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Hercynian deformation and metamorphism in the Cordillera Oriental of Southern Bolivia, Central Andes

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Abstract

In southern Bolivia the very thick Ordovician siliciclastic rocks of the Cordillera Oriental show folds and a slaty cleavage of pre-Cretaceous age. These deformations had previously been attributed to either the late Ordovician Oclóyic or to the late Devonian to early Carboniferous Eohercynian (Chanic) orogenies. Now, we present K/Ar age determinations from phyllosilicates of the Ordovician slates, which have been interpreted in relation to illite crystallinity data. High anchizonal to epizonal metamorphism is indicated for most of the investigated samples. The majority of the samples have provided ages within the 320–290 Ma interval (late Carboniferous to early Permian), indicating a late Hercynian orogeny. Traces of synchronous orogenic processes are known from different parts of the Central Andes. This points to late Hercynian orogenic activities in that region.

Keywords: Bolivia; Cordillera Oriental; Ordovician; Paleozoic orogenies; K/Ar dating

1. Introduction

The Cordillera Oriental constitutes one of the main morphotectonic units of the Central Andes. In northern Bolivia many of its summits rise above 6000 m; Mt. Illampu (6550 m) is one of the highest elevations of the Andes. In southern Bolivia mountains are, however, below 5000 m in altitude, with a few exceptions. From a geotectonic point of view the Cordillera Oriental belongs to the back-arc of the Andes, together with the Altiplano in the west and the Interandean and Subandean Ranges on its eastern flanks (Fig. 1). The magmatic arc of today is represented by the active volcanoes of the Cordillera Occidental, bordering the Altiplano to the west.

In southern Bolivia the Cordillera Oriental mainly consists of Ordovician rocks with thicknesses of 8000 m or more. Cambrian beds are confined to its eastern

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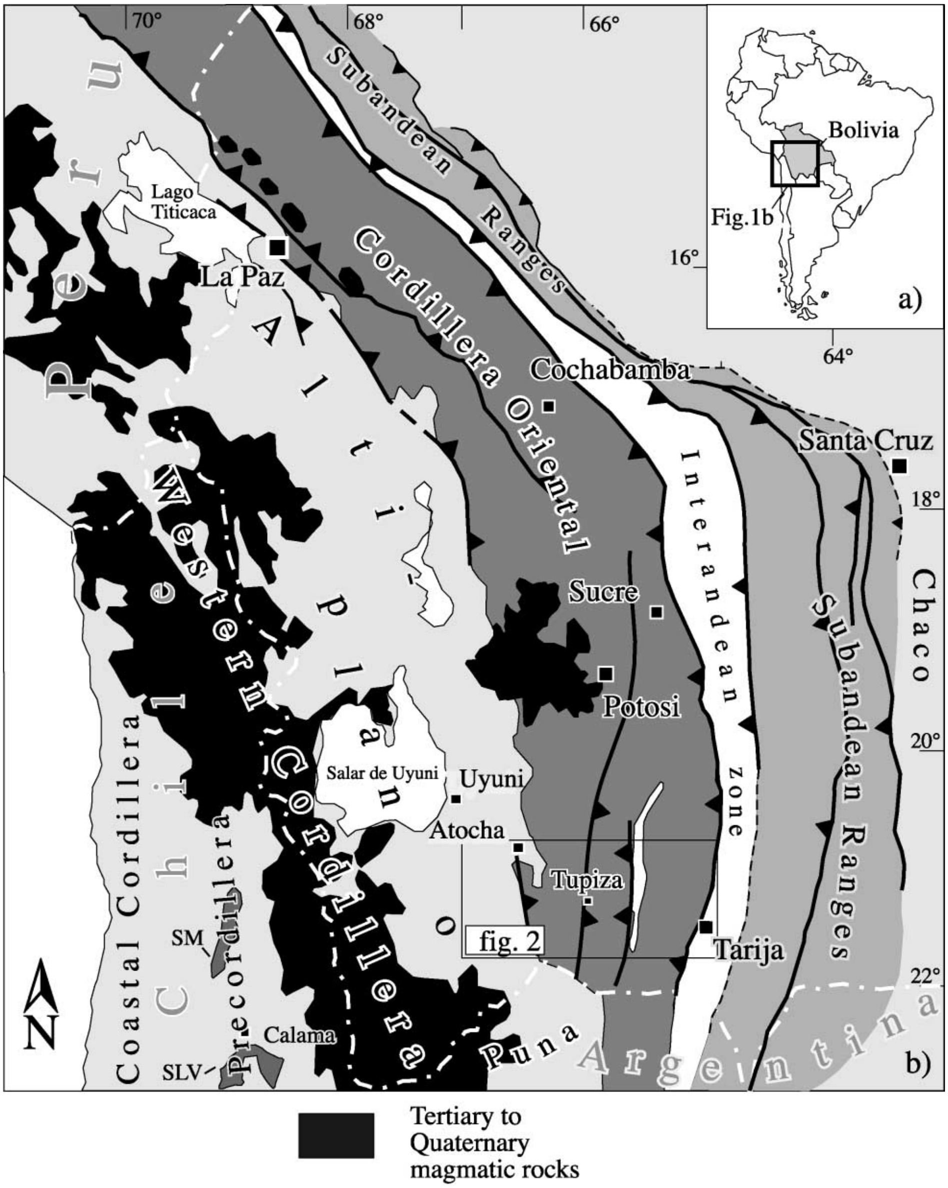

Fig. 1. Structural sketch map of the Bolivian Andes and adjacent regions, with the site of Fig. 2. SM: Sierra de Moreno, SLV: Sierra de Limón Verde.

part, and Precambrian rocks crop out only locally, at the southern border of Bolivia. Silurian and Devonian sediments are restricted to the Interandean zone, south of 20°30′. The Cambro-Ordovician basement is weakly metamorphosed (Kley and Reinhardt, 1994). All rocks of these strata are folded and show a distinct slaty cleavage. In some places, the basement is disconformably covered by Cretaceous to Paleogene sediments and/or by the Neogene infill of intramontane basins.

Two Palaeozoic orogenies have been proposed to explain pre-Cretaceous compressional deformation and metamorphism in the basement of the south Bolivian Cordillera Oriental. In adjacent areas of northern Argentina, on the one hand, these phenomena were assigned to the late Ordovician Oclóyic orogenies, which are well documented there by stratigraphic gaps and/or unconformities and by radiometric data (Turner, 1960; Coira et al., 1982; Mon and Hongn, 1991; Mon and Salfity, 1995). In Peru and northern Bolivia, on the other hand, an Eohercynian (Chanic) orogeny of late Devonian to early Carboniferous age is believed to have caused metamorphism and deformations of the basement (Dalmayrac et al., 1980; Martinez, 1980). In southern Bolivia, however, neither stratigraphic nor radiometric data had existed up to now to fix the age of the main Paleozoic orogeny. But Kley and Reinhardt (1994) found indications of a Hercynian age. From geothermometric measurements of Ordovician rocks along the transect Tarija–Tupiza–San Vicente (Fig. 3), they concluded that these rocks had been overlain during metamorphism by 4–6 km of Paleozoic sediments. Thus, at least parts of that cover are probably younger than Ordovician.

As post-Ordovician Palaeozoic deposits are absent in the basement of the South Bolivian Cordillera Oriental, it is not possible to date post-Oclóyic orogenies by stratigraphic means. Therefore, the present authors decided on radiometric dating of phyllosilicates, which had grown during the formation of the slaty cleavage. First steps in this direction have been initiated by our friend Sohrab Tawackoli, who has already presented two of the data discussed below (Tawackoli et al., 1996; Tawackoli, 1999).

2. Cambro-Ordovician basement

Within the basement of the Cordillera Oriental three segments have been distinguished: from E to W, the Yunchará, the Mochará and the Atocha segments (Erdtmann et al., 1995). Later on, Müller (2000) subdivided the Mochará segment into the Tupiza and the Mal Paso subsegments. These segments are bordered by major faults (Fig. 2), at least some of them being of pre-Andean origin. They expose different parts of the Ordovician sequence and, in addition, small changes in facies development, as is regarded subsequently.

The Ordovician of southern Bolivia has been the object of stratigraphical research for several decades. Fundamental results have been published by Rivas et al. (1969) and Rodrigo and Castaños (1978), who referred mainly on sections of the Yunchará segment. Revisions of that work and many new data from the other segments have been supplied by Erdtmann et al. (1995), Müller et al. (1996), and Müller (2000). We may summarize that the Ordovician sequences are extremely thick and monotonous. They consist of shales and sandstones of variable character, comprising neritic types (e.g. tempestites) as well as fine-grained turbidites. A stratigraphical overview is given in Fig. 3.

Within the Yunchará segment the Cambrian is overlain by about 4600 m of Ordovician rocks. Their stratigraphical sequence comprises Tremadocian to Middle Arenigian deposits, with sandstones predominating at its base (Fm. Iscayachi) and in the upper part (Fm. Agua y Toro). The Mal Paso subsegment adjacent to the west shows 3000–3400 m of Tremadocian to Upper Arenigian sediments. This sequence is very similar to that of the Yunchará segment, but with more pelites at its base. The Tupiza subsegment exhibits only Llanvirnian strata, being at least 1000–1500 m thick. Even younger are the deposits of the Atocha segment, which have yielded only Lower to Middle Caradocian ages, up to now. They are rich in fine-grained sandstones frequently showing slumping structures. The total thickness of the Atocha Ordovician is estimated to be at least 3200 m. It is an open question whether these strata are underlain by the whole Ordovician sequence known from the other segments. If so, the total thickness of the Atocha Ordovician would be 10,000 m or more.

2.1. Pre-Cretaceous deformation

Pre-Cretaceous deformations are not easily recognized, as they have been strongly overprinted everywhere by Andean tectonics in Tertiary times. Regarding the discontinuities at the base of the Cretaceous, their most obvious feature is the strong slaty cleavage of the Ordovician rocks, which does not penetrate the cover. Most of the discontinuities show very low angles ($< 10^{\circ}$), indicating open, wide-spanned folds, but it remains uncertain which of the basement folds observed today are of Paleozoic origin.

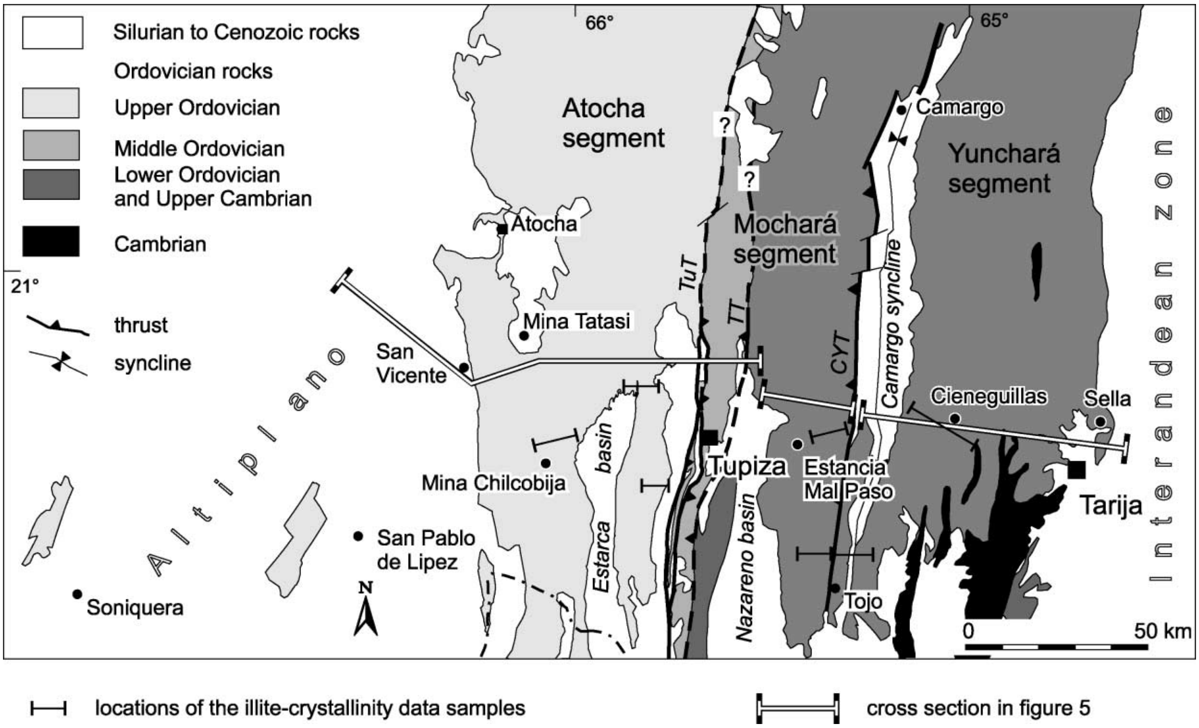

Fig. 2. The Cordillera Oriental and the Altiplano of southern Bolivia. The stratigraphic levels of outcropping Ordovician rocks shallow from E to W. Major thrusts: CT: Chilcobija thrust, CYT: Camargo–Yavi thrust, ET: Estarca thrust, NT: Nazareno thrust, QHT: Quebrada Honda thrust, SVT: San Vicente thrust, TT: Tocloca thrust, TuT: Tupiza thrust.

2.2. Metamorphism

Within the siliciclastic sequence of the South Bolivian Ordovician no minerals have yet been found which would allow a precise determination of the state of metamorphism. Thin sections from slate samples merely show the paragenesis quartz + illite/muscovite + chlorite + kaolinite + feldspar + carbonates + hematite, everywhere, with minor occurrences of pyrite, apatite, zircon, and tourmaline. It is stable over the wide range from advanced diagenesis to the formation of biotite. Therefore, illite crystallinity (IC) was measured in more than 80 samples taken along the traverse Tarija–Tupiza–San Vicente. Fig. 4 shows the distribution of their IC values in relation to the tectonic structures. Since the early studies by Weaver (1960) and Kübler (1968), it has been known that the degree of illite crystallinity depends mainly on temperature conditions, but there is also an additional relationship to deformation. Many geoscientists have accepted the IC technique as a semi-quantitative, empiric or statistic method. It provides best results in the range from low diagenesis to very low-grade metamorphism (anchizone), but it can be used for low-grade metamorphism (epizone) as well. Problems concerning the preparation of the samples and the interpretation and standardization of the IC values have been discussed since this method came in use (e.g. Kisch, 1991; Warr and Rice, 1994). To avoid mixed ages due to synkinematically grown illites intermingled with older detritic ones, we measured the < 2 μm and < 0.2 μm grain-size fractions. In cases where both fractions point to more or less the same age information (± 25 Ma), we assume that detrital illites had been adjusted to the age of the lower or medium anchizone metamorphism. If not, only the data from the < 0.2 μm fraction may indicate the age of metamorphism, whereas the < 2 μm fraction may still contain detrital components. In the temperature regime of high anchizonal to epizonal metamorphism, the < 2 μm fraction yields the reliable age information, and the

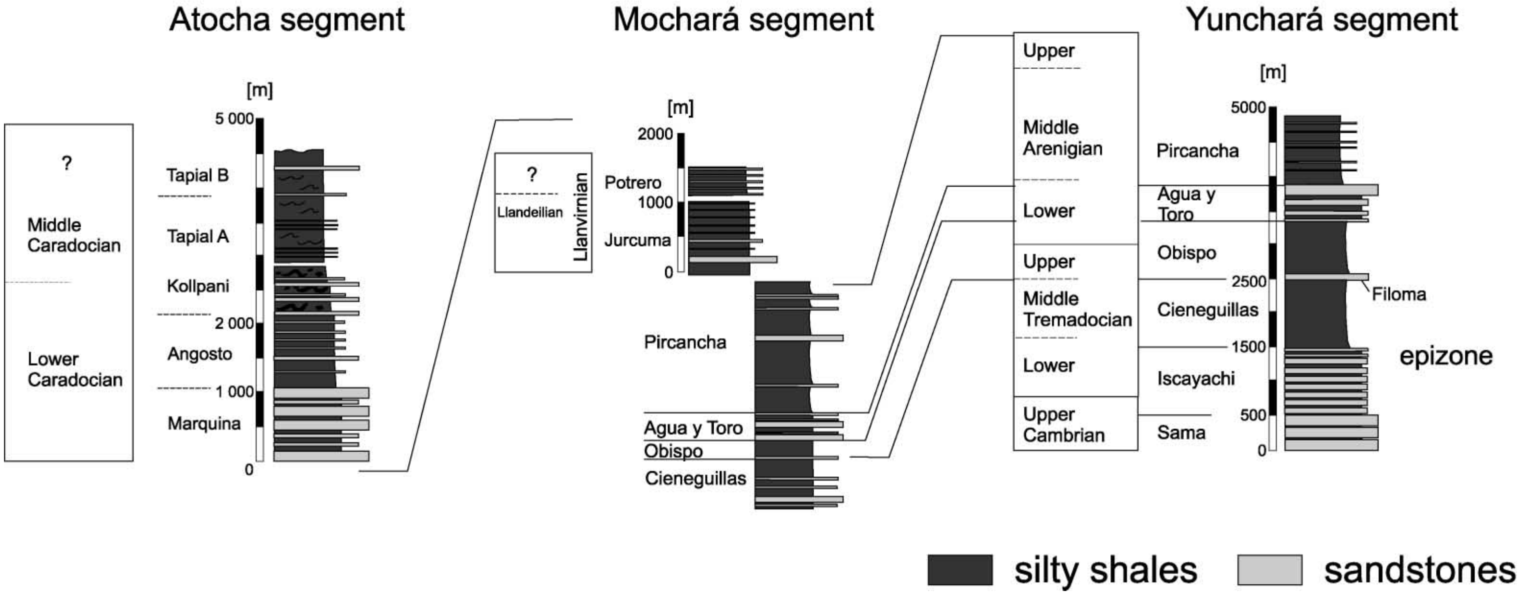

Fig. 3. Ordivician stratigraphy in the Cordillera Oriental of southern Bolivia (modified after Müller, 2000).

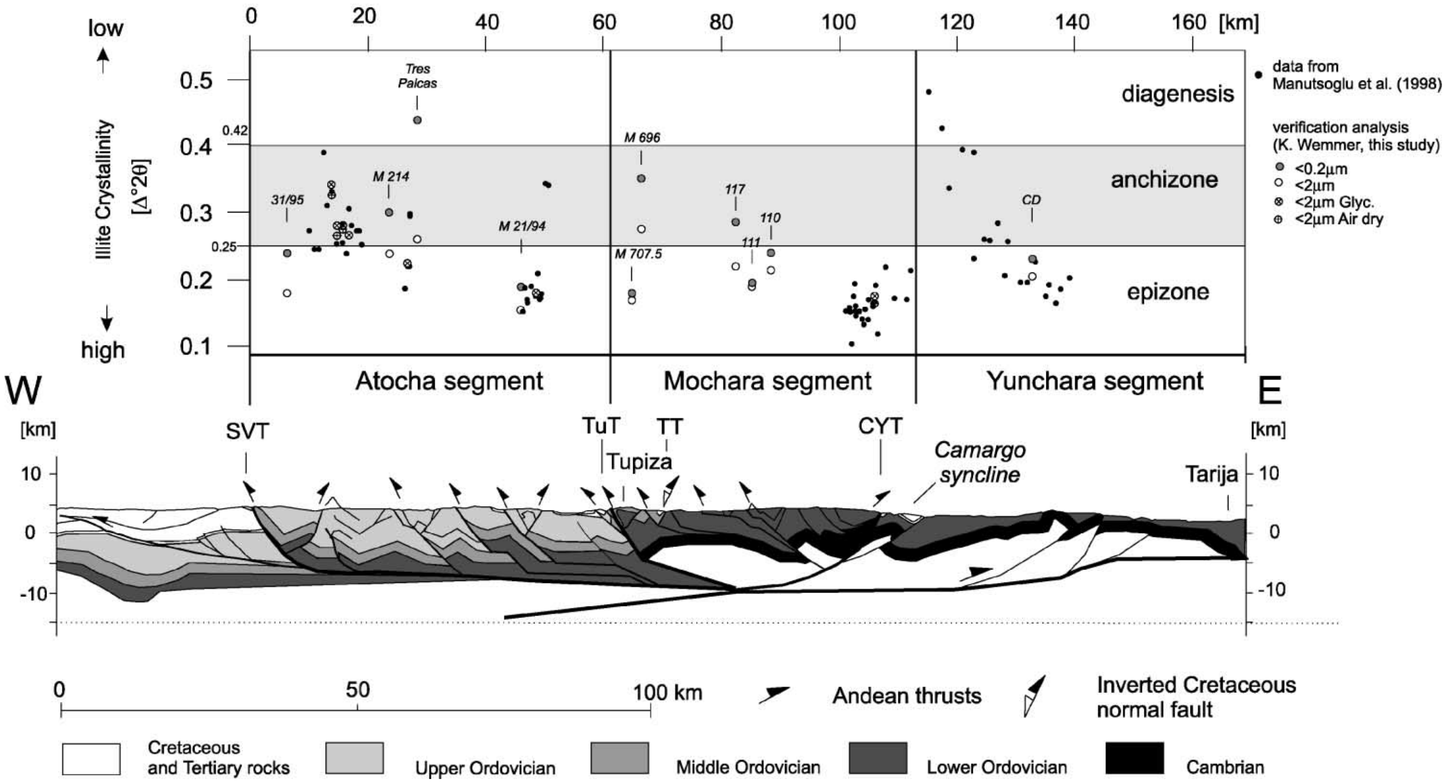

Fig. 4. Distribution of the measured IC values (Manutslogu, unpublished report, 1997) in relation to regional geology (cross-section modified after Müller, 2000).

ages of the < 0.2 μm fraction may indicate the end of metamorphism. Possible misinterpretations caused by detrital IC values can be avoided by accompanying K–Ar age determinations.

IC values reported by Manutsoglu et al. (1998) and given in this study are summarized in relation to regional geology, i.e. to a generalized cross-section along our geotraverse (Fig. 4). In the Yuncharà segment the characteristic IC values $\Delta 2\Theta$ range between 0.18 and 0.48, showing a continuous transition from epizone to the border of anchizone/diagenesis in the direction E to W. Within the Mocharà segment the $\Delta 2\Theta$ values vary from 0.110–0.230 (epizone) in the east to 0.170–0.350 (epizone to anchizone) in its western part. The Atocha segment shows an irregular distribution of the IC values, which range from 0.153 to 0.435 (epizone to diagenesis). These results correlate well with the geothermometric data of Kley and Reinhardt (1994), who have analysed vitrinite reflectance and infrared spectroscopy of organic matter, illite crystallinity, and fluid inclusions of Ordovician slates of the same region. They also correspond with the IC values of Doherr (1983), measured in late Proterozoic schists farther to the south in north-westernmost Argentina. Thus, it seems likely that the slaty cleavage of both areas may have been produced by the same orogenic process.

3. Analytical procedure

3.1. The samples

Twelve samples of Ordovician metapelites and metasiltites have been selected for K–Ar age determination. Their locations and stratigraphic positions are listed in Table 1.

3.2. Sample preparation and analytical procedure for K–Ar dating and IC measurements

Slates and siltstones of 2–3 kg were sampled to process the separation of the fine mineral fractions < 2 μm and < 0.2 μm for the K/Ar age determinations. The

Table 1
Locations and stratigraphic positions of the samples for K–Ar age determination

Sample	Region	*Y*-coords., *X*-coords. (UTM)	Zone number (spheroid = international)	Latitude/ longitude	Stratigraphic position (see Fig. 3)
31/95	Mina Tatasi	76 52,000 7 87,000	UTM19S	21°12′ 38″ S 66°14′ 08″ W	Angosto unit
M 214	Mina Chilcobija	76 36,350 8 10,000	UTM19S	21°20′ 53″ S 66°00′ 41″ W	Tapial B subunit
Tres Palcas 95	Mina Chilcobija	76 45,200 1 90,100	UTM20S	21°16′ 06″ S 65°59′ 10″ W	Angosto unit
M21/94/96	Tupiza	76 39,750 2 02,250	UTM20S	21°19′ 10″ S 65°52′ 12″ W	Marquina unit
M 707.5 and M 707.5-2	Tupiza	76 50,930 2 22,770	UTM20S	21°13′ 19″ S 65°40′ 14″ W	Fm. Jurcuma
M 696	Tupiza	76 49,900 2 23,030	UTM20S	21°13′ 53″ S 65°40′ 06″ W	Fm. Jurcuma
117	Estancia Mal Paso	76 38,000 2 38,250	UTM20S	21°20′ 27″ S 65°31′ 25″ W	Fm. Pircancha
111	Estancia Mal Paso	76 37,500 2 40,000	UTM20S	21°20′ 44″ S 65°30′ 25″ W	Fm. Obispo
110	Estancia Mal Paso	76 33,400 2 43,400	UTM20S	21°22′ 59″ S 65°28′ 29″ W	Fm. Pircancha
K 181	Estancia Mal Paso	Coordinates not defined by Tawackoli 1999			Fm. Pircancha
CD	Cieneguillas	76 35,800 2 88,350	UTM 20	21°22′ 03″ S 65°02′ 30″ W	Fm. Cieneguillas

rocks were crushed and ground in a shatter mill (vibration mill) for about 20 s and split into sizes > 63 μm and < 63 μm. The < 63 μm fractions were used to extract the < 2 μm clay fractions by settling in Atterberg cylinders. A second < 2 μm fraction was gained the same way and used to separate the < 0.2 μm fractions by means of an ultra-centrifuge. All these fine fractions were examined (XRD) for mineralogical composition and determination of the illite crystallinity (IC). IC, the peak width at half the height of the 10-Å peak, was determined using a computer program developed at the University of Göttingen. Digital measurement of IC was carried out by step scan (301 points, 7–10° (2Θ), scan step 0.010° (2Θ), integration time 4 s, receiving slit 0.1 mm, automatic divergence slit). IC values are given in ($\Delta°2\Theta$). The limits for diagenesis/anchizone and anchizone/epizone are 0.600° to 0.400° and 0.240° ($\Delta°2\Theta$), respectively. These limits were checked in the interlaboratory standardization program of Warr and Rice (1994). The given IC values are nearly identical with the crystallinity index standard (CIS).

The IC values of Manutsoglu et al. (1998) are restricted to the < 2 μm fraction. The grain size separation was carried out by centrifugation. The IC values were determined using the machine conditions recommended by Kisch (1991). Duplicate analyses in several parts of the section have shown that the IC values of this study lead to comparable results.

The argon isotopic composition was measured in a Pyrex glass extraction and purification line coupled to a VG 1200 C noble gas mass spectrometer operating in static mode. The amount of radiogenic ^{40}Ar was determined by the isotope dilution method using a highly enriched ^{38}Ar spike from Schumacher, Bern (Schumacher, 1975). The spike is calibrated against the biotite standard HD-B1 (Fuhrmann et al., 1987). The age calculations are based on the constants recommended by the IUGS, quoted in Steiger and Jäger (1977).

Table 2
Data base of K–Ar age determinations

Institut für Geologie und Dynamik der Lithosphaere, Goldschmidtstr. 3, 37077 Goettingen

Sample	Spike [No.]	K_2O [wt.%]	$^{40}Ar^*$ [nl/g] STP	$^{40}Ar^*$ [%]	Age [Ma]	2σ-error [Ma]	2σ-error [%]
110 < 2 μm	2062	5.69	64.89	98.38	323.1	6.7	2.1
110 < 0.2 μm	2063	5.19	52.23	96.89	288.0	5.9	2.1
111 < 2 μm	2060	6.10	67.02	98.28	312.2	7.0	2.3
111 < 0.2 μm	2061	6.31	63.95	97.38	289.8	6.2	2.1
117 < 2 μm	2073	6.07	71.92	98.66	334.6	7.2	2.1
117 < 0.2 μm	2074	5.91	61.37	98.07	296.4	7.4	2.5
M 21/94/96 < 2 μm	2126	7.29	33.47	86.98	137.1	3.2	2.3
M 21/94/96 < 0.2 μm	2125	7.07	31.51	84.30	133.2	4.5	3.3
M 707.5 < 2 μm	2124	6.03	45.54	96.50	220.3	5.2	2.3
M 707.5 < 0.2 μm	2123	6.31	45.01	95.50	208.7	5.5	2.6
M 707.5-2 < 2 μm	2540	6.02	46.14	98.41	223.4	4.7	2.1
M 707.5-2 < 0.2 μm	2538	5.45	37.79	98.42	203.2	4.8	2.4
M 696 < 2 μm	2536	5.92	51.54	98.61	251.7	6.5	2.6
M 696 < 0.2 μm	2534	5.84	38.02	97.68	191.5	4.1	2.2
K 181 < 2 μm	1659	5.41	59.07	98.15	310.2	6.5	2.1
K 181 < 0.2 μm	1793	5.41	53.11	97.62	281.2	5.8	2.1
M 214 < 2 μm	1661	6.29	84.50	96.95	374.8	8.0	2.1
M 214 < 0.2 μm	1791	6.57	75.33	97.60	324.5	6.9	2.1
Tres Palcas < 2 μm	1748	6.35	82.87	97.56	365.1	7.5	2.1
Tres Palcas < 0.2 μm	1749	5.28	57.90	94.19	311.5	7.0	2.2
31/95 < 2 μm	1750	6.94	85.67	95.00	347.1	7.3	2.1
31/95 < 0.2 μm	1751	6.39	64.28	88.43	287.7	7.8	2.7
CD < 2 μm	2544	6.47	71.13	97.46	312.4	7.0	2.2
CD < 0.2 μm	2542	6.78	65.39	97.75	276.9	7.3	2.6

Potassium was determined in duplicate by flame photometry using an Eppendorf Elex 63/61. The samples were dissolved in a mixture of HF and HNO_3 according to the technique of Heinrichs and Herrmann (1990). CsCl and LiCl were added as ionisation buffer and internal standard, respectively.

Table 3
Illite crystallinity values of investigated samples

Sample	Grain size	Preparation	Counts/s	IC $\Delta°2\Theta$	IC ϕ $\Delta°2\Theta$	Degree of metamorphism
31/95	< 2 μm A	Air dry	458	0.180		
31/95	< 2 μm B	Air dry	501	0.180	0.180	epizone
31/95	< 0.2 μm A	Air dry	181	0.240		
31/95	< 0.2 μm B	Air dry	171	0.240	0.240	epizone/anchizone
M 214	< 2 μm A	Air dry	648	0.240		
M 214	< 2 μm B	Air dry	672	0.235	0.238	epizone/anchizone
M 214	< 0.2 μm A	Air dry	284	0.300		
M 214	< 0.2 μm B	Air dry	310	0.300	0.300	middle to high anchizone
Tres Palcas	< 2 μm A	Air dry	1097	0.260		
Tres Palcas	< 2 μm B	Air dry	998	0.260	0.260	higher anchizone
Tres Palcas	< 0.2 μm A	Air dry	374	0.450		
Tres Palcas	< 0.2 μm B	Air dry	378	0.420	0.435	lowermost anchizone
M 21/94/96	< 2 μm A	Air dry	752	0.160		
M 21/94/96	< 2 μm B	Air dry	737	0.170	0.165	epizone
M 21/94/96	< 0.2 μm A	Air dry	663	0.180		
M 21/94/96	< 0.2 μm B	Air dry	682	0.200	0.190	epizone
M 707.5/-2	< 2 μm A	Air dry	852	0.160		
M 707.5/-2	< 2 μm B	Air dry	777	0.180	0.170	epizone
M 707.5/-2	< 0.2 μm A	Air dry	714	0.180		
M 707.5/-2	< 0.2 μm B	Air dry	734	0.180	0.180	epizone
M 696	< 2 μm A	Air dry	793	0.270		
M 696	< 2 μm B	Air dry	1273	0.280	0.275	higher anchizone
M 696	< 0.2 μm A	Air dry	620	0.310		
M 696	< 0.2 μm B	Air dry	980	0.390	0.350	middle anchizone
117	< 2 μm A	Air dry	1094	0.220		
117	< 2 μm B	Air dry	1175	0.220	0.220	lower epizone
117	< 0.2 μm A	Air dry	489	0.290		
117	< 0.2 μm B	Air dry	476	0.280	0.285	higher anchizone
111	< 2 μm A	Air dry	578	0.190		
111	< 2 μm B	Air dry	668	0.190	0.190	epizone
111	< 0.2 μm A	Air dry	579	0.200		
111	< 0.2 μm B	Air dry	671	0.190	0.195	epizone
110	< 2 μm A	Air dry	749	0.210		
110	< 2 μm B	Air dry	747	0.220	0.215	lower epizone
110	< 0.2 μm A	Air dry	397	0.250		
110	< 0.2 μm B	Air dry	553	0.230	0.240	epizone/anchizone
K 181	< 2 μm A	Air dry	520	0.220		
K 181	< 2 μm B	Air dry	546	0.210	0.215	lower epizone
K 181	< 0.2 μm A	Air dry	321	0.270		
K 181	< 0.2 μm B	Air dry	318	0.260	0.265	higher anchizone
CD	< 2 μm A	Air dry	510	0.220		
CD	< 2 μm B	Air dry	558	0.190	0.205	lower epizone
CD	< 0.2 μm A	Air dry	460	0.250		
CD	< 0.2 μm B	Air dry	624	0.220	0.235	lower epizone

Definition of boundaries: Diagenetic zone/anchizone: 0.600–0.400 $\Delta°2\Theta$; Anchizone/epizone: 0.240 ± 0.10 $\Delta°2\Theta$.
According to the suggestion by Krumm & Warr on their Very Low Grade Metamorphism Homepage (http: //www.geol.Uni-Erlangen.de/vlgm/index.html) the following correlation to mineral facies is appropriate: diagenetic zone to zeolite facies; anchizone to the prehnite–pumpellyite facies plus the pumpellyite–actinolite facies; epizone to the greenschist facies.

The analytical error for the K/Ar age calculations is given on a 95% confidence level (2σ).

4. Results

4.1. Radiometric age determination

The laboratory data and results of the age and illite crystallinity determinations of our samples are given in Tables 2 and 3. They are listed according to their position in the section from W to E.

A consistent set of ages was derived from the samples 110, 111, 117, K 181 and CD. These samples cover about 120 km of our traverse. The ages of the < 2 μm fraction scatter from 335 to 310 Ma; all IC values clearly point to epizonal conditions. The accompanying < 0.2 μm fractions yield ages from 296 to 277 Ma. Their IC reflects epizonal to highest anchizonal conditions. In this temperature regime, detrital components are reset in age or negligibly small (e.g. Hunziker et al., 1986; Clauer and Chauduri, 1999). Within these samples the differences in age between both fractions are quite small, indicating a single event for the formation of the synkinematically grown illites.

Therefore, the time span from 320 to 290 Ma can be considered to be the peak of epizonal metamorphism and the formation of the cleavage in the investigated Ordovician strata. Comparable to the above-mentioned five samples, the < 0.2 μm fraction of sample 31/95 yields an age of 288 Ma. The question why the < 2 μm fraction of this epizonal sample is significantly higher (347 Ma) cannot be answered now.

Samples M 214 and Tres Palcas show older age values in both the < 2 μm and the < 0.2 μm fractions. A detrital component and/or influences of an older metamorphism that has only partly been reset during Hercynian metamorphism have to be assumed. This assumption is in good agreement with the IC values indicating only anchizonal metamorphism temperatures.

The last four samples to be discussed show totally different age patterns. Sample M 707.5 yields K–Ar ages of the upper Triassic time (220 Ma in the < 2 μm and 209 Ma in < 0.2 μm fractions). To check the significance of these ages, a duplicate sample from the same outcrop was analysed (M 707.5-2). The age pattern of this sample confirms the upper Triassic age (223 Ma in < 2 μm and 203 Ma in < 0.2 μm). Sample M 696 located nearby was expected to show similar data, but in fact yields meaningless mixed ages (252 Ma in the < 2 μm, 192 Ma in the < 0.2 μm fractions). The corresponding IC values of middle to higher anchizone combined with a difference of 60 Ma between both fractions document a low temperature disturbance of the isotope system which has to be younger than 192 Ma. Cretaceous ages are provided by sample M 21/94/96 (137 Ma in the < 2 μm and 133 Ma in the < 0.2 μm fractions).

The interpretation of these samples is still doubtful. It is remarkable that all IC values of M 707.5, 707.5-2, and M 21/94/96 point to epizonal thermal conditions and that the differences in age of both fractions within the samples are extremely small. These analytical facts may point to thermal influences of both late Triassic and early Cretaceous magmatism.

5. Discussion and conclusions

The majority of our samples has provided K–Ar ages of the 320–290 Ma interval (late Carboniferous to early Permian). Therefore, we attribute metamorphism and slaty cleavage of the Ordovician rocks to late Hercynian orogenic processes. Traces of Eohercynian compressional deformations, which had been expected mainly by Argentinian geologists, could not be observed in the Cordillera Oriental of southern Bolivia.

Indications of orogenic processes in late Carboniferous and early Permian times have recently been found in several areas of the southern Central Andes. Within the Chilean Precordillera, adjacent to southern Bolivia, considerable compressional deformations seem to have occurred in early Late Carboniferous times (Toco event, Bahlburg and Breitkreuz, 1991). From the same range (Sierra de Moreno) as well as from the Chilean Coastal Cordillera, granitic to dioritic intrusions have been reported by Lucassen and Franz (1997), with K–Ar cooling ages of 330–270 Ma. Metamorphic rocks in contact with the Precordilleran plutons mostly yielded identical K–Ar ages, measured from amphiboles and biotites (Becchio et al., 1999), probably reflecting thermal influences during intrusion. Farther to the S in the Precordillera (Sierra de Limón Verde), Damm et al. (1990) have found indications for late Hercynian metamorphism and plutonism as well, with U–Pb zircon ages between 300 and 275 Ma.

Hitherto, structures of compressional deformation with ages around the Carboniferous/Permian boundary have never been reported from the Central Andes south of the orocline. But the late Paleozoic Chaco–Tarija basin, Bolivia, E of the Cordillera Oriental, has recently been interpreted as a foreland basin in relation with an E-vergent orogenic belt situated farther W, i.e. in the regions of the present Altiplano and the Cordillera Oriental (Isaacson and Díaz Martínez, 1995). Our new data would fit in with that view.

Summarizing, we find different traces of late Hercynian orogenic activities, being widely dispersed over the southern Central Andes. Certainly, our present knowledge is not yet sufficient to draw out the geometries of a possible late Hercynian orogenic belt in the Central Andes. But we consider our results to be a further step in that direction.

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