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Fontboté, Lluís

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Stratabound Ore Deposits in the Andes: A Review and a Classification According to Their Geotectonic Setting

L. FONTBOTÉ¹

1 Introduction

Systematic investigations of stratabound ore deposits in the Andes are relatively modern. Perhaps as a result of the very intensive Andean magmatic activity, it was not easy to break with the concept that most ore deposits are veins and replacement bodies related to late magmatic hydrothermal activity of some known or unknown intrusion. The role of the stratabound ore deposits was underestimated. As a consequence, research on stratabound ore deposits was traditionally retarded with respect to other groups of ore deposits in the Andes, such as porphyry copper or hydrothermal vein deposits. Among the first works emphasizing the role of stratabound ore deposits in the Andes are those by Amstutz (1959, 1961), Entwistle and Gouin (1955), Kobe (1960), Ljunggren and Meyer (1964), and Ruiz et al. (1971).

Stratabound ore deposits, including also some of the classic types known worldwide, such as volcanic-associated massive sulfide, Mississippi Valley-type, and red-bed type deposits, constitute, in fact, an important group in the Andes, also from the economic point of view. From 44 major Andean mining operations listed in the World Mining Map (operations with an annual gross metal value over 20 mio. DM, Metallgesellschaft 1987), 11 are stratabound. In Chile, "the porphyry copper country" par excellence, four of ten mentioned operations are stratabound ore deposits (Mantos Blancos, El Soldado, Lo Aguirre, and El Toqui), the other six being porphyry copper (Chuquicamata, El Salvador, Andina, Rio Blanco-Disputadatos Bronces, and El Teniente) and epithermal gold (El Indio) deposits.

Stratabound ore deposit is "said of a mineral deposit confined to a single stratigraphic unit" (Glossary of Geology, A. G. I. 1980). To elucidate the limits of this definition is, of course, problematic, and is not possible without clarifying the scale used in describing the "single stratigraphic unit" considered (see also discussions in Wolf 1976 and Gabelman 1976). Some of the ore deposits dealt with in the present work are stratabound only in a broad sense, and it should be pointed out that continuous transitions to nonstratabound ore deposits exist. This is, however, a convenient definition which points out one main characteristic: a stratabound ore deposit is linked to a certain stratigraphic (sedimentary or volcanic) unit. This link is of empirical nature and does not imply either genetic processes or time of formation. The term stratabound includes deposits formed

¹ Mineralogisch-Petrographisches Institut, INF 236, D-6900 Heidelberg, FRG
Present address: Dép. de Minéralogie, 13, rue des Maraîchers, CH-1211 Genève 4, Switzerland

Table 1. Metallogenic stages of stratabound ore deposits as used in this volume

 Andean Cycle

Northern Andes (North of 5°S)

NIIo Ore deposits in Mesozoic volcano-sedimentary sequences (accreted terrains and/or marginal basins) (mainly massive sulfides)

Central Andes (5° – 42°S)

Stage I (Triassic-Liassic) – Ore deposits in a carbonate platform without apparent relation to a pair magmatic arc-back-arc basin (Ia: polymetallic deposits, in part of massive sulfide type; Ib and Ic: MVT deposits; only in the Pucará basin, Peru)

Stage II (Liassic-Albian) – Ore deposits in the ensialic paleogeographic pair magmatic arc-back-arc, and in platform sediments attached to the foreland

IIa Ore deposits in volcanic sequences at the magmatic arc (Cu)

IIb Ore deposits in volcanoclastic, mainly continental basins at the magmatic arc (in part developed as intra-arc basins) (Cu, Mn, Fe)

IIc Ore deposits in volcano-sedimentary sequences in back-arc basins (in part developed as marginal basins) (Cu, Zn-Cu, Ba)

IId Ore deposits in marine sedimentary sequences of the back-arc basin (Fe, Ba, Zn, Pb, Ag)

IIe Ore deposits in platform sediments attached to the foreland (Zn-Pb-Cu, Zn-Pb, Ba-Sr, U)

Stage III (Upper Cretaceous-Cenozoic) – Ore deposits in continental intra-arc and foreland basins

IIIa Fluvial-lacustrine basins in intermediate to acid volcanic environment (polymetallic deposits)

IIIb Molasse sequences in intermontane basins, in part foreland basins [red-bed type Cu and Cu-(U-V) deposits]

IIIc Deposits related to Cenozoic alkaline volcanics, mainly in ignimbritic flows and tuffs (U)

Southern Andes (South of 42°S)

SIIc Ore deposits in Mesozoic back-arc basins (in part marginal basins?)

Sub-Andean Basins (Lower Cretaceous-Eocene)

Ore deposits in shallow-water carbonate rocks and in clastic sediments [Cu-(U, V), Pb-Zn]

Pre-Andean Cycle

P2 = Carboniferous-Permian (mainly red-bed type Cu and U)

P1 = Pre-Carboniferous, stages not further differentiated

through volcanogenic, hydrothermal, metamorphic, diagenetic, and sedimentary processes both penecontemporaneously and much later than the host rock, which can be volcanic or sedimentary.

The scope of this chapter is to give an overview of the stratabound ore deposits known in the Andes and to introduce the classification used in the organization of the present book (Table 1). An additional aim is to complement the information on deposits not dealt with in other contributions. The empirical link of ore and host rock can be used to classify the stratabound ore deposit according to the age and geotectonic position of the enclosing rock. This is the approach followed below. A systematic classification could be achieved with ore deposits hosted by rocks of the Andean Cycle (Mesozoic-Recent) because the regional geology and geotectonic interpretation of the rocks of this period are well known. Information on stratabound ore deposits of pre-Andean Cycles is more limited and a systematic classification has not been attempted.

Ore deposits and districts described in other contributions of this volume are only very briefly mentioned and no additional references are given. In other cases, the main information sources and a summary of main features is presented. Additional data can be found in the lists of ore deposits and districts arranged alphabetically and from north to south at the end of this book (Fontboté this Vol. appendix). They include the geographic coordinates and the main geologic characteristics. A summary of this information is contained also in the map of stratabound ore deposits (Frutos, Fontboté, and Amstutz, this Vol.). A discussion on the possible metal sources involved in the formation of the ore deposits of the Andean Cycle is given in Fontboté et al. (this Vol.).

Additional general reference works used in this overview are Putzer (1976), and Oyarzún (1985). Peru: Raimondi (1878), Amstutz (1961, 1978), Bellido et al. (1969, 1972), Petersen (1965), Soler (1986), Soler et al. (1986). Chile: Ruiz (1965, 1971), Ruiz and Peebles (1988), Frutos et al. (1986), Camus (1986). Argentina: Angelleli et al. (1984), Brodtkorb and Brodtkorb (1984), Sureda et al. (1986).

2 Pre-Andean Cycles

Precambrian. In Precambrian rocks only small occurrences of banded iron formations in the Arequipa Massif are known (Tarpuy, Matarani, Cardozo and Cedillo this Vol.; Fernández-Concha and Amstutz 1956).

Cambrian. The magnesite district of Alto Chapare in Bolivia occurs in a metamorphic carbonatic-evaporitic Cambrian sequence (Cristalmayu Formation). This district has been described by Franz et al. (1979). It includes the San Francisco and Minillo Mines.

Ordovician-Silurian-Devonian. In schists and volcanic rocks of Ordovician age a belt of Au-W ore deposits, which in a wide sense can in part be considered to be stratabound, occurs in Bolivia (e.g., Mina Rosario, Chilicoya; Schneider this Vol.) and in southeast Peru (e.g., Gavilán de Oro, La Rinconada; Cardozo and Cedillo this Vol.).

In Ordovician metasedimentary rocks deposited in shelf environment at the edge of the central Argentinian shield several polymetallic ore deposits are known. The most important is the Aguilar Mine hosted by the Aguilar quartzite. Sureda and Martin (this Vol.) support a syndimentary-syndiagenetic genesis, whereas for other authors (e.g., Spencer 1950) El Aguilar is the product of metasomatic skarn related to a Cretaceous granitic intrusion. Another deposit hosted by Ordovician platform carbonates is La Helvecia (Pb-Zn-Ba, Brodtkorb and Brodtkorb this Vol.). The Canota barite district is hosted by black shales of a flysch sequence deposited in deeper parts of the basin (Brodtkorb et al. this Vol.). Additional small stratabound ore occurrences in Ordovician rocks in northern Argentina are listed by Sureda et al. (1986, see also Sect. 1.4 in Oyarzún this Vol.).

In a greenstone belt of probable Ordovician to Silurian age of south-central Chile banded iron formations occur (the district Mahuilque-Relún, Collao et al. this Vol.), small sulfide massive occurrences (e.g., Pirén Alto; Alfaro and Collao

this Vol.; Schira et al. this Vol.), as well as minor manganese occurrences (e.g., Bellavista). The geologic setting is thought to correspond to an ensialic mature marginal basin (Schira et al. this Vol.).

Much more to the south, in the Otway area, the polymetallic massive sulfide ores of Cutter Cove hosted by metasedimentary and metavolcanic rocks of probable Paleozoic age (Arias-Farias 1985) are known. A small mining operation was active there in the early 1970s.

Oolitic ironstones outcrop along in N-S direction for several hundred km in northern Argentina and Bolivia. They are hosted by Silurian metamorphic wackes and sandstones of the Lipeón and Kirusillas Formations, which represents the beginning of a transgressive sequence (e.g., Zapla, Unchimé; Boso and Monaldi this Vol.).

The Sn-Bolivian belt, with the ore districts of Kellhuani and San José Amarete, is one of the classical examples of stratabound ore deposits in Paleozoic rocks in the Andes. Lehman (this Vol.) presents arguments for a genesis bound to intrusions much younger than the hosting Silurian metamorphic rocks.

The genesis of the famous Zn-Pb-Cu-Ag deposit of Cerro de Pasco in central Peru, hosted by phyllites and shales of the Excelsior Formation (Devonian), has commonly been interpreted to be related to Miocene intrusive rocks. However, Einaudi (1977), and more recently Cheney (1987), discuss also the possibility that Cerro de Pasco represents a Paleozoic massive sulfide deposit.

Carboniferous-Permian. The polymetallic massive sulfide deposit Bailadores in Venezuela is found in pyroclastic and pyllitic rocks of the Mucichaché Formation of Upper Carboniferous age (Carlson 1977). In shelf carbonate rocks of the Tarma Group (Pennsylvanian) the copper mine of Cobriza occurs. Whether this deposit is pre-tectonic in origin, as suggested by Huamán et al. (this Vol.), or related to a post-Triassic skarn, as previously assumed, is still a matter of discussion.

Subsequently to the Hercynian orogenesis and in part in relation with rifting episodes associated to intense magmatic activity, continental basins characterized by red-bed sequences developed at different areas of the Andes. Among the numerous small Cu and U deposits known in this environment are the copper mine of Negra Huanusha (Kobe this Vol.) and the uranium districts of Sierra Pintada, Guandacol-Huachal, Dr. Baulfies, and Tinogasta (Ferreyra and Lardone this Vol.).

3 Andean Cycle

From north to south the Andes can be subdivided into three segments based on the main features of the geologic evolution during the Andean Cycle (Triassic-Recent). The Central Andes (5–42°S, i.e., Peru, Bolivia, and northern and central parts of Argentina and Chile) are characterized by tectonic superposition, thick continental crust and, in part, crust destruction, in contrast to the Northern and Southern Andes, where the continental crust is thinner and accretion conditions prevailed (Frutos this Vol.). This leads to the greater geologic complexity of the Central Andes compared to the Northern and Southern Andes. The complexity

Table 2. Geotectonic position of representative ore deposits in the Central Andes

III Upper Cretaceous- Cenozoic	<i>Continental Intra-Arc and Foreland Basins</i>			<i>Sub-Andean Basin</i> (Salta Group)	
	<ul style="list-style-type: none"> a) Polymetallic Ag-bearing deposits in lacustrine basins in calc-alkaline acid volc. environment Colquijirca (Pb-Zn-Ag-Cu), El Jardín (Ag-Cu) b) Red-bed type copper deposits in intermontane, in part foreland molasse basins: San Bartolo, Corocoro. c) U deposits in alkaline acid volcanics Macusani, Sevaruyo, Aguiliri 			<ul style="list-style-type: none"> – In lacustrine sed. Río Juramento (Pb-Zn-Cu) – In detrital sed. (Cu) (U-V), (Mn) 	
II Liassic- Albian	a) <i>Magmatic Arc</i> Volcanic Sequence	c) <i>Back-Arc Basin</i> Volcano-sedimentary Sequence (in part Marginal Basin) (Cu and Zn-Ba)	d) <i>Back-Arc Basin</i> mainly Marine Sed. (Fe, Ba, Zn, Pb, Ag)	e) <i>Platform</i> <i>Sediments attached to the Foreland</i> (Pb- Zn-AG, Ba-Sr, Ba)	
Tithonian- Albian	<ul style="list-style-type: none"> – Copara Metallo- tect (Cu) – Tambogrande (Cu-Zn-Pb-Ba) – Leonila Graciela (Zn-Ba) – Palma (Zn-Pb) – Punta del Cobre (Cu) – M. Catemu [Cu-(Pb-Zn)] – El Soldado (Cu) 			<ul style="list-style-type: none"> – Bandurrias, Manolete (Fe) – Mamiña, Car- ola, Gladys [Ba-(Pb)] – Jaula (Zn-Ag) – Las Cañas (Pb-Zn) 	<ul style="list-style-type: none"> – Hualgayoc (Pb- Zn-Ag) – Santa Metallo- tect (Pb-Zn-Ag, Ba) – Mina Ragra (V) – Domeyko (Ba) – Neuquén (Ba-Sr)
Jurassic	– [Cu-(Ag)] deposits in La Negra Fm.	<ul style="list-style-type: none"> b) <i>Sediments close to the Volcanic Arc</i> (in part Intra-Arc Basins) (Cu, Mn, Fe) – detr. sed.: C. Coloso (Cu), Talcuna (Cu, Mn) – marine sed. Coquimbana (Mn), Ch Quemado (Fe) 		<ul style="list-style-type: none"> – Neuquén (Ba-Sr) – Cercapuquio (Zn-Pb) 	
I Triassic- Liassic	<p><i>Carbonate Platform without apparent Relation to a pair Magmatic Arc-Back-Arc Basin</i> (Pucará Basin)</p> <ul style="list-style-type: none"> a) Volcanic-associated ore deposits at the base of the carbonate sequence: Carahuacra-Huaripampa, Manto Katy [massive pyritic Zn-Pb-Cu-(Ag) ore] (Central Pucará) b) and c) MVT Zn-Pb deposits b) Base of the carbonate sequence: Shalipayco [Zn-Pb-(Ag)] (Central-Eastern Pucará) c) Within a thick carbonate sequence: San Vicente belt (Zn-Pb) (Eastern Pucará) 				

and plurality of geologic environments in the Central Andes is also reflected in the amount and variety of ore deposits. From the 44 major mining operations in the Andes (Metallgesellschaft 1987), all but one (Aysén) are located in this central segment.

The available information on stratabound ore deposits also refer mainly to those located in the Central Andes. For this reason the metallogenetic stages defined below apply mainly to this segment of the Andean Cordillera (Table 2). For a similar metallogenetic division of the Northern and Southern Andes additional data are still necessary.

3.1 Central Andes

Three metallogenetic “stages” can be distinguished in the Central Andes (Table 1, Fig. 1). Each stage is characterized by its tectonic style, magmatic activity, and basin evolution; and in each stage, characteristic types of stratabound ore deposits occur.

3.1.1 Stage I (Triassic-Liassic). Ore Deposits in a Carbonate Platform Without Apparent Relation to a Pair Magmatic Arc-Back-Arc Basin

Stage I (Triassic-Liassic) is a transitional period between the Hercynian and the Andean Cycles recognized only in Peru. It comprises ore deposits hosted in sediments of a wide shallow-water carbonate platform developed under extensional conditions during the Upper Triassic to Liassic along the western margin of the Brazilian Shield (Pucará Group). It follows Permo-Triassic sequences characterized by continental sedimentation, important alkaline and peralkaline volcanism, and horst and graben tectonics. As discussed by Fontboté (this Vol.), sedimentation in the Pucará basin shows no relation to a possible magmatic arc that could be located more to the west. This is a main difference compared to the next metallogenetic stages.

Several important ore deposits occur in the Pucará carbonate platform, both associated with volcanic activity (Zn-Pb-Cu-Ag) and purely carbonate-hosted (Zn-Pb). The following three main groups may be distinguished (see references and overview in Fontboté this Vol.).

- Ia) Zn-Pb(-Ag-Cu) deposits rich in Mn and Fe in part with massive sulfide parageneses located near the base of the carbonate sequence, spatially associated to volcanic and/or volcanoclastic intercalations (e.g., Carahuacra-Huaripampa).
- Ib) Mississippi Valley-type deposits at the base of the carbonate sequence (e.g., Shalipayco, Zn-Pb)
- Ic) Mississippi Valley-type deposits within the carbonate sequence (e.g., San Vicente, Zn-Pb).

3.1.2 Stage II (Liassic-Albian). Ore Deposits in the Ensialic Paleogeographic Pair Magmatic Arc-Back-Arc, in the Platform at the Continent Edge

The evolution of the Central Andes during the Mesozoic and the Cenozoic is largely related to the subduction of the Nazca oceanic plate beneath the South American continent, and the Andes have become the prototype for an orogenic belt formed at a convergent plate boundary (James 1971). Coira et al. (1982) distinguished two main stages in the Meso-Cenozoic in northern Argentina and Chile. An *early period* (Jurassic-Early Cretaceous) characterized by the development of a well-defined magmatic arc-back-arc basin pair, and a *late period* (Late Cretaceous-Recent) during which only an eastward-migrating magmatic arc was present. These stages can be recognized also in the other sectors of the Central Andes and correspond with the metallogenetic stages II (Liassic-Albian) and III (Upper Cretaceous-Cenozoic) as used in this chapter.

Eastwards of the magmatic arc, the proportion of marine sediments compared to volcanic rocks gradually increases. This W-E asymmetry is a general feature which can be recognized in Jurassic and in Lower Cretaceous times, both in Chile and in Peru (see also Cardozo and Cedillo this Vol.), and serves as the base for the interpretation of parallel belts which comprise, from west to east, magmatic arc, back-arc basin and, in some regions, platform facies at the continent edge. The distinction between the two latter environments is based on the relative influence of volcanic activity during sedimentation and on the type of basin evolution. The back-arc basin is strongly influenced by the volcanism at the magmatic arc and the basin geometry controlled by extensional tectonics. The depositional environment at the continent edge displays only subordinate volcanic activity and is characterized by platform sediments. This division corresponds to the classical distinction between eu- and miogeosynclinal facies (Auboin et al. 1973), and is especially well recognized in Peru (see also Cardozo and Cedillo this Vol.).

The "Andean Model", based only on the subduction of the Pacific oceanic plate under South America, although essentially coherent with present-day observations, does not explain all essential features of the Andean edifice (see reviews on this topic in Aguirre 1985; Pitcher and Cobbing 1985). Levi and Aguirre (1981) and Aberg et al. (1984) point out the important role played by spreading processes in the construction of the Andes in central Chile. These authors suggest a mechanism of "intracontinental spreading-subsidence" acting in conjunction with oceanic subduction. Aguirre (1987) generalizes this model for the whole Andean Cordillera, and underlines that extensional regimes were the rule during Andean evolution and that compressive intervals were short-lived. The spreading processes are of great importance for the evolution of back-arc basins during Jurassic and Cretaceous times, especially because of the creation of ensialic marginal basins, which in the Central Andes were always of "aborted" type (i.e., a back-arc basin in which spreading started but did not reach the stage of creation of oceanic crust).

Aguirre (1987) interprets the formation of marginal basins during Jurassic and Cretaceous times in the Central Andes as part of a general extensional process affecting the whole Andes, during which "true" marginal basins (i.e., with creation of oceanic crust) in the northern and Patagonian segments were developed.

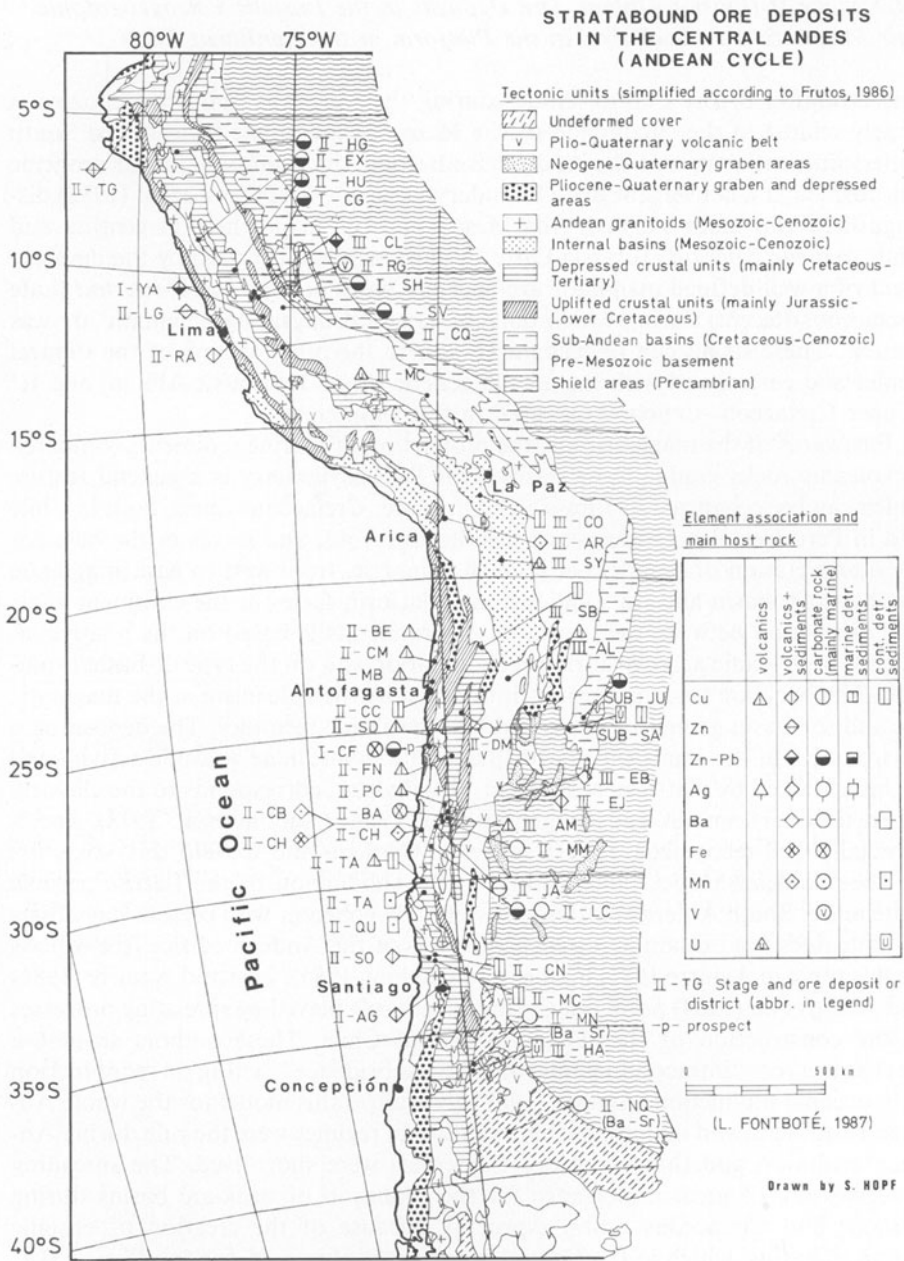


Fig. 1. Location, ore association, and host rock of representative stratabound districts (*D*), mines (*M*), and prospects (*P*) in the Central Andes. Other deposits are included in the map within the folder at the end of the book (Frutos, Fontboté and Amstutz this Vol.). See also Appendix for summary of main features of mentioned deposits

North-south transitions in the degree of thinning of the continental crust would be reflected in petrologic characteristics. According to Aguirre's hypothesis, basins with strong attenuation of the continental crust are characterized by primitive basalts and a high thermal gradient, resulting in burial metamorphism at different periods in north-central Peru and in central Chile. On the other hand, if the thinning of the continental crust is moderate, the volcanic rocks are evolved and show calc-alkaline affinities, and the thermal gradient is lower.

As a result of this geologic scenario the paleogeography of stage II is mainly characterized by a geotectonic couple consisting of a magmatic arc and a back-arc basin, in part developed as an aborted marginal basin both formed on continental crust. Towards the foreland areas platform sedimentation is recognized. Extensional conditions and generalized transgression are recorded. Stratabound ore deposits are found in a series of paleogeographic positions Fig. 2:

- IIa) Ore deposits in volcanic sequences at the magmatic arc (Cu).
- IIb) Ore deposits in volcanoclastic, mainly continental basins at the magmatic arc (in part developed as intra-arc basins) (Cu, Mn, Fe).
- IIc) Ore deposits in volcano-sedimentary sequences in back-arc basins (in part developed as marginal basins) (Cu, Zn-Cu, Ba).
- II d) Ore deposits in marine sedimentary sequences of the back-arc basin (Fe, Ba, Zn, Pb, Ag).
- IIe) Ore deposits in platform sediments attached to the foreland (Zn-Pb-Cu, Zn-Pb, Ba-Sr, U)

It is important to emphasize that this division into five "paleogeographic positions" is based on lithological and morphological criteria. Stages IIa, IIb, and IIc can correspond to different types of development of the subduction-related magmatic arc, and the three types do not necessarily coexist in a given area. Fault-induced and thermally-driven subsidence close to the magmatic arc can produce

<i>AG</i> , M Aguirre, Lo;	<i>EB</i> , M Elisa de Bodos;	<i>PC</i> , D Punta del Cobre;
<i>AL</i> , D Aguiliri;	<i>EJ</i> , M Jardín, El;	<i>QU</i> , D Corral Quemado;
<i>AM</i> , M Amolanas;	<i>EX</i> , M Extraño, El;	<i>RA</i> , M Raúl-Condestable;
<i>AR</i> , M Huachipato (Arica)	<i>FK</i> , M Frankenstein;	<i>RG</i> , M Ragra;
<i>BA</i> , M Bandurrias;	<i>HA</i> , M Huemul-Agua Botada;	<i>SA</i> , D Custodio;
<i>BE</i> , M Buena Esperanza;	<i>HG</i> , D Bella Unión;	<i>SB</i> , M San Bartolo;
<i>CB</i> , M Coquimbana;	<i>HU</i> , M Huanzalá;	<i>SD</i> , M Santo Domingo;
<i>CC</i> , M Caleta Coloso;	<i>JA</i> , M Jaula-Bellavista;	<i>SH</i> , M Shalipayco;
<i>CF</i> , P Cifuncho;	<i>JU</i> , M Cerro Plomo;	<i>SO</i> , M Soldado, El;
<i>CG</i> , P Chaglla (Hara);	<i>LC</i> , M Las Cañas;	<i>SV</i> , M San Vicente;
<i>CH</i> , D Chañar Quemado;	<i>LG</i> , M Leonila-Graciela;	<i>SY</i> , D Sevaruyo;
<i>CL</i> , M Colquijirca;	<i>MA</i> , P Macusani;	<i>TA</i> , D Talcuna;
<i>CM</i> , D Carolina de Michilla;	<i>MB</i> , M Mantos Blancos;	<i>TA</i> , D Talcuna;
<i>CN</i> , M Cerro Negro;	<i>MC</i> , D Catemu, Mantos de;	<i>TG</i> , D Tambogrande;
<i>CO</i> , M Corocoro;	<i>MM</i> , M Mamiña;	<i>YA</i> , D Yauli, Domo de
<i>CQ</i> , M Cercapuquio;	<i>MN</i> , D Mendoza, South of;	
<i>DM</i> , P Domeyko Cord., Chaco Q.;	<i>NQ</i> , D Neuquén;	

graben structures filled with volcano-sedimentary sequences. Such basins can constitute the *magmatic arc itself* which would not form a morphologically distinguishable volcanic arc. This situation, which has been compared to the Eocene Pliocene evolution of the Sumatra-Java active margin (Uliana et al. in press), is encountered during Mesozoic times in parts of Central Chile and in Peru, where magmatic arcs developed ensialic aborted marginal basins characterized by volcano-sedimentary sequences without generating true volcanic arcs. Marginal basins are usually considered to represent a type of back-arc basin in order to stress the fact that they develop under extensional tectonics; it should, however, be taken into account that actually this "back-arc" type does not need to be located behind a contemporaneous, morphologically well-developed volcanic arc.

IIa) Ore Deposits in Volcanic Sequences at the Magmatic Arc

An ensialic volcanic arc is recognized in the La Negra Formation in the coastal range of northern Chile. This formation comprises mainly thin flows of calc-alkaline basalts, basaltic andesites, and high-K basaltic andesites, as well as some volcanoclastic intercalations with a total thickness of 7 to 10 km (García 1967; Buchelt and Tellez 1988; Rogers and Hawkesworth 1989). Although for most authors La Negra Formation represents a volcanic arc Rogers and Hawkesworth (1989) suggest that the lava flows erupted in an ensialic back-arc basin rather than in the actual volcanic arc, which should have been located more to the west. The start of the volcanism of the La Negra Formation has been determined to be Sinemurian (v. Hillebrandt et al. 1986). A comparable volcanic belt is recognized also in the Lower Cretaceous in several areas of northern Chile.

In this magmatic arc of northern Chile important copper deposits occur. The grade (1.5–3% Cu) and tonnage (5 to 60 mio. t) makes these ore deposits a good economic target even at low copper prices. Subordinate silver contents (in the range of 20 g/t Ag) are also generally recovered. The most significant deposits are the Buena Esperanza Mine (Palacios this Vol.), the Carolina de Michilla district (Wolf et al. this Vol.), and the Santo Domingo Mine (Definis 1985), all located in calc-alkaline and high-K basalts, basaltic andesites, and andesites of the coastal range of the La Negra Formation. The Mantos Blancos Mine, which is the largest in the area, occurs in volcanic rocks of probable Jurassic age located 30 km east of the coastal volcanic belt but attributed by Buchelt and Tellez (1988) also to the La Negra Formation.

In the coastal ore deposits of the La Negra Formation, the ore occurs both as breccia pipe bodies and as stratiform ore bodies, which are called mantos², the

² The term "manto" is used in several senses in the Andean countries. The miners employ it in contrast to "veta" (vein) for tabular ore bodies which do not dip vertically. Usually, but *not always* it is a synonym for stratiform. In Chile, the expression "manto type" has been assigned usually to stratiform copper ore deposits (Ruiz et al. 1971), including ore deposits of very different types, for example the (in part) stratiform, volcanic-hosted deposits in the La Negra Formation, and the sediment-hosted deposits in the Mantos de Catemu and Cabildo districts. The Punta del Cobre district

latter located preferentially in amygdaloidal and/or brecciated tops of lava flows (Losert 1974; Definis 1985; Soto and Dreyer 1985; Palacios this Vol.; Wolf et al. this Vol.). The main ore minerals in the sulfide ore bodies (the production in some mines began with the exploitation of a thick zone of supergene copper minerals) are chalcocite, digenite, bornite, and, subordinately, chalcopyrite. The host volcanic rocks are affected by regional scale alteration, probably burial metamorphism which is especially visible in the flow tops. Typical alteration minerals are albite, chlorite, epidote, calcite, and quartz. In Buena Esperanza, zeolites, prehnite, and pumpellyite have also been described (Losert 1974). In addition, near the orebodies local scale hydrothermal alteration, spatially associated to barren subvolcanic intrusives, is recognized in the Buena Esperanza Mine and in the Susana Mine (Carolina de Michilla district).

The Mantos Blancos copper deposit (Chavez 1984, 1985), situated some 45 km northeast of Antofagasta, is hosted by an altered volcanic sequence consisting of rhyolites, tuffs, dacites, and andesites, cross-cut by dacitic and andesitic dykes and sills. The composition appears to be, therefore, intermediate to acid in contrast to the more basic volcanic rocks of the coastal range of the La Negra Formation. According to Chavez (1985), the volcanic sequence is Middle Jurassic or older and not Cretaceous as previously assumed. Mantos Blancos shows host rock alteration characteristics similar to those occurring in the coastal range of the La Negra Formation but the orebodies display a more irregular geometry. The ore minerals (chalcopyrite, digenite, bornite, and subordinate chalcocite) occur mainly disseminated and in veinlets and to a lesser extent in the amygdaloidal part of the andesitic flows.

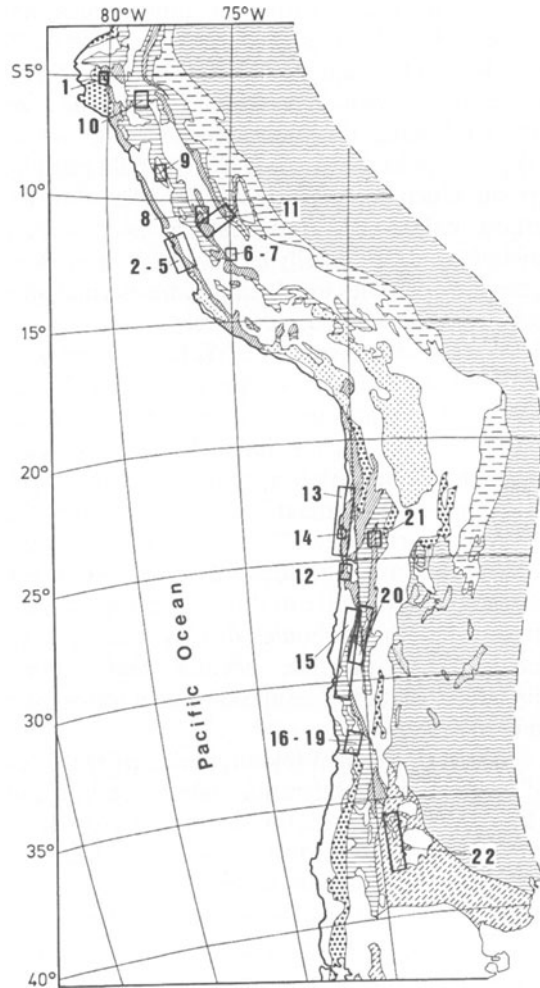
While all detailed investigations of these ore deposits recognize the existence of hydrothermal alteration related to the ore, it is difficult to elucidate the ultimate nature of the ore-forming fluids. It is also difficult to discriminate the role of burial metamorphism versus hydrothermal alteration related to magmatic processes, because both processes may lead to similar paragenesis. In this respect, Wolf et al. (this Vol.) describing the alteration in the Susana Mine, note that the ore shows a close temporal and spatial relationship to intense hydrothermal alteration, which is more intense – but similar in mineralogy – to that observed on a regional scale, probably due to burial metamorphism.

Two main hypotheses have been proposed to explain the genesis of these ore deposits. Losert (1974) carried out very detailed petrographic investigations in the Buena Esperanza Mine and distinguished two alteration types. The first is a regional scale alteration. The second type, of local extent, is superimposed on the first and is associated with the economic copper minerals. He proposes that the ore formed by leaching and concentration of copper disseminated in the volcanic rocks. Mobilization of Cu from mafic rock-forming minerals during regional

² (continued) (with only subordinate stratiform orebodies) and the El Soldado Mine (with no stratiform orebodies) have also been included in this “type” by Sato (1984). Thus, the expression “manto type” should be avoided as it actually includes different descriptive and genetic types, whereas the term “manto” can be used for tabular orebodies conformable with stratification (stratiform at the mine scale).

Ore deposits

<i>BA</i>	Bandurrias
<i>BE</i>	Buena Esperanza
<i>CB</i>	Coquimbana
<i>CC</i>	Caleta Coloso
<i>CF</i>	Cifuncho (prospect)
<i>CG</i>	Chaglla (prospect)
<i>CH</i>	Chañar Quemado
<i>CM</i>	Carolina de Michilla
<i>CN</i>	Cerro Negro
<i>CQ</i>	Cercapuquio
<i>DM</i>	Domeyko Cord., Chaco Q. (prospect)
<i>EX</i>	Extraño, El
<i>HG</i>	Bella Unión
<i>HU</i>	Huanzalá
<i>JA</i>	Jaula-Bellavista
<i>LC</i>	Las Cañas
<i>LG</i>	Leonila-Graciela
<i>MB</i>	Mantos Blancos
<i>MC</i>	Catemu, Mantos de
<i>MM</i>	Mamiña
<i>MN</i>	Mendoza, South of
<i>NQ</i>	Neuquén
<i>PC</i>	Punta del Cobre
<i>QU</i>	Corral Quemado
<i>RA</i>	Raúl-Condestable
<i>SD</i>	Santo Domingo
<i>SH</i>	Shalipayco
<i>SO</i>	Soldado, El
<i>SV</i>	San Vicente
<i>TA</i>	Talcuna
<i>TG</i>	Tambogrande
<i>UY</i>	Uyupán
<i>YA</i>	Yauli, Domo de

**Lithologic units****Peru**

- 1 Las Lomas Group
- 2 Puente Piedra Fm.
- 3 Morro Solar Fm.
- 4 Copara Group
- 5 Casma Group
- 6 Cercapuquio Fm.
- 7 Chaucha Fm.
- 8 Goyllarizquizga Fm.
- 9 Santa Group
- 10 Chulec Group
- 11 Pucará Group

Chile

- 12 Liassic Cifuncho
- 13 La Negra Fm.
- 14 Quebrada del Way Group
- 15 Bandurrias/Q. Marquesa Fm.
- 16 Lo Prado Fm.
- 17 Veta Negra Fm.
- 18 Las Chilcas Fm.
- 19 Lo Valle Fm.
- 20 Chañarcillo Group
- 21 L. Cretac. Domeyko

Argentina

- 22 Mendoza-Neuquén Basin

Fig. 2. Schematic stratigraphic position of selected stratabound ore deposits of Stages I and II. Left = situation of the considered synoptic sections.

scale alteration (and specifically regional epidotization) played an important role. Intrusive activity may have additionally promoted fluid circulation. Losert's ideas have been taken up again recently by Sato (1984). Espinoza and Palacios (1982) and Palacios (1986), without denying the existence of burial metamorphism, underline the spatial relationship of at least some of the ore deposits to volcanic necks and breccia pipes. This association appears to be especially clear in Buena Esperanza (in areas not exposed during Losert's investigations) and in the Susana Mine in the Carolina de Michilla district. Palacios (1986) proposes that late stage hydrothermal fluids related to the magmatism which formed the La Negra volcanic rocks are the major alteration and ore-forming agent. Homogenization temperatures of fluid inclusions in quartz (440–550 °C) and hypersaline compositions would support participation of magmatic processes in hydrothermal alteration (Palacios this Vol.).

The Frankenstein Mine and other copper deposits in the Altamira district (Rojas 1973) are comparable to those in the coastal range of the La Negra Formation. Copper sulfides occur in amygdaloidal volcanic rocks of Jurassic age.

Jurassic volcanic activity is also recognized in coastal areas of Peru. The earliest volcanic event linked to the subduction of the Nazca plate beneath the South American plate has a probable Sinemurian age (see discussion in Fontboté this Vol.). However, a morphologically clear volcanic arc such as that occurring in northern Chile is not known in Peru. For this reason copper deposits occurring in purely volcanic sequences are not found in Peru. It is possible that a volcanic arc located west of the Peruvian marginal basin has been tectonically eroded by the Nazca plate subduction (Audebaud et al. 1973) explaining the absence of this ore deposit type. An alternative, more probable hypothesis is, as discussed above, that the magmatic arc developed as a marginal basin without ever generating a true volcanic arc.

Iib) Ore Deposits in Volcaniclastic, Mainly Continental Basins at the Magmatic Arc (in Part Developed as Intra-Arc Basins) (Cu, Mn, Fe)

A number of stratabound copper and manganese deposits are known in northern and central Chile from Lower Cretaceous clastic sequences near the magmatic arc (in part in intra-arc basins). Copper deposits include, Caleta Coloso (Flint this Vol.) and the Talcuna district (Camus this Vol.). Stratiform manganese deposits (see also Sect. 2.11 in Oyarzún this Vol.) occur in the mines and districts of Fragua, Corral Quemado, La Negra-Coquimbana (Pincheira and Fontboté this Vol.), and Talcuna (Camus this Vol.). In addition, iron deposits occur in Chañar Quemado.

A common characteristic of many of the copper deposits located in these basins is the fact that copper minerals occur as cement of brackish, lacustrine, or shallow marine detrital volcaniclastic horizons. Hydrothermal alteration is generally not recognized, but burial metamorphism commonly affects the host sequences. Circulation of brines during diagenesis (Flint this Vol.) or burial metamorphism (Sato 1984) have been proposed as main metallogenetic factors. In addition, the participation of magmatic hydrothermal fluids has been invoked (Borić 1985).

According to Sato (1984), ore formation in the Talcuna district is bound to circulation of connate or metamorphic waters carrying cations mobilized during burial metamorphism. Many observational criteria support this hypothesis. The genetic discussion on the Talcuna district is especially interesting due to the spatial coincidence of the two stratiform ore types mentioned above: copper minerals as cement of clastic sediments and in the amygdaloidal tops of the lava flows underlying the same ore-bearing clastic horizons. This last textural type is very similar to the copper ores in amygdaloidal flow tops in the La Negra Formation (see stage IIa). However, in Talcuna, hydrothermal alteration is weak, whereas in the ore deposits in the La Negra Formation it is very intense. Therefore, the morphologic convergence between the copper ores in amygdaloidal lava flows in the Talcuna district and those in the La Negra Formation do not necessarily correspond to identical genetic processes. In both cases, the porous tops of the lava flows have increased the permeability. The circulating fluids could be, however, of very different nature, temperature, and timing. The genesis of the copper ores in the Talcuna district can be compared with that of the burial metamorphism-related Michigan copper ores, although they differ in their mineralogy, probably due to different sulphur fugacity grades. In the La Negra Formation ore forming processes are apparently linked to subvolcanic-hydrothermal activity.

IIc) Ore Deposits in Volcano-Sedimentary Sequences in Back-Arc Basins (in Part Developed as Marginal Basins) (Cu, Zn-Cu, Ba)

In this section basins characterized by thick volcano-sedimentary sequences deposited under clear extensional conditions are dealt with. The type of volcanism, recognition of burial metamorphism pointing to the presence of thermal anomalies, and the geometry of the basin indicate that in places they correspond to aborted ensialic marginal basins (see discussion above). Since no evidence of the presence of a morphologically clear volcanic arc is found west of these basins, and taking into account the very important volcanic activity registered *within* the basin, it can be suggested that they constitute the magmatic arc. They display, therefore, significant differences with the back-arc basins located east of a morphologically clear volcanic arc, which are characterized predominantly by sedimentary rocks, and which will be described under II d.

Important ore deposits, including several of the massive sulfide type, are found in volcano-sedimentary sequences of stage IIc. All of them occur in Lower Cretaceous rocks. They comprise both ore deposits closely associated with volcanic systems, and ore deposits associated with certain sedimentary facies in an overall volcanic-influenced environment. The following groups can be distinguished.

- Cu and Zn-Ba-(Cu) deposits in the central Peruvian ensialic aborted marginal basin.
- The Tambogrande Cu-Zn-(Ag) deposit in northern Peru (in an ensialic aborted marginal basin?).
- The Punta del Cobre Cu district in the Atacama basin.
- Cu and Cu-(Pb-Zn) deposits in the central Chilean aborted ensialic marginal basin.

Central Peruvian Aborted Ensialic Marginal Basin. In Lower Cretaceous rocks of the central Peruvian aborted ensialic marginal basin, important ore deposits occur. Cardozo (1983) and Cardozo and Vidal (1981) distinguish two main types according to their mineral assemblage. Each type corresponds to a different stage in the evolution of the basin:

- The association amphibole-pyrite-chalcopyrite occurs in ore deposits located in submarine, andesites, and in interbedded volcanoclastic sediments of the carbonate-volcanic lower Albian Copara Formation (e.g., the Cu mines of Raúl-Condestable, Los Icas, and other deposits of the Copara Metallo-tect).
- The association barite-sphalerite occurs in ore deposits of the middle Albian Casma Formation, which is characterized by fissure flood basalts, andesitic lavas, tuffs and hyaloclastic breccias, and neritic sediments, with sediments being progressively more abundant to the east [e.g., the Leonila-Graciela, Palma, and other barite and massive Zn-Fe-(Pb-Ag) sulfide deposits].

The Copara and Casma Formations are geochemically similar. They consist predominantly of high K-alumina basalts to basaltic andesites with some tholeiitic intercalations. A mantle origin with some crustal contamination is suggested by Atherthon et al. (1983, 1985). The attenuation of the continental crust is supported by geophysical data (Wilson 1985).

The Raúl Mine is well studied and is a good example of the amphibole-pyrite-chalcopyrite association in the Copara metallo-tect (Wauschkuhn 1979; Cardozo this Vol.).

Vidal (1987) reviews the stratabound barite and massive Zn-Fe-(Pb-Ag) sulfide ore deposits in the Casma Formation. By far the more important ones are the barite and Zn-(Pb-Ag) deposits of the Leonila-Graciela and Juanita Mines, 50 km east of Lima. Other deposits and occurrences are María Teresa (Ba-Pb-Ag), Aurora Augusta (Ba), Palma (Zn-Pb-Ag-Ba), Balducho (Ba and Zn), and Cantera (Ba). All of them occur within 50 km of Lima.

In Leonila-Graciela, although obscured by contact metamorphism and tectonic effects, a clear vertical zonation can be recognized. Lenses of barite overlie massive sulfide zones (mainly sphalerite and pyrite) located directly over a siliceous stockwork interpreted as a feeder zone. Similar feeder zones are found in Juanita, Aurora Augusta, and María Teresa. The massive sulfide beds are usually banded and locally exhibit soft sediment deformation textures. Furthermore, in Leonila-Graciela, Juanita, and Santa Cecilia, Vidal (1987) reports replacements of a first sulfide assemblage consisting of pyrite-sphalerite by chalcopyrite ± galena-tetrahedrite. On the basis of this evidence, Vidal compares these deposits to the Kuroko-type deposits in Japan, whereby the shallow-water deposition environment, and the absence of gypsum and ferruginous chert are important differences. Vidal (1987) also notes that feeder zones are not known in all deposits beneath the ore bodies; this is specifically the case of the nonmetamorphic sediment-hosted Palma prospect (Steinmüller and Wauschkuhn this Vol.).

The Tambogrande Cu-Zn-(Ag) Deposit in Northern Peru. In Upper Jurassic-Cretaceous volcanic rocks in northern Peru several stratabound massive sulfide

occurrences are known. The most important is the Tambogrande deposit with large massive pyrite bodies and Cu-Zn-(Ag)-rich zones (Pouit 1988). Barite zones, siliceous sulfide ore, and hematite chert beds are also found. Vidal (1987) compares this district to the massive sulfide ore deposits found in Mesozoic volcano-sedimentary sequences in southern Ecuador (see below).

Punta del Cobre District, Atacama Region, Chile. The Socavón Rampla and Agustina Mines in the Punta del Cobre district, near Copiapó, occur in altered (mainly Na-metasomatized) andesites in the uppermost part of the Punta del Cobre Formation (Upper Jurassic?, Lower Cretaceous?). A volcanoclastic unit with abundant pyroclastics and carbonate intercalations overlies the volcanic rocks. Camus (1980) gives an overview of the district; Hopf (this Vol.) presents a description of the Agustina Mine. Ore minerals occur within the volcanic unit in four geometric types: disseminated in the volcanic rocks; in veinlets as stockwork ore; as matrix of the brecciated volcanic rocks; and along vein zones. A complete transition exists between all these types. In addition, stratiform massive sulfide horizons occur. The ore paragenesis consists of chalcopyrite, pyrite, hematite, magnetite, and, very subordinate, sphalerite. Quartz and calcite are the main gangue minerals. In deep parts of the mine, massive bodies of magnetite and hematite are found. Camus (1980) relates ore deposition to volcanogenic hydrothermal activity, the ultimate expression of which would be the exhalative formation of stratiform massive sulfide and iron oxide orebodies at the sea floor, the other ore types being the result of precipitation along their feeder channels. Hopf (this Vol.) underlines the role played by hydrothermal alteration and points out the fact that massive sulfide stratiform bodies represent only a subordinate part of the orebody. Ongoing investigations indicate that the ore deposit is bound to a local zone of intense hydrothermal alteration with K-enrichment and Na-depletion.

A detailed investigation of the petrography and geochemistry of the Lower Cretaceous volcanism in the Atacama region is lacking. Mayer (1988) has summarized the available information and underlines the high K-content of the volcanic rocks (characteristic of shoshonitic suites) and the flat patterns of the REE diagrams, which would indicate relatively poorly differentiated and contaminated magma (i.e., characteristics also observed in the Lower Cretaceous volcanic rocks in central Chile). In the Chañarcillo Ag-district (about 70 km south of Copiapó) volcanic rocks interbedded with Lower Cretaceous marine sediments thin, noneconomic, stratiform amphibole-bearing massive sulfide horizons are found (Mayer and Fontboté 1986; Mayer 1988). They display alteration patterns similar to those in the Raúl Mine, Peru.

Central Chilean Ensialic Marginal Basin. The Lower Cretaceous in central Chile consists of thick volcanosedimentary sequences affected by prehnite-pumpellyite facies burial metamorphism (Levi 1970), which, according to Åberg et al. (1984) and Aguirre (1985), represent an aborted ensialic marginal basin. In this basin, two types of stratabound ore deposits occur. The El Soldado copper mine is the best-known example of the first type. It is characterized by discordant orebodies in intermediate volcanic rocks of the Lo Prado Formation (Holmgren 1985;

Klohn et al. this Vol.). These authors were able to discriminate between the local intense alteration associated with the hydrothermal ore-forming event and the alteration minerals produced by regional scale burial metamorphism. A genetic model related to burial metamorphism as proposed by Sato (1984) is rejected in favor of an epigenetic origin connected to hydrothermal fluids associated with alkaline (sodium-rich) magmatic activity of Aptian-Albian age (Lo Valle flood basalts). El Soldado is an example of transition between stratabound character (evidenced by their connection to distinct volcanic environments in the marginal basin) and nonstratabound hydrothermal systems associated to hypabyssal intrusions.

The stratiform Cu-(Pb-Zn) ores of the Mantos de Catemu (Camus this Vol.) and Cerro Negro (Elgueta et al. this Vol.) districts belong to the second deposit type. They are hosted in volcanoclastic and shallow-water sediments of the Las Chilcas Formation. The rapid facies changes, the abundance of volcanic and volcanoclastic material, and the inferred paleogeography of the restricted shallow-water basins, all indicate the vicinity of a volcanic arc to the west. The ores, mainly occurring as cement between volcanoclastic fragments, present textural similarities to those in detrital intra-arc basins (IIb). The ore deposits in the Mantos de Catemu district are located at the lower and, to a lesser extent, at the upper contacts of a shallow-water sedimentary intercalation in a mainly volcanoclastic continental sequence. Such a facies control, the predominant stratiform geometry of the orebodies, the paragenetic copper-lead-zinc zonation from bottom to top, which is very typical for sediment-hosted ore deposit, and the ore paragenesis and textures suggest that the ore deposits formed during diagenetic cementation and/or burial metamorphism. Waters circulating throughout the volcanoclastic sequence and sulfide precipitation at reducing zones in the contact between calcareous sediments and volcanoclastic breccias and conglomerates appears to be a suitable ore-forming mechanism.

The Cerro Negro district, located about 20 km north of Mantos de Catemu and still in the Las Chilcas Formation, displays similar characteristics, whereby part of the orebodies are spatially associated with an andesitic intrusive and the participation of magmatic fluids is likely (Elgueta et al. this Vol.). Among the many other stratabound copper mines in this area, that of Guayacán, occurring in an amygdaloidal lava flow and at the base of the overlying sediments, has been one of the economically most important (Ruiz et al. 1971). The copper mine Lo Aguirre (Ruiz 1965) presents similarities to El Soldado, and is possibly located in the southern continuation of this marginal basin.

IId) Ore deposits in Marine Sedimentary Sequences in Back-Arc Position (Fe, Ba, Zn, Pb, Ag)

This section deals with ore deposits hosted by a back-arc basin located east of a clear volcanic arc characterized by a mainly sedimentary sequence with only subordinate volcanic intercalations (in contrast to the volcano-sedimentary sequences of type IIc). This is the Lower Cretaceous back-arc basin recognized in the Atacama Region (Cisternas and Díaz this Vol.). The sediments are mainly

shallow marine carbonates with abundant volcanic and volcanoclastic intercalations. They are limited to the west by volcanic rocks of the Bandurrias Formation which constitute a morphologically clear volcanic arc and from which much of the abundant epiclastic components found in the sediments derive. Detailed facies analysis shows that the ore deposits occur within the Lower Cretaceous marine sequence of the Nantoco Formation at two well-defined paleogeographic positions or metallotects: (1) At the base of the Lower Cretaceous transgressive sequence over a volcanic and volcanoclastic unit, e.g., Jaula (Zn-Ag), Las Cañas (Pb-Zn), and (2) in an intermediate regressive episode (Upper Hauterivian), e.g., Mamiña (Ba), Triunfo-Carola (Ba-Pb), Gladys (Ba), and Bandurrias (Fe). The facies control on the ore deposits is well established. They occur in all cases in sediments deposited in peritidal environments.

The Bellavista (or Jaula) Zn-Ag Mine, is one example of ore deposits at the base of the transgressive sequence and is described by Díaz (this Vol.). Another example of ore deposits located at the base of the transgressive sequence is the Pb-Zn mine Las Cañas (Neuenschwander and Tavera 1942; Díaz 1986). This is one of the few stratabound mines which has been exploited for Pb and Zn in northern Chile. A 1.5–3 m-thick manto occurs about 20 m above the contact of the shallow-water Lower Cretaceous marine sequence with a unit consisting mainly of volcanic rocks. The manto consists of two to three 20–40-cm-thick ore-bearing levels separated by barren fine-grained limestone. The ore-bearing levels are pyroclastic breccias and volcanoclastic calcarenites cemented by galena, subordinate sphalerite, and in some cases barite and pyrite. The manto can be followed for over 2 km in a north-south direction. The ore minerals occur only in the volcanoclastic calcarenites and not in the intercalated fine-grained limestones, probably an effect of porosity.

The second paleogeographic position hosting stratabound ore deposits is the Upper Hauterivian intermediate regressive episode. It is characterized by algal mats with sulfate pseudomorphs in a sabkha-like facies (Cisternas this Vol.). According to this author, the regressive episode culminated in many areas with emergence documented by a collapse breccia horizon that can be followed intermittently for more than 100 km from north to south. This horizon contains anomalously high values for Zn and Pb, as evidenced in five lithogeochemical profiles across the sequence (Cisternas 1986; Mayer 1988). Two types of ore deposits are spatially linked to the collapse breccia: a belt of stratiform barite deposits (including Mamiña, Triunfo-Carola and Gladys; Díaz this Vol.) and the stratiform iron deposit of Bandurrias (Cisternas this Vol.; Espinoza this Vol.). Forty km N of Bandurrias, broadly in the same stratigraphic position, is located the Manolete district with stratiform magnetite and jasper occurrences in carbonatic-tuffaceous rocks.

Lead isotope investigations (Puig 1988, this Vol.; Fontboté et al. this Vol.) indicate that the metals in deposits in the Atacama back-arc basin are derived directly (exhalative processes) or indirectly (by erosion and leaching of volcanic material) from the volcanic activity in the magmatic arc. The common association of the ore horizons with tuffaceous material could indicate exhalative processes of ore formation. This possibility is emphasized by Lino and Rivera (1987), who also report anomalously high Au values in siliceous-ferruginous and evaporitic horizons in the Tres Amantes and San Pedro Mines.

*IIe) Ore Deposits in Platform Sediments Attached to the Foreland
(Zn-Pb-Cu, Zn-Pb, Ba-Sr, U)*

As indicated above, the arc-back-arc pair developed a strongly asymmetric depositional system, with a western volcanic and volcano-sedimentary belt and an eastern, predominantly sedimentary back-arc basin. In some areas of Peru and south of latitude 33°S (Neuquén Basin, Argentina) east of the typical back-arc basin, Jurassic and Lower Cretaceous marine sediments deposited in a platform attached to the foreland are found. This depositional environment could also be considered as a distal back-arc basin because it lies east of the magmatic arc, and because the basin development is in part controlled by the evolution of the magmatic arc, but it presents important differences compared with the back-arc basins discussed under II d and, therefore, it will be dealt with separately (stage II e). The main differences found in these platform sediments attached to the foreland compared to those deposited in the back-arc basin are the scarce volcanic activity and the only very subordinate amount of epiclastic components derived from the western magmatic arc. The lead isotope composition of ores is also clearly different in both paleogeographic positions and supports this subdivision, at least in Peru (Fontboté et al. this Vol.).

The sedimentary sequences in platforms attached to the foreland consist mainly of shallow marine carbonate rocks with marly and detrital intercalations. Detrital material is predominant in some sequences located near the emerged continent. Subordinate volcanic activity is also recognized. Four groups of stratabound ore deposits are known to occur in this paleogeographic situation (II e), which corresponds in part with the term miogeosyncline as used by Auboin et al. (1973) and Cobbing (1978).

- Ore deposits in Jurassic sediments in central Peru (Cercapuquio).
- Ore deposits in the Lower Cretaceous Santa Formation in central Peru (“Santa metallotect”).
- Stratiform pyrite and Zn-Pb ore bodies in the Hualgayoc district, northern Peru.
- Barite-celestite deposits in the Neuquén-Mendoza basin in Argentina.

Jurassic Sediments in Central Peru. In central and northern Peru the paleogeography of the Upper Jurassic and Lower Cretaceous marine sequences east of the marginal basin is determined by the presence of an emerged block, the Marañón geanticline, which can be followed from north to south for several hundred kilometers (Mégard 1978, 1987; Cobbing 1978). The platform sequences located west of the Marañón anticline comprise several transgressive-regressive cycles and consist mainly of neritic carbonate rocks with detrital intercalations. Volcanic activity is recognized in several localities. To the west these platform sequences grade into the predominantly volcanic and volcanoclastic marginal basin (II c). In the basin between the Marañón anticline and the Brazilian Shield clastic sedimentation prevailed. Ore deposits are known only west of the Marañón anticline, the detrital sequences east of it being poorly known.

The carbonate-hosted Zn-Pb mine of *Cercapuquio* lies west of the Marañón geanticline (Cedillo this Vol.). The main ore minerals are galena and brunckite, which mainly occur in several superimposed karst cavities spatially related to paleosols near a contact zone between peritidal evaporite minerals bearing carbonate sediments (Chaucha Formation) and underlying detrital layers (Cercapuquio Formation). Cedillo (this Vol.) proposes a genetic model based on post-tectonic supergene enrichment of previous MVT ores. In a similar paleogeographic position, at the contact of clastic facies between the Cercapuquio Formation and shallow-water carbonates of the Chaucha Formation are located stratiform Zn-Pb-Ba occurrences in Miraflores, near Azulcocha, Peru (Muñoz C. pers. commun.).

Lower Cretaceous Santa Formation. In central Peru Samaniego (1980, 1982) and Samaniego and Amstutz (1982) described approximately 80 stratabound Zn-Pb-(Ag-Cu-) ore deposits and occurrences in shallow-water carbonate and clastic facies of the Santa Formation (Late Valanginian). This work is one of the first systematic regional-scale investigations of stratabound deposits in the Central Andes. It includes previously known mines (e.g., Pachapaqui, Huanzalá, Pacllón Llamac), but the potential for new areas was first recognized using the exploration criteria developed during the investigation, as was the case in the El Extraño Mine. In several places the ore-bearing horizons display peritidal facies. These authors emphasize the pre-tectonic character of the ore deposits and the lack of genetic relations with intrusive bodies which, in some cases, produce an overprint with skarn mineral assemblages (e.g., El Extraño and Huanzalá). This interpretation contrasts with models based on skarn metasomatism (Imai et al. 1985). According to Samaniego (1982), the ore deposits in the Santa Metallotect occur at two main paleogeographic positions. The first is over a positive block at the western edge of the platform ("Río Santa positive block"), and the second at the eastern margin of the Santa Formation in the clastic facies adjacent to the western part of the Marañón anticline. Ore deposits in the western belt include the Pb-Zn mines El Extraño and Pachapaqui, and the Isca Cruz prospect (Oyón area; Flores this Vol.). Ore deposits in the eastern belt, i.e., at the western margin of the Marañón geanticline are the Zn-Pb-Cu-Ag Huanzalá (Carrascal and Sáez this Vol.) and Aída Unica deposits (partly with massive sulfide ores). The sandstone-hosted stratiform Pb-Zn occurrences in the Goyllarisquizga Formation near Milpo were included also by Samaniego (1982) in the Santa Metallotect. However, the possibility that they were formed by impregnation in relation with the Tertiary skarn deposits of the Milpo-Atacocha district (Soler 1986) is supported by lead isotopic data (Gunnesh and Baumann 1990).

A volcano-sedimentary origin for El Extraño, Huanzalá, Aída Unica, and other ore deposits has been proposed based upon trace element contents in the ores and the presence of intercalated tuffs (Soler 1986, 1987; Carrascal and Sáez this Vol.). Soler et al. (1986) explain the link between the ore deposits and certain paleogeographic positions by a distribution of the possible volcanic centers along normal faults at the border of the basin. It should be mentioned, however, that although subordinate volcanic material is common, evidence of direct volcanic activity during ore formation is not always clear.

In the *Hualgayoc district*, northern Peru, occur stratiform Pb-Zn and quartz-pyrite bodies in limestones, marls and shales in the Chulec and Pariatambo Formations (Canchaya this Vol.). The mantos appear to be linked to definite stratigraphic horizons, in part associated with thin tuffitic layers. This author suggests that the stratiform orebodies are of synsedimentary origin, in part exhalative-sedimentary. In contrast, MacFarlane (1989) proposes that the mantos are connected to Tertiary intrusions and Cu-Pb-Zn-Ag veins occurring in the same area.

A further ore type in this geotectonic environment is represented by *V-rich lenses in asphaltiferous limestones* in the Pariatambo Formation (Albian). The supergene enrichment was exploited in the now closed Mina Ragra (Cánepa this Vol.).

In Argentina during Jurassic and Lower Cretaceous an extensive evaporitic-shallow marine platform develops between the Andean basins to the west and emerged cratonic terrains to the east (the *Neuquén-Mendoza basin*). In these epicontinental sediments important barite-celestite ore deposits occur associated with three evaporitic cycles of Middle and Upper Jurassic and Lower Cretaceous age (Ramos and Brodtkorb this Vol.). The ore deposits are mainly stratiform and occur in peritidal carbonate facies which have reached burial depths over 2500 m. Strontium isotope ratios of host rocks plot in the range of contemporaneous ocean water, ore samples show slightly more radiogenic values indicating a diagenetic rather than a purely synsedimentary formation (Gorzawski et al. 1989).

3.1.3 Stage III (Upper Cretaceous-Cenozoic). Ore Deposits in Continental Intra-Arc and Foreland Basins

The extensional stress regime prevailed up to the end of Lower Cretaceous times, changing to several periods of compression during Upper Cretaceous and Cenozoic times. The volcanic centers (consisting mainly of intermediate and acid calc-alkaline suites) migrated eastwards, and only continental basins were developed. Frutos (1981) relates the compressive episodes to changes in the rate and angle of subduction. Other factors, like during Middle Cretaceous the Atlantic opening pushing the continent into the arc, as well as the subduction of aseismic ridges during the Tertiary are also important. In Cenozoic times an alkaline belt located east of the main calc-alkaline volcanic belt developed.

During this stage of the Andean orogeny (Upper Cretaceous-Cenozoic), which is of greatest importance for the genesis of other types of ore deposits (e.g., porphyry copper type, metasomatic skarn, and different types of hydrothermal polymetallic deposits), significant stratabound ore deposits also formed. The following main types of ore deposits occur.

- IIIa) Fluvial-lacustrine basins in intermediate to acid volcanic environment (polymetallic deposits).
- IIIb) Molasse sequences in intermontane basins, in part foreland basins [red-bed type Cu and Cu-(U-V) deposits].

III c) Deposits related to Cenozoic alkaline volcanics, mainly in ignimbritic flows and tuffs (U).

In addition, the following group of deposits should be mentioned: (1) manganese mantos in Pleistocene and recent intermediate to acid volcanic rocks and lacustrine sediments in the Altiplano northeast from Arica (e.g., Huachipato, Ruiz 1965; Sillitoe 1976; see also Sect. 3.7.c in Oyarzún this Vol.). (2) boron and lithium deposits formed in strongly evaporitic environments in the salares in Bolivia, Chile, and Argentina in relation to leaching of surrounding acid Plio-Quaternary volcanic rocks (Vila this Vol.; Alonso and Viramonte this Vol.). (3) the Quaternary iron-oxide flows of El Laco, in northern Chile (Frutos, Oyarzún, Shiga and Alfaro this Vol.). (4) sulfur concentrations related to Cenozoic or Quaternary exhalative activity in restricted basins (Ferraris and Vila this Vol.). (5) "Exotic" copper occurrences formed by supergene leaching of porphyry copper deposits (e.g., Exótica or Chuqui Sur, see Sect. 3.5 in Oyarzún this Vol.).

IIIa) Polymetallic Ag-Bearing Deposits in Fluvial-Lacustrine Basins in Intermediate to Acid Volcanic Environment

The Cu-Pb-Zn-Ag deposit of Colquijirca (Pasco) is one of the main silver producers in Peru, was interpreted classically as hydrothermal metasomatic (Lindgren 1935; McKinstry 1936; Vidal et al. 1984). Lehne and Amstutz (1982) suggested alternatively a syndimentary-syndiagenetic genesis related to exhalative vents associated with the rhyolitic to rhyodacitic Marcapunta volcanic complex (Lehne this Vol.).

The Cu-Ag belt south of Copiapó, Chile (Lortie and Clark 1987), with the mines Amolanas (Cu), El Venado (Cu-Ag), El Jardín [Ag-Cu-(Zn)] (Mayer and Fontboté this Vol.) and Elisa de Bordos (Ag-Hg) (Jurgeit and Fontboté this Vol.) occurs at the base of the Hornitos Formation (Upper Cretaceous?). El Jardín and Elisa de Bordos occupy different paleogeographic positions within the same ignimbritic complex. In Elisa de Bordos, located at the edge of the main ignimbritic body, the ore is sulfur-free and is formed by supergene circulation along the lower and upper contacts of the main ignimbritic body with tuff horizons. El Jardín occurs in a more central part of the ignimbritic complex in an euxinic basin formed over the irregular surface of the main ignimbritic body. The ore is probably formed during diagenetic cementation in part under euxinic conditions. Fumarolic activity during ore formation in relation with Ag-Cu-As-Hg epithermal systems located in the vicinity but not directly in the known parts of the mines is a possibility to be taken into account.

IIIb) Red-Bed Type Cu and Cu-(U-V) Deposits in Molasse Sequences in Intermontane Basins

A well-studied example of red-bed type Cu deposits in molasse intermontane basins is the mine of San Bartolo, north of the Salar de Atacama, Chile, which

is located in a clastic-evaporitic sequence of Oligocene age (Paciencia Group). According to Flint (this Vol.), copper sulfides and native copper have formed during diagenetic cementation from brines released from the detritic-evaporitic sequence. The famous Cu-Ag deposit of Corocoro in Bolivia, in the Kollu-Kollu and Caquiaviri Formations (Oligocene-Miocene) also belongs to this type (Avila this Vol.). Numerous Cu-Ag occurrences are also known in red-bed sequences in the Upper Cretaceous to Eocene Sicuani basin in southern Peru (Cadenas 1987; Córdova 1986), and in Argentina (see Sect. 3.4 in Oyarzún this Vol.).

Red-bed type Cu-(U-V) and U-(Cu-V) ore deposits occur in Upper Cretaceous-Cenozoic molasse sediments of the Riográndico Cycle in the Neuquén-Mendoza basin, Argentina (Brodtkorb and Brodtkorb 1984). The most important district is that of Huemul-Agua Botada (U-Cu), which occurs in the Diamante Formation (Upper Cretaceous, Ferreyra and Lardone this Vol.).

IIIc) Uranium Deposits Related to Cenozoic Alkaline Volcanic Rocks, Mainly in Ignimbritic Flows and Tuffs

Several important uranium ore deposits and occurrences are known along the intermediate-acid alkaline volcanic belt of Cenozoic age extending in the Central Andes of Peru, Bolivia, and northwestern Argentina over more than 1000 km in north-south direction. The peralkaline composition of this belt is explained by its "back-arc" position with respect to the main calc-alkaline volcanic arc (Coira et al. 1982). The most important are Macusani (Peru, Arribas and Figueroa 1985; Valencia and Arroyo 1985), the Sevaruyo district (Leroy et al. 1985; Pardo-Leyton 1985), and the Aguiliri district and other occurrences in the Argentinian Puna (Stipanovic et al. 1985). These deposits are associated mainly with rhyolitic and rhyodacitic ignimbrites and tuffs of Miocene-Pliocene age. Disseminated uranium content is found in definite units in the pyroclastic sequences. Secondary concentrations of economic interest are found in the ignimbritic units but also, when present, in fine- to medium-grained nonconsolidated detrital sediments. Uranium enrichments in evaporitic environment in salares are also found (e.g., Salar de Río Grande, northwestern Argentina, Stipanovic et al. 1985).

3.2 Ore Deposits of the Andean Cycle in the Northern and Southern Andes

Information on stratabound ore deposits of the Andean Cycle in Ecuador, Colombia, and Venezuela is scarce and also less available to the author. All known examples are Cu-Zn-Pb deposits of the massive sulfide type located in volcano-sedimentary sequences, probably corresponding in part to areas of a Mesozoic accreted ensimatic volcanic arc and in part to back-arc marginal basins (Ortiz this Vol.; Lehne this Vol.). They include the ore deposits and occurrences of Micogrande, El Roble, El Dovio, La Plata, and Macuchi.

In the Southern Andes is found the important Pb-Zn district El Toqui, in Aysén, Chile (Wellmer and Reeve this Vol.). It occurs in marine carbonate rocks intercalated with pyroclastic and black shale horizons of Lower Cretaceous age.

This volcanic-associated massive sulfide district appears to be linked to volcano-sedimentary sequences close to the magmatic arc and therefore its tectonic position can be compared to that of the ore deposits in the marginal basin in the Central Andes (stage IIc). The southernmost ore occurrence is the massive sulfide polymetallic ore of Beatriz in the Tierra de Fuego region hosted by dacitic and rhyodacitic volcanic rocks of the Lower Cretaceous Yahgán Formation (Zubia et al. 1989). Probably other small ore showings in Mesozoic volcano-sedimentary sequences between Aysen and Tierra de Fuego also represent stratabound ores, but no information is available on this very poorly accessible and little known region.

Relatively important stratabound uranium deposits are known in Lower Cretaceous reworked pyroclastic rocks associated to fluvial and lacustrine environments in the Patagonia. To this type belong the mines of los Adobes and Cerro Condor which were exploited in the 1970s and early 1980s (Angelelli et al. 1984).

3.3 Ore Deposits in Sub-Andean Basins

Some small stratabound ore deposits and occurrences are also known in Sub-Andean basins. Little information exists about them except for a number of ore deposits in the Salta Group in northwestern Argentina (Sureda et al. 1986).

The Salta Group (Lower Cretaceous to Eocene) comprises mainly continental sediments deposited in a basin limited to the east and south by cratonic terrains and which to the west occupies an Andine position rather than a Sub-Andine one. From bottom to top: the Pírgua, Balbuena, and Santa Bárbara Subgroups are distinguished (Salfity 1982). Ore deposits are known to occur in the former two subgroups. Sureda et al. (1986, see also Sect. 2.15 and 2.16 in Oyarzún this Vol.) distinguish three main types of ore deposits. (1) Cu-(U, V) deposits in red-bed facies of the detritic-evaporitic Pírgua Subgroup. The ore deposits are located in an area 40 to 80 km south of Salta. Custodio (Cu) is the most significant ore deposit of this type. (2) U-(Cu, V) deposits in detrital facies of the Yacoraite Formation (Maestrichtian) of the Balbuena Subgroup (e.g., Don Otto and Los Berthos (U), Ferreyra and Lardone this Vol.). (3) Pb-Zn-Cu deposits also in the Yacoraite Formation but in dolomitic limestones of a restricted carbonate environment with indirect marine influence (Marquillas and Salfity 1989; e.g., Cerro Plomo, south of Río Juramento). According to Sureda et al. (1986), erosion of cratonic terrains located south and east of the basin, as well as favorable local conditions (including the presence of organic matter) during deposition and diagenesis are the main metallogenetic controls.

It is very probable that in other Sub-Andean basins with similar facies and paleogeographic characteristics, stratabound ore occurrences also exist. However, since no large ore deposits are known, not many investigations have been done on this topic.

4 Conclusion

The preceding review shows that stratabound ore deposits are well represented in the Andes, in terms of both economic importance and typologic variety. It should

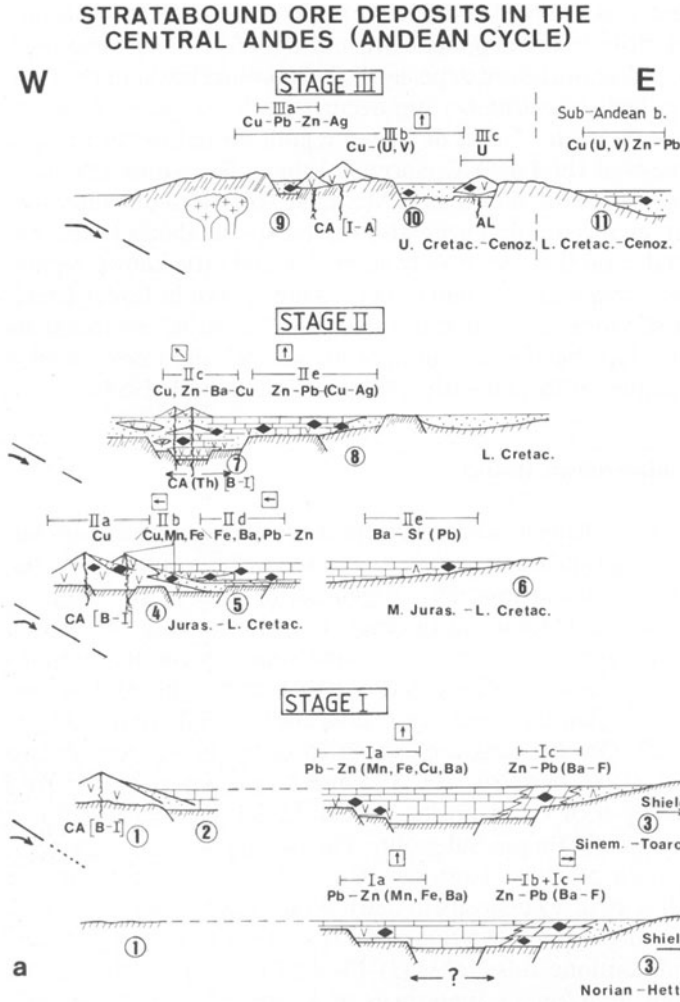


Fig. 3. a Schematic W-E cross-sections for Stages I, II and III in the Central Andes constructed on the basis of the following representative partial profiles. 1 Southern Peruvian coast. 2 Río de La Leche. 3 Ore deposits in the Pucará basin (Domo de Yauli, Shalipayco, San Vicente). 4 Ore deposits in the La Negra Formation (Carolina de Michilla, Buena Esperanza), in the Quebrada Marquesa (Talcuna, Chañar Quemado) and Bandurrias Formations (Coquimbana, La Negra). 5 Ore deposits in the Atacama back-arc basin (Bandurrias, Mamiña, Jaula). 6 Ore deposits in the Neuquén basin. 7 Ore deposits in the marginal basins in Central Peru (Raúl, Leonila Graciela) and in the Central Chile (El Soldado, Mantos de Catemu). 8 Ore deposits in the foreland platform in Central Peru. (El Extraño, Cercapuquio). 9 El Jardín, Elisa de Bordos. 10 San Bartolo, Corocoro and Aguiliri. 11 Ore deposits in the Sub-Andean basin near Salta.

CA [B-I] Intermediate-acid calc-alkaline volcanism; (Th) tholeiitic intercalation; CA [I-A] intermediate-acid calc-alkaline volcanism; AL intermediate-acid alkaline volcanism.

← Nonradiogenic lead isotope ratios; ↖ Nonradiogenic to moderately radiogenic; ↑ Moderately radiogenic lead isotope ratios; → Radiogenic lead isotope ratios (see Fontboté et al. this Vol.)

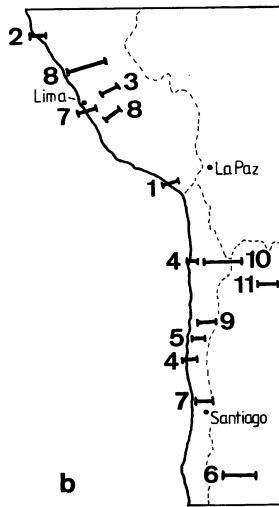


Fig. 3. b Situation of the cross-sections

be noted that the knowledge and exploration of stratabound ore deposits in the Central Andes is not complete. The real economic potential of ore belts such as the massive sulfide deposits of Ecuador, Peru, and southern Chile, the Mississippi Valley-type deposits of the eastern Pucará, and also the Cu-(Ag) deposits in the La Negra Formation, has only been recognized in the last 30 years. Although the information on Andean stratabound ore deposits is still not homogeneous, several trends are clearly recognized, and it is already possible in many cases to predict in what tectonic environments distinct types of ore deposits may occur. The ore deposits are closely coupled to regional geologic evolution, and therefore can be largely classified in a scheme based on the geotectonic position of the host rock with respect to the evolution of the Andean orogen.

The ore deposits of the Andean Cycle are commonly used as an example of metal zonation perpendicular to a convergent plate boundary (Clark et al. 1976; Sillitoe 1976). In the case of the stratabound ore deposits, west to east zonations are also recognized (Fig. 3). The stratabound ore deposits are related to geologic environments which evolved in time and space. Thus, the distribution trends are not simple, but rather respond to superimposition patterns. Therefore the zonations are better recognized by considering each stage separately (Fig. 3) or considering types of deposits instead of elements, as some elements are found in several types of deposits (e.g., Zn, Pb, Cu). In particular, the bipolarity of stage II with a magmatic arc to the west and back-arc and platform sediments to the east is perfectly reflected in the types and metal content of the ore deposits of this stage.

It should be emphasized that the zonation patterns cannot be explained just as a function of the distance to the subducting slab of oceanic crust. They correlate with geotectonic environments trending north-south, which, of course, are largely determined by the subduction mechanism, but also by spreading-sub-sidence processes in back-arc environments. Irregularities in type of subduction must also be considered. In addition, all geologic environments developed during

the Andean Cycle in the Central Andes form on continental crust. Thus, differences in the pre-Mesozoic basement are an important factor to be taken into account. Although the west-east variation patterns are predominant, differences in a north-south direction are also observed. The following are three examples: (1) Significant Zn-Pb Mississippi Valley-type ore deposits are not known south of latitude 12°S. (2) Equivalents of the important barite and/or pyrite Zn-Pb-Cu massive sulfides known of the marginal basin of Peru are absent in northern Chile. (3) Copper deposits in sequences hosted almost exclusively by volcanic rocks, as in the volcanic arc of the La Negra Formation, Chile, are absent in Peru. All these differences can be explained by the general geologic record of the Andean belt. The fact that the Andean basins are narrower south of the Arica-Santa Cruz deflection accounts for the lack of extensive platform sedimentation up to the Neuquén basin, and therefore the absence of the ore deposits linked to this environment. Massive Zn-Pb-Cu sulfides appear to be related to marginal basin development recognized in several areas all along the Andean Cordillera but not in northern Chile. In northern Chile, in contrast, copper ores occur typically associated to a morphologically well distinguishable volcanic arc which is represented mainly by the La Negra Formation. The different evolution types of the magmatic arc discussed above can explain this typological diversity. Inhomogeneities in deep sources (upper mantle), as suggested by Noble (1976), probably exist, but they are not necessary to justify the known north-south variations.

Finally, it can be concluded that the occurrence and genesis of the stratabound ore deposits in the Andes is linked to the regional geological evolution. The occurrence of stratabound ore deposits should therefore be considered as an integral element in the evolution of the Andean basins. The driving force for the overall geologic evolution during long periods is the subduction process. The supply of the metals and the actual formation process of the stratabound ore deposits is, however, not directly controlled by this mechanism. Lead isotopic investigations on ore deposits of the Andean Cycle indicate conclusively that relative to the geotectonic position, different ore sources were involved (Fontboté et al. this Vol.).

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