Relationships Between the Daily Temperature Wave And the Development of the Natural Soil Profile

R. GOETZ, German Research Association, and
S. MÜLLER, State Geological Survey of Baden-Württemberg*

•IN WELL-DEVELOPED soil profiles, characterized by dislocation of clay materials, formed on loess, lime-rich moraines, and similar substrates in central and western Europe, the transition from surface to subsoil lies with impressive regularity between 30 and 40 cm below the soil surface. At the present time the question is being investigated whether causal relationships exist between this fact and the course of soil temperature. For this purpose an automatic temperature recorder has been installed in the Würmmoraine of the Rhine glacier. Measurements are made on moraine raw soil material taken from deeper unchanged layers with which sections of the natural profile on the south and north flanks of a drumlin had been replaced.

The first measurements from the 1967 growing season show a well-marked termination, at a depth of 30 to 40 cm, of the daily absorption and emission of radiant energy and of the daily march of soil temperature and circulation of soil heat. A thermally activated upper zone is differentiated at this depth from a thermally passive lower zone. In between lies an equalizing transition layer that shows a temperature maximum during the period of heat loss.

The different microclimates occurring at the northern and southern side of the drumlins and in the different seasons produce differences in degree but not in principle. According to the literature, the depth of the daily temperature wave during the summer half-year is, under otherwise comparable conditions, quite independent of soil type and vegetative cover.

THE PEDOLOGIC PROBLEM

In the transition zone between rock and atmosphere, the native rock is permeated at all joints by air and periodically also by water. A few interconnected processes transform the rock to soil. At the beginning of the weathering phase, an essential role is played by temperature changes. These cause mechanical breakup of those rocks whose mineral components have different thermal coefficients. In cold and temperate climates, mechanical comminution is achieved mostly by the expansive force of ice formation in frequent cycles of freezing and thawing. Part of the loose particles produced are transported and secondarily accumulated under the action of gravity or of glacier ice, moving water, or wind, and also through biologic processes. The latter also produce humification and biochemical transformation of the substrate. This is accompanied by an increasing contribution from solution weathering which, in humid climates, brings about a translocation of soluble bases to greater depths.

In the case of the moraines investigated by us, which are mixtures of calcareous and siliceous materials, the first phase of solution weathering is a decalcification. The remnant, left behind in the solution process, is a colloidal clayey substance that in temperate climates is at first quite mobile. This substance characterizes the fundamental process of soil formation that is of special interest in this connection: the "lessivage" or clay permeation.

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The French pedologist, Duchaufour (4, p. 252ff), has for some time drawn attention to this previously little-noticed process. It occurs in central and west European soils under the influence of seepage water at neutral or slightly acid reaction of the soil solution. The lessivated colloids washed out of the surface soil layer (A-horizon), which has become impoverished in clay materials, are accumulated in the subsoil (B_t-horizon) as coatings on the granular soil constituents. Duchaufour assumes that the lessivation is due to the action of insufficiently humified, but soluble, organic substances (kryptomull) formed from vegetable residues of central European broad-leaf forests.

This process is responsible for the main soil types that we found in central and western Europe, the "sol lessivé" (Duchaufour) and the "Parabraunerde" (Mückenhausen, 9). In the nomenclature of the U.S. Soil Survey Staff (17), typical "Parabraunerde" would be a "typic Normudalf."

The lessivage is especially marked in substrates in which calcareous and silicate mineral components are mixed. Examples of these, in addition to the investigated moraines, are loess, calcareous sand stones, mixed gravels, and other mixed sediments. In soils developed on these materials, the regional soil survey in central and western Europe has encountered the interesting fact that the depth of abrupt transition, from the lessivated, mostly sandy, light grey-brown A-horizon to the underlying reddish-brown B_t-horizon with its clay enrichment, is of extraordinary constancy in all undisturbed soils and is between 30 and 40 cm. This line separates an upper soil layer that is usually poor in humus but possessed of small, loose aggregations and relatively rich in biologic activity, from a clayey subsoil, often of coarse prismatic structure, with larger water-holding capacity but with considerably less air-soil interface and consequently lesser potential for biologic activity.

During extensive mapping of forest soils in southwestern Germany, the suspicion arose that climatic factors are involved in the location of the line of separation of the two horizons, especially since it is more pronounced the warmer the regional climate. In cooler areas, the line of separation becomes an indistinct zone of transition (18). Whereas in other soil types the horizon boundaries at a depth of 30 to 40 cm are not as distinct as in the lessivated types, such boundaries are relatively frequent on loose substrates, even without lessivage—e.g., as boundary of humification on loose calcareous substrate or as boundary of brunification in the case of stunted "Braunerde" soils formed on loose rock that is poor in bases. In podsols too, the B-horizon often begins at this depth. In addition, precipitation of lime and accumulation of other substances often occur at this depth.

Because this phenomenon occurs on substrates which, though normally well-drained, may vary greatly in permeability, meteorological reasons suggested the working hypothesis that the constant thickness of the upper soil horizon could be correlated with the course of the soil temperature (11). Many soil temperature determinations from all over the globe show that the daily temperature wave reaches this depth during summer. Best evidence for this is furnished by the measurements of the Serbian meteorologist, Vujevic (19). During the years 1902-1906, he studied the course of soil temperature in a "humous soil" (probably chernozem from loess) at depth intervals of 10 cm. His results prove that the depth of penetration of the daily temperature wave during the warmest season of the year is 30 to 40 cm, and that belcw this, the temperature differences are damped out.

The problem is, however, complicated by the fact that a very large number of substrates are covered by allochthone layers of the same constant thickness of 30 to 40 cm. In the case of such layered substrates, the boundaries of the subsequently developed soil horizons coincide with those of the geologic strata at depth of 30 to 40 cm. This observation has caused several authors to question the existence of the lessivation process and to explain the profile of the "Parabraunerden" as a consequence of geologic stratification (14). Nobody considered the alternative and asked the question: Why do these cover strata usually have the same thicknesses?

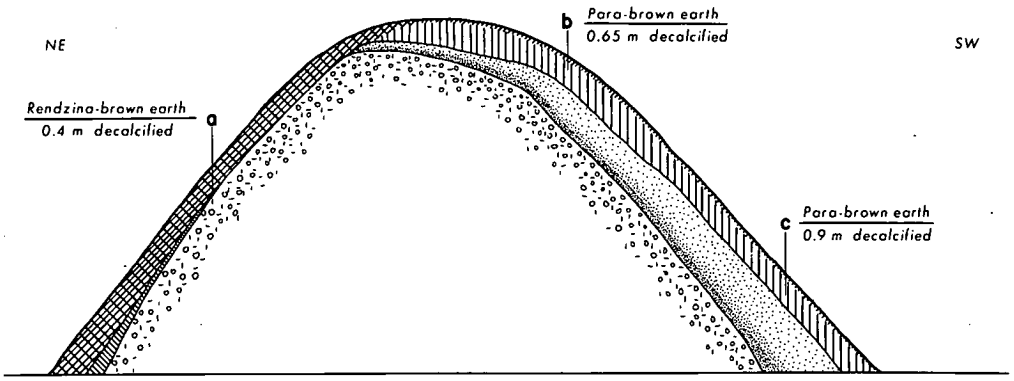


Figure 1. Cross section of a drumlin near Konstanz with asymmetric soil formation.

RESEARCH OBJECTIVE

In view of the indicated problem, it was fortunate that the forest site-mapping service of Baden-Württemberg found some "Parabraunerden" in young Wuerm glacial drumlins in the area of Konstanz on the Bodensee that were clearly formed by lessivation (12). The para-brown earths located on the narrow level crest of these hills contain no late-glacial covering layers that could have been deposited by wind action or by post-glacial soliflux. The coarse gravelly components cannot be of aeolian origin, and the preconditions necessary for soliflux are absent in the closed, level altiplains of the region.

Figure 1 shows that, depending on the exposure, different stages of soil development are observed. The pertinent relationships can be explained with great probability by the microclimate and the natural succession in the vegetative cover. One finds that in the starting stages of soil development, on the shaded NE slopes, as well as on the most extensively decalcified and developed soils of the SW flank, the surface horizons have a depth of about 40 cm. Their lower boundary is usually very sharp. The subsoils, which are enriched in clay content, often show reddish coloration in the mild vine-growing climate around the Bodensee (13, Table 95). The average yearly temperature is 8 to 9 C, the mean precipitation, 800 mm, most of which falls in summer.

The composition of the numerous drumlins of the Bodanruck of the Rhine glacier at Konstanz is quite similar. About 60 to 80 percent of the volume consists of gravel of 20 to 60 mm diameter, which is relatively loosely packed and has a high coefficient of permeability. It consists of about 60 percent alpine carbonate rock, marble, calcareous sand stones, and siliceous lime stones. The remainder is crystalline rock in which quartzites, granites, gneisses, and amphibolites prevail. The lime content varies in the finer fractions (20 to 0.6 mm) between 20 and 50 percent, which means that the content in quartz and silicates is much higher in the finely grained materials than in the gravel. The fractions below 0.6 mm amount to about 10 percent of the total weight. Their size composition is as follows:

Size Fraction (mm)	Approximate Percentage
0.6-0.1	32
0.1-0.02	48
0.02-0.002	18
<0.002	2

The fine sand fraction prevails at 20 to 30 percent lime content; these values are averages of sieve and sedimentation analyses performed at the State Geological Survey at Stuttgart.

The regularity in the variation of soil development with variation in exposure condition, and the constancy of the boundary between the upper and lower soil horizons at about 40 cm, render pairs of opposite drumlin flanks favorable objects for the study of the influence of the course of soil temperature on soil formation.

For this purpose a forest-free drumlin, named the "Walzenberg," located at the village boundary of Allensbach, was chosen. Its natural soil had been greatly changed by agri- and viniculture, and through erosion caused by these. Fertilization, employed in this soil use, produced strongly humified starting stages of soil formation (Rigosol-Pararendzina). It is interesting to note that in these stages the naturally loose moraine material is very often so well cemented, in dry condition at a depth of 30 to 40 cm, that pointed Warren hoes were required to break through this zone in digging. It is assumed that this cementation is caused by a very small amount of silicic acid that has been formed in the layer above and has been illuviated into its present location, where it forms a temporary cementing material when dry. This problem is being further investigated, but for the present, the depth location of this young hardpan is of interest.

In order to obtain useful quantitative data of the microclimatic factor acting on a drumlin, we first eliminated the many accidental variations that result from the differences in vegetative cover and from the degree of soil and humus development at a particular location. Therefore, at the test locations, raw material conditions were created that were comparable with those obtaining at the start of soil formation immediately after retreat of the ice. This could be achieved very easily by excavating, on the two drumlin flanks, pits having a cross section of 2 by 2 m down to the raw moraine material and filling these pits up to the surface with raw moraine material from the same drumlin.

The microclimatic investigations are based on the following conditions:

1. The two test areas are situated at an elevation of 450 and 500 m above sea level, in the upper third of the unforested drumlin slopes of an average slope angle of 20° toward SW(S) and NE(N), respectively.
2. The artificial filling of raw lime-rich moraine material has a single-grain structure of good permeability, and is nonplastic and hardly susceptible to erosion.
3. The surfaces of the artificial soil fills were fitted to the natural slope and were kept continuously free of vegetation.

The following microclimatic factors were determined: (a) soil temperatures at depths of 2, 5, 10, 20, 35, 50, 75 and 100 cm by continuous mechanical recording; (b) precipitation and seepage water; and (c) drainage. All microclimatic test data were evaluated in coordination with the course of the weather. For this purpose, use was made also of the measurements and records of the neighboring official climatological stations.

These investigations are financed by the German Research Association (Deutsche Forschungsgemeinschaft), and will extend over three growing seasons. At the time of this report (May 1968), only a preliminary account can be given, covering a portion of the test results obtained in 1967.

PRELIMINARY TEST RESULTS

The formulation of the problem requires average values of the course of the daily temperature in the soil over the entire growing season, April to November-December 1967. These values were obtained by adding the respective hour-values for a whole month and dividing the sum by the number of days in a month. During the recording period, we obtained a very large amount of data of variable quality. We were forced, therefore, to concentrate for a first overview on a partial evaluation of what were considered to be the most reliable data.

Suitable for this purpose appeared to be the recordings of the soil temperatures in the two months of April (mid-spring) and July (mid-summer) with their seasonally caused maximum temperature differences. For their presentation we chose the geotherms (isotherms of the soil).

Furthermore, we decided to aid in the visualization of the problem by presenting tautochrones, which show the temperature as a function of depth for a particular moment in time, from the specially suitable example of the course of the daily temperature wave in the soil on the southern flank of the moraine in the month of July (designated in the following as "July-S").

Finally, we are attempting to transmit a preliminary, comparative overview of the course of the average daily temperature for a period of six months (April 1-30; May 16-June 15; July 1-31; August 16-September 15; October 1-31; November 16-December 15, 1967). For this purpose, typical selected pairs of tautochrones are presented.

Weather During April and July

In the meteorologic characterization of the two months with respect to the long-term averages, April was classified as too cold, and July as one of the 11 hottest of this century, according to the Monthly Weather Report for Baden (published by the German Weather Service, Weather Office, Freiburg, i. Br. No. 4, April and No. 7, July 1967).

Interpretation of Results to Date

Despite the strongly contrasting starting situations with respect to weather and exposure, several common traits of the geotherms of the course of the average soil temperatures can be recognized (Figs. 2, 3, 4, 5). Most impressive—and uniquely well shown in this type of presentation—is the differentiation between an "upper zone" with more or less closely spaced geotherms and a "lower zone" with widely spaced, lightly curved or even almost rectilinear geotherms. The transition line between these two types of geotherm patterns lies with remarkable consistency at a depth of 30 to 50 cm.

We shall inspect separately the daily insolation phase ("W" = warm) in the middle of Figures 2, 3, 4 and 5, and the heat radiation phase ("C" = cold) at the left and right

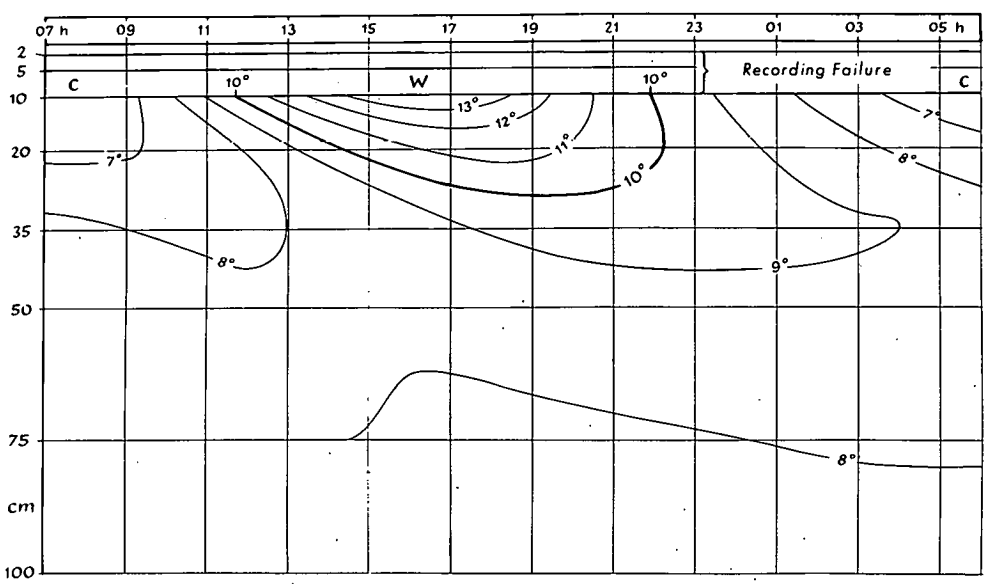


Figure 2. Geotherm of the average daily temperature course in soil for April 1967, south slope.

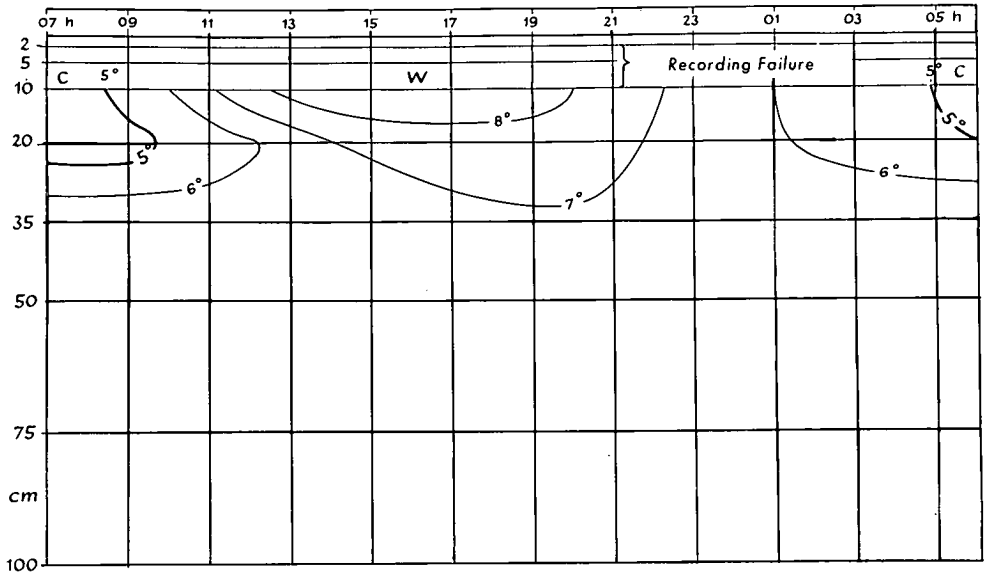


Figure 3. Geotherm of the average daily temperature course in soil for April 1967, north slope.

margins of these figures. Early in the insolation phase, the crowding toward the right hand of the geotherms in the upper zone of the north slope is indicated by the asymmetric pattern of the geotherms (Fig. 3, "W"). This crowding to the right reaches its greatest horizontal deformation in the same depth range of between 30 and 50 cm on the south slope in April as well as in the two figures for July (Figs. 2, 4, 5). We shall call this a transition layer and note the fact that in July as well as in April the dimensions of the upper zone and the depth location of the transition layer remain essentially the same. There is, however, a difference in the appearance of the zones

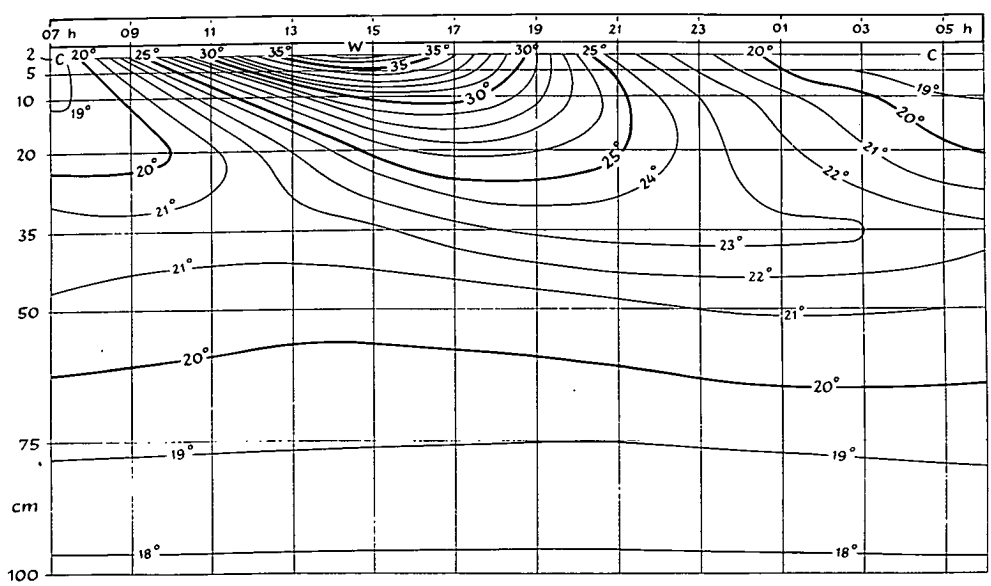


Figure 4. Geotherm of the average daily temperature course in soil for July 1967, south slope.

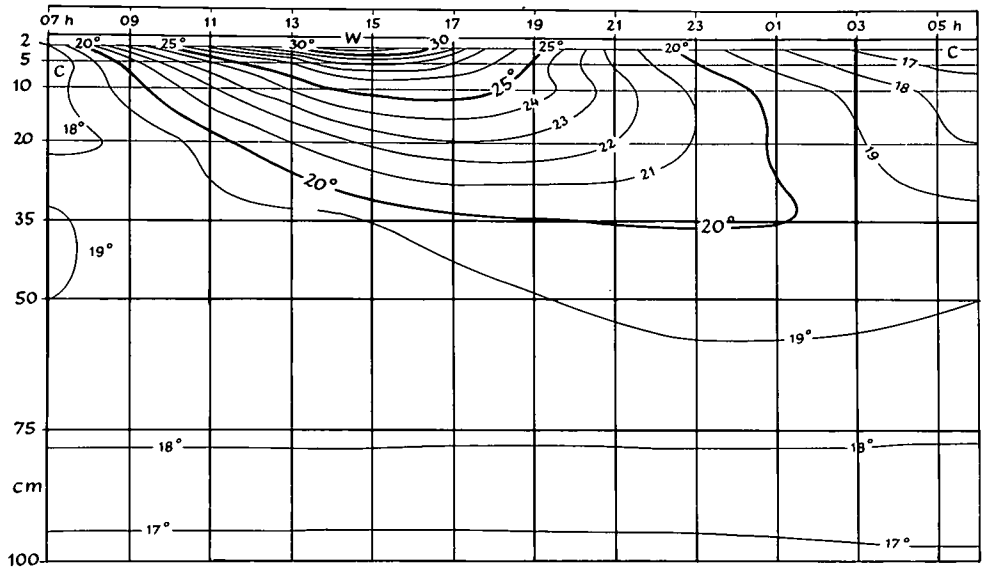


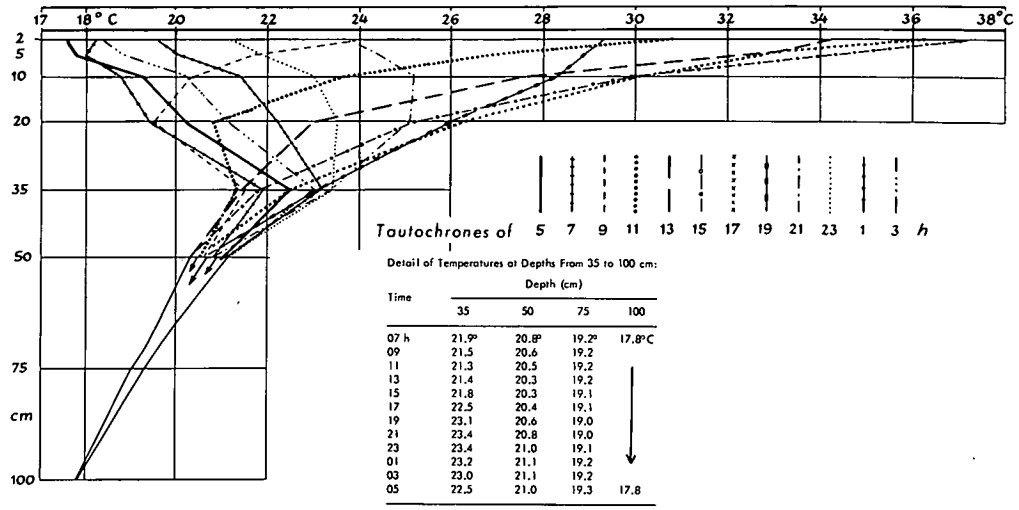
Figure 5. Geotherm of the average daily temperature course in soil for July 1967, north slope.

of maximum deformation of the July geotherms, in that this zone is strictly localized at the 35-cm depth range at the southern exposure, while it is less accentuated on the northern slope and spreads over the entire thickness of the transition layer. The geotherms for the radiation phase show the same characteristic crowding toward the right, but without reaching the same degree of deformation as shown for the insolation phase. It should be noted that all radiation phases, irrespective of season and exposure, generally move from the upper zone well into the range of the transition layer. Differences in degree between the radiation phases exist for the two slope exposures only in July; while the radiation phase loses itself gradually on the northern slope at a depth between 35 and 50 cm (Fig. 5, left margin), that on the south slope is more sharply accentuated and ends at a depth of 35 to 40 cm (Fig. 4, left). The phenomenology of the insolation and radiation phases at both exposures was quite analogous for the two months under consideration.

The daily temperature variations that express themselves in the two characteristic phases of the upper zone are noticeable in the lower zone (i.e., from about 50 to 100 cm) only as relatively weak thermal "impulses" (Figs. 2-5). Again only differences in degree can be observed between the two seasons and the two exposures.

Now our attention shall be directed to the phenomena in the "transition zone." Here in the course of the daily march of temperature—especially during the night—is developed a zone of thermal discontinuity that is connected with the marked retardation of heat penetration during the insolation period. This temperature reversal was more strictly localized on both slope sites in July than in April, and also—independent of the season—was less distinct on the north slope than on the south slope. It is, therefore, most noticeable in the horizontally-directed, strongly deformed geotherms of July-S (Fig. 4). The maximum of the daily temperature wave occurs, therefore, during the night at a depth of 35 to 40 or 50 cm, which is between the soil surface and the 1-m base line at the bottom of the test fill. This depth range can, therefore, be considered as a thermally distinct boundary layer.

Before proceeding to a general comparison of all the months in 1967 covered by this investigation, we shall treat briefly, and with the same method of presentation and analysis, the average daily temperature course obtaining in July on the south slope (Fig. 6). Tautochrones show, on the one hand, the temperatures as function of soil depth for a particular moment in time, and on the other hand, the direction of the heat flux at different depths at particular times.



Time	Depth (cm) 35	50	75	100
07 h	21.9°	20.8°	19.2°	17.8°C
09	21.5	20.6	19.2	
11	21.3	20.5	19.2	
13	21.4	20.3	19.2	
15	21.8	20.3	19.1	
17	22.5	20.4	19.1	
19	23.1	20.6	19.0	
21	23.4	20.8	19.0	
23	23.4	21.0	19.1	
01	23.2	21.1	19.2	
03	23.0	21.1	19.2	
05	22.5	21.0	19.3	17.8

Figure 6. Tautochrones of the average daily temperature course in soil for July 1967, south slope, for all odd-numbered hours.

The main characteristic that can be observed is the relatively wide fanning out of the tautochrones between soil surface and about 35 cm depth (upper zone) and a relatively narrow bunching from there to the bottom of the pit (lower zone). This is expressive of the almost discontinuous decrease of the amplitude of the daily temperature wave at the boundary layer at about 35 cm. At a depth of 100 cm, the amplitude is completely damped out. Furthermore, in the upper zone, the two phases are characterized by the directions of the tautochrones: the tautochrones of the insolation phase run from the upper right-hand to the lower left and indicate a downward heat flux (see the 15 h [3 p.m.] tautochrone in Fig. 6), while the tautochrones of the heat radiation phase indicate an upward direction of the heat flux (see 5 h [5 a.m.] tautochrone in Fig. 6). Both follow the prevailing temperature gradient. The transition between the two phases reflects itself in several inversions in the daily course (see the 9 h and 21 h tautochrones in Fig. 6). This behavior of the tautochrones is exclusively restricted to the depth range of the upper zone. The nightly radiation phase, with temperature increase in the soil, ends at a depth of about 35 cm. This is the locus for a persistent inversion; i.e., during the nightly radiation period, the temperature maximum between soil surface and 1 m depth is localized in this boundary layer (see 01 to 07 h tautochrones in Fig. 6). The direction of the bunched tautochrones in the lower zone that run from the right top to the left bottom is expressive of the downward heat flux occurring in mid-summer (Fig. 6).

In order to obtain a first general view of the typical daily march of soil temperatures during the entire growing season, April to November-December 1967, a representative pair of tautochrones was selected for every month studied. These tautochrones were characteristic for the respective insolation and heat loss or radiation phases, and represent the respective types (Figs. 7 and 8). These two tautochrones, supplied with time (hour) notation, start from the daily maximum or minimum, respectively, at the soil surface (2 cm depth in our case). Exceptions were the tautochrone pairs from April and May-June 1967, which, because of instrument trouble, started only at depths of 10 cm.

We shall omit, for the time being, consideration of the two November-December tautochrone pairs (Figs. 7-VI and 8-VI) and also of the October pair for the north slope (Fig. 8-V). In all the other pairs—irrespective of season and slope exposure—far-reaching analogies are strikingly evident. All tautochrone forks that lie in the upper zone close themselves in the depth range of 35 cm. This means that the average

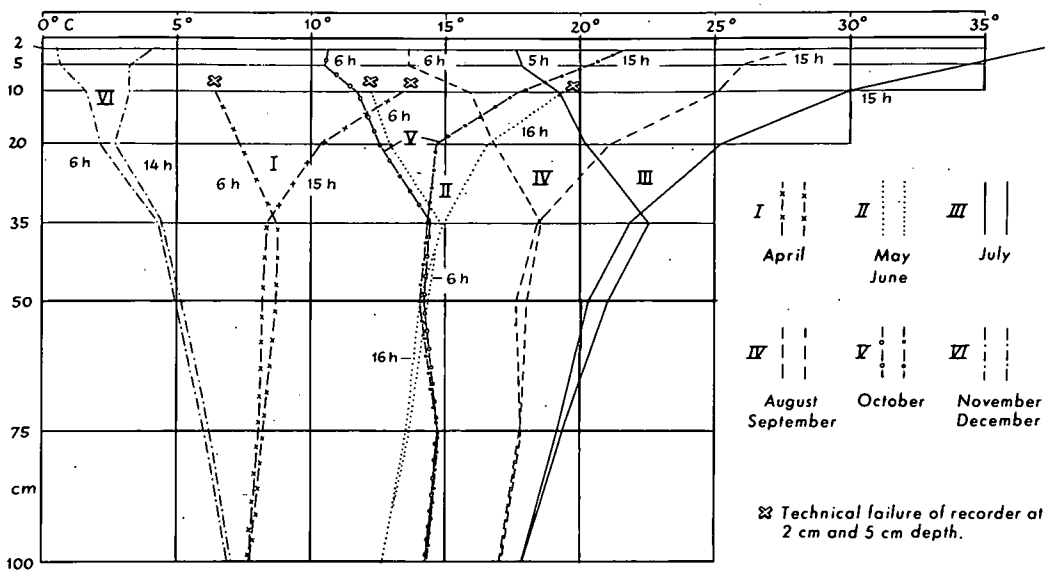


Figure 7. Selected tautochrone pairs (insolation and heat radiation types) for 6 months of the growing season of 1967, south slope.

daily temperature wave during the period from April to August-September is largely damped out in this boundary layer. Furthermore, the inversion, shown by the "radiation-loss" type in the boundary layer, is considerably less marked on the northern slope than on the southern slope. On the latter, one can observe an increasing accentuation of the inversion from April to July 1967, and thence to the fall a decrease in sharpness. The inversion of each tautochrone pair in the lower zone only reflects

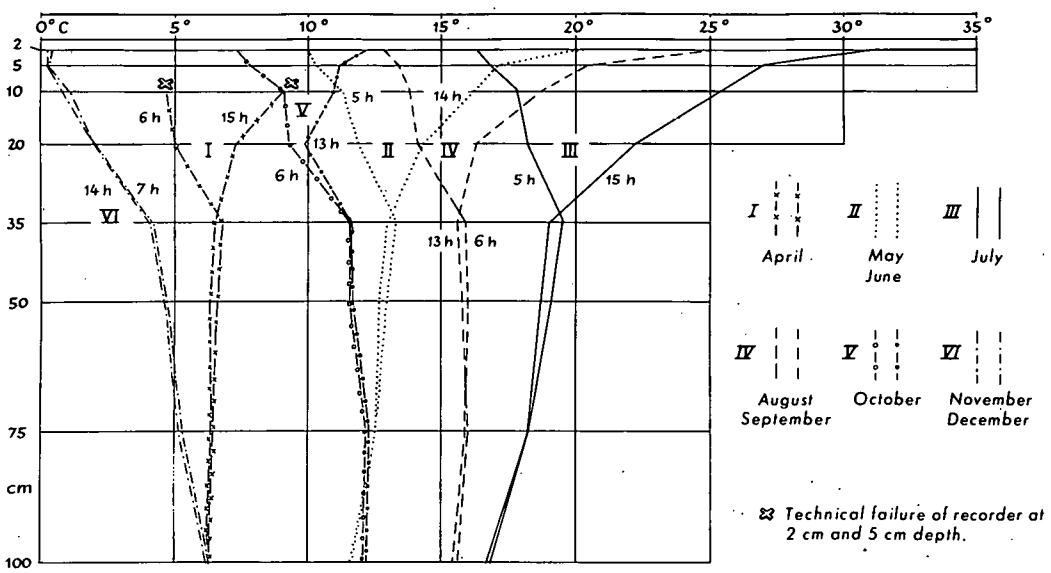


Figure 8. Selected tautochrone pairs (insolation and heat radiation types) for 6 months of the growing season of 1967, north slope.

the phase retardation of the temperature wave penetrating into the soil. Further damping and final extinction of the amplitude of the temperature wave takes place at depths from 75 to 100 cm.

The direction of the tautochrone pairs in the lower zone swings pendulum-like in the course of the growing season on both slope exposures, between practically isothermal states in April-N and August-September-N on the one hand (Fig. 8-I and IV), and a distinct downward temperature gradient in July-S and July-N on the other hand (Figs. 7-III and 8-III).

For October 1967, a fundamental difference is observed for the first time between the two tautochrone pairs deriving from the difference in exposure (Figs. 7-V and 8-V). That for the southern slope shows the general familiar features; the inversion at 35 cm depth is also still noticeable. For the northern slope, however, the insolation type (right tautochrone in Fig. 8-V) terminates at a depth of 20 cm with an inversion. Below this and down to a depth of about 75 cm a heat flux toward the soil surface predominates. Instead of the temperature inversion, hitherto observed at a depth of 35 cm, a marked change in direction of both tautochrone types is observed at the same depth. This tautochrone bent indicates a weaker heat flux in the lower zone and a relatively stronger one in the upper zone.

With a retardation of about 2 weeks, the same process takes place in the test area on the southern slope (Fig. 7-VI). Aside from the absolute temperature values, the two tautochrone pairs of October-N and November-December-S are practically congruent.

Finally, even in the upper zone there was practically no daily temperature variation on the northern exposure site during November-December 1967; i.e., differentiation between insolation and heat radiation had vanished (Fig. 8-VI). The picture is dominated by a heat flux from the bottom of the test fill to the soil surface. Instead of the previously observed formation of thermal zones, only a change in direction of the tautochrones at a depth of 35 cm is observed. This change in direction indicates a stronger heat loss flux in the upper than in the lower zone.

SUMMARY

The investigations of the soil temperatures on both slopes of the Walzenberg near Allensbach/Bodensee during the growing season 1967 have produced the following preliminary results:

1. Analysis of the 4 geotherm fields (Figs. 2-5), which represent the respective characteristic course of the daily temperature wave in the soil, renders the following thermal profile: (a) a thermally active upper zone between soil surface and about 30 cm depth, (b) a transition or boundary layer with nightly temperature reversion between 30 and 40 (50) cm, and (c) a thermally passive lower zone between 40 (50) cm and 100 cm depth (lower boundary of filled test pit).

2. With the aid of tautochrones, this division into 3 parts can be easily visualized by means of the test results for July 1967 (Fig. 6): (a) the fanning out of the tautochrones in the active upper zone, (b) the boundary layer with the localized temperature inversion during the night hours, and (c) the alignment of the tautochrones in the same direction in the passive lower zone.

3. The overview obtained with regard to the course of soil temperatures during the growing season of 1967 by means of selected tautochrone pairs leads to the recognition of subdivisions that are functions of time (Figs. 7 and 8): (a) from April (north and south slopes) to October (south slope), i.e., spring, summer, fall—the partial results enumerated in 1 and 2 are generally applicable to this time period; (b) October (north slope) and November-December (south slope), i.e., fall, winter transition—an upper zone is still active but only 20 cm thick, there is a passive lower zone from about 20 cm to the bottom of the test pit, and at the depth of the boundary layer (35 cm) temperature reversion is replaced by a change in direction of the tautochrone pair; and (c) November-December (north slope), i.e., winter—the characteristic features of the thermal profile have disappeared except for a distinct change in the direction of the tautochrone pair at the depth of the boundary layer. The results discussed under 3 are exemplified by the thermal profile sketch in Figure 9.

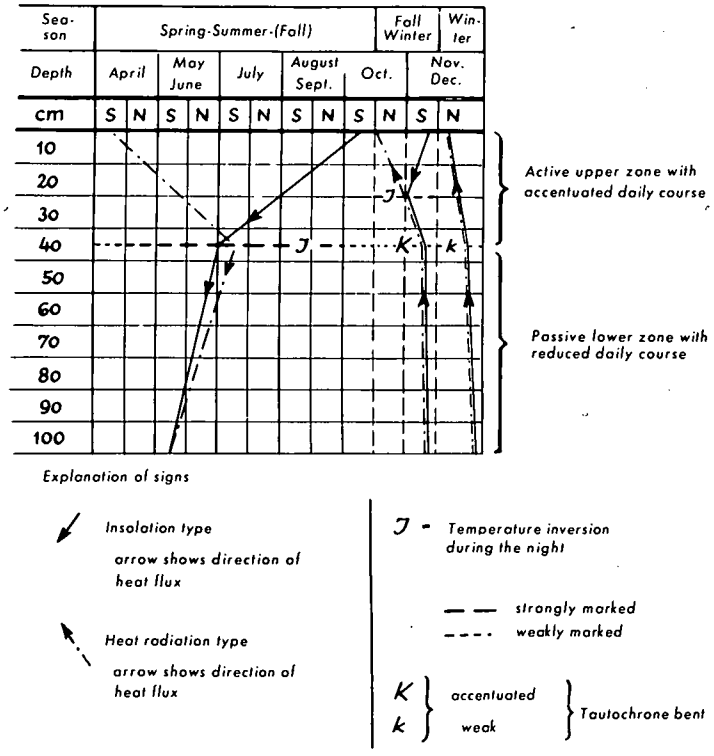


Figure 9. Comparison of the thermal profiles during the growing season of 1967.

DISCUSSION

While this research project is still in an early stage, the first results obtained are definitely significant with respect to the purpose of this study. They are in agreement with results obtained by others, especially those by Vujevic (19) and Winterkorn (22, 23).

It is brought out that the thickness of the thermally active upper zone—which from a pedologic point of view could be called the range of daily circulation of the soil heat—coincides in order of magnitude with the location of the boundary between the upper and lower soil horizons in the "Parabraunerden" of central and western Europe. The same thickness is exhibited in many locations by thin allochthone surface layers.

The following questions arise:

1. What are the causes for the constant thickness of the zone of daily heat circulation?
2. What is the effect of this thermal zone on soil genesis?

Question 1

The data show that the constant zone of the daily heat circulation in the warm months is connected with the predominance of the insolation phase. As soon as the heat loss by radiation prevails in the daily thermal picture (winter season), the zone of daily thermal circulation moves closer to the surface. An essential role seems to be played by the time rhythm in which the insolation phase and the phase of heat-loss by radiation encounter each other. On July days a temperature maximum is observed on the soil surface between 2 and 3 p.m., while at the same time the temperature at the boundary layer is still on the negative side, showing that the effect of the nightly heat loss is only now reaching the boundary layer and that, at a depth of about 40 cm, the daily minimum coincides with the maximum on the surface (see also Winterkorn and

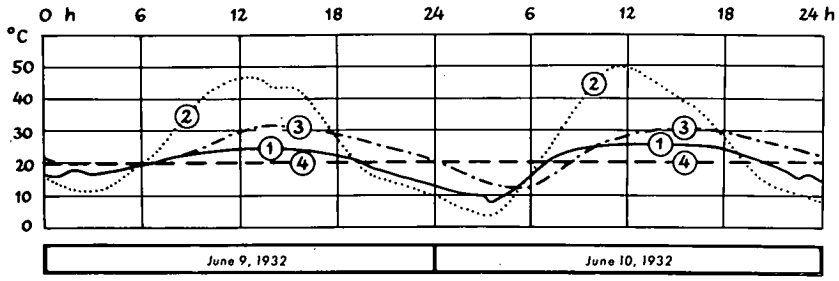


Figure 10. Daily temperature variation in air and soil, Gobi desert at Etsin Gol (after N. G. Hörner, 1933, from R. Brinkmann, Textbook of General Geology, Vol. 1, Stuttgart, 1964, p. 61): 1—temperature of air; 2—temperature of soil surface; 3—temperature of soil at 10 cm; 4—temperature of soil at 50 cm.

Eyring, 22). Since the temperature minimum on the surface occurs between 2 and 4 a.m., one could assume a twelve-hour rhythm of opposing heat impulses, which more or less compensate each other in the boundary layer. But the experimental data do not quite agree with this explanation; the influence of the soil texture, too, appears to be very small. This has already been pointed out by Chudnovskii (5), who, for soil thermal problems, differentiates only between fine, medium, and coarse granular soils (see also Winterkorn, 23). Our experimental data and those by Vujevic (19)—who very probably worked with loess-chernozem in Belgrade—show that even medium- and coarse-grained soils react in a very similar fashion. Only heavy clay soils appear to react differently, if the opposite conclusion regarding the depth of the daily heat circulation is permitted from the lesser thickness (15-20 cm) of their surface horizons. However, more experimental data are needed before a definitive statement can be made on this matter. There are two different possibilities:

1. The constant zone of thermal circulation, which in medium- and coarse-grained soils shows little dependence on environment, could follow a layer formation that is predetermined by other causes, e.g., a stratification of soil moisture. As a matter of fact, curves of average soil moisture contents show quite distinctly a boundary at about 40 cm on moist-warm summer days; this has been discussed thoroughly in a previous paper (11). But what is here cause and what is effect?

In the development of the soil profile, water is without doubt the strongest factor. But when the dimensions of the thermal circulation zone are the same in medium-grained soils with reduced permeability, and in coarse-grained soils of unhindered drainage, in arid as well as in temperate climates (Fig. 10), even in arctic thawing zones (Fig. 11), then one may justifiably doubt the primary influence of moisture stratification. With regard to this question, also, further investigations are needed.

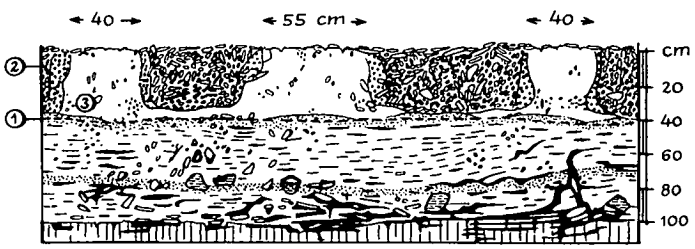


Figure 11. Kryoturbation soil on Barents Island in Spitzbergen at 402 m anove sea level (after J. Büdel, 2, p. 356): 1—surface of the permafrost soil; 2—ice pavement; 3—silt and clay cores.

Purely theoretically, other primary stratifications could be assumed which bring about stratification of the zones of thermal circulation and moisture content, e.g., a different primary electric potential in the upper and lower horizons. In this area, too, more experimental data are needed. However, it is not very probable that a primary electric potential governs soil moisture behavior since the available evidence shows a secondary dependence of the electric soil potential upon moisture content and surface area.

2. Instead of being a consequence of a preformed stratification, the constant thickness of the zone of daily heat circulation could be the combined result of thermal impulses and soil dynamic response. The general uniformity of this phenomenon is observed only on soils which, at least at the start of their development, possess a large pore space and hence a large air content. It is, therefore, easy to suspect that the soil air may play a determinant role because of its great mobility and its tendency to flow in response to even small temperature gradients. Many soils have a pore space of 30 to 60 percent, the largest part of which is occupied by air. Even though the interconnection between soil pores is often imperfect, and free interchange of soil air is often obstructed, air is still the most mobile phase in a soil. There exists, therefore, the possibility that a primary zone of daily air circulation and of consequently increased evaporation in the upper soil is responsible for the formation of the thermally active upper zone. This concept is supported by the observation that the special characteristics of the daily temperature wave on the south slope are most sharply accentuated during the driest season, i.e., at a time when the soil air dominates the behavior of the upper soil horizon.

Although a number of other questions arise at this stage, we may propose as a working hypothesis that, in porous soils, a thermally active upper zone is formed at conditions of positive heat balance and that the depth of this zone corresponds with that of the daily air circulation. An important question in this connection is whether rhythmic air pressure variations—as in the daily double air pressure wave—are playing a role in this phenomenon.

Such a primary role of the air circulation could account for the widespread constancy of the thickness of the thermally active upper zone and its lack of dependence on the magnitude of the thermal impulses received at the surface. An air circulation zone established at a positive heat balance, and of generally similar dimensions, would explain many facts in the simplest manner; the sharp bend of the tautochrones at the boundary would then correspond to the division line between the penetration of the dynamic portion of the daily wave, which is strongly accentuated by the air circulation, and the much weaker "linear" continuation of the daily wave into the subsoil, which is mainly a function of the thermal conductivity of the solid and liquid phases of the soil.

All this, however, must remain in the nature of a general discussion until more experimental data have been obtained and properly evaluated. The importance of soil thermal behavior should, however, be clearly established even though many factors and relationships are still unknown (see Winterkorn, 23).

Question 2

The second question, "How does the circulation zone affect pedogenesis?" can be answered thus:

1. In the entire thermally active zone, there is great activation of the soil biologic potential if permitted by the other environmental factors. This is shown by the distribution of heavy minerals of volcanic origin, which in relatively recent time were wind-deposited on the Roman limes in southwest Germany. Today these minerals are uniformly distributed in the approximately 40-cm thick upper soil horizon of the "Parabraunerde" that has formed on this artificial embankment since the time of the Romans (5). This means that the thermal circulation zone is also a zone of "bioturbation" in which the edaphon is so active that, with time, the entire zone becomes completely mixed up through the action of soil-burrowing animals, especially rain worms. This is also a zone of intense root development. In many raw soils, this biologically active

zone is distinguished from the underlying zone by its stronger root formation. The thermally more passive lower zone shows comparatively little life. Its boundary is often characterized by illuviation and cementation, as reported previously.

2. If the circulation zone of the estival daily heat wave also represents a zone of bioturbation in the soil, then it is easy to understand why thin allochthone surface layers often have a thickness of about 40 cm. Within the range of bioturbation, thin covering strata that possess an original thickness of perhaps 20 to 30 cm become mixed with material from the layers underneath and with newly formed organic matter. The zone of bioturbation, with its larger internal surface and finer structure, develops, with time, a distinct boundary against the underlying material. Because of the allochthone admixtures, the entire zone of bioturbation is then considered as an allochthone cover stratum. However, sedimentation and mineralogic analysis of the finer grain size materials almost always shows components from the substrate.

3. A soil genetic translocation process such as lessivation is, in undisturbed soils, restricted to the zone of thermal circulation and bioturbation. The internal surfaces of soils rich in colloidal materials undergo strong reactions within the thermally active zone of the upper soil layer. Biogenic comminution, temperature and moisture changes, and loss of bases favor decomposition of the soil colloids, while conservative tendencies prevail in the thermally passive lower layers. If this concept is correct, then elutriation of mobile soil colloids does not take place progressively from the surface down, but more or less simultaneously from the thermally active and biologically activated zone. Deposition in the thermally passive, low-porosity subsoil takes place along the narrowing seepage paths.

In southwest Germany hundreds and thousands of years are required for the formation of distinct soil profiles by these processes. A morphologic differentiation, but without translocation of clay, can be observed at a depth of about 40 cm on an embankment built of loess loam (the "Eppinger Linien") in 1695-1697, in the wine cultivation climate of North Württemberg. This can probably be considered as a structural boundary that is due to bioturbation. A "Parabraunerde," with clay translocation, was developed in the same climate on the Upper German limes, built of loess soil in the second century A.D. to denote the borders of the Roman Empire. The characteristic boundary between upper and lower soil horizon is at 40 cm depth. Obviously much time is required before the weak daily temperature wave, acting through many different processes, can produce visible proof of its role in soil genesis.

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