Groundwater exploration and wellfield development in the Pampa Lagunillas and Pampa Lirima areas, Provincia de Iquique, Chile

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ABSTRACT

A successful groundwater exploration and development program was conducted in the Pampa Laguni las and Pampa Lirima groundwater basins, in the Prealtiplano of northern Chile. The objective of the program was to develop a wellfield capable of providing 120 liters per second of good quality groundwater for industrial use at the Cerro Colorado copper mining complex for an estimated mine life of 30 years. Wellfield development of the Pampa Lagunillas basin consisted of construction and testing of four large-diameter high-yield production water wells. Results of the exploration and development programs indicated that large quantities of recoverable groundwater are stored in the aquifer systems in each basin. The most favorable conditions for development of a large and reliable groundwater supply occur in the Pampa Lagunillas basin, where groundwater storage in the saturated alluvial sediments in the Pampa Lagunillas basin is in the magnitude of 450 million cubic meters.

Key words: Groundwater development, Hydraulic properties, Groundwater chemistry, Hydrogeology, Salar basins, Pampa Lagunillas, Pampa Lirima, Chile.

RESUMEN

Exploración de aguas subterráneas y desarrollo de un campo de pozos en las áreas de Pampa Lagunillas y de Pampa Lirima, Provincia de Iquique, Chile. Se llevó a cabo un exitoso programa de exploración y desarrollo de agua subterránea en las cuencas de Pampa de Lagunillas y Pampa Lirima, en el prealtiplano del norte de Chile. El objetivo del programa fue desarrollar un campo de pozos de extracción capaz de producir 120 litros por segundo de agua subterránea de buena calidad para uso industrial en el complejo minero de Cerro Colorado por una duración estimada de 30 años. En Pampa Lagunillas, el desarrollo consistió en la construcción y prueba de cuatro pozos de alta productividad. Los resultados del programa de exploración y desarrollo revelaron la presencia de grandes cantidades de agua subterránea recuperable, almacenada en los acuíferos de cada cuenca. Las condiciones más favorables para el desarrollo de un sistema de abastecimiento confiable ocurren en Pampa de Lagunillas, donde la acumulación de agua subterránea en sedimentos aluviales saturados es del orden de 450 millones de metros cúbicos.

Palabras claves: Agua subterránea, Propiedades hidráulicas, Química de aguas, Hidrogeología, Salares, Pampa Lagunillas, Pampa Lirima, Chile.

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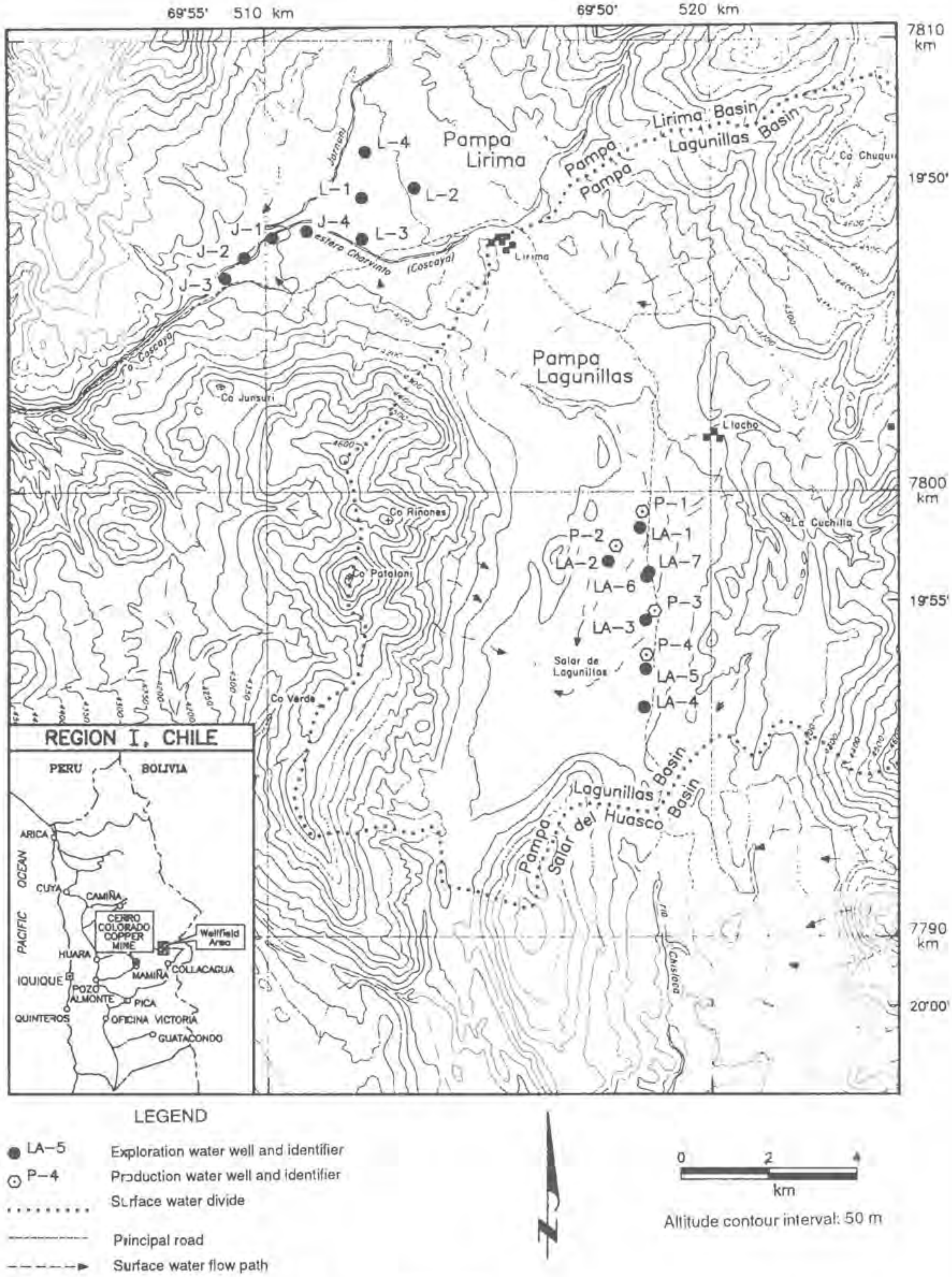

FIG. 1. Location map for Pampa Lagunillas and Pampa Lirima areas.

[1] 1978. Cuadrángulo Collacagua y Salar del Huasco (Inédito), *Instituto de Investigaciones Geológicas*, 27 p.

[2] 1972. Hidrografía de las zonas desérticas de Chile: Investigaciones de las recursos hidráulicos en el Norte Grande. *Programa de las Naciones Unidas para el Desarrollo*, 188 p.

INTRODUCTION

At the request of Compañía Minera Cerro Colorado Ltda., a hydrogeologic investigation project was conducted to develop a reliable water supply of 120 l/s for the Cerro Colorado copper mining complex, located near Mamiña, Iquique (I Region), Chile. Location of the mine is shown in figure 1.

In 1981, a reconnaissance groundwater investigation in the Cerro Colorado copper mine region was completed; results suggested favorable groundwater conditions in the Pampa Lagunillas and Pampa Lirima basins. These basins are located about 50 km east from the mining complex (Fig. 1). In 1982, following the reconnaissance investigation, a groundwater exploration program was conducted in the Pampa Lagunillas and Pampa Lirima groundwater basins. Exploration water wells numbered LA-1 through LA-7 were constructed in the Pampa Lagunillas groundwater basin; locations for these wells are shown in figures 1 and 2. Exploration water wells L-1, L-2, L-3, and L-4 were constructed in the Pampa Lirima groundwater basin; locations are shown in figures 1 and 3. Air-lift pumping tests were completed for each exploration well. Favorable sites for construction of production water wells were selected in the Pampa Lagunillas groundwater basin based on the results of the exploration program; production water wells P-1, P-2, P-3, and P-4 were constructed and tested in 1992.

PREVIOUS INVESTIGATIONS

A summary of groundwater development conditions in salar basins in arid zones of the prealtiplano is given by Montgomery and Harshbarger (1985). A study of the geologic units found in the study area is given in Vergara and Thomas (1984). Results of geologic investigation for nearby areas are given by J. Sayes (1978)[1] and Vergara (1978). A review of the geology of salars in northern Chile was reported by Stoertz and Ericksen (1974). Hydrogeologic conditions in arid zones of northern Chile were reported by E. Klohn (1972)[2], J. Karzulovic and F. García (1979)[3], and Harza Engineering Co. (1978)[4].

A groundwater exploration program for the Pampa Lirima area was conducted by the Japan International Cooperation Agency (JICA) during the period February-October, 1977, and included construction of four groundwater exploration wells in the west part of the Pampa Lirima basin (JICA, 1978)[5]. JICA wells are identified as J-1, J-2, J-3, and J-4; locations are shown in figure 3. Short-term pumping tests were conducted for these wells by JICA; pumping rates ranged from 0.02 to 4.6 l/s. Natural artesian discharge occurred from three of the wells at rates ranging from 0.03 to 1.0 l/s.

HYDROGEOLOGIC CONDITIONS

The Pampa Lagunillas and Pampa Lirima groundwater basins are located in the arid prealtiplano of the I Region , Northern Chile. This region is situated between the Central Valley, or Pampa del Tamarugal, on the west and the Altiplano of Bolivia on the east. The arid prealtiplano region of Northern Chile comprises an undulatory plateau interrupted by north-trending ridges and chains of volcanic peaks with intervening valleys and basins, many of which have internal drainage (Stoertz and Ericksen, 1974).

PAMPA LAGUNILLAS

Pampa Lagunillas is located in an endorheic, or closed topographic basin with internal drainage. Surface water and groundwater move to naturally occurring discharge areas where the water is lost to the atmosphere by evaporation. The area of the alluviated basin floor is approximately 30 km^2 (Fig. 2). The basin floor slopes gently to the southwest toward the salt-encrusted flats at Salar de Lagunillas.

[3] 1978. Desarrollo de los recursos de agua en el Norte Grande, Chile: El Proyecto Chi-69/535 CORFO. *Programa de las Naciones Unidas para el Desarrollo Dirección General de Aguas*, Informe Principal, 88 p.

[4] 1979. Evaluación de recursos hídricos, Provincia de Iquique, I Región: Tarapacá (Inédito). *Dirección de General de Aguas-Secretaría Regional de Planificación*, 171 p.

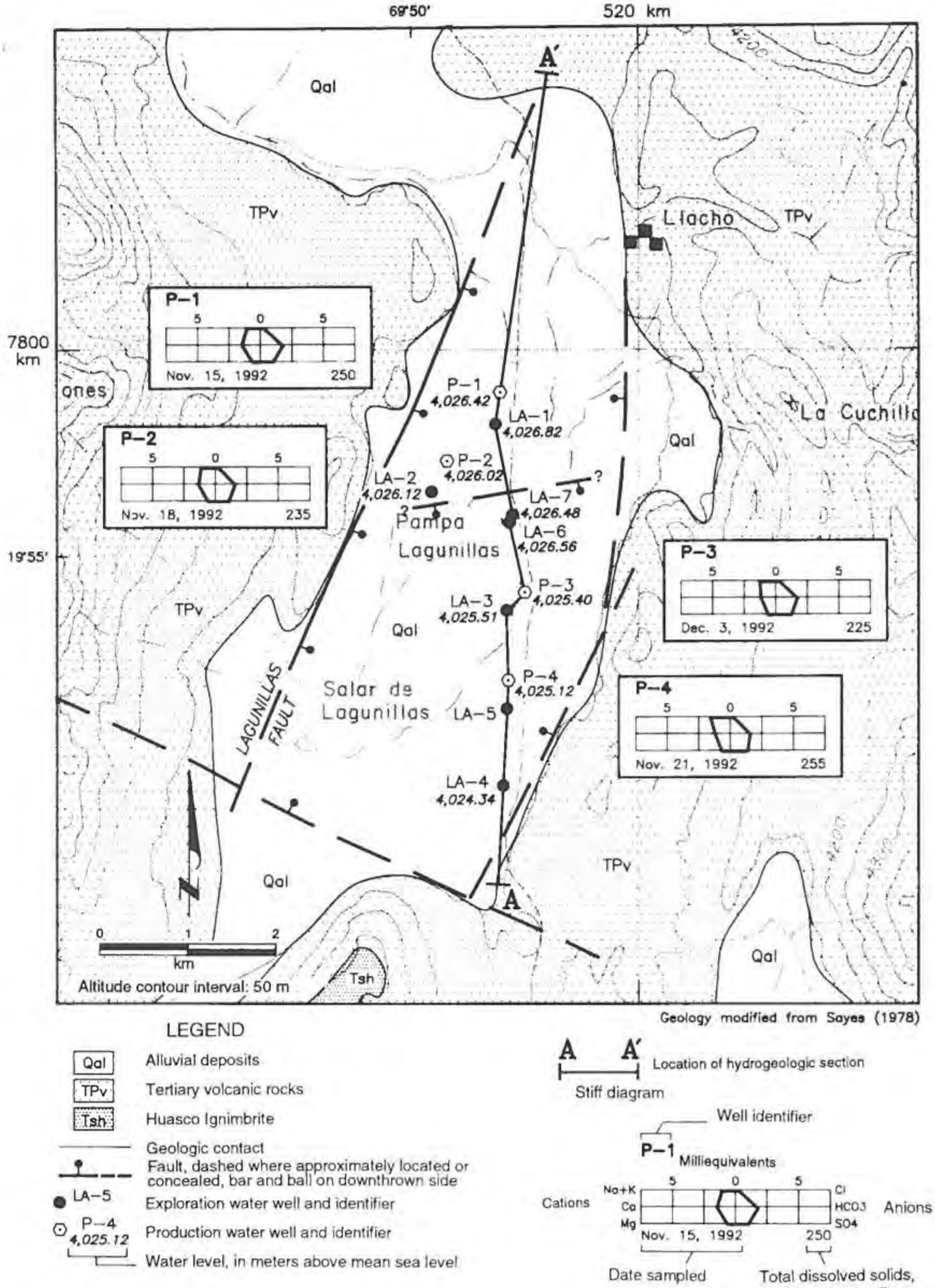

FIG. 2. Hydrogeologic features, Pampa Lagunillas.

The altitude of the basin floor ranges from approximately 4,000 to 4,100 m a. m. s. l.

The drainage basin for Pampa Lagunillas encompasses an area of about 125 km². Snow-capped mountains, which reach an altitude of approximately 4,800 m at the northeast margin of the drainage area, are the source for perennial streams which drain to the basin floor. After the streams reach the alluviated basin floor, they become intermittent and ephemeral. A surface water divide occurs on the north margin of the basin between Pampa Lagunillas and Pampa Lirima, and on the south margin between Pampa Lagunillas and the Salar del Huasco basin (Fig. 1).

PAMPA LIRIMA

The Pampa Lirima basin comprises the headwater region for westward flowing Río Coscaya. The area of the alluviated basin floor is approximately 45 km² and the basin floor slopes gently to the southwest (Fig. 3). The altitude of the basin floor ranges from approximately 4,000 to 4,200 m.

The drainage area for Pampa Lirima encompasses an area of about 180 km². Snow-capped mountains, which reach an altitude of approximately 5,900 m, are the source for perennial streams which drain to the basin from the north and the east. Small amounts of streamflow are derived from Lirima hot springs which discharge to the Río Coscaya in the west part of the basin (Fig. 3).

HYDROGEOLOGIC UNITS

The principal hydrogeologic units in the basins include alluvial and volcanic pyroclastic deposits of Quaternary age, the Pastillos Formation of Quaternary age, volcanic rocks of Tertiary age, the Huasco Ignimbrite of Tertiary age, and the Cerro Empexa Formation of Cretaceous age. Outcrop patterns for these units, surface traces of faults, and locations of hydrogeologic sections are shown in figures 2 and 3. Figures 4 and 5 are hydrogeologic sections showing subsurface relations for the hydrogeologic units at Pampa Lagunillas and Pampa Lirima.

ALLUVIAL DEPOSITS

Alluvial deposits crop out in the basin floors of Pampa Lagunillas, Pampa Lirima, and other nearby basins (Figs. 2 and 3). The deposits comprise a heterogeneous interbedded sequence including: fluvial deposits consisting chiefly of gravel, sand, silt, and clay; lake bed deposits consisting chiefly of silt and clay; and volcanic ash deposits. Thickness of alluvial deposits penetrated by wells in the Pampa Lagunillas and Pampa Lirima groundwater basins ranges from 29 to 292 m (Figs. 4 and 5).

The alluvial deposits have been informally divided into three units which are designated, in descending order, as Units A, B, and C. Interbeds of sand and gravel, clay, and volcanic ash occur in each unit. The relationships between the alluvial units are shown in figures 4 and 5.

Unit A consists chiefly of unconsolidated fluvial gravel, sand, and clay deposits. Thickness of Unit A penetrated by wells in Pampa Lagunillas and Pampa Lirima ranges from 29 to 134 m (Figs. 4 and 5). These deposits are highly permeable and comprise an unconfined aquifer which is believed to be in hydraulic connection with perennial streams which flow into the basins.

Unit B consists chiefly of poorly lithified, clay lake-bed deposits and unconsolidated volcanic ash. Interbedded lenses of gravel and sand occur locally. Thickness of Unit B penetrated by wells in the Pampa Lagunillas and Pampa Lirima areas ranges from 14 to 156 m (Figs. 4 and 5). Unit B was not encountered during drilling at wells LA-1 and P-1 and drilling at wells LA-7 and P-3 was terminated prior to fully penetrating the unit. Results of pumping tests for exploration and production water wells in the basins indicate that Unit B comprises a poorly permeable confining unit which strongly retards vertical movement of groundwater.

Unit C consists chiefly of poorly lithified, fluvial gravel, sand, silt, and clay deposits. Thickness of Unit C penetrated by wells in the Pampa Lagunillas ranges from 11 to 94 m (Fig. 4). Unit C was not encountered during drilling at wells LA-4 and P-2 in the Pampa Lagunillas basin, and was not encountered in Pampa Lirima. Because Unit A and Unit C sediments are similar in grain-size distribution and lithology, the proper assignment of coarse-grained deposits encountered in wells LA-1, P-1, and P-2 in the north part of the Pampa Lagunillas basin is uncertain (Fig. 4). Unit C deposits, where overlain by fine-grained deposits of Unit B, comprise a confined or semiconfined aquifer. Results of pumping tests for exploration and

[a] 1978. Infrastructural survey report for the development of Cerro Colorado Mine in the Republic of Chile (Inédito). *Japan International Cooperation Agency*, 190 p.

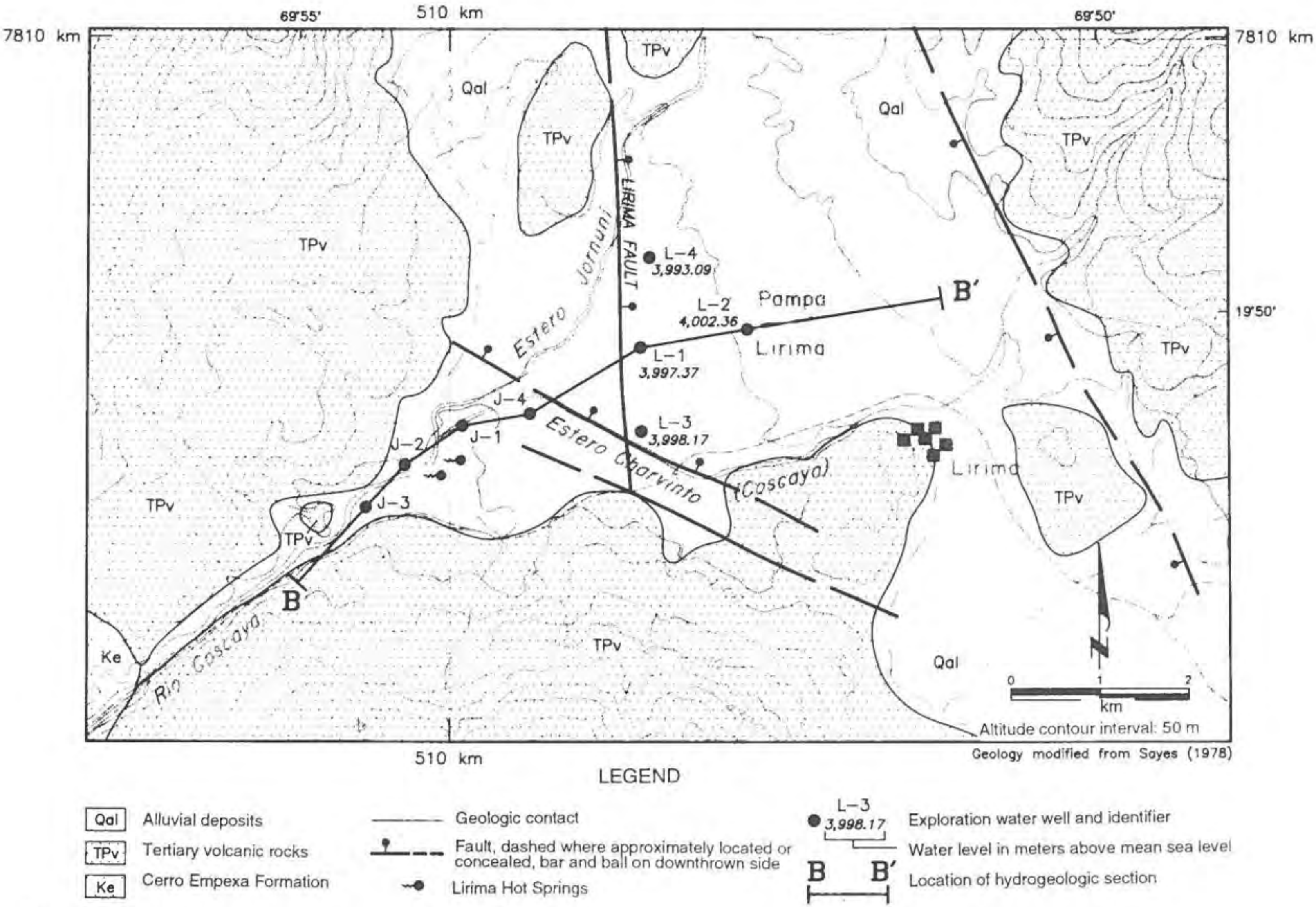

FIG. 3. Hydrogeologic features, Pampa Lirima.

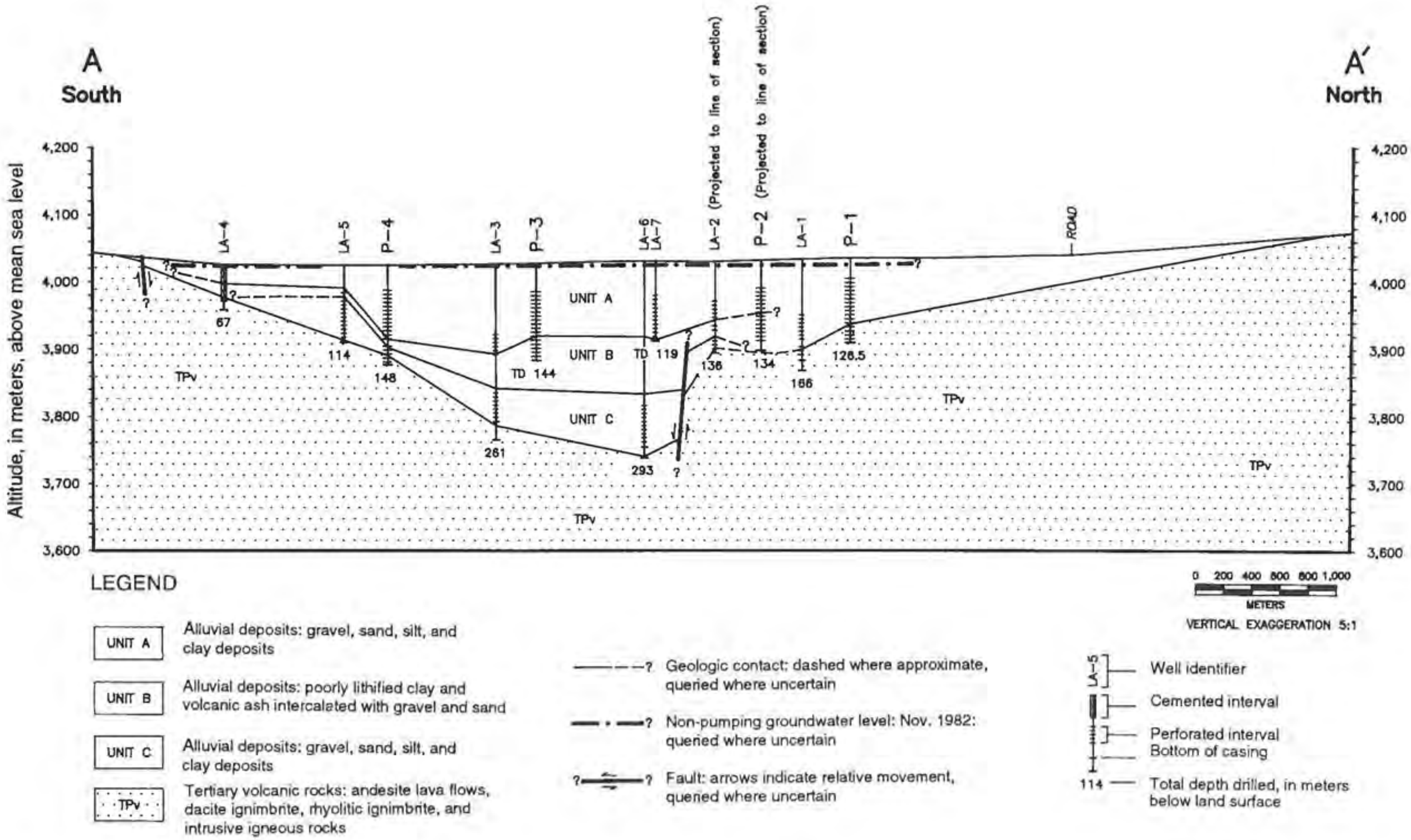

FIG. 4. Hydrogeologic section A-A'.

production water wells in the basins indicate that the fluvial sand and gravel deposits are moderately to highly transm ssive, and where saturated, yield large amounts of water to wells.

PASTILLOS IGNIMBRITE

Rocks in the project area classified by J. Sayes (1978)[1] (*op. cit.*) as the Collacagua Formation crop out about 4 km south from the Pampa Lagunillas groundwater basin. It is possible that these rocks are equivalent to rocks in the Huasco basin area classified as the Pastillos Ignimbrite (Vergara, 1978). J. Sayes (1978)[1] (*op. cit.*) indicated that in the nearby Collacagua and Salar del Huasco areas, the formation comprises a sequence of sedimentary lake bed deposits consisting of silt and clay interbedded with sand and conglomerate toward the base of the sequence, and interbedded with volcanic ash toward the top of the sequence. Vergara (1978) described the Pastillos Ignimbrite as consisting of mostly welded ash deposits interbedded with fine-grained mud and diatomaceous deposits.

Although the Pastillos Ignimbrite is recognized in outcrops south from Pampa Lagunillas, it is not distinctly recognized in the subsurface. However, the lake-bed deposits and the volcanic ash sequence informally identified as Unit B alluvial deposits may, possibly, represent subsurface occurrences of the Pastillos Ignimbrite.

TERTIARY VOLCANIC ROCKS

Tertiary age volcanic rocks comprise the intrusive, extrusive, and pyroclastic igneous rocks of the mountains and hills which form the boundaries of the Pampa Lagunillas and Pampa Lirima basins (Figs. 2 and 3). J. Sayes (1978)[1] (*op. cit.*) referred to these rocks as the Sillillica Formation and postulated that the unit consists of, at least, three extrusive phases. The first phase consists of andesitic lava flows, the second consists of dacitic ignimbrites, and the third consists of rhyolitic ignimbrites. The ignimbrites are widespread in the region.

Results of field investigations in 1982 by Montgomery and Associates in the Pampa Lirima, Salar de Michincha, and Salar del Huasco basins indicate small hydraulic conductivity for these rocks. However, results of exploration water well construction and testing in the Pampa Lagunillas basin indicate that locally, the permeability of fractured ignimbrites included in this group is large and the saturated parts of the unit may contain large volumes of groundwater in storage. Ignimbrite, believed to be part of this group, was encountered in wells in the Pampa Lagunillas and Pampa Lirima areas at depths ranging from 49 to 292 m (Figs. 4 and 5). Where the ignimbrite strata are strongly welded and contain abundant fractures, such as at exploration well LA-4, the ignimbrite comprises a prolific aquifer.

HUASCO IGNIMBRITE

Rocks classified by Galli (1957) as Member 4 of the Altos de Pica Formation, and currently classified as the Huasco Ignimbrite (Vergara and Thomas, 1984) crop out in the southwest part of the Pampa Lagunillas groundwater basin (Fig. 2) and are unconformably overlain by Tertiary volcanic rocks and by alluvial deposits. In the Pampa Lagunillas area, the formation is composed chiefly of dense reddish-brown to grayish-white rhyolitic ignimbrite and has a columnar or massive structure.

The Huasco Ignimbrite is faulted and fractured; several northeast-trending lineations which cut the formation are visible on aerial photographs of the Pampa Lagunillas area. Results of field investigations conducted in other nearby basins indicate that these rocks, where abundantly fractured, are highly transmissive and may comprise a prolific regional groundwater reservoir (Montgomery and Harshbarger, 1985). The Huasco Ignimbrite has not been recognized in the subsurface in Pampa Lagunillas or Pampa Lirima, although the reddish ignimbrite encountered at the base of several of the wells in Pampa Lagunillas may, possibly, be properly classified as Huasco Ignimbrite.

CERRO EMPEXA FORMATION

Rocks classified by Galli and Dingman (1962) as the Cerro Empexa Formation crop out approximately 2 km southwest from the Pampa Lirima area (Fig. 3). In that area outcrop a complex suite of plutonic and volcanic rocks, metamorphic rocks, and well indurated sedimentary rocks intruded by a massive granodiorite-tonalite pluton. Field investigation in 1982 did not reveal the Cerro Empexa Formation to be a useful source of groundwater in the Pampa Lagunillas and Pampa Lirima areas.

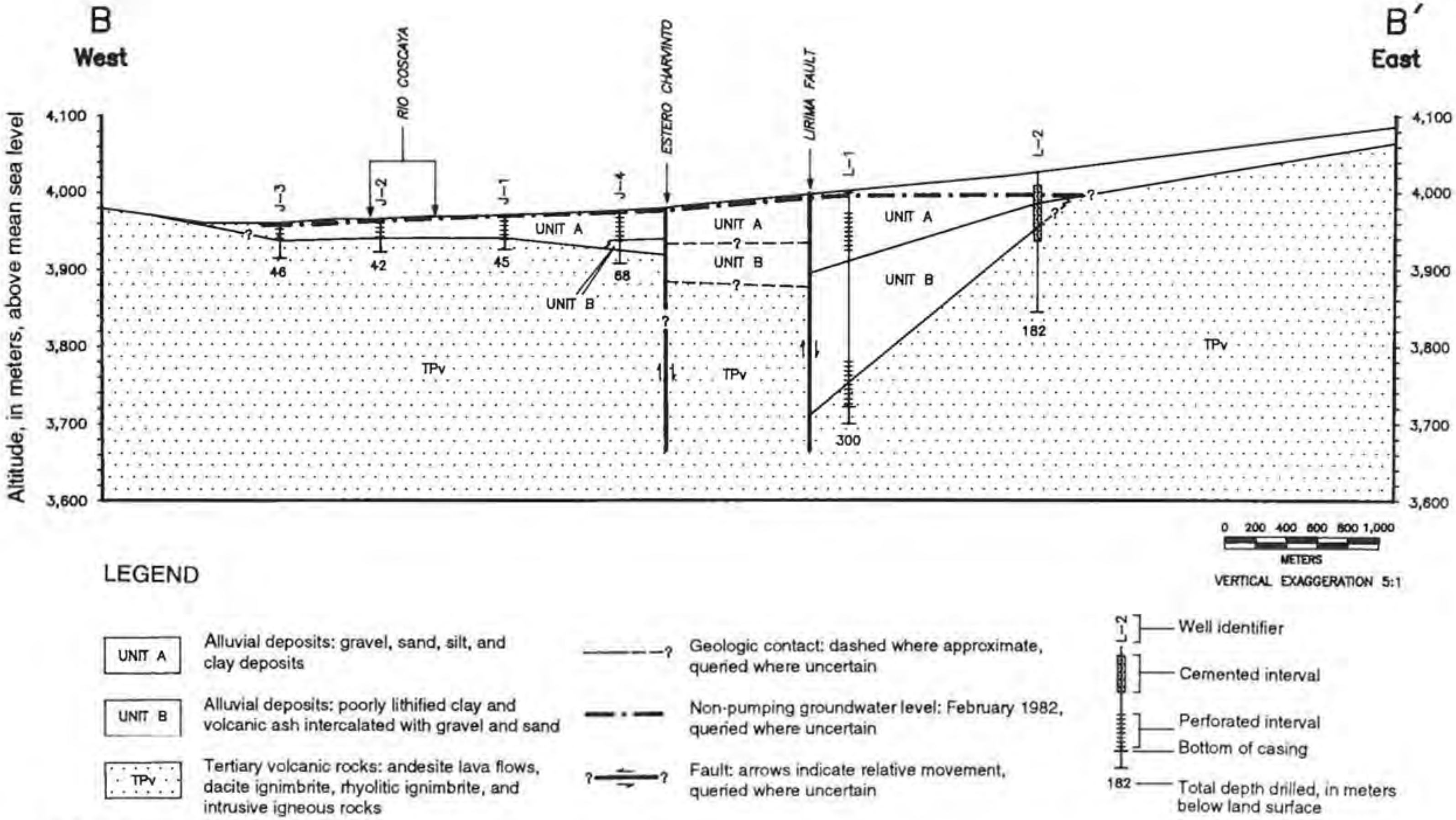

FIG. 5. Hydrogeologic section B-B'.

STRUCTURAL FEATURES

A prominent northeast-trending fault informally designated as the Lagunillas fault occurs along the west margin of Pampa Lagunillas (Fig. 2). Movement on the Lagunillas fault is down to the east. The Lagunillas fault, and a northeast-trending fault at the east margin of the basin, appear to form the west and east boundaries of a geologic structural basin. Inspection of figure 4 suggests that additional faults may occur in the basin.

A prominent north-trending fault informally designated as the Lirima fault occurs in the western half of Pampa Lirima (Fig. 3). Principal movement along the Lirima fault is down to the east. The Lirima fault appears to form the west boundary of a deep geological structural basin (Fig. 5). The basin is bounded on the south by northwest-trending faults, and on the east by a north-trending fault.

GROUNDWATER CIRCULATION

Two important sources of groundwater recharge to the aquifers are believed to occur in the Pampa Lagunillas and Pampa Lirima groundwater basins and are: 1- infiltration from surface water in perennial streams which enter the basins from the east, and **2-** groundwater inflow from the fractured rock aquifers which underlie and surround the basin floors. Prior to pumping from wells, all groundwater discharge in the Pampa Lagunillas area is believed to have occurred by evaporation. Groundwater discharge in the Pampa Lirima area is believed to occur by evaporation and by discharge to the Río Coscaya.

GROUNDWATER STORAGE AT PAMPA LAGUNILLAS

The groundwater reservoir in the Pampa Lagunillas basin consists of saturated alluvial deposits and fractured ignimbrite which underlie the alluvial deposits. Because little is known of the water bearing properties of the fractured ignimbrite, computations for groundwater storage are limited to the alluvial deposits aquifer.

Average specific yield for Units A, B, and C of the alluvial deposits was estimated to be 0.15 based on estimated porosity of drill cuttings and on experience with long-term yield of saturated alluvial deposits in similar geologic environments. Total volume of saturated alluvial deposits aquifer was computed to be about 3 billion m^3. The product of specific yield and saturated volume indicates that the amount of recoverable groundwater in storage in the alluvial deposits aquifer in the Pampa Lagunillas groundwater basin is in the magnitude of 450 million m^3.

The computed amount of recoverable groundwater from the alluvial deposits is believed to be conservative for the entire Pampa Lagunillas basin because it does not include groundwater stored in the underlying fractured ignimbrite aquifer, additional inflow of groundwater to the alluvial deposits from long-term drainage to the alluvial deposits from less permeable rocks surrounding the basin, and inflow from annual recharge.

PRODUCTION WATER WELL DRILLING AND CONSTRUCTION

Based on aquifer parameters obtained during the exploration program, and on anticipated water demand of 120 l/s, it was projected that four production water wells in Pampa Lagunillas would be adequate to supply groundwater to the Cerro Colorado copper mining complex during the life of the mine. The wells were designed so that only two or three of the wells would need to be pumping at any given time, to supply the needed amount of water to the mining complex. This procedure would always provide one to two wells available for use when pumping wells require servicing, or in case of failure of pumps.

Production water wells P-1, P-2, P-3, and P-4 were completed in 1992. The production wells were drilled and constructed by Geotec Boyles Brothers, S.A., using an Ingersoll Rand T-5 conventional rotary drilling rig and using polymer-based drilling mud. Locations for production water wells are shown in figure 2. Construction details for the production wells are summarized in table 1. Figure 6 is a schematic diagram for the Lagunillas production water wells.

TABLE 1. WELL CONSTRUCTION DETAILS FOR PRODUCTION WATER WELLS

Well identifier	Date completed	Altitude of land surface (m.s.l.)[a]	Total depth (m)[b]	Borehole Diameter (inch)	Borehole Depth (m)	Casing Diameter (inch)	Casing Depth (m)	Perforated interval (m)	Cemented interval (m)
P-1	10-07-92	4,035.70	126	24 18 7.5	0-6 6-126 126-126.5	20 14	0-6 0-122	30-122	0-6
P-2	10-12-92	4,031.93	126	24 18 7.5	0-6 6-126 126-134	20 14	0-6 0-122	42-122	0-6
P-3	10-24-92	4,027.54	144	24 18	0-6 6-144	20 14	0-6 0-140	42-140	0-6
P-4	10-18-92	4,024.96	148	24 18	0-6 6-148	20 14	0-6 0-146	36-109.5 121.5-146	0-6

[a] Meters above mean sea level. [b] Meters below land surface.

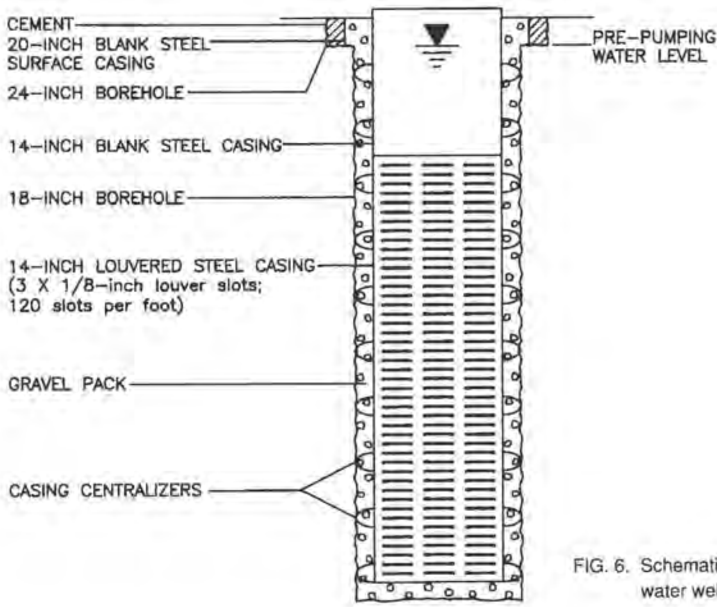

FIG. 6. Schematic diagram for Pampa Laçunillas production water wells.

PUMPING TEST OPERATIONS

Following construction, step-discharge and 24-hour constant-yield pumping tests were conducted for production water wells P-1, P-2, and P-4; a step-discharge and 10-day constant-yield pumping test was conducted for well P-3. Hydrogeologic data from the pumping tests are summarized in table 2.

PUMPING TEST PROCEDURES

Each production water well was tested using a diesel-powered, 5-stage line-shaft turbine pump. Step-discharge pumping tests were conducted at the beginning of each constant-yield pumping test, and

TABLE 2. SUMMARY OF HYDROGEOLOGIC DATA FROM PUMPING TESTS FOR PRODUCTION WATER WELLS.

Pumped well	Observation well	Distance from pumped well (m)	Date pumping test started	Duration of pumping period (h)	Average pumping rate (l/s)[a]	Pre-pumping water level (m b.l.s.)	Maximum water level drawdown during pumping	Specific capacity after pumping 24 hours (l/s-m)[b]
P-1		-	11-14-92	24	77.4	9.44	17.84	4.3
	LA-1	372	-	-	-	7.70	3.08	-
P-2		-	11-17-92	24	52.9	5.92	37.62[c]	1.4
	LA-1	675	-	-	-	8.18	0.64	-
	L-2	401	-	-	-	4.38	1.74	-
P-3		-	11-23-92	240	77.6	2.14	17.02	4.3
	LA-1	1,930	-	-	-	7.79	0.22	
	LA-2	1,541	-	-	-	4.32	0.48	
	LA-3	293	-		-	1.17	2.63	-
	LA-4	2,204	-	-	-	2.01	0.22	-
	LA-6	820	-	-	-	4.12	0.36	-
	LA-7	877	-	-	-	4.50	0.89	-
	P-2	1,734	-		-	5.74	0.25	
	P-4	1,018	-	-	-	0.05[d]	0.71	-
P-4		-	11-20-92	24	80.0	-0.16[d]	12.14	6.6
	LA-3	796	-	-	-	1.12	0.49	

[a] l/s- liters per second.

[b] l/s/m- liters per second per meter of drawdown.

[c] Maximum water level drawdown near the end of the pumping period; maximum water level drawdown occurred during step 3 of the step discharge test and was 40.782 m.

[d] Pre-pumping groundwater level above land surface.

- = Not applicable.

consisted of three steps; the rate for each step being larger than the previous step. Steps 1 and 2 for each step-discharge test continued until the rate of drawdown stabilized. The pumping rate for step 3 was maintained for the remainder of the constant-yield pumping test at wells P-1, P-3, and P-4.

Pumped water was discharged 300 m from the pumped well to avoid potential water level interference from recharge of pumped water. After pumping stopped, depth to groundwater level was measured for a period equal to the pumping period.

During each pumping test, drawdown and recovery of water levels were also measured at nearby observation wells. Results for observation wells during the pumping tests are given in table 2.

ANALYSIS OF PUMPING TEST RESULTS

Measurements of water level drawdown obtained during the pumping tests were analyzed for transmissivity and storage coefficient using the modified non-equilibrium equation semilogarithmic graphical method developed by Cooper and Jacob (1946), the log-log graphical method developed by Neuman (1975), and the semilogarithmic distance *versus* water level drawdown graphical method based on the Thiem (1906) equation. Water level recovery data were analyzed for transmissivity using the Theis (1935) recovery method.

TRANSMISSIVITY

Magnitude of computed aquifer transmissivity at the wells is related to lithology and hydraulic conductivity of the aquifer, and to the effective saturated thickness of the aquifer at the well and is an index of ease of groundwater movement in the aquifer. Transmissivity is computed from drawdown and recovery measurements from the pumped well and from nearby observation wells. Analysis of pumping test results for the production wells in the Pampa Lagunillas basin indicates that transmissivities computed using water level drawdown measurements from the late part of the pumping period are in good agreement with those calculated from water level recovery measurements. The most reliable values of transmissivity for the unconsolidated basin-fill deposits aquifer are believed to be 450 m^3 per day, per meter width of aquifer at 1:1 hydraulic gradient (m^2/day) at well P-1, 325 m^2/day at well P-2,700 m^2/day at well P-3, and 775 m^2/day at well P-4.

Results from air-lift pumping tests conducted in 1982 for exploration wells in the Pampa Lagunillas area indicate transmissivity of about 400 m^2/day at well LA-1, 250 m^2/day at well LA-2,1 675 m^2/day at well LA-3, 1,250 m^2/day at well LA-4, 1,175 m^2/day at well LA-5, 75 m^2/day at well LA-6, and 100 m^2/day at well LA-7.

The large range in transmissivities obtained from analysis of pumping test results suggests that substantial vertical and lateral heterogeneity is present in the aquifers in the Pampa Lagunillas groundwater basin. These heterogeneities appear to be related to variations in clay, silt, and ash content and in degree of lithification.

Driscoll (1986) indicated that when transmissivity values are less than 1,000 gallons per day, per foot (gpd/ft) or 124 m^2/d, wells are generally adequate only for domestic or other small water use purposes. When transmissivity values are 10,000 gpd/ft or larger, well yields can be adequate for industrial, municipal, or irrigation purposes. All transmissivities computed for the Lagunillas production water wells greatly exceed the transmissivity recommended for industrial use water wells.

HYDRAULIC CONDUCTIVITY

Average hydraulic conductivity of the aquifer at each production well was computed as transmissivity divided by the perforated interval of the well. Average hydraulic conductivities were: 4.6 m^3 per day, per square meter of aquifer at 1:1 hydraulic gradient (m/day) (or 5.3×10^{-3} cm/s) at well P-1; 4.1 m/day (4.8×10^{-3} cm/s) at well P-2; 7.1 m/day (8.2×10^{-3} cm/s) at well P-3; and 7.9 m/day (9.2×10^{-3} cm/s) at well P-4. These values for hydraulic conductivity are in the range of silty sand and medium-grained clean sand aquifers (Heath, 1982).

STORAGE COEFFICIENT

Storage coefficient for the Pampa Lagunillas groundwater basin was computed from analysis of water level measurements from observation wells during the pumping tests, and ranged from 4.3×10^{-4} to 6.4×10^{-3}. Magnitude of these coefficients indicates confined and semiconfined aquifer conditions, and is consistent with storage coefficients computed for alluvial aquifers following short-term pumping periods. However, long-term pumping is required to effectively drain the part of the aquifer dewatered by the cone of depression, and to compute long-term effective storage coefficient and specific yield. Based on the lithologic character of the aquifer, storage coefficient and specific yield of about 0.15 is believed to be representative for the unconfined alluvial deposits aquifer in the Pampa Lagunillas groundwater basin under long-term pumping conditions.

CHEMICAL QUALITY OF GROUNDWATER

Groundwater samples for laboratory chemical analyses from production water wells P-1, P-2, and P-4 were obtained near the end of the pumping period during the 24-hour constant-yield pumping tests. The initial groundwater sample for production water well P-3 was obtained after about 24 hours of pumping, and a second groundwater sample was obtained near the end of the pumping period during the 10-day constant-yield pumping test. Results of analyses for groundwater samples for common and trace constituents and routine parameters are summarized in table 3.

Stiff diagrams for the groundwater samples are shown in figure 2. Stiff diagrams are used to classify waters by their principal chemical characteristics (Hem, 1985). Inspection of the Stiff diagrams indicates that groundwater in the alluvial deposits aquifer in the Pampa Lagunillas basin is the sodium-calcium-bicarbonate water type.

The second groundwater sample from well P-3 was obtained near the end of the 10-day pumping test. Comparison of the results of the two groundwater samples from well P-3 indicates that no substantial change in water chemistry occurred as a result of continuous pumping for 10 days.

With the exception of arsenic, chemical quality of the groundwater meets all Instituto Nacional de Normalizacion (INN) drinking water standards for the chemical constituents analyzed (INN, 1984)[5] (*op. cit.*). Arsenic was detected in the groundwater sample from well P-4 at a concentration of 0.057 mg/l (Table 3), which exceeds the INN drinking water standard of 0.050 mg/l. Average concentration of arsenic for groundwater samples from the Pampa Lagunillas groundwater basin is about 0.035 mg/l. Blending of water from well P-4 with that from wells P-1, P-2, and P-3 will effectively lower the level of arsenic in the groundwater to a level below the drinking water standard. Chemical quality of groundwater samples from the basin is adequate for the industrial purposes for which the water is intended.

[5]1984. Norma Chilena Oficial, Agua Potable - Parte 1: Requisitos: NCh409/1. Oficio 84. *Instituto Nacional de Normalización*, 4 p.

TABLE 3. SUMMARY OF COMMON AND TRACE CONSTITUENTS AND ROUTINE CHEMICAL PARAMETERS FOR WATER SAMPLES.

Well identifier Sample number Date sampled		P-1 7076 11-15-92	P-2 7075 11-18-92	P-3 7073 11-24-92	P-3 7072 12-03-92	P-4 7074 11-21-92
Common constituents	**Detection limit**					
Cations (mg/l)[a]						
Calcium	0.1	28	26	25	25	22
Magnesium	0.1	7.9	6.3	6.8	7.1	6.7
Sodium	0.1	19.8	22	24	25	29
Potassium	0.1	6.6	6.5	8.0	7.8	8.9
Anions (mg/l)						
Bicarbonate (as HCO_3)	2.6	110	98.3	102	104	94.8
Carbonate	2.6	nd	nd	nd	nd	nd
Chloride	1.8	9.2	8.9	9.2	10	9.2
Sulfate	5	49	52	52	56	65
Nitrate/Nitrite (as NO_3)	0.4	2.7	3.1[c]	3.5[c]	3.1[c]	3.5[c]
Fluoride	0.05	0.15	0.22	0.22	0.25	30
Routine parameters						
Alkalinity (mg/l as$CaCO_3$)	3	90.1	80.6	83.6	85.2	77.7
Hardness (mg/l as $CaCO_3$)	0.3	102	90.9	90.4	91.7	82.5
Total dissolved solids (mg/l)	10	250[c]	235[c]	235[c]	225[c]	255[c]
MBAS (Surfactants) (mg/l)	0.02	nd[c]	nd[c]	nd[c]	nd[c]	0.05[c]
pH (field)	--	7.95	7.85	8.22	8.01	8.06
pH (lab)	0.1	7.6	7.6	7.5	7.9	7.7
Electrical conductance[b] (field)	--	276	294	297	303	320
Electrical conductance (lab)	1.0	330	320	330	340	340
Temperature (degrees Celsius)	-	10.4	12.7	9.9	10.5	13.2
Trace constituent (mg/l)						
Aluminum	0.050	nd	nd	nd	nd	nd
Iron	0.050	nd	nd	nd	nd	nd
Manganese	0.010	nd	nd	nd	nd	nd
Copper	0.010	nd	0.012	0.012	nd	nd
Zinc	0.010	nd	nd	0.010	nd	nd
Arsenic	0.002	0.015	0.026	0.034	0.037	0.057
Barium	0.100	nd	nd	nd	nd	nd
Cadmium	0.005	nd	nd	nd	nd	nd
Chromium	0.010	nd	nd	nd	nd	nd
Lead	0.005	nd	nd	nd	nd	nd
Mercury (total)	0.0002	nd	nd	nd	0.00029	nd
Selenium	0.002	nd	nd	nd	nd	nd
Silver	0.010	nd	nd	nd	nd	nd

[a] mg/l = miligrams per liter.
[b] Specific electrical conductance in micromhos per centimeter.
[c] Samples were analyzed after the recommended laboratory holding times for nitrate/nitrite (as NO_3). Total Dissolved Solids, and MBAS.
nd = not detected or detected below practical quantification limit.
--- = not applicable.
MBAS = Methylene Blue Activated Substance.
Note: Laboratory analyses were conducted by BC Laboratories, Bakersfield, California.

CONCLUSIONS

Results of exploration and development of groundwater indicate that a sufficient quantity of excellent quality groundwater is available from the Pampa Lagunillas groundwater basin for industrial use at the Cerro Colorado copper mining complex for the life of the mine and beyond. Although abundant groundwater occurs in the alluvial deposits and underlying fractured ignimbrite aquifers, the Lagunillas production water wells solely exploit the alluvial deposits aquifer in the basin. Average hydraulic conductivity for the alluvial deposits in the Pampa Lagunillas basin ranges from 4 to 8 m/day (4.6 x 10^{-3} to 9.2 x 10^{-3} cm/s). Based on results from exploration and testing, the alluvial deposits aquifer in the Pampa Lagunillas groundwater basin may contain as much as 450 million m^3 of usable groundwater; additional amounts of groundwater are stored in the underlying fractured rock aquifers. Groundwater recharge to the basin is believed to occur from infiltration of streamflow in the alluvial deposits aquifer, and from fractured rock aquifers surrounding the basin. The Pampa Lagunillas basin is an internal drainage basin with respect to ground-water and surface water; prior to groundwater pumping, discharge from the Pampa Lagunillas basin was solely by evaporation from Salar de Lagunillas.

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REFERENCES

Cooper Jr., H.H.; Jacob, C.E. 1946. A generalized graphical method for evaluating formation constants and summarizing well-field history: *American Geophysical Union Transactions*, Vol. 27, No. 4, p. 526-534.

Driscoll, F.G. 1986. Groundwater and wells (2nd edition). *Johnson Division*, St. Paul, Minnesota, 1089 p.

Galli, O.C. 1957. Las Formaciones geológicas en el borde occidental de la Puna de Atacama, Sector de Pica, Tarapacá. *Minerales*, Vol. 12, No. 56, p. 14-26.

Galli, O.C.; Dingman, J.R. 1962. Cuandrángulos de Pica, Alca, Matilla y Chacarilla con un estudio sobre los recursos de agua subterránea, Provincia de Tarapacá. *Instituto de Investigaciones Geológicas*, Nos. 7-10, Vol. 3, 125 p., (1:50.000).

Heath, R.C. 1982. Basic groundwater hydrology. *U.S. Geological Survey, Water-Supply Paper*, No. 2220, 84 p.

Hem, J.D. 1985. Study and interpretation of the chemical characteristics of natural water. *U.S. Geological Survey, Water-Supply Paper*, No. 2254, 263 p.

Montgomery, E.L.; Harshbarger, J.W. 1985. Ground water development for mineral industry in arid zones of the Andean Highlands. *South America Mining Engineering*, p. 45-48.

Neuman, S.P. 1975. Analysis of pumping test data from anisotropic unconfined aquifer considering delayed water table response. *Water Resources Research*, Vol. 2, No. 2, p. 329-342.

Stoertz, G.E.; Ericksen, G.E. 1974. Geology of salars in northern Chile. *U.S. Geological Survey, Professional Paper*, No. 811, 65 p.

Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *American Geophysical Union Transaction*, Vol. 16, p. 519-524.

Thiem, G. 1906. Hydrologische methoden. *J. M. Gebhardt*, Leipzig, 56 p.

Vergara, H. 1978. Cuadrángulo Ujina. Región de Tarapacá. *Instituto de Investigaciones Geológicas, Carta Geológica de Chile*, No. 32, 44 p.

Vergara, H.; Thomas, A. 1984. Hoja Collacagua. Región de Tarapacá. *Instituto de Investigaciones Geológicas, Carta Geológica de Chile*, No. 59, 79 p.

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