

# Lower Ordovician graptolite biozonation and lithofacies of southern Bolivia: relevance for palaeogeographic interpretations

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**Abstract** – The interpretation of the lithofacies and basin evolution of the early Ordovician of southern Bolivia is based on a number of sections on an E–W transect. Lithostratigraphic units are extremely diachronous and only the available data on the graptolite biostratigraphy enabled an interpretation of the basin evolution. The newly proposed graptolite biozonation includes the biozones of *Rhabdinopora flabelliformis*, *Adelograptus* sp., *Araneograptus murrayi*, *Hunnegraptus copiosus*, *Tetragraptus phyllograptoides*, *Expansograptus protobalticus*, *Expansograptus holmi*, *Baltograptus minutus*, *Azygograptus lapworthi* and *Isograptus victoriae*. *Isograptus victoriae* is the first isograptid identified from Gondwanan South America. The early Ordovician succession of southern Bolivia is the most complete one documented from South America and can be used as a standard for this continent. The faunas are most easily correlated with the faunal succession of Scandinavia and without doubt belong to the Atlantic graptolite faunal province. They show distinct differences from coeval faunas of the Argentine Precordillera, referable to the Pacific faunal province.

Keywords: Ordovician, biostratigraphy, graptolites, South America, Bolivia.

## 1. Introduction

The lower Palaeozoic of southern Bolivia includes a fairly complete and extremely thick succession of early Ordovician siliciclastic rocks with strongly diluted, but biostratigraphically highly significant, graptolite faunas. Egenhoff (2000) documented the lithostratigraphy and palaeogeography of the region, encompassed by the provinces of Tarija, Potosi and Chuquisaca, and redefined the lithostratigraphic units. We describe for the first time the early Ordovician graptolite succession from a number of localities (Fig. 1) and propose a biostratigraphic zonation. The faunal succession is the most extensive such early Ordovician succession so far found world-wide. The graptolite faunas are moderately well preserved, but often strongly tectonized. They belong to the Atlantic faunal province and can be regarded as typical of most parts of Gondwana, except for the Pacific-type faunas found in the Argentine Precordillera (Maletz & Ortega, 1995). Similar faunas are well known from northern Argentina (Moya *et al.* 1994; Monteros, Moya & Monaldi, 1996; Toro, 1993, 1996, 1997*a,b*, 1999*a,b*). There, the succession is more incomplete and is cut off in the early Arenig, whereas in southern Bolivia

younger mid- to late Arenig faunas are preserved below a post-Palaeozoic unconformity.

The presence of Ordovician graptolite faunas in Bolivia has been known since Wood (1906) described Llanvirm pendent didymograptids, phyllograptids, diplograptids and glossograptids from Cule (northern Bolivia). Two dendroid graptolites were described shortly afterwards by Courty (1907) from the Tarija area, and Steinmann & Hoek (1912) added further to the record of early and middle Ordovician graptolite faunas from southern Bolivia. Bulman (1931) gave the first more comprehensive description of the graptolite faunas of the whole of South America. Graptolite research in South America started to gain speed in the last two decades and Turner's (1959) compilation is now outdated. Silurian graptolite faunas were recently found in Bolivia and an overview can be found in Maletz, Suárez-Soruco & Egenhoff (2002).

The discovery of a useful and complete succession of early Ordovician graptolite faunas in the thick siliciclastic succession of southern Bolivia also has considerable impact on the lithostratigraphic correlation and palaeogeographic interpretation of the region. The data indicate serious problems for the sole use of lithostratigraphic correlation of sections as the recovered faunas prove the presence of extremely diachronous lithological units and strong lateral facies variations.

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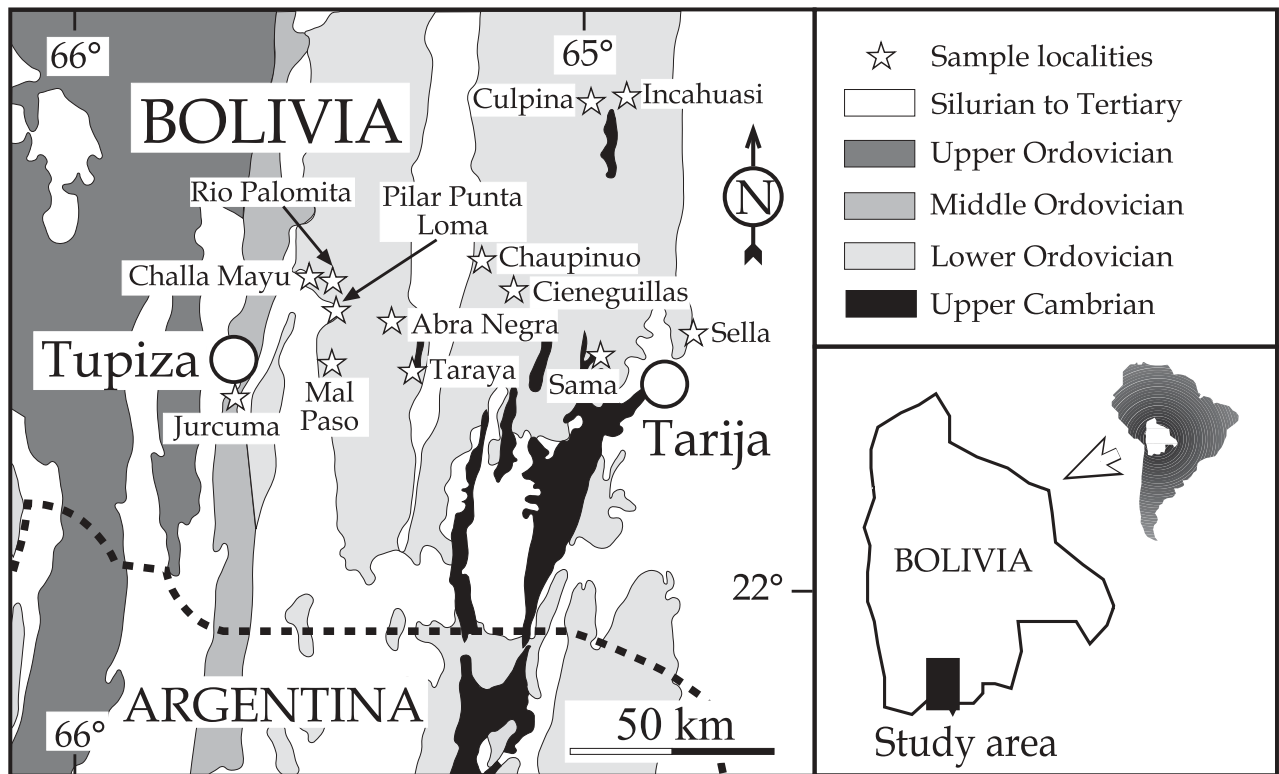


Figure 1. Geological map of the study area in southern Bolivia. The investigated localities are marked with white stars. Most of the sections are aligned along an E–W profile perpendicular to the N–S-running Ordovician shoreline.

## 2. Evolution of the early Ordovician shelf in southern Bolivia

The evolution of the early Ordovician shelf is documented from 13 measured sections (Figs 1, 2), most of them aligned on an E–W transect perpendicular to the N–S-trending coastline in the Ordovician (Gohrbandt, 1992). The graptolite faunas clearly demonstrate that the lithological units are diachronous (Fig. 3) and a pure lithostratigraphic correlation of the sections is not advised. In southern Bolivia the generally N–S-extending basin started to form in late Cambrian times. Extensional movements led to the formation of a half-graben with a steeper western and a more gently inclined eastern flank, extending from southern Peru in the north to northwestern Argentina, crossing through the whole of western Bolivia (Gohrbandt, 1992).

In earliest Ordovician times, a delta system governed the sedimentation, leading to the deposition of sandstone-shale intercalations of the Iscayachi Formation (Fig. 3). This basal unit crops out in the three localities, Sama, Cieneguillas and Taraya, all situated in the eastern to central part of the study area (Fig. 1). The sediments are characterized by storm-influenced prodelta to delta front deposits, bearing graptolites only in the upper part. The Iscayachi Formation probably has a latest Cambrian age at Taraya, whereas further to the east, it is entirely early Tremadoc in age.

Around latest Cambrian to earliest Ordovician times, a horst structure developed on the central shelf, characterized by condensed sedimentation. This facies is documented in the Taraya Formation at the locality Taraya.

After a major transgression in the earliest Tremadoc, large parts of the shelf fell below storm wave base, and the submarine ramp of the Obispo Formation developed, characterized by laminated mudstones and turbidite lobes. The Obispo Formation is widely distributed in the study area and crops out in the localities Rio Palomita, Pilar Punta Loma, Mal Paso, Abra Negra, Cieneguillas, Culpina and Incahuasi. Its base is exposed only in the eastern part of the study area and is of early Tremadoc age.

In early Arenig times, the extensional rift basin evolved into a compressional foreland basin. The change in basin geometry caused an uplift of the eastern part of the modern Eastern Cordillera region, and as a result, a delta complex prograded more than 80 km westwards, leading to the sub-aerial exposure of large parts of the shelf. In the late Arenig, the westward-shifting coastline had reached a position some tens of kilometres east of Tupiza (Figs 1, 4). The Pircancha, Rumi Orkho and Sella formations represent the progradational deltaic units of this shift. They crop out at Sella, Cieneguillas/Chaupinuo and in various outcrops further west of Pilar Punta Loma and Rio Palomita.

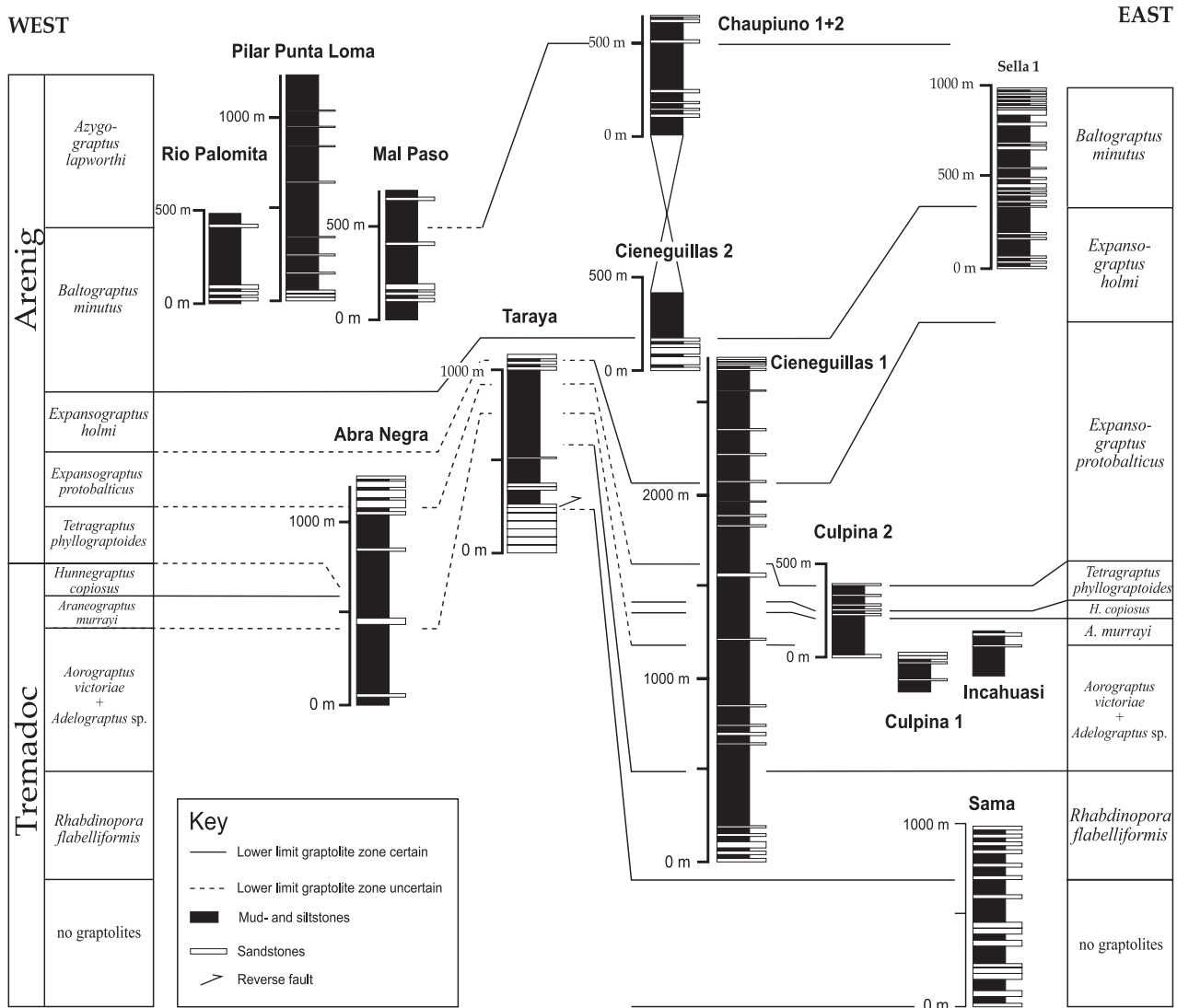


Figure 2. The Bolivian sections and their biostratigraphic correlation. Note the enormous thickness of the succession.

The transition from the Obispo Formation to the overlying deltaic Pircancha Formation is highly diachronous: at Cieneguillas it is located in the *Expansograptus holmi* Biozone, whereas further to the west, its position may be as high as the mid- to late Arenig *Azygograptus lapworthi* or *Isograptus victoriae* biozones. The top of this unit is middle to late Arenig in age and also is probably older in the east than in the west.

It is likely that the position of the coastline was largely stable during Middle Ordovician times, indicated by Darriwilian shallow-marine storm-influenced deposits at Jurcuma near Tupiza (Egenhoff, 2000; Egenhoff *et al.* 2002). In the Caradoc, the existence of the foreland basin active since the Arenig can still be proven for southern Bolivia in the modern western part of the Eastern Cordillera and the Altiplano region (Egenhoff, 2000). Deep-marine Caradoc turbidites are overlain by Ashgill mass-flow deposits and glacial diamictites, the latter reflecting the worldwide sea-level

fall due to the Late Ordovician glaciation (Sempere, 1995).

At Sella, the Ashgill diamictites are exposed on top of the Arenig sandstones (*Baltograptus minutus* Biozone or *Azygograptus lapworthi* Biozone). In Chaupiuno, a Cretaceous succession unconformably overlies the Ordovician delta deposits of the *Baltograptus minutus* Biozone. In the locality Challa Mayu only a few tens of kilometres NE of Tupiza, the exposed strata bear *Isograptus victoriae* and represent the youngest sediments known deposited on the subsequently exposed early Ordovician shelf.

The early Palaeozoic rocks in southern Bolivia were folded and faulted during two major tectonic events in the Late Devonian/Early Carboniferous and during the Andean Orogeny (Kley, 1993; Kley & Reinhard, 1994). Nevertheless, extensive and biostratigraphically undisturbed successions can be documented in various localities in great detail. Moderate to strong tectonic

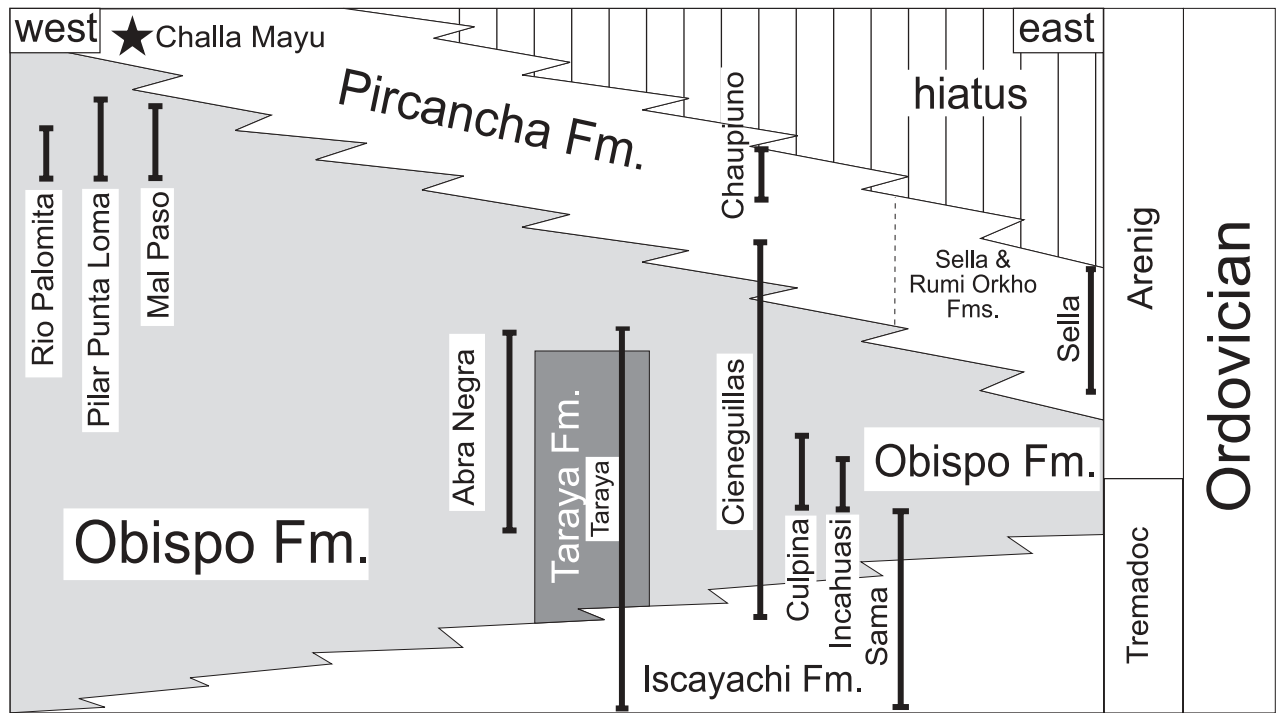


Figure 3. Lithofacies correlation of Lower Ordovician sections, based on the graptolite biozonation established for southern Bolivia.

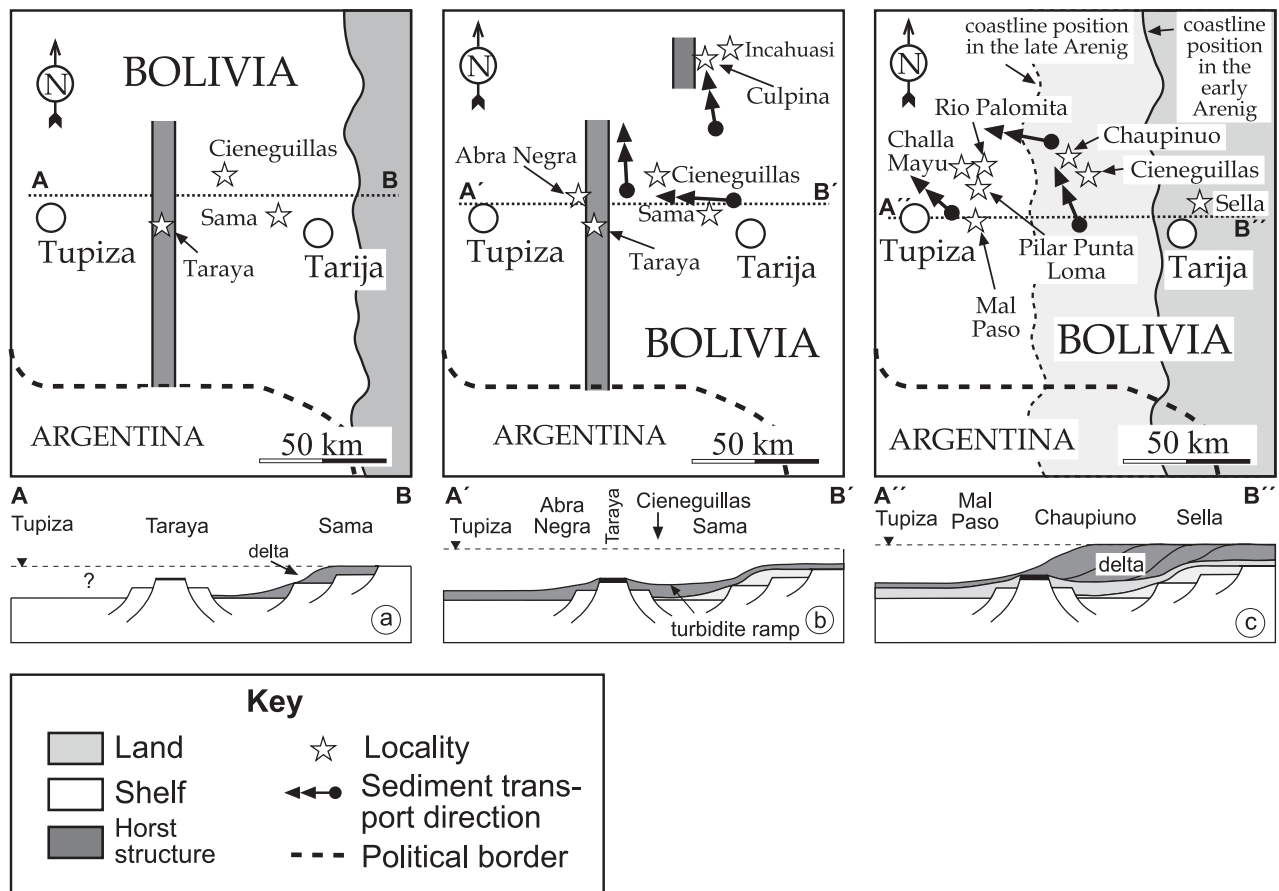


Figure 4. Palaeogeographic reconstruction, based on sedimentological data of Egenhoff (2000) and the biozonation presented in this study. (a) In the early Tremadoc, the eastern part of the Eastern Cordillera was characterized by delta sedimentation, and a structural high had been developed at Taraya. (b) After a major transgression still in the early Tremadoc, the study area fell below storm wave base and developed into a submarine ramp. At Taraya, the horst block was still characterized by condensed sedimentation. (c) In the *Expansograptus holmi* Biozone, the environment showed a marked shallowing, and a major delta complex prograded more than 80 km westwards, exposing large parts of the shelf.

distortion is clearly expressed by the graptolite preservation as pressure-shadow minerals on shales.

Graptolites are quite common within the Tremadoc succession. In the Arenig, however, they are more rare. Although the sedimentation rates are high throughout the early Ordovician shelf evolution, one important reason for the relative scarcity of graptolites in the Arenig strata might be the higher sediment input due to the progradation of the delta front.

### 3. Graptolite biostratigraphy

The Ordovician graptolite biostratigraphy of southern Bolivia is little known. Suárez-Soruco (1975) described the *Dictyonema flabelliforme* to *Didymograptus murchisoni* zones in the early and middle Ordovician as well as the *Dicranograptus nicholsoni* and *Orthograptus truncatus* zones in the late Ordovician. Maletz, Kley & Reinhardt (1995), for the first time identified faunas of the *Tetragraptus approximatus* Zone of early Arenig age in the Tarija region and established a biozonation for the Arenig interval sampled up to this time. Maletz, Egenhoff & Erdtmann (1999) and Maletz & Egenhoff (2001) discussed the graptolite faunas around the base of the Arenig and concluded that the faunal succession in southern Bolivia is remarkably complete.

The faunal lists include all species collected from the intervals, but not necessarily all faunal elements are associated and the various levels within the individual biozones might include a number of slightly different associations. The definition of the biostratigraphic intervals is always based on local first occurrences (FAD) and the defined units are intended to be local biozones, not chronostratigraphic units. As the individual faunal intervals are fairly thick and the faunas have only been recorded from relatively few beds, the FADs of the recorded graptolite species are unfortunately not very reliable, and more detailed investigation will result in a refined definition of the zones, based on corrected biostratigraphic ranges. Each graptolite zone is defined in a certain section, where the local earliest occurrence of the index species of the interval is documented. The detailed sections with collection levels are given in Egenhoff (2000). Specimens from the sections were figured previously by Maletz, Egenhoff & Erdtmann (1999) and Maletz & Egenhoff (2001). All figured graptolite specimens are preserved in the type collection at Forschungsinstitut Senckenberg (Frankfurt/Main, prefix SMF).

#### 3.a. The *Rhabdinopora flabelliformis* Biozone

**Definition.** The base of the zone is taken at the first occurrence of *Rhabdinopora flabelliformis parabola* at the 570 m level in the Taraya section. The same species also appears in sample Ca-96-3 in the Cieneguillas section (Egenhoff, 2000, p. 142).

**Fauna.** *Rhabdinopora flabelliformis parabola*, *Rhabdinopora flabelliformis* ssp.; possibly other subspecies are present, but not yet differentiated.

**Remarks.** Several forms of *Rhabdinopora flabelliformis* (Fig. 6a) were found in the sections, but need more detailed investigation before a subdivision of this broad interval is possible based on the successively evolving subspecies (Cooper *et al.* 1998). There is no confirmed record of *Staurograptus* in the lowermost Tremadoc of Bolivia. The genus *Anisograptus* was also not recorded from Bolivia, and thus the *Anisograptus* Zone cannot be differentiated. This does not mean that the zone is not represented, but it has not been recognized as yet, making a finer subdivision of the broad *Rhabdinopora flabelliformis* Biozone impossible.

Cooper *et al.* (1998) redefined the early Tremadoc graptolite biozonation and differentiated a number of biozones. It is not possible to identify these in Bolivia, as the faunal record is poor and the graptolites are too strongly tectonized for unequivocal identification of the subspecies of *Rhabdinopora flabelliformis* at present. However, *Rhabdinopora flabelliformis* is fairly characteristic and can be identified in several localities where it is generally found in monospecific assemblages. Other faunal elements are as yet unknown from this time interval in southern Bolivia.

#### 3.b. The *Adelograptus* Biozone

**Definition.** The base of the zone is taken at the first occurrence of *Adelograptus* spp. at the 475 m level in the Cieneguillas section (coll. Cd-97-1).

**Fauna.** *Adelograptus* spp.

**Remarks.** A number of *Adelograptus* species (Maletz & Egenhoff, 2001, fig. 8/7, SMF 75395) might be present as is indicated from the quite variable size of the specimens, but the material is too poor for a specific identification at the moment. Even though the faunas are poorly known and the taxonomy of the middle to late Tremadoc graptolites is still vague, the interval can easily be identified. In the Cieneguillas 1 section and at Culpina a number of levels with the fauna of this zone have been discovered (Egenhoff, 2000).

#### 3.c. The *Aorograptus victoriae* Biozone

**Definition.** The base of the zone is taken at the first occurrence of *Aorograptus victoriae* at Clp97-1 in the Culpina section. The Tremadoc to early Arenig part of the succession was figured by Maletz, Egenhoff & Erdtmann (1999) and is found in Egenhoff (2000), where the complete section was discussed. The *Aorograptus victoriae* Biozone is also present at Cieneguillas (Egenhoff, 2000; Maletz & Egenhoff, 2001).

*Fauna.* *Aorograptus victoriae*, *Adelograptus* spp., ?*Tetragraptus* sp.

*Remarks.* The zone is easily identified by its eponymous species *Aorograptus victoriae* (Maletz, Egenhoff & Erdtmann, 1999: fig. 1A, SMF 75399), a generally common species in certain layers. A number of *Adelograptus* specimens are associated with *Aorograptus victoriae*, but due to their poor preservation, specific identifications were not possible. *Aorograptus victoriae* ranges into the *Araneograptus murrayi* Zone but is not found in the overlying *Hunnegraptus copiosus* Biozone (Maletz & Egenhoff, 2001).

### 3.d. The *Araneograptus murrayi* Biozone

*Definition.* The base of the zone is taken at the first occurrence of *Araneograptus murrayi* at the 1200 m level in the Cieneguillas 1 section (sample Cd-97-33).

*Fauna.* *Araneograptus murrayi*, *Paradelograptus norvegicus*, *Kiaerograptus supremus* Maletz & Egenhoff, 2001, fig. 8/5, SMF 75393), *Paradelograptus* sp., *Tetragraptus bulmani*.

*Remarks.* *Araneograptus murrayi* (Maletz & Egenhoff, 2001, fig. 8/10, SMF 75398) is a common and highly characteristic species in the Lower Ordovician of Bolivia and was found in large masses of specimens in a number of mud- and siltstone layers. Often the material clearly indicated some current transport of the rhabdosomes. Some specimens are even preserved as casts in sandstone beds. Lindholm (1991b) redescribed *Araneograptus murrayi* from the type material and specimens collected from boreholes in Scandinavia. Due to its robust rhabdosome it should not be mixed with the much older and less robust genus *Rhabdinopora*.

### 3.e. The *Hunnegraptus copiosus* Biozone

*Definition.* The base of the *Hunnegraptus copiosus* Biozone is taken at the first occurrence of its index species at the 1400 m level (CIN 12) in the Cieneguillas 1 section.

*Fauna.* *Hunnegraptus copiosus*, *Paradelograptus norvegicus* (Maletz & Egenhoff, 2001, fig. 8/4, SMF 75392), *Clonograptus* sp. cf. *Clonograptus multiplex*, *Tetragraptus bulmani*.

*Remarks.* *Hunnegraptus copiosus* (Maletz & Egenhoff, 2001, fig. 8/9, SMF 75397) is a typical species of this interval and is restricted to it. It appears to be a fairly short-lived species that formerly was thought to be an endemic faunal element of Scandinavia. It is, however, a world-wide occurring form with a high potential for exact biostratigraphic correlation. *Hunnegraptus copiosus* can easily be identified by its long first order stipes, the simple dichograptid thecae

and the presence of a sicular bitheca (Lindholm, 1991b; Maletz & Egenhoff, 2001). It is very often associated with *Adelograptus norvegicus*.

### 3.f. The *Tetragraptus phyllograptoides* Biozone

*Definition.* The base of the zone is taken at the first occurrence of *Tetragraptus phyllograptoides* at the 1440 m level (CIN 13R) in the Cieneguillas 1 section.

*Fauna.* *Tetragraptus phyllograptoides*, *Tetragraptus amii*, *Tetragraptus* sp., *Holograptus expansus*, *Clonograptus* sp. cf. *C. multiplex* (Maletz, Egenhoff & Erdtmann, 1999, fig. 1), ?*Expansograptus* sp., *Araneograptus* sp., *Expansograptus demissus* (Maletz & Egenhoff, 2001, fig. 8/6, SMF 75394), *Expansograptus rigoletto* (Fig. 5c), *Pendeograptus* sp. cf. *Pendeograptus fruticosus*.

*Remarks.* The *Tetragraptus phyllograptoides* Biozone was previously known exclusively from Scandinavia, where it formerly was defined to include a lower subzone bearing this species and an upper subzone without it (Lindholm, 1991a,b; Maletz, Löfgren & Bergström, 1995, 1996). The name is here restricted to the lower subzone bearing *T. phyllograptoides*. This interval is easily recognized in southern Bolivia, where *T. phyllograptoides* (Maletz, Egenhoff & Erdtmann, 1999, fig. 1H, SMF 75402; Maletz & Egenhoff, 2001, fig. 8/1, SMF 75389) is common and bears a fauna identical to that of Scandinavia. Maletz, Kley & Reinhardt (1995) identified the *Tetragraptus phyllograptoides* Biozone in the Sama-Chaupiuno area based on the occurrence of *Baltograptus geometricus*, a species known to be restricted to the upper *Tetragraptus phyllograptoides* Biozone (*Expansograptus protobalticus* Biozone herein).

### 3.g. The *Expansograptus protobalticus* Biozone

*Definition.* The base of the zone is taken at the first occurrence of *Expansograptus protobalticus* (Fig. 5j) and *Baltograptus geometricus* (Maletz, Egenhoff & Erdtmann, 1999, fig. 1I, SMF 75403) at the 1650 m level (CIN 18) in the Cieneguillas 1 section (Maletz & Egenhoff, 2001).

*Fauna.* *Expansograptus protobalticus* (Fig. 5j), *Baltograptus geometricus*, *Tetragraptus approximatus*, *Tetragraptus acclinans*, *Clonograptus multiplex*, *Clonograptus flexilis*.

*Remarks.* The *Expansograptus protobalticus* Zone replaces the upper *Tetragraptus phyllograptoides* Zone of Maletz, Löfgren & Bergström (1995, 1996) and Egenhoff (2000). In the Hunneberg sections in Västergötland, Sweden, *Baltograptus geometricus* and *Expansograptus protobalticus* appear only a few centimetres above the last record of *Tetragraptus phyllograptoides*. An overlap of these species with the

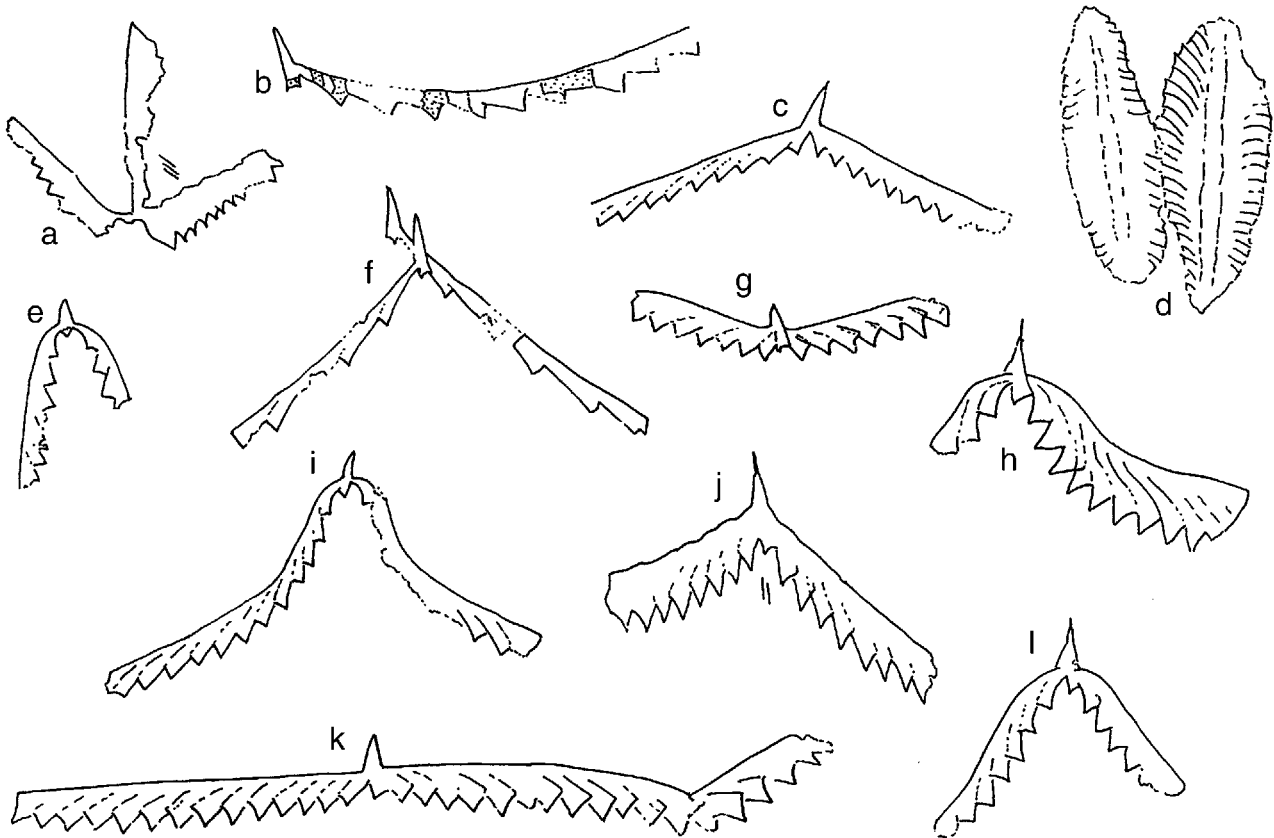


Figure 5. (a) *Tetragraptus serra* (Brongniart), strongly tectonized specimen, BO/CUL13A02, SMF 75375. (b) *Azygograptus lapworthi* Nicholson, Chaupi Uno, coll. 387 (Maletz *et al.* 1995), SMF 75376. (c) *Expansograptus rigoletto* (Maletz, Rushton & Lindholm). BO/CIN15/009, SMF 75377. (d) *Pseudophyllograptus* sp., two associated specimens, BOL/CIN42B/001A, SMF 75378. (e) *Baltograptus minutus* (Tullberg), BOL/CIN42A/004, SMF 75379. (f) *Azygograptus* sp., Ja01/1, SMF 75380. (g) *Expansograptus urbanus* (Monsen), typically reflexed specimen, slender stipes, SMF 75381. (h) *Baltograptus calidus* group, Sella, SMF 75382. (i) *Baltograptus* cf. *deflexus* (Elles & Wood). BOL/CIN42H/001, SMF 75383. (j) *Expansograptus protobalticus* (Monsen). Strongly reclined specimen, tectonically distorted, CLP29.5, SMF 75384. (k) *Expansograptus holmi* (Törnquist). BO/CUL15F05, SMF 75385. (l) *Baltograptus vacillans* (Tullberg), BO/CUL15F22, SMF 75386. CUL, CLP = Culpina; CIN = Cineguillas. Lines near (a) and (j) indicate tectonic lineation. Magnification for all specimens:  $\times 5$ , except (a)  $\times 4$ , (d)  $\times 2.5$ .

range of *Tetragraptus phyllograptoides* is not found in Bolivia or Scandinavia.

*Expansograptus protobalticus* is commonly associated with *Baltograptus geometricus* in Scandinavia and was also found to be associated with this species in Bolivia. The faunal association in Bolivia lacks a few slender elements found in Scandinavia, especially of the genus *Paradelograptus*, but this might be due to the strong tectonization of the material, in which slender species might easily be missed. Better preserved material is necessary to document the true faunal diversity at this level.

Interestingly, *Tetragraptus approximatus* (Maletz & Egenhoff, 2001, fig. 8/2,3, SMF 755390, 75391) appears only in the *Expansograptus protobalticus* Biozone in Bolivia, thus its local first appearance is in younger strata than it is in the Hunneberg region of Sweden, where the earliest specimens are associated with *Tetragraptus phyllograptoides* in the basal *Tetragraptus phyllograptoides* Biozone (Maletz, Löfgren & Bergström, 1996). The reason for this

delayed first occurrence is not known but may be related to the paucity of this species in the lower part of its range and the extremely thick Bolivian succession, where the chance to find certain graptolites is relatively low.

### 3.h. The *Expansograptus holmi* Biozone

**Definition.** The base of the zone is taken at the first occurrence of *Expansograptus holmi* (Fig. 5k) at the 2100 m level (CIN 28, Cb-96-6) in the Cieneguillas 1 section.

**Fauna.** *Expansograptus holmi*, *Expansograptus urbanus* (Fig. 5g), *Pseudophyllograptus* sp. (Fig. 5d), *Baltograptus vacillans* (Fig. 5l), *Baltograptus* sp. cf. *Baltograptus deflexus* (Fig. 5i), *Tetragraptus serra* (Fig. 5a), *Tetragraptus amii*, *Acrograptus filiformis*.

**Remarks.** At the base of the *Expansograptus holmi* Biozone, horizontal expansograptids have their first occurrence. *Expansograptus holmi* and *Expansograptus urbanus* are usually common and easily identified

in Scandinavia in this interval (Maletz, Löfgren & Bergström, 1996) and have been discovered in Bolivia. Slightly later the first declined *Baltograptus* forms appear in Bolivia, followed by deflexed species of the genus.

### 3.i. The *Baltograptus minutus* Biozone

**Definition.** The *Baltograptus minutus* Biozone is defined at Cieneguillas-Chaupiuno, where the species appears about 150 m above the base of the Pircancha Formation (Heuse, Grahn & Erdtmann, 1999, fig. 4). This level corresponds to *c.* 200 m in Cieneguillas 2 section of Egenhoff (2000, p. 148).

**Fauna.** *Baltograptus minutus* (Fig. 5e), *Baltograptus* sp. cf. *Baltograptus deflexus*, *Tetragraptus serra*, *Baltograptus calidus* group (Fig. 5h), *Tetragraptus amii*, *Pseudophyllograptus* sp.

**Remarks.** Maletz, Kley & Reinhardt (1995) first used the *Baltograptus minutus* Biozone for this interval in the Sama-Chaupiuno region, based on the most common and easily identified pendent didymograptid. *Baltograptus minutus* is well known from the *Pseudophyllograptus densus* Biozone of Scandinavia (Monsen, 1937). Due to uncertainties in the identification of many phyllograptids and pseudophyllograptids it is here preferred to use *Baltograptus minutus* as the index species for this interval as well. Phyllograptids are also rare in southern Bolivia and the poor preservation precludes specific identifications in most cases.

### 3.j. The *Azygograptus lapworthi* Biozone

**Definition.** The base of the zone is taken at the first occurrence of *Azygograptus lapworthi* at the top of the Pircancha Formation in the Cieneguillas-Chaupiuno section of Heuse, Grahn & Erdtmann (1999, fig. 4).

**Fauna.** *Pseudophyllograptus angustifolius elongatus*, *Azygograptus lapworthi* (Fig. 5b), *Tetragraptus amii*, *Tetragraptus serra*, *Expansograptus* sp. indet. or *Xiphograptus* sp. indet.

**Remarks.** The base of the *Azygograptus lapworthi* Biozone is here taken at the first occurrence of this species. Graptolite faunas of this interval are rare in the southern Bolivian sections and it might be difficult to recognize the interval. However, recent field-work produced specimens of *Azygograptus* (Fig. 5f) from the northern end of the Camargo syncline (see Heuse, Grahn & Erdtmann, 1999, fig. 1), north of the study area. These specimens appear more slender and bear widely spaced thecae and thus are not included in *Azygograptus lapworthi*. *Azygograptus* seems to be quite common a few metres below the erosional unconformity with the Cretaceous.

### 3.k. The *Isograptus victoriae* Biozone

**Definition.** The base of this Biozone is not defined here, as the data are too poor for any reliable identification of this unit.

**Fauna.** *Isograptus victoriae*, *Xiphograptus* sp. cf. *Xiphograptus lofuensis*, *Pseudophyllograptus* sp., *Tetragraptus* sp.

**Remarks.** Isograptids were previously unknown from Bolivia and most of the Gondwanan part of South America. Müller (J. Müller, unpub. Ph.D. thesis, Freie Univ. Berlin, 2000) discovered this material at Challa Mayu. The strongly tectonized specimens of *Isograptus victoriae* (Fig. 6b) are associated with a number of other graptolites.

A single specimen of *Isograptus caduceus* cf. *nanus* was figured by Bahlburg *et al.* (1990) from Cordon de Escaya in the northern Puna of Argentina representing the only further record of isograptids from the Gondwanan part of South America. Isograptids are, however, common in the late Arenig and early Darriwilian of the Argentine Precordillera (Turner, 1959; Ortega, Toro & Brussa, 1993; Brussa, Mitchell & Astini, 1998; Ortega & Albanesi, 1999).

### 3.l. Middle and Upper Ordovician graptolites

Middle and Upper Ordovician graptolite faunas are known to occur in a number of localities to the west, but have not been investigated in detail. Bulman (1931) described Llanvirn and Caradoc faunas. Finney & Branisa (1984) described the peculiar *Gymnograptus floweri* from the locality Iskay Mokho. The species is known from five specimens not associated with other fossils. Steinmann & Hoek (1912) and Turner (1959) apparently figured material originating from the same locality. These faunas are mostly not collected from measured sections and the true biostratigraphic relationships are uncertain. Thus, a biozonation is not proposed here for this time interval. Egenhoff *et al.* (2002) discussed the Middle Ordovician graptolites of the Jurcuma Formation of southern Bolivia and concluded that they belong to *Urbanekograptus retioloides* (Wiman), a species known from the *Hustedograptus teretiusculus* Biozone of Scandinavia.

## 4. Biostratigraphic correlation

Biostratigraphic correlation is best with sections in Scandinavia and Gondwana (Fig. 7). The graptolite faunas of these regions share important faunal elements (Maletz & Ortega, 1995; Lehnert, 1995) and belong to the Atlantic faunal province. The Bolivian succession clearly belongs to the Atlantic faunal realm, as is seen from many species, especially *Hunnegraptus copiosus*, *Tetragraptus phyllograpoides*, the *Baltograptus* species and *Azygograptus* in the late Tremadoc to mid-Arenig.



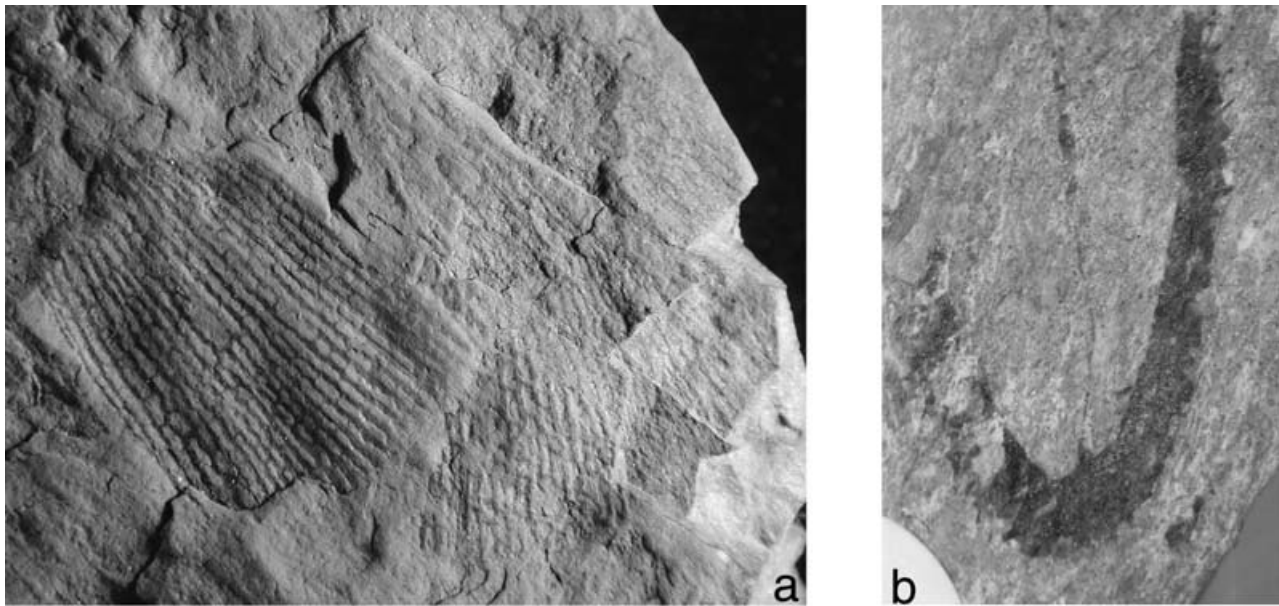


Figure 6. (a) *Rhabdinopora flabelliformis* ssp., Ca-96-3, 80 m level, SMF 75387,  $\times 2.5$ . (b) *Isograptus victoriae victoriae* (Hall), Challa Mayu, SMF 75388,  $\times 7.5$ .

ORDOVICIAN	MIDDLE	ARENIG	Bolivia	Scandinavia	Eastern North America	Australasia
			<div style="border: 1px solid black; padding: 2px; text-align: center;"> <i>Isogr. victoriae</i> </div> <i>Azygogr. lapworthi</i> <i>Baltograptus minutus</i> <i>Expansograptus holmi</i> <i>Expansogr. protobalticus</i> <i>Tetragr. phyllograptoides</i> <i>Hunnegraptus copiosus</i> <i>Araneograptus murrayi</i> <i>Aorograptus victoriae</i> <i>Adelograptus sp.</i> <i>Rhabdinopora flabelliformis</i>	<i>Didymograptus hirundo</i> <i>P. ang. elongatus</i> <i>Pseudophyllogr. densus</i> <i>Expansogr. balticus</i> <i>Expansogr. protobalticus</i> <i>Tetragr. phyllograptoides</i> <i>Hunnegraptus copiosus</i> <i>Araneograptus murrayi</i>  <i>Adelograptus tenellus</i> <i>Rhabdinopora f. anglica</i> <i>Anisograptus matanensis</i> <i>Rhabdinopora f. parabola</i> <i>Rhabdinopora praeparabola</i>	<i>Isograptus victoriae maximodivergens</i> <i>Isograptus v. victoriae</i> <i>Isograptus v. lunatus</i> <i>Didymograptellus bifidus</i> <i>Pendeograptus fruticosus</i> <i>T. akzharensis</i> <i>T. approximatus</i>  <i>Araneograptus murrayi</i>  <i>Aorograptus victoriae</i> <i>Adelograptus sp.</i> <i>Rhabdinopora f. anglica</i> <i>Anisograptus matanensis</i> <i>Rhabdinopora f. parabola</i> <i>Rhabdinopora praeparabola</i>	<b>Ca 3-4</b> <b>Ca 2</b> <b>Ca 1</b> <b>Ch 1-2</b> <b>Be 1-4</b> <b>La 3</b>  <b>La 2</b>  <b>La 1b</b>  <b>La 1a</b>
Upper Cambrian		TREMADOC	<b>no planktic graptolites</b>	<b>no planktic graptolites</b>	<b>no planktic graptolites</b>	

Figure 7. Correlation chart for the Lower Ordovician of Bolivia, Scandinavia, North America, Australasia.

The pandemic elements, however, are an important part of the faunas also and enable the detailed international correlation. *Araneograptus murrayi* and *Tetragraptus approximatus* represent the most typical and widely distributed pandemic faunal elements. *Tetragraptus approximatus* has even been used to define the base of the Arenig. It was unknown from South America, except for the record by Martin, Malanca & Sureda (1987), and regarded as a Pacific faunal element (Cooper, Fortey & Lindholm, 1991; Berry, 1992).

The Darriwilian, Middle Ordovician graptolite faunas of Bolivia have not been investigated here.

Bulman (1931) described graptolite faunas from a number of localities including pendent didymograptids and a few biserials. The pendent didymograptids clearly belong to the Llanvirn types (Cooper & Fortey, 1982; Maletz, 1994) of Gondwanan or Atlantic faunal province with a long supradorsal part of the slender sicula and a very low origin of the first theca. The Arenig *Didymograptellus* from the Pacific faunal province bears a wide and short sicula with a prosicular origin of the first theca, but is unknown from South America except from the Argentine Precordillera.

#### 4.a. South America

Lower Ordovician graptolite faunas are well known from South America and have been described extensively from Argentina. Unfortunately the information is scattered in numerous papers dealing with individual faunal assemblages. Maletz & Ortega (1995) gave a short overview of faunas described at that time and referred them to the Atlantic faunal province. Moya *et al.* (1994) described a number of faunal associations from the eastern Cordillera of Argentina that ranged from the earliest Tremadoc to the early Arenig. Specimens identified as *Isograptus* sp. (Moya *et al.* 1994, pl. 4, figs 9, 10) and referred to the mid-Arenig *Isograptus* Biozone (assemblage 10) are among the youngest graptolites recorded from the region. They have to be reassigned to *Tetragraptus phyllograptoides* of earliest Arenig age, however, as is the specimen on their plate 4, figure 12 found in assemblage 11. Faunal assemblage 9 bears *Araneograptus murrayi*, identified as *Dictyonema yaconense* by Moya *et al.* (1994). Moya, Monteros & Monaldi (1998) used graptolites of the *Tetragraptus phyllograptoides* Biozone to date the Tumbaya unconformity in the Eastern Cordillera of the Argentinian Andes. Ortega, Albanesi & Rao (1998) described further graptolite faunas from the *Tetragraptus phyllograptoides* Biozone of the eastern Cordillera of Argentina.

Toro (1993, 1997a) for the first time documented the succession from the Eastern Cordillera of Argentina in more detail. The presence of *Baltograptus turgidus* (Lee) and *Baltograptus kunmingensis* (Ni) in the *Baltograptus deflexus* Biozone of Bolivia is important for the correlation of this interval and the first time that these conspicuous faunal elements were described from outside of China. The species of the *Baltograptus calidus* group (Maletz, 1994) were previously known only from southwest China, but not described from established successions. Toro (1999a,b) also recognized the peculiar *Baltograptus bolivianus* for the first time from outside its type locality (Finney & Branisa, 1984). Toro (1994, 1997a) described the *Didymograptellus bifidus* Zone faunas as the youngest faunas from the Eastern Cordillera. The presence of the Pacific faunal province type *Didymograptellus bifidus* in this region of apparent Atlantic province relationships still needs to be explained. Comparable early Ordovician graptolite faunas with *Tetragraptus phyllograptoides* and a number of *Baltograptus* species are also known from the Sistema de Famatina (Toro, 1997b; Toro & Brussa, 1997).

#### 4.b. Scandinavia

The early Tremadoc succession of Scandinavia was revised by Cooper *et al.* (1998) and includes four biozones, mainly based on different subspecies of *Rhabdinopora flabelliformis*. This interval can easily

be correlated with the *Rhabdinopora flabelliformis* Biozone of Bolivia, even though a finer subdivision has not been possible in this region so far. *Rhabdinopora flabelliformis parabola* has been identified at the 570 m level at Taraya by Egenhoff (2000), who indicated a thick early Tremadoc interval below the first appearance of this species, based on the occurrence of Tremadoc trilobites (B. Weber, pers. comm. 1999). The next younger graptolitic level is about 440 m higher up and already belongs to the *Tetragraptus phyllograptoides* Biozone.

The *Adelograptus* Biozone is documented in Bolivia through the common occurrence of *Adelograptus* specimens and can be correlated with the *Adelograptus tenellus* Biozone used by Maletz & Egenhoff (2001) for Scandinavia. In Scandinavia the fauna of this zone is poorly known except for the index species. Westergård (1909) described a number of forms from this interval that indicate a more diverse faunal composition in strong need of revision. The correlation with the *Bryograptus ramosus* Biozone of Scandinavia is uncertain, as this species has never been positively recorded outside Scandinavia and the fauna of this interval is not well known.

Maletz & Egenhoff (2001) discussed the international correlation of the *Kiaerograptus kiaeri* Biozone of Scandinavia with the *Aorograptus victoriae* Biozone of eastern North America. Unfortunately, true *Kiaerograptus* specimens, except for *Kiaerograptus supremus* Lindholm, have not been discovered in Bolivia or Argentina to support this correlation, even though *Aorograptus victoriae* is common at certain levels in monospecific assemblages.

*Araneograptus murrayi* appears to be a long-ranging species with its last occurrence in the basal *Tetragraptus approximatus* Biozone (Maletz & Egenhoff, 2001). It is generally rare in Scandinavia (Lindholm, 1991a,b), but was recorded as very common in certain layers in southern Bolivia. A *Kiaerograptus supremus* Biozone was not differentiated by Maletz & Egenhoff (2001), because both species first occur at the same level in Bolivia. Therefore, the authors suggested that the presence of *Kiaerograptus supremus* below *Araneograptus murrayi* in the Krapperrup core of southern Scandinavia might be due to local ranges or the limited data available from the core samples.

Faunas of the *Tetragraptus phyllograptoides* and *Expansograptus protobalticus* biozones are well known from Scandinavia and were recently discussed by Maletz, Löfgren & Bergström (1996), but faunas of the *Expansograptus balticus* to *Pseudophyllograptus angustifolius elongatus* biozones have not been analysed since Monsen's (1937) monograph of the Tøyen Shale (Unterer *Didymograptus* Schiefer) faunas of Norway. Identifications of phyllograptids from the interval are especially difficult and the differentiation of the *Pseudophyllograptus densus* and *Pseudophyllograptus angustifolius elongatus* biozones

remains problematic. Investigation of the type material of *Pseudophyllograptus angustifolius elongatus* from the Llanvirn of Bolivia (Bulman, 1931) indicates that the species belongs to the genus *Glossograptus*. It is not identical to the mid-Arenig species identified by Monsen (1937) as *Pseudophyllograptus angustifolius elongatus*. As *Baltograptus minutus* is common in the *Pseudophyllograptus densus* Biozone in Norway (Monsen, 1937; Maletz, 1994), a correlation with the *Baltograptus minutus* Biozone of Bolivia is easily possible.

Isograptids appear first in the *Didymograptus hirundo* Biozone in Scandinavia (Monsen, 1937; Spjeldnaes, 1953), but typical *Isograptus victoriae* have not been found. Nevertheless, the *Isograptus victoriae* level of Bolivia can be correlated with a level within the lower part of the Scandinavian *Didymograptus hirundo* Biozone.

#### 4.c. North America

The Tremadoc faunal succession of North America was correlated internationally by Cooper *et al.* (1998) and Maletz & Egenhoff (2001) in some detail. The faunas are in most aspects similar to those of southern Bolivia, except for the lack of distinct endemic Atlantic faunal elements. The Arenig graptolite faunas of eastern North America are well documented from the Cow Head Group of western Newfoundland (Williams & Stevens, 1988), and conflicting interpretations were expressed for the correlation of the base of the *Tetragraptus approximatus* Biozone by Williams *et al.* (1999) and Maletz (1999). The fauna of the *Pendeograptus fruticosus* Biozone can be compared with that of the Scandinavian *Didymograptus balticus* Biozone, in which *Pendeograptus fruticosus* is a common element (Monsen, 1937). That species was not found, however, in Bolivia. Also the *Didymograptellus bifidus* and *Isograptus victoriae lunatus* biozones of North America can only indirectly be correlated to the Bolivian succession as they share few elements.

#### 4.d. Australasia

As the biozonation of Australasia mostly relies on individual layers with graptolites separated by thick unfossiliferous intervals, the correlation shows a fairly incomplete record. The La 1a is represented by a single graptolite fauna of the *Rhabdinopora scitulum* Biozone that is interpreted to correlate with the uppermost part of the *Rhabdinopora* interval (VandenBerg & Cooper, 1992). *Rhabdinopora scitulum*, however, appears to be identical to *Rhabdinopora flabelliformis parabola*. The associated *Anisograptus compactus* and *Anisograptus delicatulus* possess a quadri-radial proximal end (VandenBerg & Cooper, 1992, fig. 3b,c; misnamed *Adelograptus* in figure caption) and might represent juveniles of *Rhabdinopora flabelliformis parabola*. If

this can be substantiated, the fauna of the La 1a can be referred to the earliest Ordovician biozone of *Rhabdinopora flabelliformis parabola*, a species also found in the Taraya section of southern Bolivia.

The correlation of the La 1b or the *Psigraptus* Biozone is uncertain, but the level is likely to be within the *Aorograptus victoriae* Biozone as *Psigraptus* is phylogenetically closely related to the genus *Kiaerograptus* (Maletz & Egenhoff, 2001). *Psigraptids* are not known from Bolivia and even from South America so far.

There is no doubt about correlating the La 2 with the *Araneograptus murrayi* and *Hunnegraptus copiosus* biozones, even though *Hunnegraptus copiosus* was not found in Australasia. The exact correlation of the Bendigonian (Be 1-4) is not clear, but is certainly with the *Expansograptus protobalticus* and *Expansograptus balticus* (or *Expansograptus holmi*) biozones of Bolivia and Scandinavia. The Bendigonian may start at about the base of the *Expansograptus balticus* Biozone as can be interpreted from the burst in diversity at this level in Australasia. The appearance of a number of expansograptids and multiramous dichograptids is also typical of the *Expansograptus balticus* Biozone in Scandinavia (Maletz, Löfgren & Bergström, 1996). The *Expansograptus protobalticus* interval cannot be differentiated in Australasia, most probably because it is characterized by endemic faunal elements of the Atlantic faunal province. It is here included in the La 2 or the *Tetragraptus approximatus* Biozone.

The correlation of the Chewtonian and Castlemainian follows closely the succession of the North American biozonation. It is difficult to correlate with the Bolivian succession as the Bolivian faunas are more strongly endemic and direct correlation is only possible with the Scandinavian and Gondwanan biozonations.

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