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Spatial Distribution of Near-Surface Soil Resistivity in the Cerro Chascón Science Preserve

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Abstract

We examined near-surface soil resistivity of twenty-one locations in the Cerro Chascón science preserve area in the Wenner method with a fixed electrode spacing of 2 m. There were systematic differences in soil resistivity near the surface (down to a few meters): The values in the Pampa La Bola area were around 1000 Ω m, whereas those in the Llano de Chajnantor area were much higher and > 4400 Ω m in most locations topographically suitable for antenna pads. Special treatment may be needed for each pad to meet the Chilean regulation for grounding. A factor ~ 1.3 difference expected from the 1.8°C temperature difference between the Llano de Chajnantor and Pampa La Bola areas is not enough to explain all of the measured difference. The trend that ridges systematically had higher values than their adjacent valleys supports the idea that the difference primarily reflects probable difference of water content due to local topography and drainage.

1 Introduction

Near-surface soil resistivity is a basic parameter to the design of effective grounding and lightning prevention/protection system. In our previous work on the resistivity sounding of eight locations in the Cerro Chascón science preserve area [1], we obtained thickness of the upper layer at each location consistent with that of the weathered layer measured with a borehole. This result was important in that it demonstrated the feasibility of sounding the thickness of the weathered layer in more convenient and inexpensive way than excavation. We also noted that the resistivity of the first layer significantly varied from a point to another, while that of the second layer was nearly uniform. Difference in water content in the upper soil layer due to local topography and drainage was proposed as a possible cause of the difference. The present work is basically a follow-up of our previous resistivity soundings to test the proposed hypothesis. Results of measurements of twenty-one locations in a day with a fixed electrode spacing of 2 m are reported.

2 Measurements and Analysis

The measurements were conducted during the daytime of 2000 September 14 with Yokogawa Type 3244 surface resistivity instrument. Methodology of the measurements is basically the same to our previous report except that we fixed the electrode spacing of the Wenner configuration to be 2.0 m to survey near-surface soil resistivity of increased numbers of points in a day. The spacing was selected so that the measured apparent soil resistivity represents that of the weathered layer near the surface (down to a few meters), which is crucial to the practical design of effective grounding and lightning prevention/protection system. The depth of each electrode was set at about 10 cm so that the measurements are not affected by the depth of the electrodes.

Measured points were twenty-one in total and included all eight locations where previous sounding measurements were carried out. The locations were selected also to included some of the ridges and valleys along a probable 10 km configuration of ALMA. Coordinates of the locations measured with a navigation GPS are shown in Figure 2 and are tabulated in Table 1.

3 Results and Discussion

3.1 Near-Surface Soil Resistivity

3.1.1 Spatial Distribution

Summarized in Figure 2 is a spatial distribution of apparent soil resistivity at twenty-one locations in the Cerro Chascón science preserve measured with a short electrode spacing (2 m). This value primarily reflects resistivity of the upper weathered layer. The near-surface soil resistivity was $\sim$ 1000 Ω m in the Pampa La Bola area and it gradually increased as we approached to the Llano de Chajnantor area where it exceeded 4400 Ω m. Important difference is that the resistivity of the weathered layer at Llano de Chajnantor was higher than that of the bedrock ($\sim$ 2000 Ω m [1]), whereas the weathered layer at Pampa La Bola had lower values than that of the bedrock. There is a hint of weak correlation of the soil resistivity with altitude as we see in Figure 3.

Besides this global trend, we confirmed significant point-by-point variation, which we have pointed out in our previous report. Ridges tend to have larger near-surface soil resistivity than their adjacent valleys (Figure 3).

3.1.2 Seasonal Variation

Because we measured seven common locations both in our previous June–July and in the present September runs, we may evaluate seasonal variation of the near-surface resistivity. Summarized in Table 2 is a comparison of the values measured in these two different periods. The values in June–July were estimated via interpolation of our previous sounding data taken with various electrode spacings and were rounded by 10 Ω m.

The values at the three locations (ID 01, 03, 04) in the Pampa La Bola area show reasonable agreement with the previous values, while possible seasonal variation of the near-surface resistivity was found at the three locations (ID 19, 20, 21) in the Llano de Chajnantor area and at the Chascón-Chajnantor Saddle point (ID 10). Unexpectedly, the resistivity was found even larger in early spring (middle of September) than in mid winter (late June–early July). Since subsurface temperature measured near the NRO containers at Pampa La Bola indicates that temperature difference between the first and the second runs was less than a few °C (Figure 4), it is unlikely that this seasonal variation is due to seasonal variation of the subsurface temperature.

3.1.3 Origins of Spatial and Seasonal Variations

Significant difference exists in the surface values of the soil resistivity between the Llano de Chajnantor and Pampa La Bola areas. Besides this global trend, ridges tend to have higher resistivity than their nearby valleys. Seasonal variation also seems to exist. There are several possible factors that may influence the soil resistivity near the surface. The key factors include water content, ionic content, and temperature of the soil, as well as physical property of the soil as a material. What is the key factor that affects to the soil resistivity in this region?

As for the physical property of the soil as a material, we learned through previous geotechnical studies in these areas [4, 5] that the material of the subsurface layer is ignimbrite and is almost identical throughout the area except for the Chajnantor–Chascón saddle point. It is also very unlikely to be significant difference and seasonal variability in the ionic content of the soil.

There is an experimental background to expect that the difference of subsurface temperature plays a role to realize the measured global trend. Normal soil with a 15% water content, for example, will have a specific resistivity of 99 Ω m at $+10°$C, 130 Ω m at $+0°$C, 300 Ω m at $-0°$C, 790 Ω m at $-5°$C, and 3300 Ω m at $-15°$C [6]. Hence expected difference of the resistivity due to the 1.8°C temperature difference of the Llano de Chajnantor and Pampa La Bola areas is a factor of ~ 1.3.

The difference of the subsurface temperature do not explain all of the measured global trend as we evaluated above. Alternative is probable difference in water content of the weathered rocks near the surface, since the resistivity of normal soil is a sensitive function of the water content: 220 Ω m, 130 Ω m, and 90 Ω m with a water content of 10%, 16%, and 20%, respectively [6]. In general, water content of soil is complicated functions of the porosity of the soil and the balance of water supply/drainage, and here we test what dominates the present case. First, difference in porosity cannot explain at the same time that the resistivity of the weathered layer at Llano de Chajnantor was higher than that of the bedrock (zero porosity), while the resistivity at Pampa La Bola was lower than that of the bedrock. As for the difference in water supply, or precipitation, more precipitation in the Pampa La Bola area is needed to explain the measured global trend. However, common wisdom suggests more precipitation in the upwind slopes of mountains (e.g., Llano de Chajnantor) than in the downwind slopes (e.g., Pampa La Bola). Actually there is no evidence for more rain/snow in the Pampa La Bola area [7]. Precipitation may explain seasonal variation but may not explain the measured positional difference. From the viewpoint of local topography that affects water drainage, the Llano de Chajnantor area is more undulating, whereas the Pampa La Bola area is very flat. It is thus suggested that the soil resistivity is very high at some of the locations in Llano de Chajnantor because water drainage is more effective there to keep the upper soil layer very dry.

To summarize, more efficient water drainage and lower temperature in the Llano de Chajnantor area make the upper soil resistivity in this area much larger than that in the Pampa La Bola area. Because the mean temperature in this area is very close the freezing/melting point of water, the 1.8°C systematic temperature difference due to the 250 m height difference could introduce very large difference in the soil resistivity between the Llano de Chajnantor and Pampa La Bola areas during early summer when lightning hazard is concerned.

3.2 Implications to Grounding Design

Given very high surface resistivity at the candidate sites in this region, it seems not easy to realize satisfactory grounding resistance[1] by equipping conventional grounding system for each antenna pad. To illustrate this, we provide in the following some of the parameters of the prototypical grounding methods shown in Figure 5.

The simplest way is to use a grounding rod. A grounding rod with a radius r driven into

[1]The generally accepted practice is to have the grounding resistance not exceed 25 Ω. However, to protect sensitive electronic instruments such as computers and receivers, the grounding resistance might be required to be less than 3 Ω, and in some cases less than 1 Ω. Chilean regulation requires 4 Ω for lightning rods.

the soil of resistivity ρ to the depth d ($d \gg r$) [8, 9] will give a grounding resistivity R,

$$R \simeq \frac{\rho}{2\pi d}\left(\ln\frac{4d}{r} - 1\right), \tag{1}$$

and a 110 m borehole is needed to achieve a 25 Ω ground resistance with $\rho = 2000\ \Omega$ m and $2r =$ 0.066 m. Given this large depth of the grounding rod, local variation of near-surface resistivity will have negligible contribution, and will be impractical to adopt this method throughout this area.

A grounding line, or counterpoise, with a radius r and a length l ($l \gg r$) buried in the soil at the depth of d ($d \ll l$) [9, 10] will give a grounding resistivity approximated by,

$$R \simeq \frac{\rho}{\pi l}\left(\ln\frac{2l}{\sqrt{2rd}} - 1\right). \tag{2}$$

A ring with a radius P that consists of a conductor (radius r) buried in the soil at the depth of d ($d \ll l$) [9] will have,

$$R \simeq \frac{\rho}{2\pi^2 P}\ln\frac{8P}{\sqrt{2rd}} . \tag{3}$$

Thus a 170 m counterpoise or a 58 m diameter ring (180 m circumference) buried at the depth of 0.5 m, for example, is needed to achieve a 25 Ω ground resistance with $\rho = 2000\ \Omega$ m and $2r$ $= 0.066$ m.

In the case of a rectangular metal mesh of size $a \times b$ buried in the soil at the depth of d [11], achieved grounding resistivity will be approximated by,

$$R \simeq \frac{AM\rho}{4\sqrt{ab/\pi}}\left(1 - \frac{4d}{\pi\sqrt{ab/\pi}}\right), \tag{4}$$

where A is a correction factor for the aspect ratio, M is a correction factor for the finite number of mesh, and $\sqrt{ab/\pi}$ is the equivalent radius of the rectangle and was assumed to be $\gg d$. The factor A is 1.0 for a square and reduces to 0.86 for a 5:1 rectangle. The factor M is 1.0 for a mesh with its mesh number ≥ 100 and increases up to 1.4 for the most sparse mesh (a frame). It is thus concluded that an increase of soil resistivity by a factor will enlarge needed area to realize given grounding resistance by approximately the square of the factor. The immeasurably high surface resistivity in the Llano de Chajnantor area makes it more difficult and expensive than in the Pampa La Bola area to realize satisfactory grounding resistance by burying a metal mesh beneath the restricted area near each antenna pad: A metal mesh of > 80 m $\times$ 80 m area is needed to achieve a 25 Ω ground resistance with $\rho > 4400\ \Omega$ m at Llano de Chajnantor, whereas the same ground resistance will be achieved with an 18 m $\times$ 18 m area for the 1000 Ω m soil at Pampa La Bola.

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Table 1: Locations and Soil Resistivity of Examined Locations

ID	East	North	Altitude	Resistivity	Description
01	0637710	7457280	4630 m	811 Ω m	Flat and sandy. Borehole site #6 (Chascón E.).
02	0633650	7460200	4800 m	2036 Ω m	Flat. Candidate ALMA array center. Borehole site #1 (Pampa La Bola).
03	0633170	7459680	4800 m	943 Ω m	Flat. NRO testing site.
04	0632940	7459040	4800 m	748 Ω m	Flat. ASTE candidate site. Borehole site #2 (ASTE).
05	0632230	7458320	4850 m	603 Ω m	Valley.
06	0632080	7458120	4850 m	1407 Ω m	Ridge.
07	0630920	7457100	4870 m	496 Ω m	Valley.
08	0630980	7456770	4960 m	930 Ω m	Valley.
09	0631220	7456120	4950 m	741 Ω m	Flat.
10	0631250	7455850	4900 m	1634 Ω m	Flat. Borehole site #5 (Saddle point).
11	0630920	7455450	4940 m	1282 Ω m	Valley.
12	0630320	7455350	4950 m	936 Ω m	Valley. With vegetation.
13	0629930	7455290	4970 m	2262 Ω m	Ridge.
14	0629550	7454840	4980 m	2488 Ω m	Ridge.
15	0629510	7454740	4980 m	2394 Ω m	Valley. Sandy.
16	0628410	7454960	5020 m	1891 Ω m	Ridge.
17	0628190	7453870	5040 m	> 4398 Ω m	Ridge.
18	0627800	7454110	5050 m	1276 Ω m	Valley.
19	0627410	7454050	5030 m	> 4398 Ω m	Ridge. Candidate ALMA array center. Borehole site #3 (Chajnantor N.).
20	0627770	7453770	5050 m	> 4398 Ω m	Ridge. NRAO/ESO testing site.
21	0627610	7452850	5030 m	> 4398 Ω m	Ridge. Candidate ALMA array center. Borehole site #4 (Chajnantor S.).

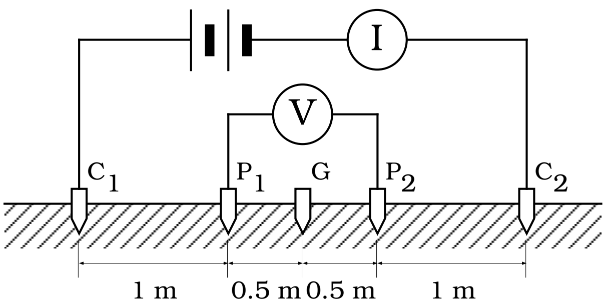

Figure 1: The Wenner electrode configuration. Current is injected into the ground through a pair of current electrodes (C_1 and C_2), and the potential difference is measured between a pair of potential electrodes (P_1 and P_2). Depth of the electrodes was set at about 10 cm.

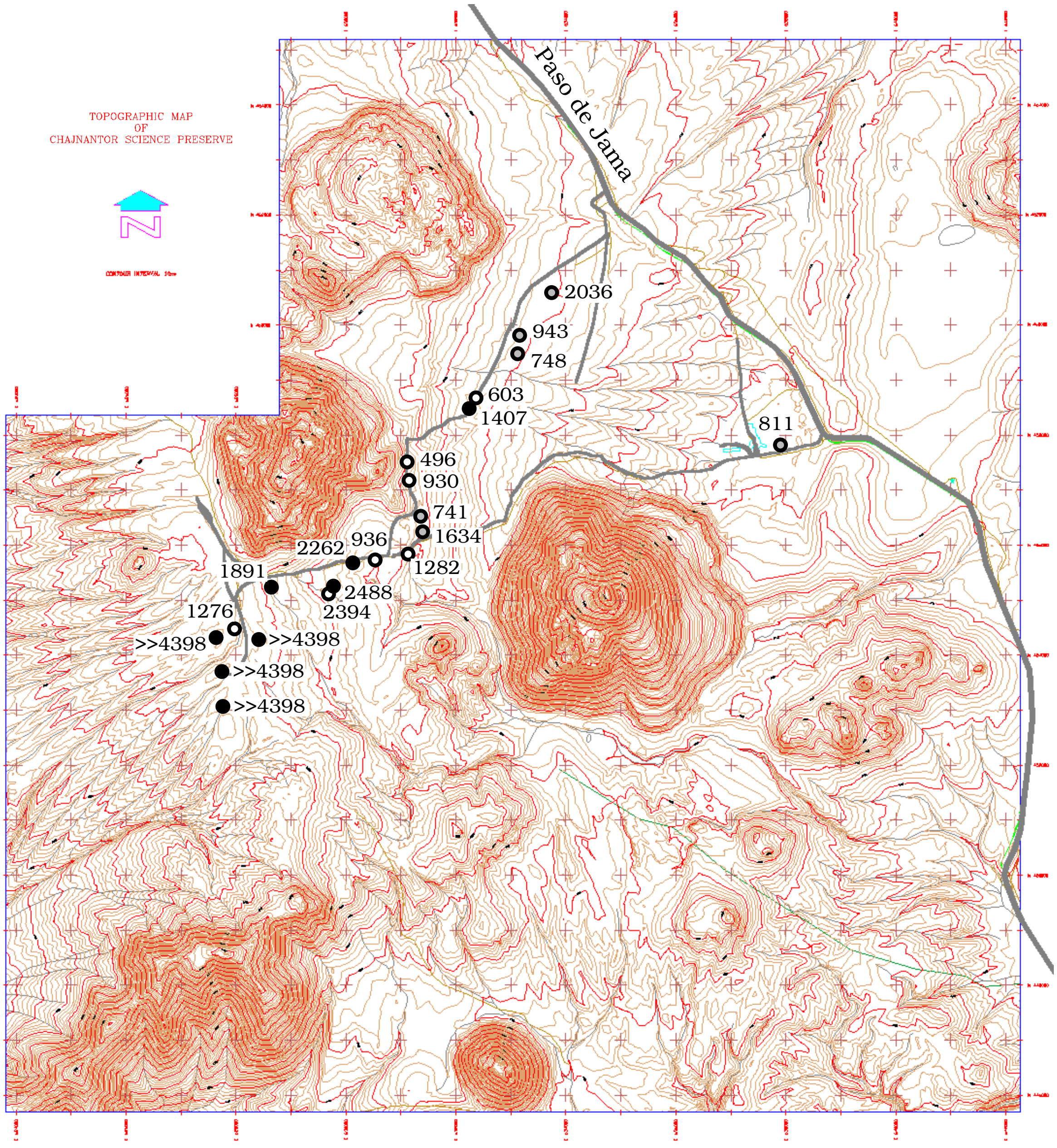

Figure 2: Apparent resistivity at the twenty-one locations measured with a fixed Wenner electrode spacing (2 m), overlaid on the topographic map of the Cerro Chascón science preserve area [2]. Filled circles, shaded circles, and open circles indicate that the topography of the corresponding location is ridge, flat, or valley, respectively. The absolute coordinates in this map may contain errors up to a few 100 m. Ticks are spaced by 1 km. Contour spacing is 10 m with thick contours every 50 m.

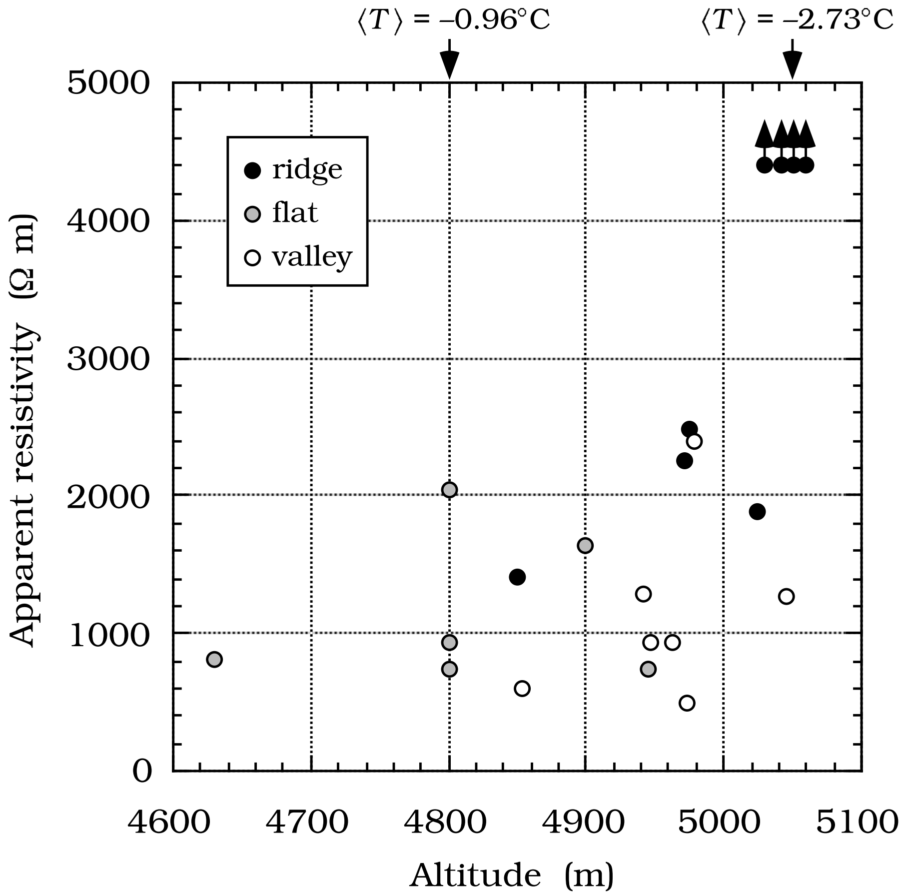

Figure 3: Apparent resistivity at the twenty-one locations measured with a fixed Wenner electrode spacing (2 m) as a function of the altitude. Filled circles, shaded circles, and open circles indicate that the topography of the corresponding location is ridge, flat, or valley, respectively. Mean atmospheric temperature measured at Pampa La Bola (4800 m) and Llano de Chajnantor (5050 m) [6], which will be reflected in the subsurface temperature, is also indicated on the top.

Table 2: Seasonal Variation of Near-Surface Soil Resistivity

ID	Resistivity (Ω m)		Variation	Description
	June–July	September	(%)	
01	830	811	-2	Borehole site #6 (Chascón E.).
03	1200	943	-21	NRO testing site.
04	740	748	$+1$	Borehole site #2 (ASTE).
10	1120	1634	$+46$	Borehole site #5 (Saddle point).
19	> 4100	> 4398	...	Borehole site #3 (Chajnantor N.).
20	2750	> 4398	$> +60$	NRAO/ESO testing site.
21	3380	> 4398	$> +30$	Borehole site #4 (Chajnantor S.).

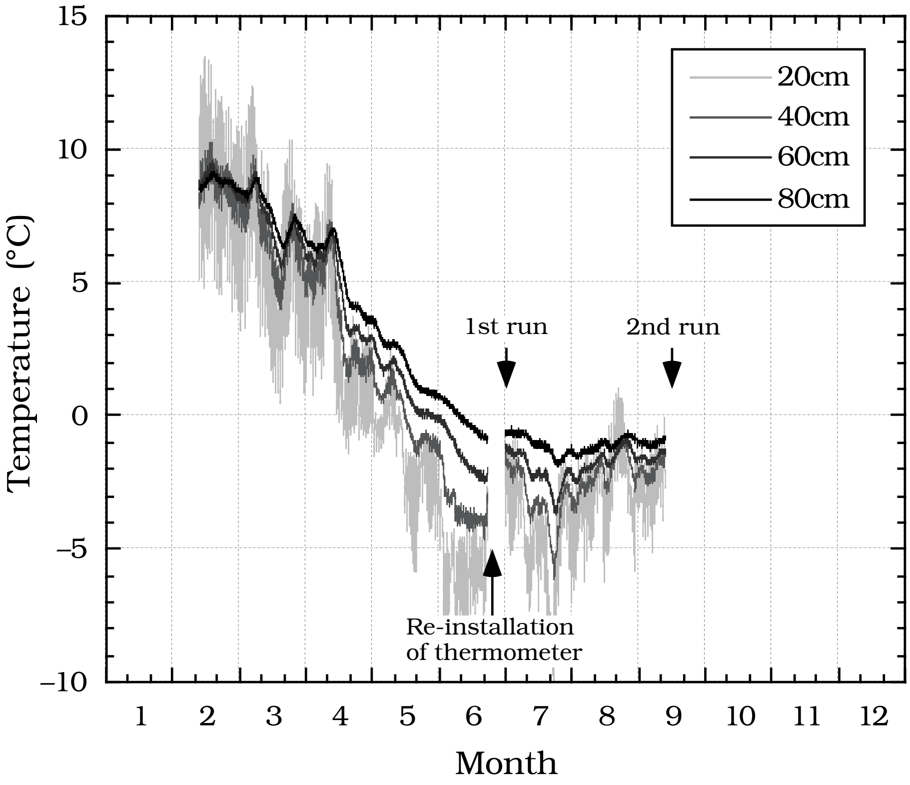

Figure 4: Subsurface temperature measured at Pampa La Bola (4800 m) during the year of 2000 as a function of depth [3]. Periods of our previous and present measurements are shown with arrows.

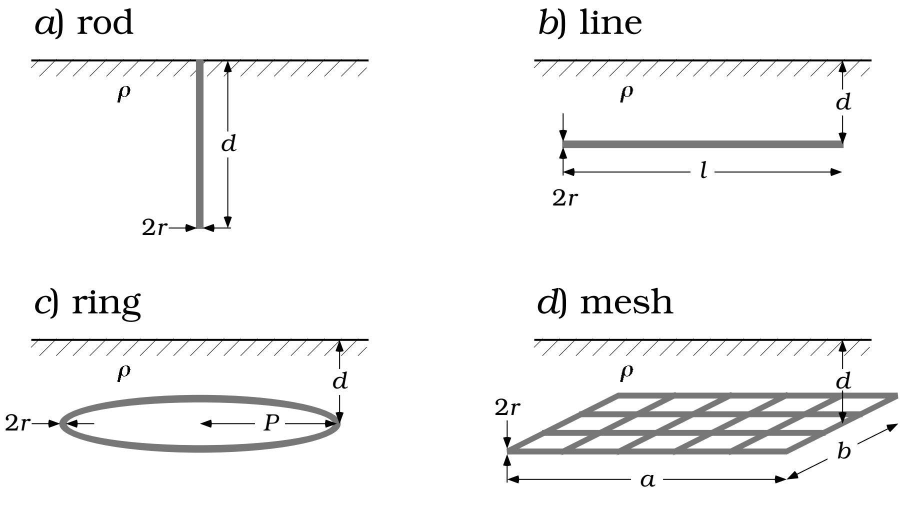

Figure 5: Configurations of prototypical grounding methods: (a) a rod, (b) a line, (c) a ring, and (d) a mesh (mesh number 15).