The Late Permian Peine and Cas Formations at the eastern margin of the Salar de Atacama, Northern Chile: stratigraphy, volcanic facies, and tectonics

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ABSTRACT

A late Permian 2 km thick volcaniclastic succession is well exposed in the area between the Cerros de Cas and Cerro Lanquir at the eastern margin of the Salar de Atacama in northern Chile. From base to top it consists of the three members of the Peine Formation and the three members of the Cas Formation. The terrestrial succession is dominated by products of andesitic to rhyodacitic effusive and explosive volcanism. Only in the Middle Member of the Peine Formation sedimentary deposits are predominant. Here, lacustrian, flood and braid plain facies interfinger laterally in a basin-basin margin setting. Deposition was accompanied by extensional tectonics. From sedimentary and volcanic paleocurrent indicators of the Peine and Cas Formations, and geochemical data of magmatic rocks of the region, it is inferred that the succession was formed at the eastern margin of an extensional intra-arc basin. Volcanic facies analyses reveal that, at least, some of the basic and silica-rich volcanic centres were located close to or even within the field area. The thick ignimbrites and proximal fall out deposits of the Middle Member of the Cas Formation are supposed to belong, together with ring dyke and central intrusions, to a late Permian caldera complex, which is located in the Cerro Lanquir area (Lanquir Caldera Complex).

Key words: Late Permian, Peine Formation, Cas Formation, Stratigraphy, Volcanism, Intra-arc extension, Northern Chile.

RESUMEN

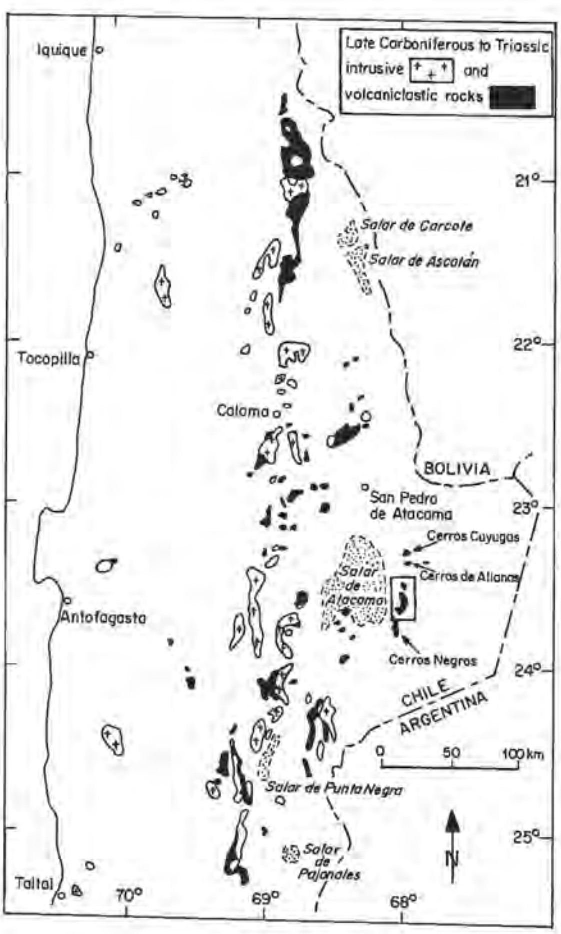
Las formaciones Peine y Cas del Pérmico tardío en el margen oriental del Salar de Atacama, norte de Chile: estratigrafía, facies volcánica y tectónica. Una sucesión volcaniclástica del Pérmico tardío, de 2 km de espesor, aflora excepcionalmente en el área entre Cerros de Cas y Cerro de Lanquir, en el margen oriental del Salar de Atacama. De la base al techo, la sucesión consiste en los tres miembros de la Formación Peine y los tres miembros de la Formación Cas. Las rocas terrestres se componen, principalmente, de productos andesíticos a riodacíticos de un volcanismo efusivo y explosivo. Sólo en el Miembro Medio de la Formación Peine predominan depósitos sedimentarios, con facies lacustre, de planicies de inundación, y de planicies de ríos anastomosados, que engranan lateralmente en un ambiente de cuenca y de margen de cuenca. La deposición estuvo acompañada por una tectónica extensional. En base a indicadores de paleocorrientes sedimentarias y volcánicas en las formaciones Peine y Cas, además de datos geoquímicos de rocas magmáticas de la región, se presume que la sucesión se formó al borde oriental de una cuenca intra-arco extensional. El analisis de facies volcánicas indica que por lo menos, algunos de los centros volcánicos tanto de bajo como de alto contenido de sílice, estuvieron situados en, o cerca del área estudiada. Se supone que los depósitos ignimbríticos de gran espesor, los depósitos proximales de caída de pómez del Miembro Medio de la Formación Cas, así como de las intrusiones centrales y anulares forman parte de un complejo de caldera pérmico tardío, en el área de Cerro Lanquir (Complejo Caldera Lanquir).

Palabras claves: Pérmico tardío, Formación Peine, Formación Cas, Estratigrafía, Volcanismo, Extensión intra-arco, Norte de Chile.

Revista Geológica de Chile, Vol. 22, No. 1, p. 3-23, 11 Figs., 3 Tables, 2 Pls., July 1995.

INTRODUCTION

Spectacular outcrops of late Paleozoic volcanic and sedimentary rocks are known from the eastern margin of the north Chilean Salar de Atacama. Preliminary lithological and stratigraphic accounts have been given by García (1967) and Moraga *et al.* (1974); a more detailed description has been provided by Ramírez and Gardeweg (1982). The successions form part of the Peine Group (Bahlburg and Breitkreuz, 1991), which comprise all late Carboniferous-Triassic volcanosedimentary rocks in northern Chile (text-Fig. 1). Among the outcrops of the Peine Group, most attention has been paid so far to the stratigraphy, depositional facies and geochemistry of the successions cropping out in the vicinity of the Salar de Atacama (Ramírez and Gardeweg, 1982; Marinovic and Lahsen, 1984; Davidson *et al.*, 1985; Osorio and Rivano, 1985, Breitkreuz, 1986, 1991, Breitkreuz *et al.*, 1989; Breitkreuz *et al.*, 1992; Flint *et al.*, 1993; Breitkreuz and Zeil, 1994).



Text-FIG. 1. Late Carboniferous to Triassic intrusive and volcaniclastic rocks in northern Chile between 20° and 26°S (after Breitkreuz and Zeil, 1994); box marks location of text-figure 2.

At the eastern margin of the Salar de Atacama, Late Paleozoic volcanic and sedimentary rocks crop out, from north to south, in the Cerros Cuyugas, and Cerros de Allana, in a large area between Cerros de Cas and Cerro Lanquir, northeast of Peine, and south of Peine in the Cerros Negros area (text-Figs. 1, 2); Ramírez and Gardeweg, 1982). The relative stratigraphy between the isolated outcrops, which are separated by Cenozoic sediments and volcanic rocks, is not well established. One ignimbrite of the succession at Cerros Cuyugas has been dated as 268±6 Ma (K/Ar, Gardeweg, 1988). Good age control has been gained recently on the succession cropping out between the Cerros de Cas and Cerro Lanquir. Here, 4 ignimbrite samples, one from the base of the succession (I Pyroclastic Flow Deposit, Peine Formation; Table 1), and three from the upper third (VIII Pyroclastic Flow Deposit, Cas Formation and equivalents), yielded similar ages within the error ranges. Breitkreuz and Van Schmus (in press) concluded that these rocks formed within a range of 1 to 6 Ma during the Late Permian (U/Pb zircon age of 249±3 Ma). No age constraints are known for the successions south of Peine.

This contribution summarizes the general geology, the relative stratigraphy, the volcanic facies, and the tectonic elements of the nearly 2 km thick volcaniclastic succession between the Cerros de Cas and the Cerro Lanquir. The sedimentary facies has been studied by Lüdtke (1994) and will be published separately (Breitkreuz, 1991; Breitkreuz and Lüdtke, 1993). Geochemical analyses of the calc-alkaline volcanic rocks have been included in Breitkreuz (1991); Breitkreuz *et al.* (1989) and Breitkreuz and Zeil (1994). Preliminary reports on the postdepositional processes, which include moderate burial and extensive hydrothermal overprint, have been given by Breitkreuz and Schmidt (1994) and Breitkreuz *et al.* (1994a, b).

TABLE 1. LITHOSTRATIGRAPHIC SCHEME OF THE PEINE AND CAS FORMATIONS IN THE AREA BETWEEN QUEBRADA MAL PASO AND CERRO CHUNAR (SEE TEXT-FIGURE 2 FOR LOCATIONS).

<table>
<tr><th></th><th></th><th>Quebradas Mal Paso and Cerros de Cas</th><th>Quebrada Algarrobilla</th><th>Quebrada Caballo Muerto</th><th>Mina Sicipo</th><th>Quebrada Sicipo</th><th>SW' Cerro Pinusca</th><th>N' and W' Cerro Chunar</th></tr>
<tr><td rowspan="9">Cas Formation</td><td>Upper Member</td><td></td><td></td><td>?</td><td></td><td></td><td></td><td>IX Lava Flow Deposit</td></tr>
<tr><td rowspan="3">Middle Member</td><td>Pyroclastic Flow Deposit</td><td></td><td></td><td></td><td colspan="3">IX Pyroclastic Flow Deposit</td></tr>
<tr><td>Lava Flow Deposit</td><td></td><td></td><td></td><td></td><td></td><td>Red Beds</td></tr>
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<tr><td rowspan="5">Lower Member</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">VIII Lava Flow Deposit</td></tr>
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<tr><td></td><td></td><td></td><td colspan="4">V Pyroclastic Flow Deposit</td></tr>
<tr><td rowspan="16">Middle Member</td><td></td><td></td><td></td><td colspan="4">III Conglomeratic Braid Plain Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">V Lake Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">II Mixed Pyroclastic Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">II Conglomeratic Braid Plain Deposit</td><td>V Lava Flow Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">IV Lake Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">I Conglomeratic Braid Plain Deposit / II Sandy Braid Plain Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">IV Pyroclastic Flow Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">III Flood Plain Deposit / Alluvial Channel Deposit / I Sandy Braid Plain Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">III Pyroclastic Flow Deposit</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">II Flood Plain Deposit</td><td></td><td></td></tr>
<tr><td></td><td></td><td>?</td><td>IV Lava Flow Deposit</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td>III Lake Deposit</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>I Flood Plain Deposit</td><td></td><td></td><td></td><td></td></tr>
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<tr><td colspan="3">I Lake Deposit</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Lower Member</td><td colspan="3">II Lava Flow Deposit</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">II Pyroclastic Flow Deposit</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">I Pyroclastic Flow Deposit</td><td></td><td colspan="3">Lava Flow Deposit:? Lower Member?</td></tr>
<tr><td colspan="3">I Mixed Pyroclastic Deposit</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">I Lava Flow Deposit</td><td></td><td></td><td></td><td></td></tr>
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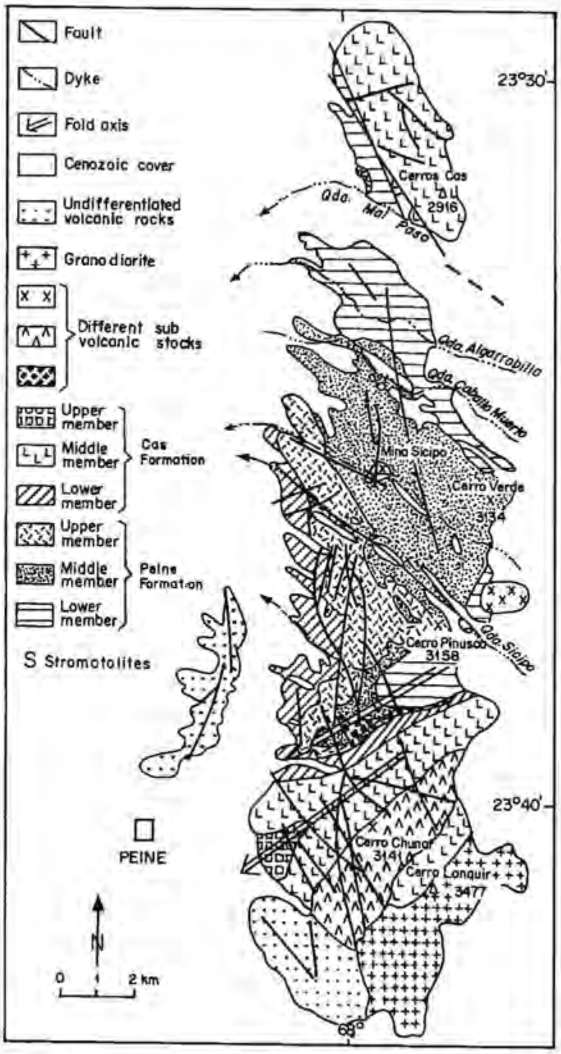
STRATIGRAPHIC RELATIONS AND VOLCANIC FACIES

Extended field work, carried out in the area northeast of Peine since 1984, resulted in some modifications of the map published by Ramírez and Gardeweg (1982). As shown in text-figures 2 and 3, the volcaniclastic succession comprises the three members of the Peine Formation (Ramírez and Gardeweg, 1982), overlain by the three members of the Cas Formation. Ramírez and Gardeweg showed faults separating the Peine Formation from the silica-rich successions of the Cas Formation at Cerros de Cas and in the Cerro Chunar area, and assumed that the Cas Formation is older than the Peine Formation. However, detailed mapping of the area between Cerro Pinusca and Cerro Chunar revealed a depositional contact, where the Cas Formation rests on all three Members of the Peine Formation with an erosional unconformity (text-Figs. 2 and 3). A southwest-northeast trending dacitic subvolcanic intrusion with northwest trending apophyses was emplaced in the area of the erosional unconformity. As it will be discussed below, lithological and isotopic similarities point to a simultaneous formation of the silica-rich volcanic rocks at Cerros de Cas and the Cas Formation at Cerro Chunar, as assumed already by Ramírez and Gardeweg (1982). South of the village of Peine, a succession of basic volcanic rocks crops out (Estratos Cerros Negros; Ramírez and Gardeweg, 1982). On the basis of lithological similarity, Ramírez and Gardeweg correlated this succession with the basic lavas and red beds which overlie the Upper Member of the Peine Formation, north of Peine (text-Fig. 2). Since there are no stratigraphic data for a correlation with the Estratos Cerros Negros south of Peine, the author proposes to call the succession north of Peine, the 'Lower Member' of the Cas Formation (Table 2).



Text-FIG. 2. Geological map of the area northeast of Peine (modified after Ramírez and Gardeweg, 1982 and Breitkreuz and Zeil, 1994); for location see text-figure 1.

TABLE 2. STRATIGRAPHIC DEFINITION OF THE CAS FORMATION FOR THE AREA BETWEEN CERROS DE CAS AND CERRO DE CHUNAR*.

Ramirez and Gardeweg 1982	Breitkreuz and Zeil 1994	This paper
Cas Formation	Chunar III Beds	Upper Member, Cas Formation
Cas Formation	Chunar II Beds	Middle Member, Cas Formation
Estratos Cerros Negros	Chunar I Beds	Lower Member, Cas Formation

* On the suggestion of one of the reviewers, the author used in this contribution the name 'Cas Formation' instead of 'Chunar Beds' as in Breitkreuz and Zeil (1994).

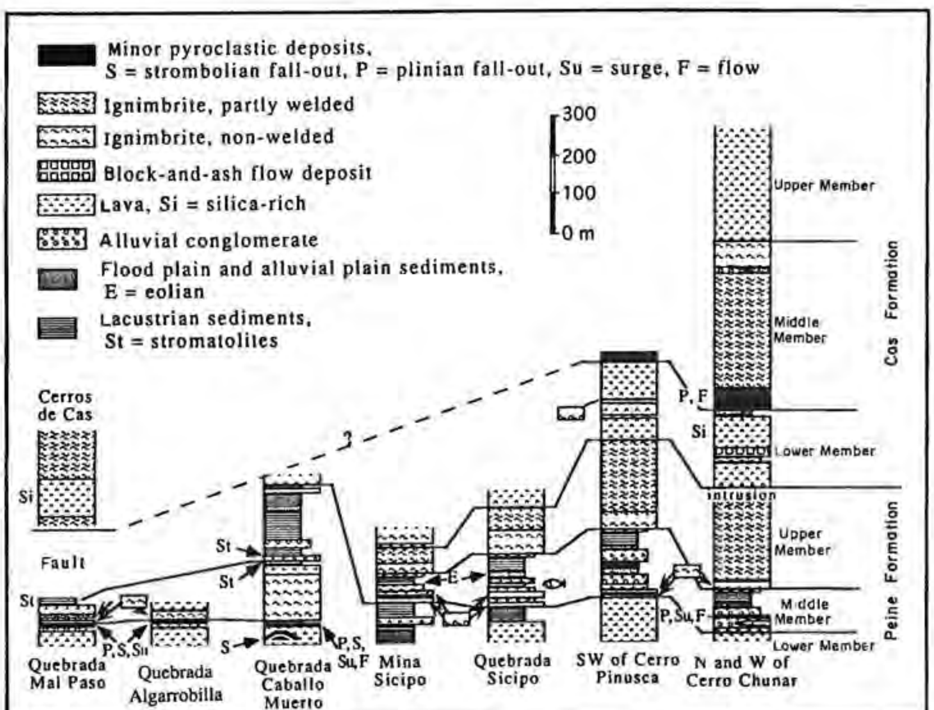
PEINE FORMATION

Lower Member

The volcanic rocks and minor alluvial sediments of the Lower Member of the Peine Formation (Tables 1 and 3) are exposed in the quebradas Mal Paso, Algarrobilla and Caballo Muerto and in some areas between these valleys (text-Figs. 2 and 3). The lowermost beds are andesitic lavas, which crop out to the north of Quebrada Algarrobilla. However, the base of the Lower Member and thus, of the Peine Formation is not exposed. The pile of andesitic lavas that forms the core of a southwest-plunging anticline south of Cerro Pinusca is tentatively correlated with the Lower Member. However, no criteria are available to exclude a younger formation age for these lavas, namely, during Middle Member time.

Magnificent exposures of the subaerial volcanic facies of the Lower Member can be observed in the southern wall of the Quebrada Algarrobilla (text-Fig. 4). The valley floor and lower part of the walls are characterized by andesitic lavas and coarse-grained volcaniclastic deposits. The latter consists mainly of basic scoria and lava fragments which are organized in coarsely parallel- to low-angle dipping beds. In the western part of the outcrop two relicts of scoria cones with obliquely dipping beds of agglutinates can be recognized (text-Fig. 4). This indicates that, at least, some basic volcanic centres were located within the field area during Lower Member time. The basic volcanic deposits are overlain by a mixed pyroclastic succession (I Mixed Pyroclastic Deposit), which is exposed in the quebradas Mal Paso, Algarrobilla, Caballo Muerto and north of Cerro Verde. As depicted in text-figures 4 and 5, it consists of silica-rich fall out, surge and flow deposits alternating with silica-poor fall out and surge deposits as well as reworked volcaniclastic beds and one eolian sandstone. No paleodirectional indicators have been found in the volcanic units. Some lee-set measurements in cross-bedded fluvial and eolian deposits in the Quebrada Caballo Muerto section (text-Fig. 5) point to a sedimentary transport from western and northern directions during Lower Member time.

The southern shoulder of the Algarrobilla canyon is marked by a silica-rich ignimbrite (I Pyroclastic Flow Deposit, Tables 1 and 3; text- Fig. 4), which can be traced from the Quebrada Mal Paso to the Quebrada Caballo Muerto, and which forms the key stratigraphic bed of the Lower Member (text-Fig. 3). The non-

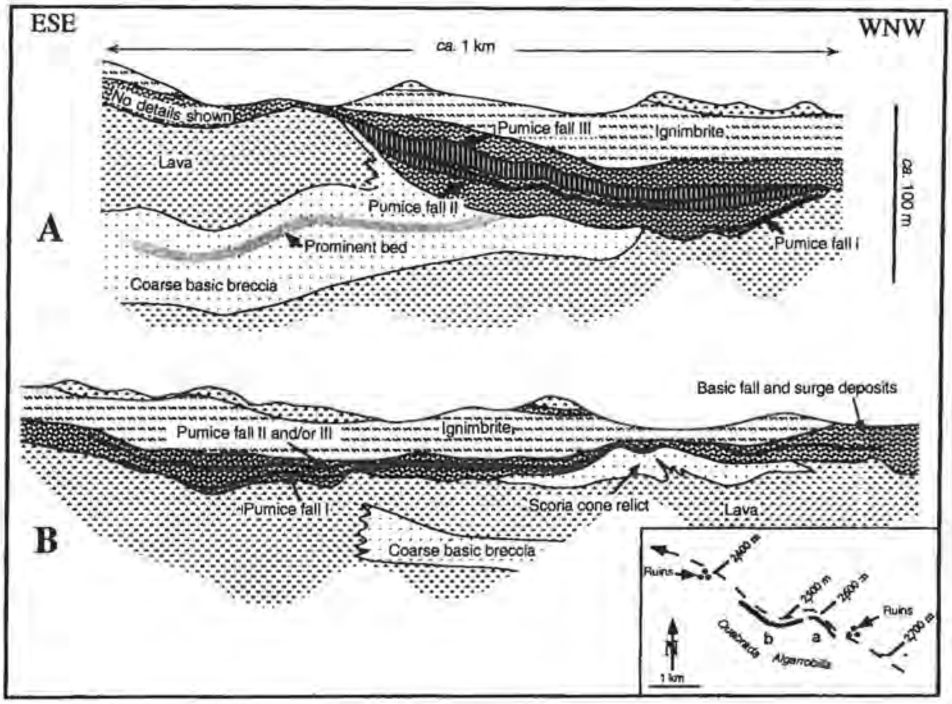


Text-FIG. 3. Lithostratigraphic columns of the Peine and Cas Formations between Quebrada Mal Paso and Cerro Chunar, for location see text-figure 2.

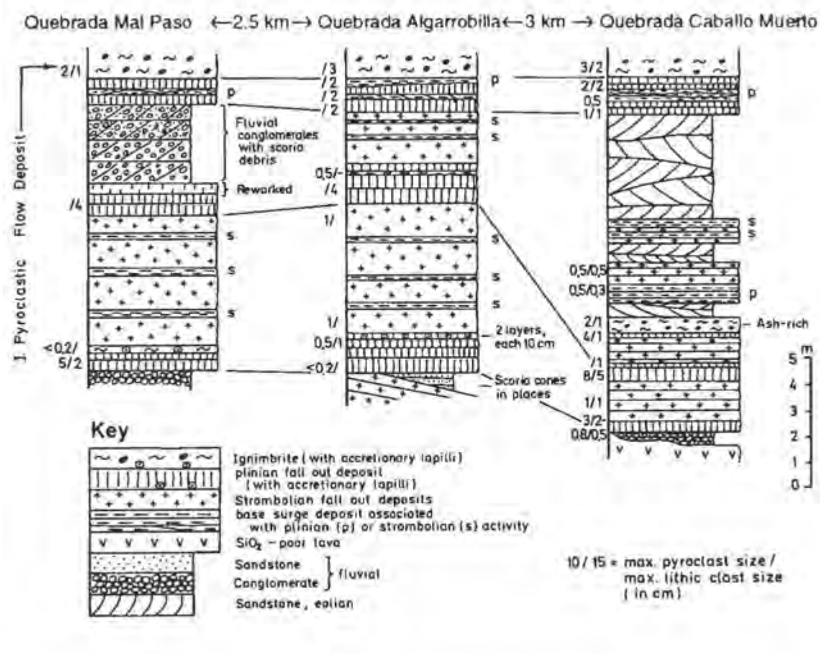
TABLE 3. VOLCANIC DEPOSITS OF THE PEINE AND CAS FORMATIONS.

		Lithostratigraphic unit	Texture	Geochemical facies	Volcanic facies	Phenocrysts	Lithics
Cas Formation	* Upper Member	Pyroclastic Flow Deposit	partly welded	rhyodacite	ignimbrite	plg, pyx	(volcanic)
		Lava Flow Deposit	obsidian breccia	rhyodacite	subaerial lava	qz	
		IX Lava Flow Deposit	aphanitic/porphyritic	andesite	subaerial	plg, cpx, opx	
	Middle Member	IX Pyroclastic Flow Deposit	non-welded	rhyodacite	ignimbrite	(plg, qz)	(volcanic)
			partly welded	rhyodacite	ignimbrite	qz, plg, kf, bt	(volcanic)
		VIII Pyroclastic Flow Deposit	partly welded	rhyodacite	initial flow/fall	qz, plg, kf, bt	volcanic
	Lower Member	VIII Lava Flow Deposit	porphyritic	rhyodacite	subaerial lava	plg, cpx, hbl	
		Block-and-ash Flow Deposit	massive	rhyodacite	block-and-ash flow deposit	plg, hbl	
		VII Lava Flow Deposit	porphyritic	andesite	subaerial lava	plg, cpx, opx	
		VII Pyroclastic Flow Deposit	non-welded	rhyodacite	ignimbrite	qz, plg, bt	(volcanic)
		VI Lava Flow Deposit	porphyritic	andesite	subaerial lava	plg, cpx, opx	
Peine Formation	Upper Member	VI Pyroclastic Flow Deposit	partly welded	rhyodacite	ignimbrite	plg, opx	(volcanic)
		V Pyroclastic Flow Deposit	non-welded	rhyodacite	ignimbrite	plg, (qz, ?kf)	volcanic
	Middle Member	II Mixed Pyroclastic Deposit	non-welded	rhyodacite	surge/fall/flow	plg	volcanic
		V Lava Flow Deposit	porphyritic	andesite	subaerial lava	plg, cpx, opx	
		IV Pyroclastic Flow Deposit	non-welded	rhyodacite	ignimbrite	plg	volcanic
		III Pyroclastic Flow Deposit	non-welded	rhyodacite	ignimbrite	plg, (qz, pyx)	volcanic
		IV Lava Flow Deposit	porphyritic	basaltic andesite	partly subaquatic	plg	
		III Lava Flow Deposit	porphyritic	andesite	subaerial lava	plg, cpx, opx	
	Lower Member	II Lava Flow Deposit	trachytic	andesite	subaerial lava	plg, cpx, opx	
		II Pyroclastic Flow Deposit	non-welded	rhyodacite	ignimbrite	plg,? kf	volcanic
		I Pyroclastic Flow Deposit	non-welded	rhyodacite	ignimbrite	plg	volcanic
		Lava Flow Deposit*	porphyritic	andesite	subaerial lava	plg, cpx	
		I Mixed Pyroclastic Deposit {		andesite	fall/surge	plg	volcanic, sedimentary
				andesite-dacite	surge	plg	volcanic, sedimentary
			non-welded	rhyodacite	ignimbrite	(plg)	volcanic
				rhyodacite	fall	(plg)	volcanic, sedimentary
		I Lava Flow Deposit	trachytic	andesite	subaerial lava	plg, cpx	

* Succession on top of the VII Pyroclastic Deposit- equivalent at Cerros de Cas. * stratigraphic position unclear; () subordinate.



Text-FIG. 4. Sketch of the Lower Member (Peine Formation) cropping out at the SSW wall of Quebrada Algarrobilla, redrawn from various slides, scales are approximate.



Text-FIG. 5. Detailed sections of the I Mixed Pyroclastic Deposit and the base of the I Pyroclastic Flow Deposit (Table 1): outcrops in quebradas Ma. Paso, Algarrobilla and Caballo Muerto.

welded ignimbrite is composed of several depositional units which contain different amounts of lithic clasts, and which in places are separated by ash-rich thin beds or lenses. Across the entire outcrop the thickness ranges between 10 and 20 m. However, where the Quebrada Caballo Muerto cuts through the deposit, the thickness cumulates to approximately 100 m (text-Fig. 3), pointing to a paleodepression or -valley located in that area at the time of flow emplacement. The top of the Lower Member consists of andesitic lavas.

Middle Member

The Middle Member is dominated by lacustrine, flood plain and braid plain deposits. Five lake deposits can be distinguished vertically in the Middle Member (Table 1), which contain horizons rich in conchostracans (Ramírez and Gardeweg, 1982; Gallego and Breitkreuz, 1994) and some fish remains (Richter and Breitkreuz, in press). Flint *et al.* (1993) reported an unpublished study on palynomorphs from the Middle Member, that points to a late Permian-early Triassic? age. This stratigraphic range coincides with the radiometric data of Breitkreuz and VanSchmus (in press) mentioned above.

The lowermost lacustrine unit of the Peine Formation has been defined by the author as the base of the Middle Member. Outcrops in the Quebrada Caballo Muerto show that these lacustrine deposits formed in a sandy delta complex. The orientation of the foresets indicates progradation towards the south (Lüdtke, 1994). The delta front complex is overlain by a delta top association which consists of siliciclastic deposits and a stromatolithic carbonate platform exposed in the area north of Quebrada Mal Paso, north of Quebrada Caballo Muerto, and at the northwestern slope of Cerro Verde (text-Figs. 2, 3).

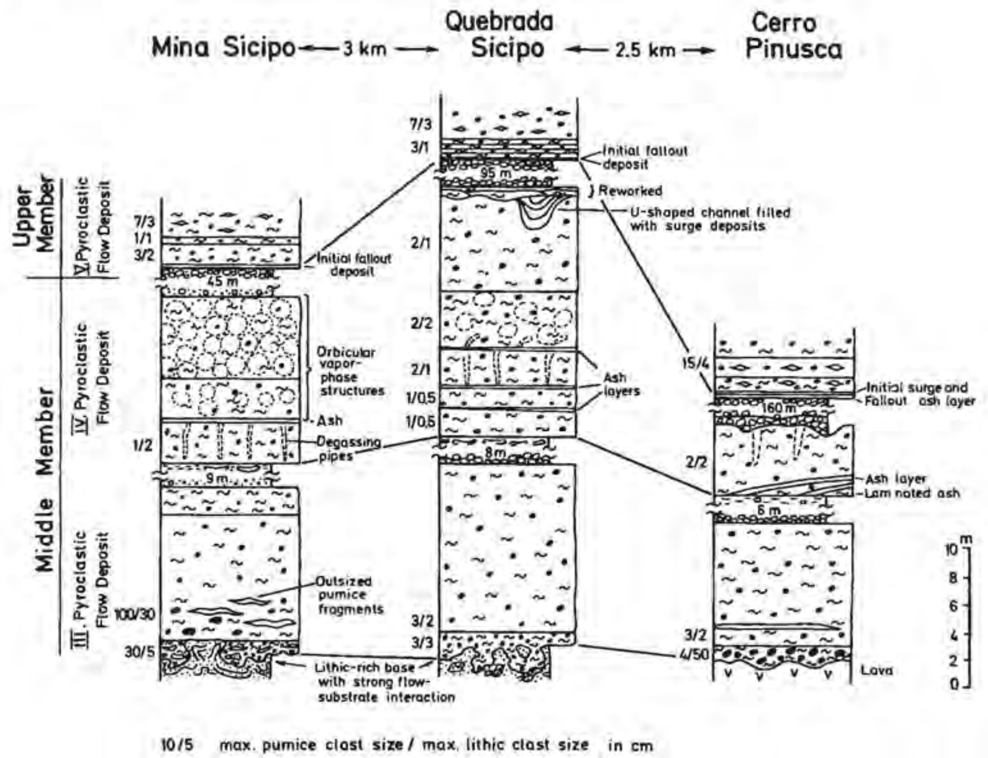
Also in the Quebrada Caballo Muerto area, a lava flow (III Lava Flow Deposit) overlies the delta deposits (Tables 1 and 3). The porphyritic andesite pinches out towards the Cerro Verde area. The top is covered in places by stromatolithic beds which, in turn, are overlain by thick deep-lacustrine delta plain deposits (II Lake Deposit). Coarse-grained mass flow deposits which contain high amounts of basic hydroclasts (Breitkreuz, 1991, Fig. 8) give further evidence of basic volcanic activity during the lower Middle Member. Still in the Quebrada Caballo Muerto, the transition to red flood plain deposits is exposed.

This transition marks the base of the **Upper Middle Member**, which is characterized by two laterally interfingering facies associations. These are: **a-** an open flat basin with alternating flood plain, shallow lacustrine facies and one eolian interval, exposed in the area between Quebrada Caballo Muerto and Quebrada Sicipo, and **b-** a basin margin association with high-energy braid plain deposits exposed in the area southwest of Cerro Pinusca (alluvial facies definition according to Miall, 1985; Blair and McPherson, 1994). Three braid plain progradations are documented in the form of conglomeratic sheets in the basin facies association. Numerous measurements of lee sets and clast orientations in the alluvial deposits of both facies associations reveal transport directions from the east and southeast (Lüdtke, 1994).

In the Middle Member, two further **basic lava units** are intercalated (Tables 1 and 3). The IV Lava Flow Deposit is of basaltic-andesitic composition and strongly porphyritic in places with plagioclase phenocrysts up to 10 cm in size. In the Quebrada Mina Sicipo, pillow lavas indicate a local subaquatic emplacement (Breitkreuz *et al.*, 1989, Fig. 11). The V Lava Flow Deposit is intercalated in the II Conglomeratic Braid Plain Deposit and crops out in the hinge area of the anticline southwest of Cerro Pinusca.

Three **silica-rich pyroclastic deposits** have been recognized in the Middle Member. The III Pyroclastic Flow Deposit, which serves as a key stratigraphic bed for correlation in the area between the Quebrada Caballo Muerto and southwest of Cerro Pinusca (text-Figs. 3 and 7; Tables 1 and 3), is a non-welded 8-12 m thick ignimbrite sheet with a lithic-rich ground layer. The movement and emplacement of this flow on an obviously wet flood plain, resulted in strong interaction with the substrate (text-Fig. 6); (Breitkreuz, 1993, in prep.). Paleoflow indicators, such as the orientation of slump axes and syndepositional faults, point to a northwestward-directed flow (text-Fig. 7). It reflects the local topography at the basin margin during the emplacement rather than a direction away from the eruptive vent (Breitkreuz, 1993, in prep.). The assumption of a northwest or southeastward slope dip is supported by numerous northwest-southeast directed channels cut into the surface of the flow deposit southwest of Cerro Pinusca (text-Fig. 7).

The **IV Pyroclastic Flow Deposit** can be traced from the Quebrada Mina Sicipo to the area southwest of Cerro Pinusca, separated by less than 10 m of sediments from the flow described above. Like the III Pyroclastic Flow Deposit, it is a non-welded ignimbrite

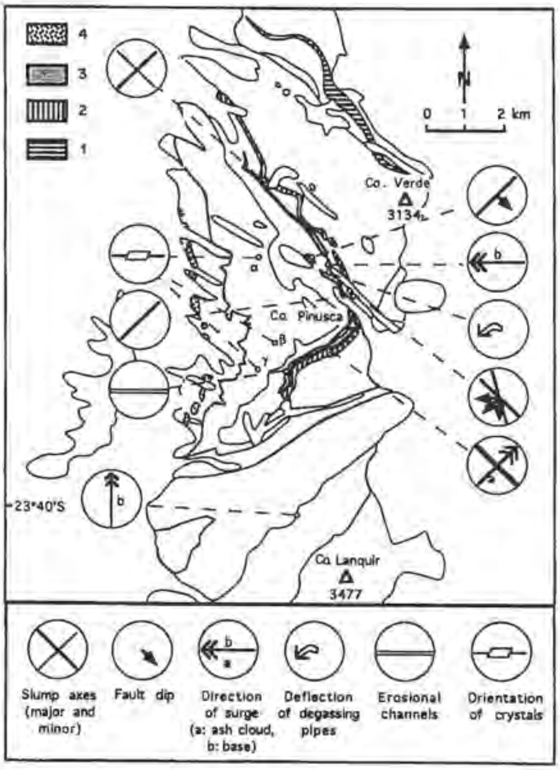


Text-FIG. 6. Detailed sections of the III and IV Pyroclastic Flow Deposit and the base of the V Pyroclastic Flow Deposit (Table 1): outcrops near Mina Sicipo, in Quebrada Sicipo and southwest of Cerro Pinusca.

with a sheet-like geometry and several depositional units separated by ash-rich layers. The maximum thickness of 18 m is exposed in the Quebrada Sicipo, where the IV Pyroclastic Flow Deposit is composed of 5 depositional units (text-Fig. 6). Southwest of Cerro Pinusca, the first two depositional units pinch out towards the southwest (text-Fig. 8; Pl. 1, Fig. 1). No criteria are known from the area to distinguish between an axial pinching out of a southwest directed flow and a lateral 'over bank' effect associated with a northwestward directed flow. Degassing pipes in the third and fourth unit are frequent (Pl. 1, Fig. 3). In the Quebrada Sicipo the pipes in one unit are bent uniformly towards the west, indicating a westwardly directed last movement during settling and degassing (text-Fig. 7). West-east directed channels cut into the surface of this flow deposit in the Cerro Pinusca area, and are in favor of a west- or eastwardly dipping slope. Together with the sedimentary paleocurrent data, these observations support a westwardly dipping slope (text-Fig. 7).

In the outcrop depicted in text-figure 8, large ignimbritic clasts (Ø ≤ 1 m) occur at the base of the IV Pyroclastic Flow Deposit. The clasts rest on the surface of volcaniclastic braid plain deposits that underlie the flow deposit. In the vicinity of one large clast, the sediment is slumped and pushed aside in a way typical for impact structures (Pl. 1, Fig. 2). The large clasts might represent ballistic lithic blocks that have been ejected during the initial explosions of the eruption, which successively led to the formation of the IV Pyroclastic Flow Deposit. If this assumption is true, the vent of this eruption should be located within a few kilometers. Furthermore, judging from the assymetry of substrate deformation (Pl. 1, Fig. 2), the bombs came from an easterly direction (*e.g.*, Bogaard and Schmincke, 1984).

The II Mixed Pyroclastic Deposit is intercalated in the II Conglomeratic Braid Plain Deposit (Table 1). Pumice-rich and lithic-poor fall out, surge and flow facies alternate laterally and vertically in the non-welded deposit which is up to 2 m thick. Erosion and reworking during Middle Member time led to a discontinuous preservation.

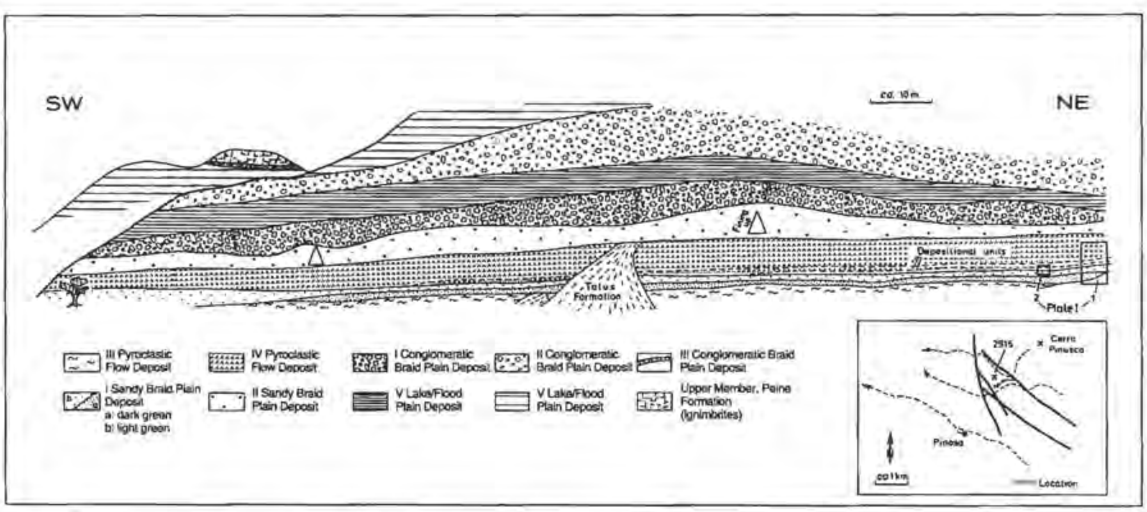


Text-FIG. 7. Paleocurrent indicators found in pyroclastic deposits of the Peine and Cas Formations; the map shows the area between Quebrada Caballo Muerto and Cerro Lanquir with the outlines of the geological formations sketched in text-figure 2; key: 1- I Pyroclastic Flow Deposit; 2- III Pyroclastic Flow Deposit; 3- IV Pyroclastic Flow Deposit; 4- VII Pyroclastic Flow Deposit (Table 1). Greek letters are sample locations referred to in text-figure 9.

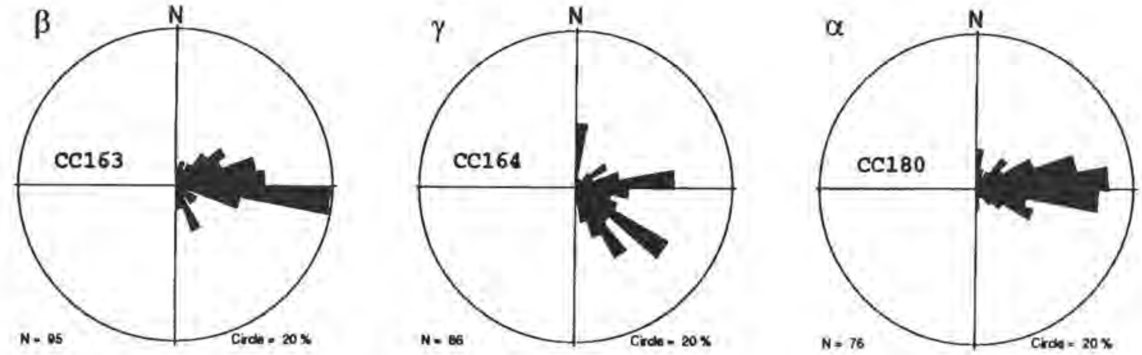
Upper Member

Towards the top of the Middle Member fine-grained lacustrian facies occurs from Quebrada Mina Sicipo to the area southwest of Cerro Pinusca. This points to a southwestward directed transgression of the basin facies onto the basin margin facies in the course of the Middle Member accumulation (text-Fig. 3). The very top of the Middle Member is marked by a continuous sheet of alluvial conglomerates and sandstones resting on the lake deposits (III Conglomeratic Braid Plain Deposit; Table 1; text-Fig. 3). Desiccation cracks and soils below the conglomerate indicate a time of exposure prior to the braid plain progradation. The conglomerate is overlain by a thick sheet of silica-rich ignimbrites which comprise the Upper Member of the Peine Formation and which forms a pronounced morphological step in the recent topography of the area (text-Figs. 2 and 3).

The Upper Member comprises a lower non-welded, lithic-rich ignimbrite and an upper crystal-rich ignimbrite which is partly welded (Table 3). Initial ash-rich surge and pumice-rich fall out deposits are preserved at the base of the **V Pyroclastic Flow Deposit** (text-Fig. 6 and Pl. 1, Fig. 4). The overall thickness of the V Pyroclastic Flow Deposit is about 50 m in the Quebrada Sicipo area. From there, the thickness decreases towards the north and south (text-Fig. 3). West- and northward directed pinching out of lower depositional units has been observed in the area west and southwest of Cerro Pinusca, however, no unambiguous paleocurrent indicators are known from this flow deposit.



Text-FIG. 8. Sketch of the northwestern wall of a quebrada 2 km southwest of Cerro Pinusca, showing the upper part of the Middle Member of the Peine Formation (see insert map for location and position of important faults), for depositional units see table 1; redrawn from various slides, scale is approximate.



Text-FIG. 9. Rose diagrams of crystal orientation measured in three oriented samples from the VI Pyroclastic Flow Deposit, for location see greek letters in text-figure 7.

The **VI Pyroclastic Flow Deposit** accumulated a feldspar-rich ignimbrite, which is almost 200 m in the area of the anticline southwest of Cerro Pinusca (text-Figs. 2 and 3). It rests on the V Pyroclastic Flow Deposit with a planar contact, which is marked in places by lenses of 15 cm thick, normally graded fall out tuff (Pl. 2, Fig. 1). The lower two thirds of the ignimbrite sheet have a pink color and are strongly welded and compacted. The upper third shows a non-welded texture and whitish colors. A pronounced erosional topography developed on the upper surface.

Crystal orientation has been measured in oriented samples taken from the second depositional unit, 2-4 m above the base of the VI Pyroclastic Flow Deposit (text-Fig. 7). A preferred west-east orientation of the plagioclase laths in three samples points to a west to east or east to west directed last movement of the flow (text-Fig. 9). However, the frequency of crystal imbrications is not sufficiently high to determine, unambiguously, the flow origin (Chapin and Lowell, 1979).

CAS FORMATION

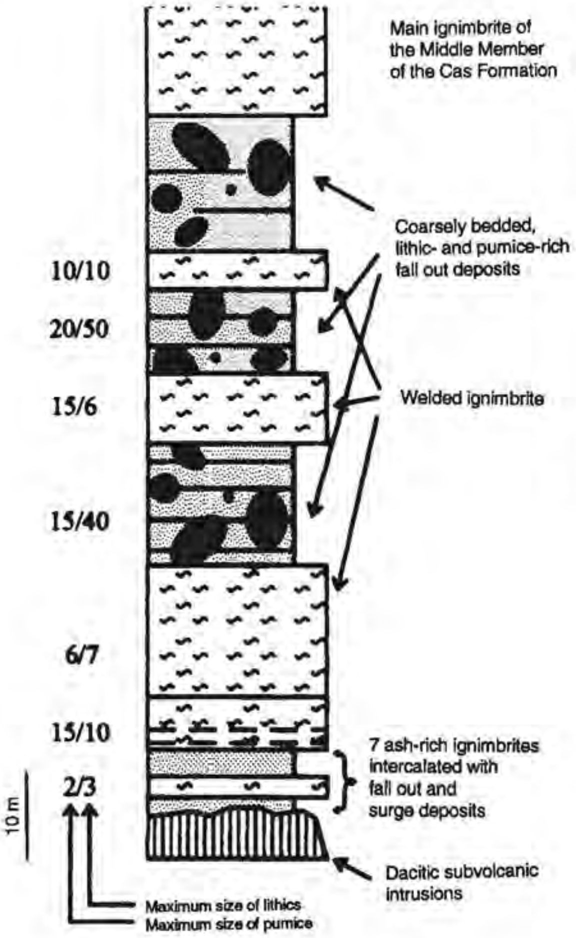
Lower Member

As mentioned above, the andesitic lavas of the Lower Member of the Cas Formation rest on the Peine Formation with an erosional unconformity (text-Fig. 2, Table 2). West of Cerro Pinusca, the lavas and red beds of the Lower Member filled a relief cut into the top of the Upper Member of the Peine Formation. South of Cerro Pinusca, the Cas Formation rests unconformably on the Middle Member and Lower Member of the Peine Formation, suggesting a stronger pre-Cas Formation erosion in that area.

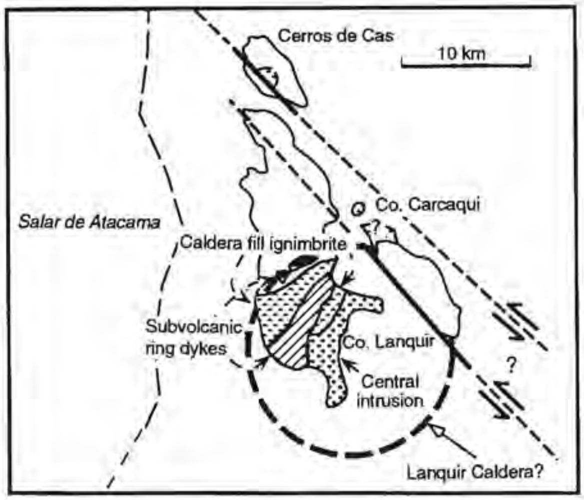
The lower part of the Lower Member comprises andesitic lavas with some red beds and soil horizons. In the area west of Cerro Pinusca, a non-welded ignimbrite is intercalated (VII Pyroclastic Flow Deposit; Tables 1 and 3; text- Fig. 7). Towards the top of the Lower Member more andesitic lavas and thick rhyodacitic lavas crop out. North of Cerro Chunar, the silica-rich lavas cover an almost monomict clastic mass flow deposit. Since the main clast type consists of angular fragments from silica-rich lava, a block-and-ash flow origin is likely for this bed (Tables 1 and 3; text-Fig. 3).

Middle Member

The main unit of the Middle Member is a 300 m thick succession of red crystal-rich welded ignimbrites (VIII Pyroclastic Flow Deposit; text-Fig. 3). It forms part of the southwest plunging syncline near Cerro Chunar (text-Fig. 2). At the base of the thick ignimbrite, an approximately 70 m thick mixed pyroclastic succession occurs, which is magnificently exposed at Cerro Chunar and in small outcrops on the northwest limb of the syncline. As depicted in text-figure 10, it consists of coarsely bedded, coarse-grained fall out deposits with intercalated welded gnimbrites (Pl. 2, Figs. 2, 3). A cross bedded pyroclastic layer in the lower part has been interpreted as a dune deposit of a base surge. The orientation of the lee set indicates a northward directed transport (text-Fig. 7). The top of the Middle Member includes an andesitic lava, red beds and another non-welded ignimbrite (text-Fig. 3: Tables 1 and 3).



Text-FIG. 10. Detailed section of the proximal fall out and flow deposits at the base of the Middle Member of the Cas Formation, near the abandoned Mina Chunar; all ignimbrites shown have a welded texture.



Text-FIG. 11. Sketch of the elements of the presumed Lanquir Caldera Complex (LCC), redrawn from a satellite image; also shown are prominent northwestern-southeastern faults cropping out in the Cerros de Cas and Cerro Carcaqui (Ramirez and Gardeweg, 1982) and the presumed sinistral sense of strike-slip (see text for discussion).

At Cerros de Cas, a succession of silica-rich lavas and ignimbrites is exposed (text-Figs. 2 and 3; Tables 1 and 3). The base of the succession consists of a crystal-rich welded ignimbrite which is strongly brecciated with clasts up to 10 m in diameter. Its strong lithological similarity to the main ignimbrite of the VIII Pyroclastic Flow Deposit at Cerro Chunar and their almost identical U/Pb isotope systematics, is the base for the tentative correlation shown in text-figures 2 and 3, and table 1. At Cerros de Cas, the succession continues on top of the brecciated ignimbrite, with thick rhyodacitic lavas, and another succession of partly welded ignimbrites. Presumably, another outcrop of the VIII Pyroclastic Flow Deposit occurs at the Cerro Carcaqui (text-Fig. 11), as suggested by the presence of boulders of this ignimbrite in quebradas which have their source at Cerro Carcaqui.

LANQUIR CALDERA COMPLEX

In the following, other magmatic units of the Cerro Lanquir area are described, which, together with the thick welded ignimbrite exposed in the syncline, are considered to be cogenetic products of a Late Permian caldera complex. This assumption is based on lithological, volcanological, isotopic and field relations. The possible elements of the herewith called **Lanquir Caldera Complex (LCC)** are sketched in text-figure 11. At Cerro Lanquir, a grey crystal-rich magmatic body with strongly compacted fiammae crops out, which displays a strong lithological similarity to the main welded ignimbrite (Middle Member of the Cas Formation). Furthermore, samples from the main ignimbrite and from this massive ignimbrite body show similar U/Pb-isotopic patterns and ages (Breitkreuz and VanSchmus, in prep.). Taking these observations and the large thickness of the welded deposits into account, the author infers that this body and the main ignimbrite formed as a caldera fill deposit during the climactic LCC eruption. The large pile of welded ignimbrite must have formed in a deep topographic structure such as a circular caldera, which is hypothetized in text-figure 11, or in a narrow deep (half) graben, which might have formed as a piecemeal structure during the eruption (Branney and Kokelaar, 1994). The sheet-like extended outcrops of the Peine Formation and the Lower Member of the Cas Formation renders unlikely the existence of such a deep topographic structure prior to the deposition of the VIII Pyroclastic Flow.

Furthermore, the mixed pyroclastic unit at the base of the Middle Member is considered as the product of an **early explosive phase** of the LCC eruption (text-Fig. 10, and Pl. 2, Figs. 2 and 3). Between Cerros Chunar and Lanquir, green and black dacitic, subvolcanic stocks and dykes crop out (text-Figs. 2 and 11), which might be considered as ring intrusions of the LCC. It is possible that the northeast-southwest-oriented subvolcanic stock which intruded the area between Cerros Pinusca and Chunar (text-Figs. 2 and 11) represents another LCC element. Finally, south and east of Cerro Lanquir a granodiorite forms a semicircular outcrop (Ramírez, 1978). This apparently ring-shaped pluton might resemble the **central intrusion** of the LCC, a hypothesis which has to be tested by future work including radiometric dating of the granodiorite.

It is conceivable, that the coarse-grained ignimbrite breccia, which forms the base of the Cas Formation at Cerros de Cas, represents a lag facies close to the rim of a caldera and that the silica-rich lavas on top resemble final extrusions of a caldera system. In this context, text-figure 11 features the idea that the outcrops at Cerros de Cas and Cerro Carcaqui form part of blocks which might have been displaced by sinistral movements along northwest-southeast faults, that crop out in the southwest of Cerros de Cas and Cerro Carcaqui (Ramírez and Gardeweg, 1982, and text-figures 2 and 11). Restoring this hypothetical sinistral dislocation of maximum 20 km would place the ignimbrite and silica-rich lavas from the Cerros de Cas and Carcaqui back to the eastern side of the proposed LCC. However, the nature of the northwest-southeast striking faults and their sense of movement is still unknown.

Upper Member

An almost 300 m thick succession of andesitic lavas and minor red beds crops out on top of the IX Pyroclastic Flow Deposit in the hinge area of the southwest-plunging syncline, west of Cerro Chunar. This succession is herewith called the Upper Member of the Cas Formation (text-Figs. 2 and 3; Tables 1, 2 and 3).

TECTONIC ACTIVITY

SYNDEPOSITIONAL EXTENSION

The formation of voluminous silica-rich ignimbrite sheets is, in most cases, related to an extensional or transtensional regime of local or regional importance. Thus, for the formation of the ignimbrite sheets of the Peine and Cas Formations, volcanic activity under extensional or transtensional tectonic conditions can be assumed. Apart from this general point, the following observations support an extensional tectonic regime during the late Permian in the studied area:

- In the Quebrada Caballo Muerto, clastic dykes up to 1 m thick cut through lake deposits of the lower Middle Member of the Peine Formation. Furthermore, magmatic dykes and sills used north-south trending faults as conduits and caused soft-sediment deformation during their emplacement. This indicates the syndepositional existence of north-south trending extensional faults.
- In the upper Middle Member of the Peine Formation, pumice-rich braid plain deposits, intercalated between the III and IV Pyroclastic Flow Deposit pinch out laterally towards both the southwest and the northeast beyond the outcrop shown in text-figure 8, being replaced by coarse-grained conglomerates. The location of the lateral facies change coincides with the position of northwest-southeast-running faults (text-Fig. 2 and insert map in text-Fig. 8), suggesting their syndepositional existence.
- As described above, the upper Middle Member of the Peine Formation is characterized by two facies associations, a low energy basin facies in the northwest and a high energy alluvial facies association in the southeast with northwest- and westwardly directed paleocurrents. In the course

of the upper Middle Member deposition, the basin association transgressed towards the southeast on top of the high energy alluvial association (text-Fig. 3). This is characteristic of extensional basin settings (Blair, 1987).

- The Cas Formation overlies the Peine Formation with a pronounced erosional unconformity. The Lower Member of the Cas Formation rests, from west to east, on successively older units of the Peine Formation (text-Fig. 2). Thus, differential uplift and erosion prior to the deposition of the Cas Formation must have taken place. The movement is considered to have been controlled by normal faulting at the basin margin, resulting in a relative uplift of eastern blocks.

On the basis of these observations and of the sedimentological and volcanological data, it is concluded that the succession formed at the eastern margin of an extensional basin. Syndepositional normal movements along north-south and northwest-southeast striking faults took place in the area. The fault system presumably controlled the depositional facies and the magmatic activity at the basin margin.

Dextral transtension and transpression along the Gondwanaland plate margin occurred during the late Carboniferous (Bahlburg and Breitkreuz, 1991; Fernández-Seveso *et al.*, 1993). Sinistral transtension controlled the geodynamic processes during the late Triassic-Jurassic (Pichowiak *et al.*, 1990; Scheuber *et al.*, 1994). For the late Permian in northern Chile, however, no data are available to distinguish between simple extension and transtension.

YOUNGER COMPRESSIONAL TECTONICS

As depicted in text-figure 2, the area between Cerros de Cas and Cerro Lanquir displays two contrasting patterns of deformation. In the north, the strata are gently tilted towards westerly directions, whereas south of Cerro Pinusca, a southwest plunging anticline-syncline pair is present with steeply inclined strata between the two axes. Since the Upper Member of the Cas Formation is involved in the local folding, the deformation, which might have been caused by west-east, northwest-southeast or north-south directed compression, is younger than the late Permian Cas Formation. Fission track data reveal that the Peine and Cas Formations have been lifted up as early as during the Jurassic and cooled below 100°C during the early Cretaceous (Breitkreuz *et al.*, 1994b). Assuming that the folding occurred prior to the final uplift, the compressional event took place sometime during the Triassic-early Cretaceous.

CONCLUSIONS

During the late Permian, magmatic activity at the continental margin of Gondwanaland, was at its peak, since magmatic products of this age can be traced from the Peruvian Andes (Mitu Group, Kontak *et al.*, 1990) to northern Chile (Peine Group) and the Argentine Andes to 40°S (Choiyoi Group, Kay *et al.*, 1989; Zeil, 1981). For the southern Andes, a Permian intra-continental extension is presumed to have controlled the extensive silica-rich magmatism (Kay *et al.*, 1989, Mpodozis and Kay, 1992). In contrast, geochemical data obtained from Permian magmatic rocks of the Salar de Atacama region reveal a magmatic arc signature, with a moderate extensional signal in some rocks (Baeza and Pichowiak, 1988; Breitkreuz *et al.*, 1989; Breitkreuz, 1991; Breitkreuz and Zeil, 1994). This, together with the age constraints, depositional facies and paleocurrent indicators found in the Peine and Cas Formations suggests that the area between Cerros de Cas and Cerro Lanquir was located at the eastern margin of an extensional magmatic arc, during the Late Permian.

The Cenozoic geology of the Salar de Atacama area demonstrates that lava flows, and especially pyroclastic flows can travel large distances away from their vent (Ramírez and Gardeweg, 1982). Thus, the mere presence of a volcanic deposit does not necessarily indicate a vent located in its vicinity. So far, evidence for late Paleozoic magmatic centres in northern Chile came mainly from the Cordillera Domeyko, where numerous plutons and caldera complexes have been mapped and dated (Fig. 1; Davidson *et al.*, 1985; Baeza and Pichowiak, 1988; Mpodozis *et al.*, 1993). The results presented here indicate that, at least, some of the vents, from which the volcanic deposits of the Peine and Cas Formations originated, were located close to, or even in the field area. Some basic volcanic centres of the Lower Member of the Peine Formation can be recognized in form of scoria cone relicts. The vent position for the silica-rich volcanic products is less certain. Paleocurrent indicators found in the pyroclastic flow deposits of the Middle and Upper Member of the Peine Formation reflect the local topography, *i.e.*, a west- or northwestwardly dipping slope at the eastern margin of a basin, and not necessarily the vent position. The presence of large ballistic blocks at the base of the IV Pyroclastic Flow Deposit (Middle Member of the Peine Formation) suggests the existence of a silica-rich vent located closely to the field area.

A network of north-south and northwest-southeast trending faults (text-Fig. 2) formed syndepositionally as a part of an extensional basin-margin fault system on the east side of the Late Paleozoic magmatic arc. During that period magma used some of these faults as conduits forming the numerous dykes and sills.

The model of the LCC has to be confirmed by further mapping and age determinations. However, the coarse grain size of the fall out deposit at the base of the Middle Member of the Cas Formation and the caldera fill facies indicate a vent position in the Cerro Lanquir area. The LCC is the first example of a Late Paleozoic caldera located that far east in the north Chilean segment of the Gondwanaland margin. This and other volcanic features described above clearly indicate that the Permian magmatic arc was active as far east as the eastern margin of the Salar de Atacama area.

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PLATE 1

Volcanological features of the silica-rich pyroclastic deposits

Figures

1 Detail of the Middle Member of the Peine Formation southwest of Cerro Pinusca (see text-Fig. 8 for location); from base to top, the upper surface of the III Pyroclastic Flow Deposit (1), the volcaniclastic braid plain sediments (a dark green lower and a light green upper unit), and the first three depositional units of the IV Pyroclastic Flow Deposit ('2' at the base) separated by ash-rich layers (A); as sketched in text-figure 8, the first two units pinch out farther to the southwest. See hammer in circle for scale.

2 Ballistic block (ignimbrite clast Ø 60 cm) at the base of the IV Pyroclastic Flow Deposit (for location see text- figure 8); the braid plain sediments below the flow deposit display an assymetric deformation (S), which is supposedly the result of an oblique impact of the block from an eastern direction (see text for discussion; left side of the picture is to the southwest).

3 Lithic-rich degassing pipe in the third depositional unit of the IV Pyroclastic Flow Deposit (Quebrada Sicipo; compass lid is 7 cm across).

4 Parallel-to low-angle crossbedded fall out and surge deposits at the base of the V Pyroclastic Flow Deposit (text-Fig. 6; southwest of Cerro Pinusca); the hammer head rests on the III Conglomeratic Braid Plain Deposit.

PLATE 1

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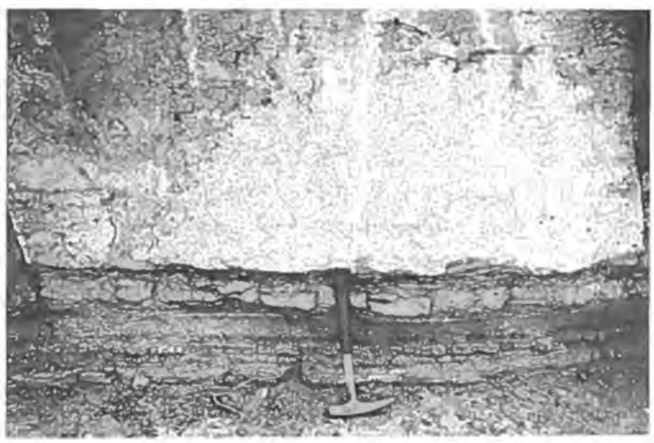

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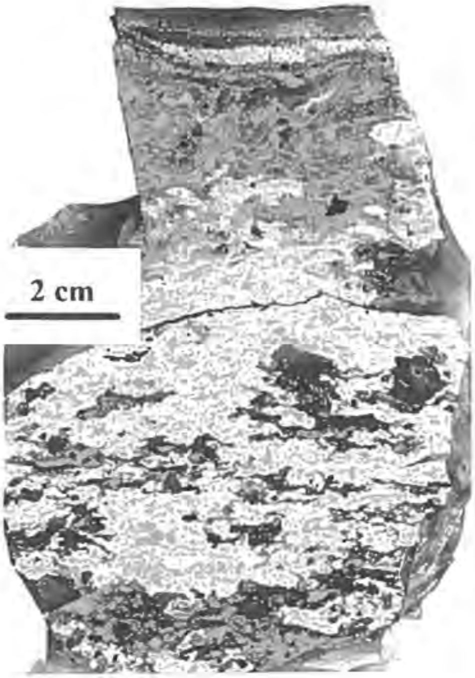
PLATE 2

Figures

1	Graded fall out-deposit at the base of the partly welded VI Pyroclastic Flow Deposit (southwest of Cerro Pinusca; polished rock cut, embedded in epoxy).
2, 3	Mixed pyroclastic deposits at the base of the VIII Pyroclastic Flow Deposit (Cerro Chunar, see text-figure 10): initial deposits of the Lanquir Caldera Complex?
2	Detail of the crudely bedded, proximal, lithic-rich fall out deposits.
3	Detail of a welded crystal-rich ignimbrite.

PLATE 2



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