were processed using conventional acid etching techniques (Stone, 1987) for the recovery of conodonts. Only samples LIC1 (2.4 kg, 555 conodont elements), LIC3 (1.2 kg, 332 conodonts), LIC8 (1.2 kg, 103 elements), and LIC11 (1.2 kg, 27 elements) were productive, yielding a total of 1017 conodont elements that represent the Pygodus serrae, P. anserinus, Amorphognathus tvaerensis, and A. superbus zones. Some of these conodonts are moderately preserved showing signs of attrition, probably because of sedimentary transport as coeval intraclasts in early biostratigraphic phases. All of collected conodont elements show CAl 3 indicating overburden paleotemperatures around 200ºC. Conodont specimens from samples LIG17, 20, 22, 23 and 24 are preserved as casts on bedding plane surfaces of shales, including species that represent the Pygodus anserinus and Amorphognathus superbus zones. Conodont elements from samples LIC1 and LIC3 were reworked from eroded lower strata. They show the same CAl 3 as the authochthonous elements, but their surfaces are slightly worn with a less vitreous reflectance. These conodont specimens are most probably referable to the Floian Stage, i.e., the Priioniodus elegans and Oepikodus evae zones.

All recorded species, illustrated in Figs. 6 and 7, are well-known taxa and were fully described by previous authors (see references in the following discussion of conodont zones). Additional comments on the taxonomy of these forms are not considered in present contribution.

Pygodus serrae Zone

The conodont association recovered from sample LIC1 includes authochthonous and reworked specimens. The latter specimens are determined because of their restricted range to lower levels than those of the bearer bed, whose age is constrained by the dominant fauna. The latter taxa include, Costiconus ethiingtoni (Fähræus), Drepanodus reclinatus (Lindström), Erissodus sp., Erraticodon sp., Periodon macrodentata (Graves and Elliston), and Spinodus sp. The ranges of these species are restricted to the Darrwilian Stage (Albanesi et al., 1998), and the appearance of the genus Erissodus probably represents the Eoplacognathus suecicus to Pygodus serrae zonal interval, since the oldest members of the genus were recorded within the late Darrwiliian in North American localities (cf. Harris et al., 1979; Bauer, 1987, 1994). The guide species P. serrae (Hadding) was recorded in the study area of the La Invernada Range. It was recovered from a new section, between the Cerro Bayo and Vallecito localities, located about 15 km to the south of present profile, in a stratigraphic position that correlates closely with the location of level LIC1. Accordingly, it is possible to propose a confident assignment of the bearer level to the P. serrae Zone, despite the absence of the guide species in the collection of the study section.
The associated stratigraphic ranges of recorded reworked specimens span the time interval represented by the *Prionidus elegans* and *Oepikodus evae* zones: i.e., the Floian Stage of the Lower Ordovician Series. These species are *Paroistodus proteus* (LINDSTRÖM), *Protopanderodus gradatus* SERPAGLI, *P. leonardii* SERPAGLI, *Rossodus barnesi* ALBANESI, *Scolopodus krummi* (LEHNERT), and *Tropodus sweeti* (SERPAGLI). A similar species assemblage was recovered from transported clasts of basal conglomerates in the lower section of the Sierra de La Invernada Fm that crops out along the provincial road nº 436. The guide species *Oepikodus evae* is present in the conodont collection yielded by allochthonous clasts; in turn, this material is included in a matrix where the authochthonous assemblage is mid Darriwilian in age (Albanesi, unpublished collections).

The *P. serra* Zone was originally defined by Bergström (1971) in the Kalgrärde Limestone, which is exposed at Dalarna, south-central Sweden. The intercontinental correlation of this unit and the lineage of *Pygodus* were discussed by Bergström (1983) and Zhang (1998). In the Argentine Precordillera, the *P. serra* Zone was identified firstly by Hünicken and Ortega (1987) in the Los Azules Fm of Central Precordillera, and subsequently recorded in dissimilar stratigraphic settings of the region (e.g., Albanesi et al., 1995; Heredia, 2001). A recent paper by Albanesi et al. (2007) discusses the correlation of this interval with the *P. anserinus* Zone. Since the first appearance of *N. gracilis* in the studied section is a few meters above level LIC3, it is probable that the conodont fauna represents the lower subzone of the *Pygodus anserinus* Zone.

Significant information regarding the *P. anserinus* Zone, its associated fauna and biostratigraphic problems concerning the involved stratigraphic interval, was published by Bergström et al. (1987), and Bergström (1990) on the Welsh borderlands and the Girvan succession at south-west Scotland. Dzik (1994) provided related information on the Mójcza limestone, Poland, and Pålsson et al. (2002) on the Jämtland succession, central Sweden. Important referece papers that discuss the *P. anserinus* Zone in localities around the Laurentian margin are those by Bergström et al. (1974) in Newfoundland, Bergström (1978) in the Marathon area, west Texas, and Harris et al. (1979) in the Great Basin and Rocky Mountains. A recent paper by Agematsu et al. (2007) deals with significant information regarding the distribution of the *Pygodus* fauna in the southern peninsular Thailand. Zhen et al. (2003) recovered representatives of this fauna from the Warring Limestone in Central New South Wales.

In the Argentine Precordillera, the *Pygodus anserinus* Zone has been recognized at several localities. Conodont associations of this unit were reported for the upper part of the Ponón Trehué Fm (= Linderó Fm of other authors), Mendoza Precordillera, which represents shallower environments than correlative studied strata of the Sierra de la Invernada Fm (Lehnert et al., 1999; Heredia, 2001). The nominal species of the *P. anserinus* Zone was also recorded from deeper water facies of the San Juan Precordillera in the Las Aguaditas Fm at Los Blanquitos Range (Keller et al., 1993) and Los Azules Fm at La Chilca Hill (Albanesi, unpublished data), south of Jáchal River.

Significantly, in the Central Precordillera of San Juan Province, an important hiatus that partly involves the
Pygodus serra and P. anserinus zones was documented in classical study localities, such as the Potrerillo Mountain (Albanesi et al., 1998) and Viejo Hill (Ottone et al., 1999). This hiatus corresponds to the Guandacol phase of the Ocloyic Orogeny (Furque, 1972), the name given to the extentional tectonics that caused deposition of thick slope megabrecchias, turbidites, and hypabisal intrusive bodies of Darriwilian age in different sectors of the Precordillera (Gosen, 1992; Ramos, 2004).

The conodont fauna from the late Darriwillian and early Sandbian of the Sierra de La Invernada Fm is largely dominated by Periodon and Protopanderodus species, which represent over 70% of the total fauna. This faunal composition was described by several authors as a recurrent conodont association or biofacies for deep-cold-water environments from platform margin to upper slope (Rasmussen, 1998). The conodont assemblage, which mostly comprises pandemic pelagic forms, refers to the Open-Sea Realm as defined by Zhen and Percival (2003). The fact that some Laurentian (warm) taxa, such as Cahabagnathus, occur in the samples from the Sierra de La Invernada Fm, suggests a temperate domain for the conodont paleobiogeography of the Precordillera at the end of Mid Ordovician times. Conodont paleoenvironmental constrains for the Pygodus zones in the Ponón Trehue Fm of the Cuyania terrane were published by Lehnert et al. (1999) and Heredia and Rosales (2006), who revealed the changing environmental conditions through the sedimentary unit by variations in the relative proportion of genera. The highest abundance of the genera Periodon and Protopanderodus corresponds to shelf margin environments, while Periodon is commonly replaced by Pygodus in deeper slope environments. Similar faunal changes are verified in the Sierra de la Invernada Fm although larger collections are required for statistical studies.

**Amorphognathus tvaerensis Zone**

The species assemblage yielded by sample LIC8 includes Amorphognathus tvaerensis BERGSTROM, Baltionidodus alobatus (BERGSTROM), Drepanoistodus suberectus (BRANSON and MEHL), Icriodella superba RHODES, Plectodina tenuis (BRANSON and MEHL), Periodon granidis (ETHINGTON), Protopanderodus liripipus KENNEDY, BARNES and UYENO, and Rhodesognathus elegans (RHODES). Although most of determined species were previously documented in the Precordillera from other formations (e.g., Heredia et al., 1990; Albanesi et al., 1998; Ortega and Albanesi, 1998), the presence of B. alobatus, which is here recorded for the first time from the Argentine Precordillera, indicates the homonymous subzone of the A. tvaerensis Zone as it was defined by Bergström (1971) in the Dalby Lime-stone of Sweden (upper Sandbian Stage). Apart from those localities with records of B. alobatus in the Baltoscandin region (Bergström, 1983) the biostratigraphic interval represented by this species has not been reported frequently, the data provided by Kennedy et al. (1979) is one of the few reports for North America. The characteristic and widespread species I. superba, P. liripipus and R. elegans make their first appearances in this interval and continue upwards through the next several Ordovician conodont zones. A remarkable example for these records is documented by Bergström and Mitchell (1992) dealing with the Mohawkian Utica Shale in the Eastern Midcontinent region of North America. In a recent work, Leslie (2000) demonstrates that the Phragmodus undatus – Plectodina tenuis zonal boundary of the North American scheme projects into Baltoscandian Baltionidodus alobatus Subzone of the Amorphognathus tvaerensis Zone on the basis of K-bentonite bed correlation (see discussion below).

**Amorphognathus superbus Zone**

A number of specimens of Amorphognathus superbus Rhodes (Fig. 7) were recorded as casts on bedding plane surfaces of shales from the upper part of the...
studied section (samples LIG17, 20, 22, 24). The topmost calcareous sample of this section (LIC11) provided few remains of *Amorphognathus* associated with the dominant deep-water *Periodon grandis* - *Protopanderodus liripipus* conodont association. *A. superbis* is well known from cold-water environments in Europe and North America, its multielemental apparatus was fully described, and its evolutionary lineage depicted in detail (e.g., Bergström, 1983; Dzik, 1983, 1994).

*A. superbis* is the key index taxon for the homonymous zone of the Baltoscandian scheme, as originally defined by Bergström (1971) in Swedish reference sections. Although this author discussed the *Amorphognathus tvaerensis* - *A. superbis* zonal boundary to be near the top of the Dalby Limestone (near the Kinnelulle K-bentonite Bed), recent work by Leslie (2000) indicates that this zonal boundary could be within the overlying Skagen Limestone. In North America, the base of the *A. superbis Zone* is well above the Millbrig K-bentonite Bed (Bergström and Mitchell, 1994), supporting the correlations of Leslie (2000). Following the global chronostratigraphic standard, the *A. superbis* Zone spans in the lower Katian stage of the Upper Ordovician Series.

So far, the only record of related forms from the Argentine Precordillera was determined as *Amorphognathus aff. A. superbis* by Albanesi et al. (1995). This form was recorded in middle levels of the siliciclastic Trapiche Fm in the Potrerillo Mountain, Central Precordillera of San Juan Province.

**CONCLUSIONS**

According to the present study, the ancient layers (Darriwilian) of the Sierra de La Invernada Fm crop out in the eastern part of the investigated section in the northern La Invernada Range.

The upper Sierra de La Invernada Fm is divided on the basis of its sedimentary architecture and the nature of involved deposits into shallower and deeper environments recorded by changing facies intervals. The stratigraphic record resulted from response to sea level changes, which were in turn also reflected by variations of the graptolite-conodont faunal compositions throughout the surveyed column.

Six upper Middle to lower Upper Ordovician graptolite biozones are determined in this section; i.e., the *Pterograptus elegans* (tentative assignment), *Hustedograptus teretiusculus*, *Nemagraptus gracilis*, *Climacograptus bicornis*, *Diplacanthograptus caudatus*, and *Climacograptus tubuliferus* zones.

The *Pygodus serra* conodont zone is identified for the lower part of the section. The *P. anserinus*, *Amorphognathus tvaerensis*, and *A. superbis* conodont zones are recognized in the middle-upper section.

According to the graptolite and conodont records, the upper part of the Sierra de La Invernada Fm is referable to the upper Darriwilian, Sandbian and lower Katian stages, following the new global nomenclature (see ISOS-IUGS web site: http://www.ordovician.cn; Bergström et al., 2006), which correlates with the upper Llanvirn to upper Caradoc Series of the British scale.

**ACKNOWLEDGEMENTS**

The authors wish to thank CONICET for support to develop this research under grant nº 6389 to G. Ortega. Present work was possible thanks to the laboratory facilities of the Paleontology Museum, FCEFyN, National University of Córdoba, Argentina. The CRICyT (CONICET) at Mendoza, and the National University of San Juan, Argentina, are acknowledged for important support to carry out present project as well. We thank Mr. Arturo Curatola for his hospitality and assistance during the development of this research work in his own property at La Invernada Range. The reviewers Juan Carlos Gutiérrez-Marco and Daniel Goldman helped us to improve significantly a first version of our manuscript. Their comments and corrections are appreciated and greatly acknowledged. This is a contribution to IGCP project 503.

**REFERENCES**


Or dovician graptolites and conodonts from Central Precordillera, Argentina


Zhen, Y-Y., Percival, I.G., Webby, B.D., 2003. Conodont faunas from the Mid to Late Ordovician Boundary interval of the Wahringa Limestone Member (Fairbridge Volcanics), Central New South Wales. Proceedings of the Linnean Society of New South Wales, 125, 141-164.

Manuscript received November 2007; revision accepted April 2008; published Online May 2008.