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Ground temperature regimes and geomorphological implications in a Mediterranean mountain (Serra da Estrela, Portugal)

Gonçalo Teles Vieira[a,*], Carla Mora[a], Miguel Ramos[b]

[a]*Centro de Estudos Geográficos, Universidade de Lisboa, Faculdade de Letras, Alameda da Universidade, 1600-214 Lisbon, Portugal*
[b]*Departamento de Física, Facultad de Ciencias, Universidad de Alcalá de Henares, Ctra Madrid-Barcelona,*
km 33,600, 28871 Alcalá de Henares, Spain

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Abstract

Air and shallow ground temperatures from two monitoring sites at the Serra da Estrela (Portugal) are analysed. The Cântaro Gordo site is located at 1875 m ASL and the Fraga das Penas at 1640 m ASL. The climate of the study area is Mediterranean and very irregular, both on a yearly and monthly basis. This is particularly significant during winter, when differences in snow cover have direct influence on the ground thermal regimes and therefore on geocryological processes. To assess the significance of the ground thermal regimes for the geomorphological dynamics, bi-hourly records of temperature are studied at a daily basis. Eight types of daily regime were identified: isothermal unfrozen, non-isothermal unfrozen, surficial freeze–thaw, surficial freeze–thaw and subsurficial frost, surficial and subsurficial freeze–thaw, subsurficial frost, surficial and subsurficial frost and surficial frost but no daily rhythm. The occurrence of these regimes is analysed and their geomorphological significance is presented. Based on the altitudinal differences of the two monitoring sites, on the occurrence of the different regimes and on field observations, a conceptual model for the altitudinal and seasonal zoning of the daily thermal regimes of the ground is presented. This model was prepared for the Serra da Estrela, but it can be used in other Mediterranean or tropical areas if altitude and seasonal precipitation differences are taken in explanation.
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Keywords: Ground temperature; Periglacial; Frost; Freeze–thaw; Mediterranean mountain

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1. Introduction

1.1. Short review of studies on daily frost action environments in the world

Daily fluctuations of temperature, moisture, and the physical character of the ground are significant controls on the occurrence of a variety of freeze–thaw-induced processes that affect the ground at shallow depth, like frost creep, needle-ice creep, shallow solifluction, or upfreezing of granules (Washburn, 1979; Williams and Smith, 1989). Despite the commonly small movement that is normally associated to daily freeze–thaw, their cumulative amount can be considerable in some areas (Matsuoka et al., 1998).

Several forms are related to the occurrence of daily freeze–thaw cycles in non-cohesive ground materials, and are controlled primarily by shallow segregation of

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[*] Corresponding author.
E-mail addresses: gtvieira@ceg.ul.pt (G.T. Vieira), cmora@ceg.ul.pt (C. Mora), miguel.ramos@uah.es (M. Ramos).

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ice and thaw. The more common are small-scale patterned ground, thin solifluction sheets (cf. Matsuoka, 2001) and terracettes. Other kinds of microforms, often of transient character, are associated to the action of needle-ice and include needle-ice raked ground, gaps around stones, nubbins, fine-earth flags (Washburn, 1979), rock dams (Pérez, 1987), turf exfoliation and needle-ice pans (Hastenrath, 1977; Pérez, 1992a). Studies on this small-scale morphology were conducted in different areas of the world, highlighting the significance of daily freeze–thaw in periglacial and marginal areas. Some of them are stated below.

Extensive occurrence of patterned ground is well known in the Andes and is described by Pérez (1987, 1988, 1992a,b) in the Venezuelan Páramo (4300 m ASL), by Francou et al. (2001) in the Bolivean Andes (above 4700 m ASL) and by Hastenrath (1977) in the Peruvian Andes (above 4600 m ASL). The good development of patterned ground is a function of the high elevation and poor thermal seasonality of the tropical mountains, which induces an extreme number of freeze–thaw cycles. Hastenrath (1973) showed that in Mt. Kilimanjaro, periglacial forms appear above 3400 m ASL and somewhat higher in Mt. Kenya and are dominated by turf exfoliation and a "stripe-like arrangement of the fine material" (needle-ice raked ground). Further south, in the High Drakensberg, Southern Africa (2950 m ASL), Grab (1997) showed the ephemeral character of miniature patterned ground and studied daily freeze–thaw cycles and their consequences in needle-ice growth (Grab, 2001). In the Natal Drakensberg, South Africa (3140–3300 m ASL), Boelhouwers (1991, 1994) described active micropatterned ground and thin stone-banked sheets, suggesting frost penetration to 10–20 cm depth.

Mediterranean mountains are also favourable environments for the occurrence of shallow frost. A strong seasonality in temperature and precipitation marks those environments, particularly in what concerns to the dryness of the warm season and wetness of the cold season (Strahler, 1975). The Western Cape Mountains (South Africa) were studied by Boelhouwers (1995, 1998), which showed the significance of frost action above 1600 m ASL, with needle-ice and frost creep, upfreezing and patterned ground formation. Beaty (1974) described the influence of wind on the formation of needle-ice raked ground at 3800 m ASL in the White Mountains of California. Gómez Órtiz and Salvador Franch (1998) indicate that in Sierra Nevada (Spain), the periglacial zone occurs above ca. 2500 m ASL, altitude at which miniature patterned ground, terracettes and solifluction lobes are active.

In the Swiss Alps, a field site where detailed studies on high mountain slope dynamics (including daily freeze–thaw cycles) are conducted is maintained by the University of Tsukuba (e.g., Matsuoka et al., 1997). Matsuoka et al. (1997) showed that low magnitude but high-frequency daily frost heave prevails on crest debris slopes and gives origin to small sorted stripes. Daily frost depth is typically about 5 cm and rarely exceeds 15 cm (Matsuoka et al., 1998). In the Basses–Alpes (France), Pissart (1972, 1973, 1982) conducted a classical research on the genesis of miniature patterned ground and terracettes.

In the Southern Japanese Alps, Matsuoka (1996, 1998) stressed the significance of daily freeze–thaw in the slope dynamics at ca. 3000 m ASL, generating frost creep, needle ice creep and near-surface ice lenses. The importance of daily cycles for the occurrence of frost creep was also pointed by Sato et al. (1997) in the Taisetsu Mountains (Hokkaido, Japan) at 2150 m ASL.

Another area, where daily freeze–thaw is important, is the Subantarctic Islands, where needle ice has been pointed as a major factor in the morphogenesis, contributing to the formation of patterned ground (Marion Island—Hall, 1979; Kerguelen Island—Hall, 1983). At other high-latitude islands where daily freeze–thaw occurs, research indicates that miniature patterned ground is widespread (e.g., Faeroe Islands—Humlum and Christiansen, 1998; and East Falklands—Wilson and Clark, 1991).

1.2. Studies on active frost action in the Portuguese mountains

Studies on ground temperatures and their geomorphological consequences in the Portuguese mountains are very scarce. Daveau (1978) and Ferreira (1981, 1985) used air temperature data from meteorological stations to estimate the geomorphic importance of ground frost in Portugal. Vieira (1998) used a similar approach in the Serra da Estrela. The only study of ground temperatures and their geomorphological implications is that of Ferreira (1985). He used daily data from three meteorological stations during cold spells to evaluate the depth of frost penetration in the ground and concluded that its geomorphic significance is small.

Brosche (1978) and Daveau (1978) reported the occurrence of a periglacial belt in the Serra da Estrela. Daveau suggested 1750 m ASL as its lower boundary, since above that, microgelivation on rock surfaces was widespread. Brosche suggested that a very marginal periglacial belt was located above 1850 m ASL and was characterized by the occurrence of incipient solifluction lobes. More recently, Vieira (1997, 1999) underlined the polygenic nature of the geomorphological dynamics in the Estrela. The dominant geomorphic processes are related to high-intensity rainfall, but multiple processes play significant roles in the morphogenesis, being difficult to indicate the prevailing process. Therefore, a periglacial environment, even in sensu latu, corresponding to the areas where frost action and permafrost-related processes dominate (French, 1996) is not observed in the Estrela range.

Recent observations in the Serra da Estrela brought new light into the contemporary geomorphological dynamics, since several cryogenic microforms were identified. These include miniature sorted stripes and nets, microforms related to needle-ice activity, incipient solifluction sheets, terracettes, signs of microgelivation and evidence of upfreezing of granules (unpublished data, Vieira). Therefore, a frost action environment (cf. Boelhouwers, 1998) is present in the plateaus of the Serra da Estrela. The need for a better knowledge on the environmental characteristics and on the geocryological activity led to the monitoring of ground and air temperatures. The results and their geomorphic significance are presented here.

2. The study site

The Serra da Estrela (40°20′ N, 7°35′ W) is the highest mountain in Portugal (1993 m ASL—Torre plateau, Fig. 1). The study area is granitic and presents different plateau surfaces between 1400 m ASL and the summit. Most of the western plateau area was glaciated during the Last Glacial Maximum (Lautensach, 1929, 1932; Daveau, 1971; Daveau et al., 1997; Vieira et al., 2001) and its morphology is dominated by glacial landforms. Outside it, a tor and bornhardt morphology with regolith prevails.

The climate is Mediterranean with dry warm summers and the wet season is from October to May. Mean annual precipitation is ca. 2500 mm in the summit and the plateaus record more than 2000 mm (Daveau et al., 1997). In the area above 1400 m ASL, mean annual air temperatures are below 7 °C and for the Torre plateau, Vieira and Mora (1998) estimated ca. 4 °C. Available data on snow are of poor quality and insufficient for purposes of climate analysis. Andrade et al. (1992) indicate a median of 40–50 days with snowfall at 1400–1600 m ASL. However, there is a large irregularity and snow cover rarely lasts more than a few consecutive weeks per year below 1700 m ASL. Wind regimes are complex and show large spatial variations (Vieira and Mora, 1998). The more frequent directions are west and northwest.

Two sites at different altitudes were chosen for the monitoring of air and shallow ground temperatures (Fig. 1). The Cântaro Gordo site is a ridge at 1875 m ASL. The sensors were installed in a flat sector of the summit where a ca. 20-cm-thick mountain ranker develops. The soil is sandy–silty and formed in medium-grained muscovitic granite bedrock. The soil surface is coarse grained and is a polygenic lag-surface originated by deflation, wash and upfreezing of granules. The Fraga das Penas site (1640 m ASL) is a gently sloping interfluve in porphyritic coarse-grained biotitic and muscovitic granite. It has a decimetric layer of coarse weathering material where incipient sandy–silty rankers developed. The soil surface is very coarse grained and also constitutes a polygenic lag-surface.

3. Methodology

3.1. Instrumentation

The apparatuses for the collection of temperature data are miniature data loggers (Tiny Talk II®) and were adapted for measuring air and ground temperatures at different depths (Vieira et al., 2000). At each study site, one data logger was used for the monitoring of air temperatures and four for the ground (1, 5, 10 and 15 cm deep). The 8-bit data loggers have 2Kb EEPROM memory enabling 1800 records and use NTC100 thermistor probes. For good contact with the ground particles, the thermistors were attached to

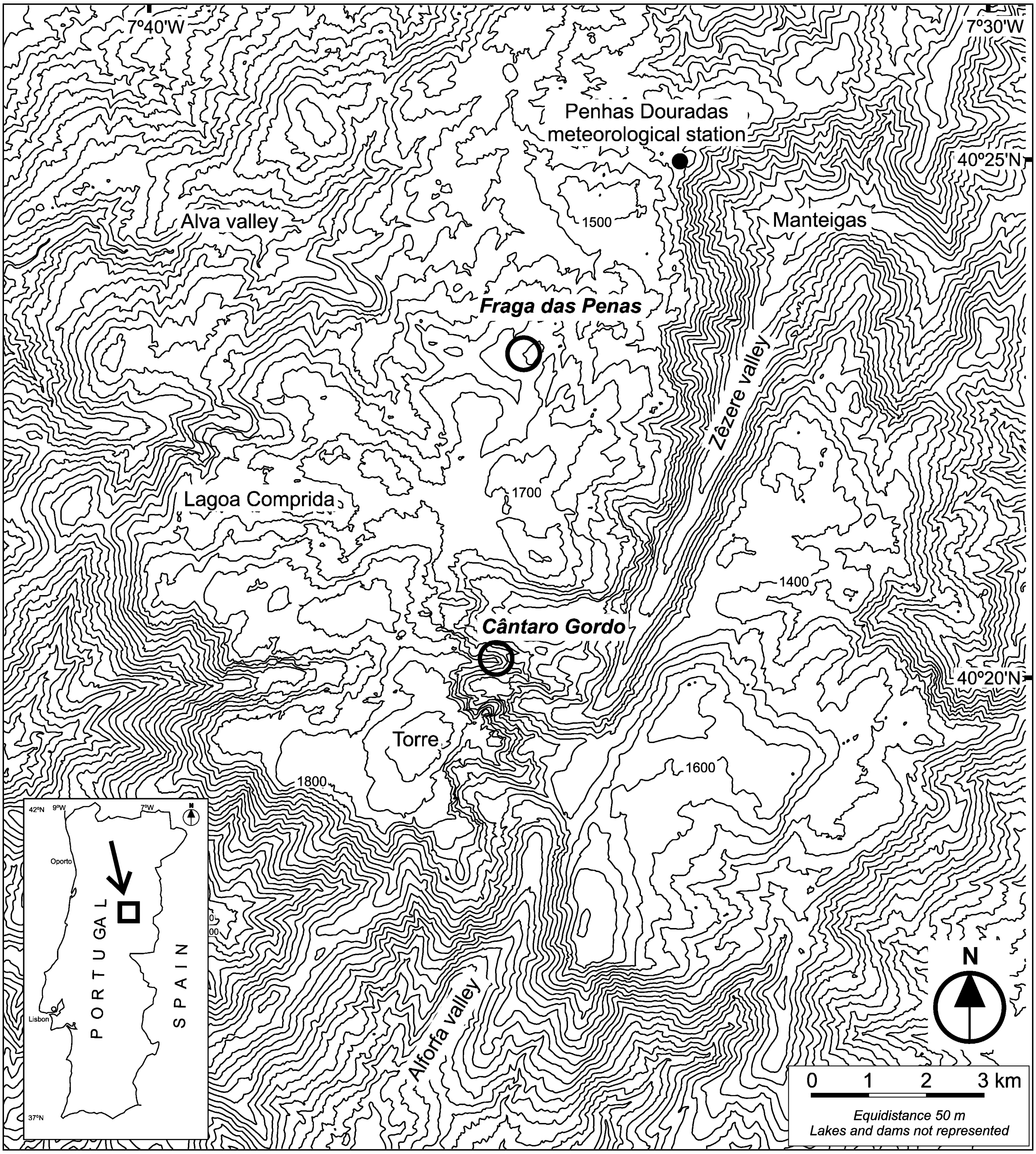
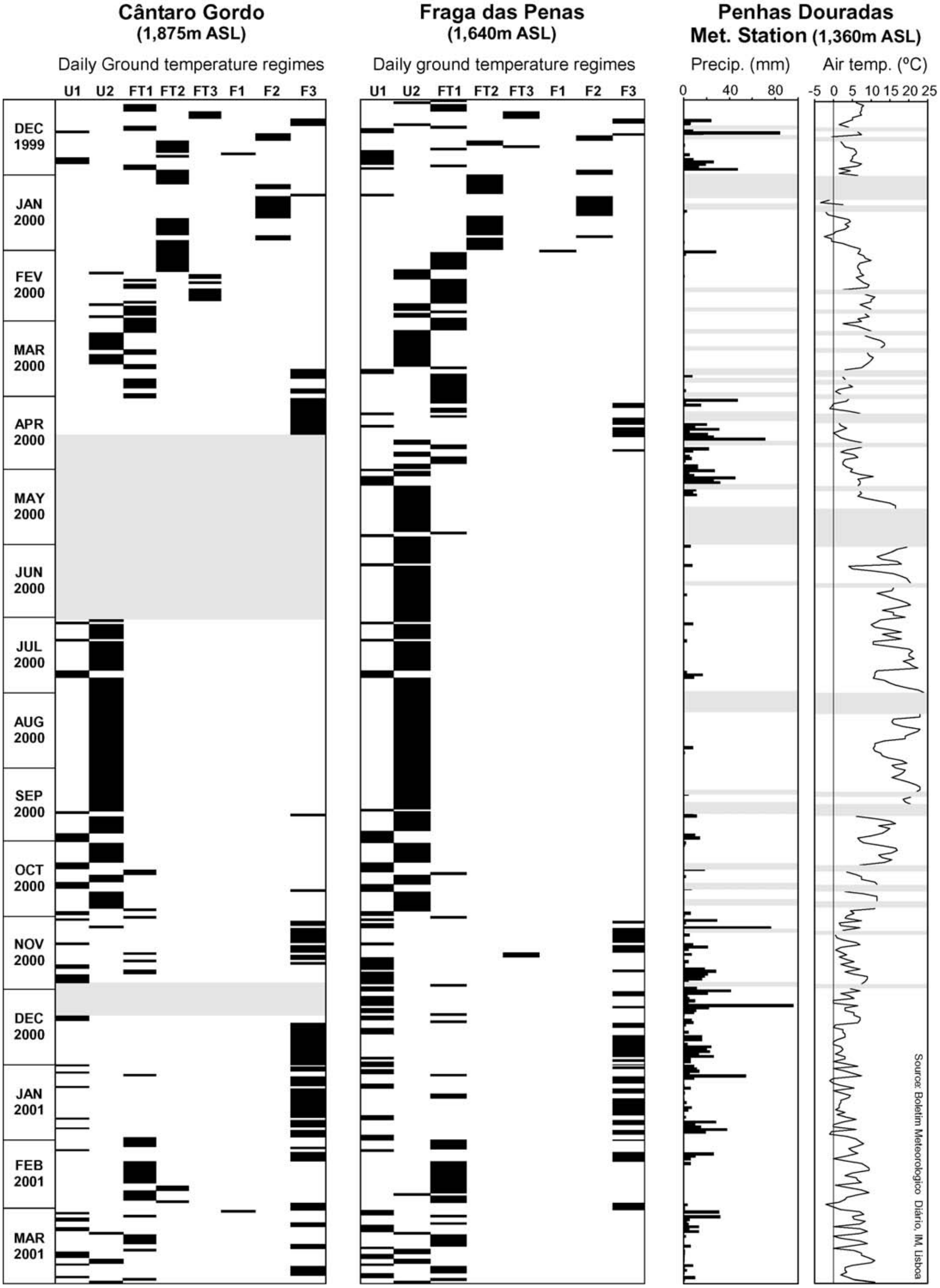


Fig. 1. Location of the study sites and of the Penhas Douradas meteorological station in the Serra da Estrela.

high-diffusivity aluminium plates (Ramos, 1995; Ramos et al., 1998; Vieira et al., 2000). The box of the ground data loggers was buried to reduce heat conduction through the sensor cables. No movement affected the thermistor probes during the recording period.



Source: Boletim Meteorologico Diário, IM, Lisboa

Fig. 2. Shallow ground daily temperature regimes at the Cântaro Gordo and Fraga das Penas sites, and daily temperature and precipitation data from the Penhas Douradas meteorological station (Instituto de Meteorologia) from December 1999 to March 2001. Shaded areas represent periods without data.

3.2. Data collection and analysis

The data loggers were programmed to measure at 2 h intervals from December 1999 to March 2001. This corresponds to 5844 records for each sensor at the Fraga das Penas site; to 4752 records for the ground sensors and 3441 for the air sensor at the Cântaro Gordo. The differences were caused by problems in data collection (severe weather in April 2000 and failure of the air temperature sensor at Cântaro Gordo).

To evaluate the meteorological conditions during the study period, data from the station at Penhas Douradas (Meteorological Institute—IM, 1360 m ASL) were used (Figs. 1 and 2). Mora and Vieira (2001) showed that temperature and precipitation records from this station are statistically significant at a regional level. These data were used to evaluate the character of each month, and in some situations, air temperatures, precipitation and ground temperature regimes were compared to estimate the presence of snow cover. The station does not measure snow thickness and snow cover data are not available. Long time-series of mean monthly temperatures were used for evaluating the thermal character of some months.

4. Monthly average air and ground temperatures

4.1. Air temperatures

The monthly average air temperatures from December 1999 to January 2001 had a similar evolution in the two study sites (Table 1). The coldest month was January 2000 with − 0.8 °C in Cântaro Gordo and − 0.4 °C in Fraga das Penas. The absolute minima were − 9.2 and − 7.7 °C at each site. The comparison with the time-series from 1953 to 1984 of Penhas Douradas shows that it was a moderately cool month (between the first quartile and the median). The irregularity of the Mediterranean climate is clear in the values from February 2000, with 4.9 °C at Cântaro Gordo and 5.2 °C at Fraga das Penas; and also from April of the same year, with a cooling to − 0.7 and 0.9 °C at each site.

4.2. Ground temperatures

The monthly average ground temperatures at 1 cm depth showed similar curves to the air temperatures, but a larger range (Table 1). During summer, the ground temperatures were generally 5–6 °C higher, and in winter were up to 2 °C lower than the air temperatures. These differences reflect the higher summer and the lower winter insolation, the negative net energy balance of the ground during clear winter days and the influence of snow cover.

The influence of the insolation is clear in the monthly absolute maximum temperatures at 1 cm depth (Table 1). Cântaro Gordo presents the highest values in the summer and also in winter during the dry months (i.e., January, February and March 2000). This is influenced by the altitude and higher radiative inputs, but more probably by textural and physical properties of the ground (Geiger, 1965; Williams and Smith, 1989), which were not identified macroscopically. During wet and overcast months, the radiative

Table 1
Monthly air and shallow ground temperatures at the Cântaro Gordo and Fraga das Penas sites from December 1999 to March 2001

			Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Air temperatures	Cântaro Gordo	Average	1.7	− 0.8	4.9	3.3	− 0.7	7.8	13.3	13.7	14.2	12.5	6.5	0.5	–	–	–	–
		Min	− 9.7	− 9.2	− 2.7	− 7.7	− 8.7	− 0.1	− 2.7	3.1	3.1	− 0.6	− 3.5	− 6.7	–	–	–	–
		Max	10.6	11.3	13.1	15.6	4.6	21.6	23.4	27.0	26.3	26.6	18.8	12.4	–	–	–	–
	Fraga das Penas	Average	2.3	− 0.4	5.2	4.3	0.9	9.0	14.3	14.4	14.6	12.8	7.2	2.0	1.7	0.5	2.0	3.7
		Min	− 8.2	− 7.7	− 2.2	− 7.2	− 7.7	0.7	− 1.0	1.9	3.1	1.1	− 1.8	− 5.3	− 7.2	− 8.2	− 6.7	− 3.1
		Max	12.0	11.3	13.8	16.7	6.9	23.0	26.6	27.4	28.1	28.1	19.8	11.3	9.5	10.6	13.5	14.9
Ground temperatures (1 cm)	Cântaro Gordo	Average	0.5	− 2.2	2.7	5.1	− 0.1	–	–	21.5	20.8	16.3	6.9	1.5	0.1	− 0.2	0.9	2.7
		Min	− 5.8	− 8.7	− 2.2	− 2.7	− 1	–	–	3.1	2.7	0.7	− 0.1	− 1	− 3.1	− 1.8	− 4	− 1.8
		Max	9.9	6.2	17.4	22.7	7.7	–	–	51.4	48.9	44.1	24.1	7.7	5.4	4.6	12.8	18.4
	Fraga das Penas	Average	1.7	− 1.4	3.7	5.7	2.0	10.7	19.0	20.3	20.4	15.8	7.6	2.6	1.6	0.7	2.0	4.2
		Min	− 3.5	− 8.2	− 1.0	− 1.4	− 0.6	− 0.1	0.7	5.0	3.5	1.9	− 0.1	− 0.6	− 1.4	− 1.0	− 2.2	− 1.0
		Max	11.7	5.0	16.3	23.0	13.1	29.9	42.8	49.9	46.9	42.8	22.3	18.4	8.4	9.9	13.8	18.4

heating of the ground is limited and sensible heat transfer with the air and particularly with rainwater dominates. This occurred from November 2000 to January 2001, when the maxima were highest in Fraga das Penas. The high volumetric heat capacity of moist ground also mitigates the temperature oscillations (Williams and Smith, 1989). On the contrary, during the summer, the ground dries enabling quick responses to radiative inputs and temperatures at 1 cm depth commonly surpass 40 °C.

The monthly absolute minima at 1 cm depth were lower at Cântaro Gordo (Table 1). They show an irregular curve controlled by the intensity of the coldest atmospheric events and do not reflect directly a seasonal control.

5. The daily ground temperature regimes and their geomorphic significance

The freeze–thaw regime of the ground in the Serra da Estrela is characterized by short periodicity and marked, in most of the cases, by a daily rhythm. The analysis of the temperatures between 1 and 15 cm depth enabled the detection of eight types of regime (Figs. 2 and 3). They were identified according to the depth and cyclicity of freeze–thaw on a thermal basis. A freeze–thaw cycle was considered when temperature crossed 0 °C, a definition with some limitations, because it does not reflect a direct relationship with the formation of ice in the ground. This is specially significant in moist conditions due to the zero curtain effect induced by latent heat release during freezing (Williams and Smith, 1989) and also in dry events, due to the absence of moisture for ice segregation. Particular caution should therefore be taken when analysing the data. Thermal range and irregularities in the regime were not used in the classification.

The classification comprises two types of unfrozen regimes, three types of regimes with freeze–thaw cycles and three types of frozen regimes (Fig. 3). *Isothermal unfrozen regimes* (U1) group the days without frost and simultaneously near-isothermal at least in the two shallower sensors. *Non-isothermal unfrozen regimes* (U2) exhibit a distinct temperature daily rhythm, particularly near the surface. *Days with surficial freeze–thaw* (FT1) present a cycle around 0 °C at 1 cm depth and a distinct temperature rhythm. At and below 5 cm, the ground remains unfrozen. *Surficial freeze–thaw and subsurficial frost days* (FT2) are characterized by frost at depth but surficial (1–10 cm) freeze–thaw cycles. *Surficial and subsurficial freeze–thaw days* (FT3) show freeze–thaw cycles down to at least 5 cm depth. *Subsurficial frost days* (F1) display frost only at depth. *Surficial and subsurficial frost days* (F2) show temperatures below 0 °C down to at least 5 cm depth. *Surficial frost without daily rhythm events* (F3) reveal stable and nearly isothermal conditions close to 0 °C.

5.1. Isothermal unfrozen regime (U1)

The origin of these events is generally related to moist ground (due to rainfall and less often to snowmelt) or to overcast days. They occur mostly from autumn to spring with lower frequency in winter, particularly when the days are colder or drier, but show high incidence in wet and warm winter months. In winter, this regime is more frequent in Fraga das Penas (Fig. 2), due to the lower altitude and higher temperatures.

U1 days are the third more frequent situation in Fraga das Penas and fourth in Cântaro Gordo (Fig. 4). Table 2 shows that when Fraga das Penas records this regime, the higher parts of the mountain are frequently affected by F3 conditions. This is due to differences in snow cover, which is the head control on the latter regime. Geomorphic consequences of U1 regimes are not studied, since they are unrelated to cryogenic processes. However, it is worth to note their high frequency during the cold semester.

5.2. Non-isothermal unfrozen regime (U2)

These events are irrelevant for the geocryological dynamics, but dominated during the study period (Fig. 4). They are typical of dry and warm summers with large solar radiation and large long-wave radiation losses. However, they were also observed in other seasons, when air temperatures were high, there was direct insolation and the ground was dry. Such a condition occurred several days in February–March 2000, and in March 2001, during anticyclonic events that are frequent during the winter in Portugal (Ramos, 1987). This regime occurred mainly during long-lasting episodes (Fig. 2).

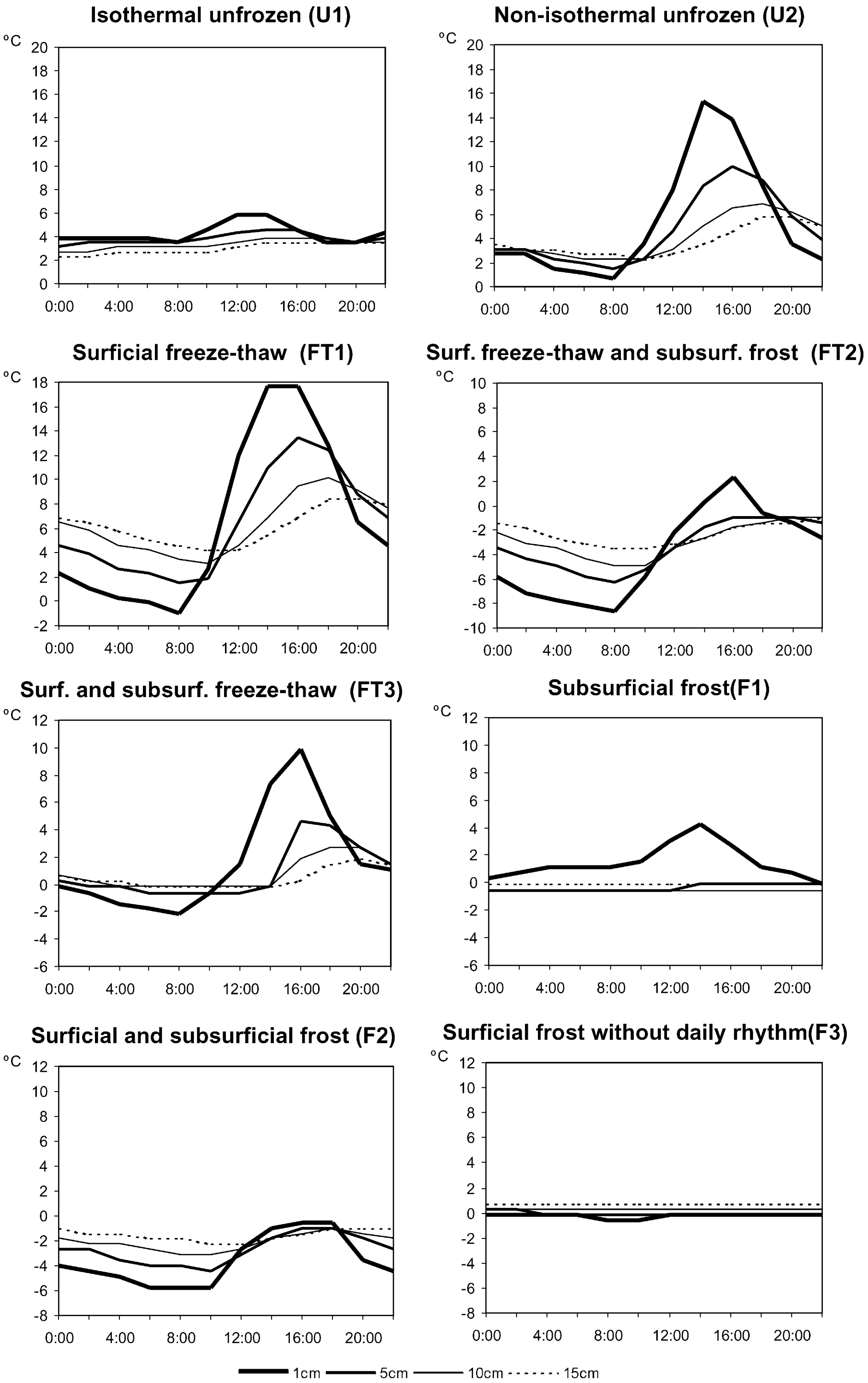


Fig. 3. Types of shallow ground daily temperature regimes identified in the period from December 1999 to March 2001.

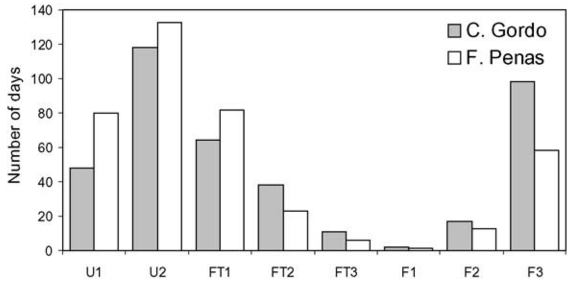


Fig. 4. Total frequency of the shallow ground daily temperature regime from December 1999 to March 2001 at the Cântaro Gordo and Fraga das Penas sites.

It is significant that U2 days were more frequent at the lower site (Fig. 2) but normally occurred simultaneously. When U2 events were recorded at Fraga das Penas, Cântaro Gordo also experienced them in 86% of the cases, but in 8%, it showed surficial freeze–thaw (FT1)(Table 2). This was due to the higher altitude. On the other hand, when Cântaro Gordo recorded U2 regimes, Fraga das Penas also experienced them in 97% of the situations (Table 3).

5.3. Surficial freeze–thaw (FT1)

Surficial freeze–thaw is a regime associated with radiative dominated heat transfer conditions, particularly during cloudless events. Throughout the period of study, FT1 was the second more frequent regime at Fraga das Penas and third at Cântaro Gordo (Fig. 4). At the lower site, it was the most significant regime with ground frost and the second at the higher. This difference is due to the larger number of days with snow cover at the latter. FT1 days occurred from October to May with higher frequency in February and April (Fig. 2). These situations were more frequent at the higher site during the transition months and at the lower site during the winter. A downward migration of this regime along the cold semester is noticeable as cold conditions advance.

Table 2
Ground temperature regimes recorded at Fraga das Penas and regimes that occurred simultaneously at Cântaro Gordo (%)

		Cântaro Gordo							
		U1	U2	FT1	FT2	FT3	F1	F2	F3
Fraga das Penas	U1	56	4	8	3	–	3	–	28
	U2	2	86	8	1	2	–	–	2
	FT1	–	–	57	15	7	–	1	20
	FT2	–	–	–	83	–	–	17	–
	FT3	–	–	17	17	–	–	50	17
	F1	–	–	–	100	–	–	–	–
	F2	–	–	–	15	–	–	85	–
	F3	–	–	1	–	–	–	2	97

U1—isothermal unfrozen regime; U2—non-isothermal unfrozen regime; FT1—surficial freeze–thaw; FT2—surficial freeze–thaw and subsurficial frost; FT3—surficial and subsurficial freeze–thaw; F1—subsurficial frost; F2—surficial and subsurficial frost; F3—surficial frost without daily rhythm.

Table 3
Ground temperature regimes recorded at Cântaro Gordo and regimes that occurred simultaneously at Fraga das Penas (%)

		Fraga das Penas							
		U1	U2	FT1	FT2	FT3	F1	F2	F3
Cântaro Gordo	U1	94	6	–	–	–	–	–	–
	U2	3	97	–	–	–	–	–	–
	FT1	9	16	72	–	2	–	–	2
	FT2	5	3	32	50	3	3	5	–
	FT3	–	25	75	–	–	–	–	–
	F1	100	–	–	–	–	–	–	–
	F2	–	–	5	20	15	–	55	5
	F3	23	2	16	–	1	–	–	58

U1—isothermal unfrozen regime; U2—non-isothermal unfrozen regime; FT1—surficial freeze–thaw; FT2—surficial freeze–thaw and subsurficial frost; FT3—surficial and subsurficial freeze–thaw; F1—subsurficial frost; F2—surficial and subsurficial frost; F3—surficial frost without daily rhythm.

When FT1 regimes occurred at Fraga das Penas, they also took place at Cântaro Gordo in 57% of the cases (Table 2). However, in 20% of the cases, Cântaro Gordo recorded surficial frost without daily rhythm (F3), in 15% surficial freeze–thaw and subsurficial frost (FT2) and in 7%, it showed surficial and subsurficial freeze–thaw (FT3). Therefore, at high altitude, two types of situation occurred: one with more severe frost (FT2 and FT3) and another with an insulating snow cover (F3—see explanation below). When FT1 occurred in Cântaro Gordo, the Fraga das Penas had similar conditions in 72% of the situations, U1 and U2 regimes in 25% and other ground frost regimes merely in 4% of the cases (Table 3).

The surficial freeze–thaw regimes (FT1) are of outermost importance to the geomorphological dynamics, since they often originate needle-ice, which is recognised as an important cryogenic process in the Portuguese mountains (Vieira, 1996, 1998; Ferreira et al., 2000). In agreement with that, very fresh needle-ice raked ground was observed on 3 December 1999 at 1700 m ASL (Fig. 5), during FT1 events both at Cântaro Gordo and at Fraga das Penas.

5.4. Surficial freeze–thaw and subsurficial frost (FT2)

FT2 events occurred during cold cloudless days, dominated by radiative heat transfer. They took place, both with the ground cooling downwards and when it was thawing. The first centimetres of the ground surface behaved as a miniature active layer with high-frequency freeze–thaw. This regime was identified in 38 days at Cântaro Gordo and 23 at Fraga das Penas (Fig. 4) and occurred only in winter (Fig. 2), during or after cold anticyclonic episodes.

FT2 regimes generally developed after a cold event with ground frost at all monitored depths (Fig. 2). That explains the larger number of cases at higher altitude. When FT2 events occurred at Cântaro Gordo, Fraga das Penas only showed an analogous regime in 50% of the cases, and FT1 events in 32% of the cases (Table 3). However, when FT2 occurred at Fraga das Penas, Cântaro Gordo recorded similar regimes in 83% and F2 conditions in 17% of the cases (Table 2).

Surficial freeze–thaw and subsurficial frost regimes can give origin to small-scale solifluction and detachment slides. Miniature surficial solifluction-like forms were observed in some occasions in the Fraga das Penas area, where vegetation cover is sparse. They occurred in patches with a northwesterly aspect, located near gullies and constituted of a mix of granite regolith and gruss (Fig. 6). However, no field observations of the process were attempted during the monitoring period. The forms shown in the figure were observed on 10 April 2001, shortly after the end of the data collection. The occurrence of several FT1 episodes in the end of March 2001 at Fraga das Penas, a few hundreds of meters from the spot where the picture was taken, and the aspect of the location, suggest that FT2 or FT1 events probably occurred there, at least, some days before. The phenomena can also be triggered by rainfall over a surficial frozen layer.

5.5. Surficial and subsurficial freeze–thaw (FT3)

FT3 events were recorded 11 times at Cântaro Gordo and 6 at Fraga das Penas (Figs. 2 and 4) with a sporadical occurrence during the cold semester and not synchronically at both sites. This regime was preceded by different events, being specially significant the FT1 type, since a slight cooling may be enough to generate frost penetration to at least 5 cm

Fig. 5. Needle ice raked ground at the Charcos area on 3 December 1999 (1700 m ASL).

Fig. 6. Miniature surficial solifluction-like forms at Fraga das Penas (1610 m ASL).

depth (Fig. 3). When observed at Fraga das Penas, Cântaro Gordo was in 50% of the cases affected by F2 events, and in 17% of the cases with other ground frost regimes (Table 2). When FT3 occurred at Cântaro Gordo, at Fraga das Penas 75% of the cases were FT1 regimes and 25% of the type U2 (Table 3).

The geomorphological significance of FT3 conditions is mainly the reduction of bulk density and loosening of the ground due to ice segregation and possibly, also to formation of ice lenses, as suggested by Matsuoka (1998). Such soil loosening facilitates the action of other geomorphic processes (e.g., deflation, runoff and creep). The absence of needle-ice is connected to the fast migration of the freezing front in the ground (Outcalt, 1971; Branson et al., 1992).

5.6. Subsurficial frost (F1)

F1 days correspond to events with damp positive air temperatures that kept the ground surface thawed and occurred twice at Cântaro Gordo and once at Fraga das Penas (Figs. 2 and 4). They show poor representativeness and do not demonstrate a clear geomorphological significance, but potentially can originate micro-detachment slides or flows, after the occurrence of rainfall or snowmelt.

5.7. Surficial and subsurficial frost (F2)

F2 events occurred in 17 days at Cântaro Gordo and 13 at Fraga das Penas (Figs. 2 and 4). They are related to cold events and mostly occurred in the winter of 1999–2000, hence their significance varies considerably. In some situations, they can be favoured by snowfall that keeps ground temperatures low. The larger significance at higher altitude is demonstrated also in Tables 2 and 3. With F2 events at Fraga das Penas, in 85% of the cases they also occurred at Cântaro Gordo and in 15%, they were FT2 regimes. However, with F2 regimes at Cântaro Gordo, only in 55% of the cases they also took place at Fraga das Penas. In 20% of the situations, Fraga das Penas recorded FT2 events, and FT3 in 15%.

These deeper frost events can originate ice segregation and ground heave. Upfreezing of buried painted granules to a depth of 5 cm was observed at Fraga das Penas and, considering the different types of regime, it should occur preferentially under F2 conditions. Wooden stakes buried to 8 cm depth were also pulled out of the ground in all probability by freeze–thaw action. Ground thaw, especially with high water content (probably accompanied by ice lenses), can cause thin solifluction and micro-detachment slides. The presence of thin solifluction sheets above 1850 m ASL (Fig. 7) supports the greater geomorphological significance of this thermal regime at higher altitude.

5.8. Surficial frost without daily rhythm (F3)

F3 events were the most important type of situation with ground frost at Cântaro Gordo (98 days) and the second at Fraga das Penas (58 days) (Fig. 4). The ground temperatures during these days are controlled directly by the insulating effect of snow cover (Barry, 1992; Oke, 1987; Williams and Smith, 1989; Smith, 1993) and in some cases, by surficial riming that forms under the influence of supercooled clouds (Barry, 1992; LaChapelle, 1992), as observed during field work. It is a regime that occurs all over the cold semester, more often during cold and wet months with snowfall or when snow covers the ground. The frequency of these events in a year basis varied significantly (Fig. 2). They were rare in the winter of 1999–2000, with higher values in April (more snow cover). However, in the following winter, they were more frequent. In 20% of the cases at Fraga das Penas and 11% at Cântaro Gordo, this regime was preceded by U1 conditions (Fig. 2). This was due to the gradual transition from rainfall to snowfall episodes that characterize such a medium altitude meridional mountain. The control exerted by altitude is clear in Tables 2 and 3. When F3 regimes occurred at Fraga das Penas, they were also observed at Cântaro Gordo in 97% of

Fig. 7. Thin solifluction sheets at Fonte dos Perús, Torre plateau at 1860 m ASL.

the days. However, when they occurred at Cântaro Gordo, at Fraga das Penas the regimes were diverse: 58% of the cases they were equal, in 23% of the days they were U1, and in 16%, the FT1 type prevailed. These observations agree with the significance of snow cover on controlling F3 regimes.

F3 days do not seem to have very significant geocryological consequences. However, there may be an influence on the growth of shallow ice lenses, a fact that needs further research. Longer lasting situations of this type are generally a period of geomorphic stability. But after them, if there is a considerable snow cover, there will be significant geomorphic impacts during melting, particularly in surface and subsurface wash processes.

6. Discussion and conclusions

The analysis of the ground thermal regimes enabled a better understanding of the ground climate in the Serra da Estrela and of the way it influences the geocryological dynamics. It confirmed, as suggested by Ferreira (1985), that ground cooling is small and ground frost is shallow. Ground thermal conditions along the year are difficult to characterize because they are marked by irregularity. The dominating pattern is the difference between the dry and warm summer with unfrozen ground, and the cool and irregular, but predominantly wet winter, with a large diversity of frost regimes. Intermediate seasons show various conditions.

The location of the study sites allowed the recognition of a spatial and temporal control of altitude on ground thermal regimes. Their possible geomorphic implications were discussed. Based on this, a conceptual model is proposed for the seasonal ground thermal regimes and geomorphic dynamics in the Serra da Estrela. The model is supported on the altitudinal succession of the different regimes (Fig. 8). Naturally, there are chances of horizontal coexistence due to different moisture, snow cover, land use, topography or ground properties.

In summer, the usual situation is the non-isothermal unfrozen (U2). This occurs all over the mountain during dry and cloudless periods. However, if wet conditions arise, the ground tends to show isothermal unfrozen conditions (U1). With the approach of autumn, temperatures decline and regimes with surficial freeze–thaw (FT1) appear, first at higher altitude, while the lower sites still retain unfrozen regimes. If a wet situation arrives, snow may accumulate in the higher areas, initiating surficial frost without daily rhythm regimes (F3), while lower sites will experience isothermal unfrozen regimes (U1). With the approach of winter, the downward movement of the

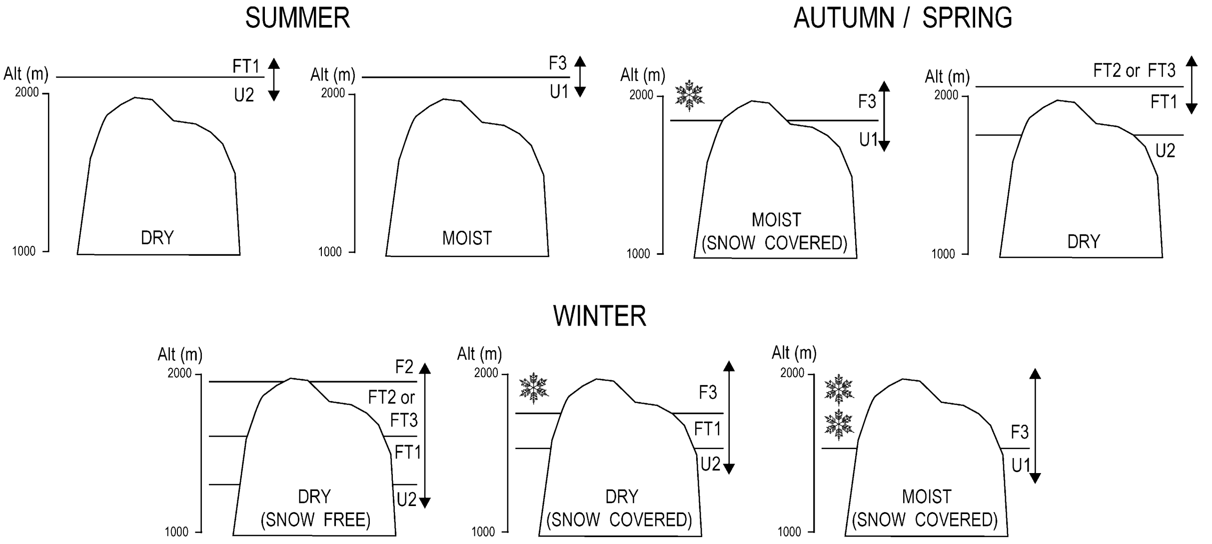


Fig. 8. Altitudinal and seasonal zoning of the daily temperature regimes of the ground in the Serra da Estrela.

belts becomes more probable, but since the climate of the Serra da Estrela is very irregular, warm events may push them upwards. For that reason, typical winter conditions are difficult to assess, but two types of situation prevail: one when the summits are under snow cover and another with snow-free conditions. Under dry and snow-free conditions, the higher parts of the mountain are usually affected by a oscillating belt ranging from non-isothermal unfrozen ground (U2) to surface and subsurface frost regimes (F2), passing through the other intermediate types. If it is a warm event, all the mountain can be affected by non-isothermal unfrozen regimes (U2). But if the conditions are cooler, several belts with distinct types of frost regimes will affect the mountain depending on the altitude. In wet and cool winter events, snow will accumulate in the higher areas and conditions similar to the ones described for autumn are prone to occur. But the lower winter temperatures favour a longer lasting snow cover in the higher parts of the plateau. If this situation is followed by a dry and cold spell, a belt with surficial freeze–thaw cycles (FT1) will form between the snow covered area and the lower areas with unfrozen regimes. These conditions occur frequently. During spring, the circumstances tend to be similar to autumn, but generally with higher moisture availability, given that they follow the wet season, and also with a cooler ground at depth.

The model is a simplification of the conditions of the study area. Changes in topography, ground properties and vegetation cover induce limitations at the micro and local scales. However, it works well as an overview at a mesoscale and as an altitudinal zoning, and is valuable for a better geomorphological perception, since as field observations suggest, there is a general agreement between the ground thermal regimes and the geocryological dynamics (Table 4). The model agrees with the observations by Brosche (1978) on the existence of incipient solifluction phenomena above 1850 m ASL. The stable thermal character of the summit area when it is under the influence of the snow cover, and surficial freeze–thaw occurring at lower altitudes, are particularly interesting. This active belt, between around 1400 and 1700 m ASL, coincides with a poor vegetation cover, sparse scrub formations and open patches of gruss and regolith with annual species. The continuous but irregular altitudinal movement of the belt system shows that it is difficult to define a precise periglacial zone, since yearly conditions vary enormously. In this sense, even small climatic changes, both in temperature and precipitation, would affect the belts and

Table 4

Tentative evaluation of the ground thermal regimes and their geomorphological consequences based on the field observations from the Serra da Estrela (– none; + low; ++ medium; +++ high)

Type of regime	Geocryological significance (magnitude)	Geocryological significance (frequency)	Main processes	Geomorphological effects
Isothermal unfrozen regime (U1)	–	–	–	–
Non-isothermal unfrozen regime (U2)	–	–	–	–
Surficial freeze–thaw (FT1)	+	+++	Needle ice	Miniature patterned ground, nubbins, gaps around stones, fine-earth flags, soil desegregation
Surficial freeze–thaw and subsurficial frost (FT2)	+	+	Solifluction, flows and slides	Surficial solifluction and micro-detachment slides
Surficial and subsurficial freeze–thaw (FT3)	++	+	Ice segregation	Upfreezing of granules (scarce due to little moisture available)
Subsurficial frost (F1)	++	+	Slides	Micro-detachment slides
Surficial and subsurficial frost (F2)	+++	+	Ice segregation, solifluction and frost heave	Upfreezing of granules, solifluction, terracetes
Surficial frost without daily rhythm (F3)	–	–	–	–

influence the geomorphic dynamics and stress on the vegetation. Taking into account its intrinsic limitations, the authors think that this conceptual model may be used in other Mediterranean mountains considering their altitudes (e.g., during summer, higher mountains would already experience frost regimes) and perhaps, even to tropical high mountains with a different seasonal control.

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