[AMERICAN JOURNAL OF SCIENCE, VOL. 263, MAY 1965, P. 416-428]

THERMOLUMINESCENCE AS A FUNCTION OF CLIMATE AND TEMPERATURE

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ABSTRACT. The theory of thermoluminescence as a function of temperature was tested by measuring the natural thermoluminescence of samples of limestone collected from several climatic areas. The agreement between the theory and the experimental results is satisfactory. It is concluded that in non-polar regions of the world, with average erosion rates and average geothermal gradient, the number of electrons responsible for the 230°C glow-curve peak for calcite is in equilibrium with the average temperature of the hottest month. In polar areas the equilibrium is not reached, as frigid conditions have not existed in the area for the necessary length of time.

Samples from Victoria Land, Antarctica, indicate that a climate which did not exceed 0°C in its warmest month existed in the area for more than one million years. It should be noted, however, that certain samples collected very near present sealevel at Marble Point show a much shorter duration for frigid conditions. In these cases it is probable that the collecting sites were inundated during the interglacial periods and the contact with the relatively warmer sea water produced the observed effect.

INTRODUCTION

The amount of thermoluminescence produced by a crystal is proportional to the number of electrons trapped in the crystal lattice. The natural glow-curve of calcite consists of two well-defined peaks, one at about 230°C and the other at about 315°C. Artificial irradiation produces another peak at about 110°C which decays when the sample is kept at room tempearture. The 230°C glow-curve peak is caused by electrons escaping from traps having an activation near that of climatic temperatures on the surface of the earth. Previous work (Ronca, 1964; Zeller and Ronca, 1963a) has resulted in the determination of a set of equations that approximate the behavior of the trapped electrons in the energy distribution of the 230°C glow-curve peak. The agreement between the equations and the experimental data, presented below, shows that the equations are at least a good approximation of the phenomenon.

The number of electrons in the traps, measured in terms of the area of the glow-curve peak, is given by:

$$A(t) = me^{[\eta e^{(-\gamma t)}]}\, t - \int_0^t I_0 e^{[\mu(e^{-\lambda t} - 1)]}\, dt \qquad (1)$$

where m, η, and γ are constants depending on the growth of thermoluminescence that occur at 0°K, μ and λ are constants depending on the escape rate of the electrons from the traps due to temperature, and t is time.

The constant μ is characteristic of the crystal lattice, while the constant λ varies with the temperature according to:

$$\lambda = \lambda_0 e^{-r\left(\frac{1}{T} - \frac{1}{T_0}\right)} \qquad (2)$$

where r is a constant (m was used for this constant in Ronca [1964]; here it is changed to r to avoid ambiguity with m of equation [1]).

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The quantity I_0 is a function of the temperature and of the number of trapped electrons, according to:

$$I_0 = \frac{A_{t=0} + b}{a_0 \, e^{p\left(\frac{1}{T} - \frac{1}{T_0}\right)}} \tag{3}$$

where a_0, b, and p are constants, T is the temperature which is applied to the sample having $A_{t=0}$ trapped electrons, measured in terms of the area of the glow-curve peak.

By imagining the thermal decay as a step-like function of intervals, as explained in the previous article, $A_{t=0}$ becomes A_t, the value of A at any time t. The integration of equation (1) cannot be solved in analytical form; however several properties can be deduced. It is possible to show that, if the temperature is kept constant, an equilibrium position A_{eq} will be asymptotically approached, where the number of electrons entering the traps will equal the number of electrons escaping from the traps.

The equilibrium position is given by:

$$A_{eq} = a_0 \, e^{p\left(\frac{1}{T} - \frac{1}{T_0}\right)} \, m \, e^{\mu} - b \tag{4}$$

Equation (5) shows an approximation for equation (1). This equation is valid for values of A that are not near the equilibrium position at that temperature and for large values of t. The time necessary for the growth from A_1 to A_2 at a temperature T, provided both A_1 and A_2 are far from A_{eq} at that temperature and provided that time is large, is approximated by:

$$\Delta t = \frac{A_2 - A_1}{m - \frac{A_2 + b}{a_0 \, e^{p\left(\frac{1}{T} - \frac{1}{T_0}\right)} \, e^{\mu}}} \tag{5}$$

Special care must be taken in measuring the area of the 230°C glow-curve peak, particularly in samples having a large 315°C glow-curve peak. Figure 1 shows one of these cases. The solid line shows the glow-curve, while the dashed lines show the real form of the peaks. To obtain the true area of the 230°C peak, it is necessary to drain the 230°C peak by interrupting the glow-curve at 230°C and letting the sample cool. When the temperature is increased again the shape of the 315°C glow-curve peak will be obtained. By subtracting the 315°C glow-curve peak from a regular glow-curve, the real shape and size of the 230°C glow-curve peak is determined.

Samples were collected from several parts of the world in order to check the validity of the equations. The hypothesis is made that in areas where the present climate has been essentially unchanged for a sufficiently long time, equilibrium should be established. Minor variations in the number of trapped electrons from winter to summer are thought to be unmeasurable. Because of the property of trapped electrons that allows them to be untrapped quickly as a result of increasing temperature, it is to be expected that the equilibrium position for samples of a region should be a function of the maximum tempera-

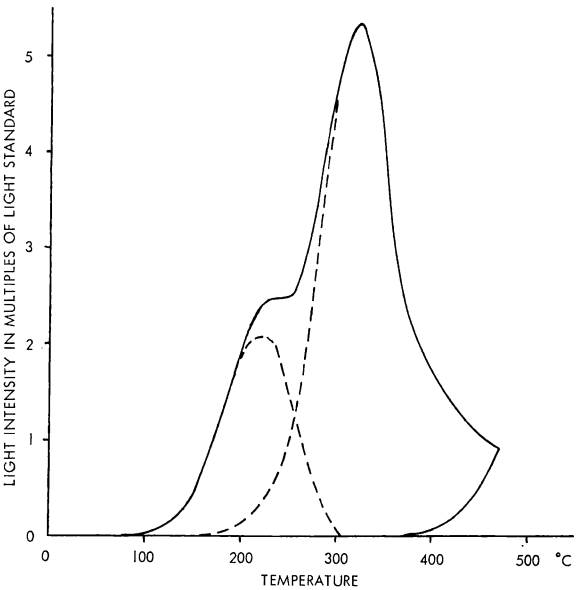

Fig. 1. A typical glow-curve showing the difference between the apparent and the real height of the 230°C-peak. The solid line represents the glow-curve, the dashed line the true form of the peaks.

ture of the region rather than the yearly average. It can be shown that the equilibrium is not reached in polar areas because frigid conditions have not existed for the necessary length of time. It is this fact that permits the calculation of the length of time that has elapsed since the climatic change occurred.

EXPERIMENTAL RESULTS

A direct comparison between glow-curves of different limestones may result in serious errors. Differences in lithologies cause differences in transparency and trap density which mask the effect of different thermal environments. Only when the same limestone bed is in two different thermal environments is there the possibility of comparing glow-curves directly.

One such case is to be found at Spring cave in South-Central Kansas, 6 miles south of the town of El Dorado. The Fort Riley limestone (Wolfcampian) is present in a gully at the mouth of the cave and can be followed into the cave. A perennial stream keeps summer temperatures inside the cave lower than those outside. Barr (1961, p. 25) says that the temperature in a cave with fairly restricted air circulation is equivalent to the average annual surface temperature. Figure 2 shows the amount of thermoluminescence of the 230°C glow-curve peak versus the location relative to the entrance of the cave. As a result of the higher summer temperatures outside the cave, the 230°C glow-curve peak from samples inside the cave is larger than the peak from samples outside the cave.

Another case in which the same lithology is found in different climatic environments is the Leadfield mine in the Funeral Mountains, near Death

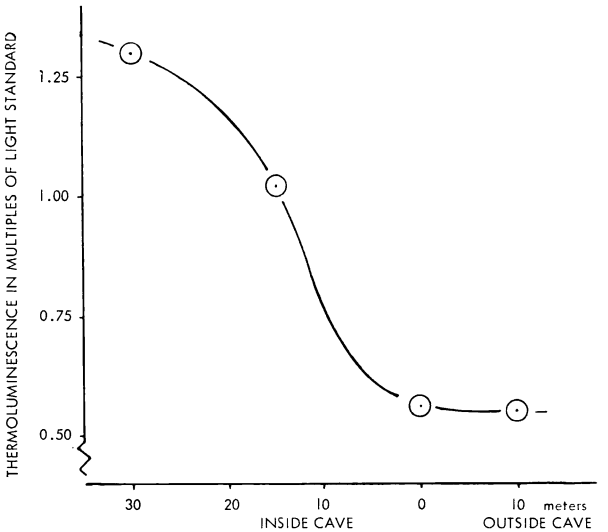

Fig. 2. The height of the 230°C glow-curve peak in light standard units versus location relative to the entrance of the cave.

Valley. Samples were collected inside the mine *in situ* and from the dump outside the mine as fragments from the same bed. The dump is known to be 37 years old, thus the outside sample has been exposed to the hot desert climate of the area for that period of time. The 230°C glow-curve peak of the sample from inside the tunnel measures 2.93 units, while the sample from the dump has been reduced to 1.60 units.

Limestone samples were collected from one bed at Rosenlaui glacier, Switzerland. Those samples collected under the glacier measure 12.2 units, while samples at about 30 meters from the front of the retreating glacier show 11.0 units. Table 1 summarizes the data.

In order to compare glow curves from different limestones, the best practice is to determine the constants of the equations. However, because of the time required to determine the constants directly, a faster method was devised. The samples were first drained of the 230°C glow-curve peak by gently heating

TABLE 1

Locality	Natural	Plateau	Percent Nat. to plateau
Canyon outside Spring cave, Butler County, Kans.	0.55	4.0	13.7
Entrance of Spring cave, Butler County, Kans.	0.56		
15 m inside Spring cave, Butler County, Kans.	1.02		
30 m inside Spring cave, Butler County, Kans.	1.30	4.3	30.2
Leadfield mine, Funeral Mtns., Inyo County, Calif.	2.93	52.	5.6
Dump of Leadfield mine, Inyo County, Calif.	1.60	40.	4.0
Rosenlaui, Switzerland, under the glacier	12.2	39.	31.3
Rosenlaui, Switzerland, 15 m from glacier	11.0	39.	28.2

them to 200°C. They were then kept at this temperature for about two hours, before permitting them to cool very slowly to room temperature. This heating is insufficient to drain completely the 315°C glow-curve peak, but it is sufficient to drain the 230°C peak without destroying a significant number of traps. The drained sample was subjected to artificial irradiation by exposure to cobalt 60, and a calibration curve was obtained. Some examples of calibration curves are shown in figure 3. The calibration curve has a definite plateau, representing the saturation value of the sample. When the artificial irradiation causes the production of new traps to a measurable extent (Levy, 1964), the plateau shows a slope. In these cases a value for the plateau is determined by extrapolating the slope of the plateau to the Y-axis of the graph.

By measuring the natural 230°C peak as a percentage of the plateau of the corresponding calibration curve, the effects of ranges in transparency and trap densities are compensated. In this way the glow curves of different limestones can be compared meanfully. However, when this procedure is used for studies of the thermal environment of a sample, an important provision must be made. A percentage of the plateau can be used only if the distribution of the trap energy is the same for all samples. For example, if two samples are in equilibrium with the same temperature and if both have the same trap-energy distribution, their natural thermoluminescence should be X percent of their respective plateaus. However, if sample A has its trap-energy distribution moved toward higher energy than sample B, sample A would be able to retain more electrons in the traps, and the natural thermoluminescence would become (X + C) percent of the plateau. However, for limestones of average purity this seems to be only a minor factor as shown by the remarkable similarity between

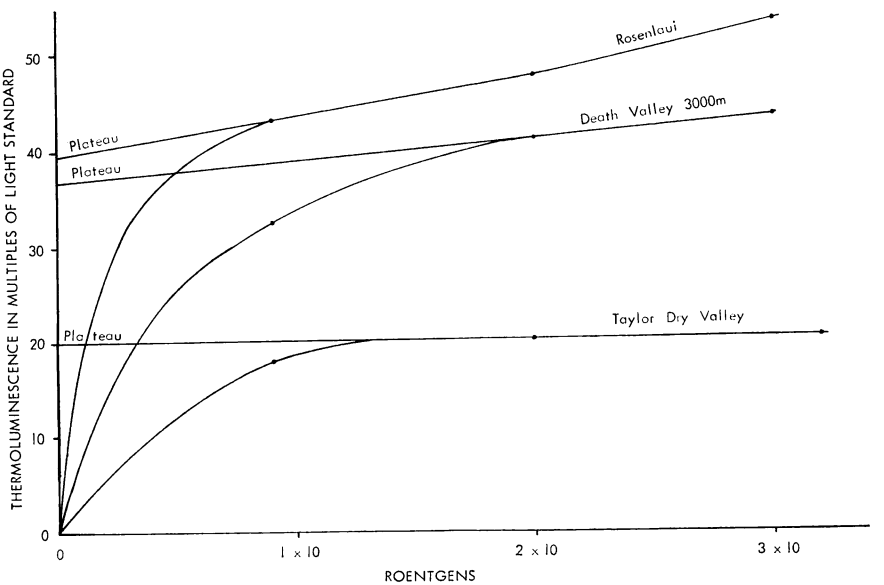

Fig. 3. Examples of calibration curves showing the position of the plateau.

the position of the peaks of the glow curves of all limestones. Limestones that have been subjected to intense tectonic deformation show a peak at about 280°C (d'Albissin, Fornaca-Rinaldi, and Tongiorgi, 1962). It is possible that the trap-energy distribution of the 230°C glow-curve peak of these samples is affected by the appearance of the new peak, thus making any conclusion on the thermal environment of such limestone unreliable.

Another possible source of error may be introduced by great variations in the radioactive impurities of different limestones. Radioactive impurities are responsible for filling the traps, while temperature is responsible for emptying them. The number of electrons that are expelled from the traps per unit time is proportional to the temperature and also to the number of electrons in the traps. A higher radioactive-impurity content has the effect of producing a higher electron concentration, which results in a larger decay rate. In other words, a higher radioactive-impurity content causes a higher rate of build-up and a faster rate of decay. Thus differences in the natural radioactive-impurity content are minimized, and the equilibrium position expressed as a percentage of the plateau is mainly a function of the temperature alone.

Table 2 gives the list of all the samples studied with the values of the natural 230°C glow-curve peak, the plateau of the calibration curve, and the percentage of the natural peak to the plateau. The annual average temperature and the average temperature of the hottest month are also given. Except where otherwise stated, samples were collected at about 20 centimeters below the surface. The relationship between temperatures of the area of collection and the percentages of the natural peak to the plateau is quite good.

The samples from the Sahara and the Simplon Tunnel were essentially devoid of the 230°C glow-curve peak. Samples from the Death Valley area ranged from 0.07 percent for the samples below sealevel to 3.4 percent for samples collected at Rogers Peak at 3000 meter elevation. Samples from Puerto Rico ranged from 3.9 percent to 5.1 percent. One sample from Malaya gave 8.3 percent. Samples collected in northeastern Kansas ranged from 9.1 to 10.0 percent. Samples from Northern Italy, one collected on the Carsic Plateau and the other on the Southern Alps, gave 13.4 and 15.8 percent respectively.

Samples collected in frigid areas have shown a much larger peak value than samples from warmer regions. Limestone from Rosenlaui glacier gave a value of 28.2 to 31.3 percent. Samples from Ward Hunt Island in the Canadian Arctic ranged from 30.0 to 60.9 percent, and samples from Thule, Greenland, ranged from 40.5 to 61.2 percent. Limestones from Antarctica ranged from 21.3 percent for samples collected at sealevel to 72.0 percent from samples collected on Mt. Nussbaum in Taylor Dry Valley. A sample from Tunnel Mountain near Banff, Canada, had a value of 34.6 percent.

THEORETICAL CONSIDERATIONS

Before the data of table 2 are compared with the equations of thermoluminescence, the meaning of the normalization process used must be discussed. An easy way to normalize glow-curve peaks from different materials is to use the plateau of the calibration curve as the unit of measure; however, certain difficulties are presented. The plateau of the calibration curve represents the

TABLE 2

Locality	Natural	Plateau	Percent Nat. to plateau	Yearly Avg Temp	Avg Temp hottest month
Simplon Tunnel	<0.01	50	<0.02	>50°	>50°
Sahara #1	<0.005	6	<0.08	>30°	>35°
Sahara #2	<0.005	10	<0.05	>30°	>35°
Death Valley, Calif., elev –76 m	0.04	53	0.07	32°	45°
Death Valley, Calif., elev –76 m	0.34	50	0.68	32°	45°
Death Valley, Calif., elev 3000 m	1.07	37	2.9		
Death Valley, Calif., elev 3000 m	2.95	87	3.4		
Puerto Rico #1	0.29	7.5	3.9	24°	27°
Puerto Rico #2	0.27	5.3	5.1	22°	27°
Malaya	0.25	3.0	8.3	27°	27°
Kansas, Douglas County #1	0.19	1.9	10.0	13°	27°
Kansas, Douglas County #2	0.20	2.2	9.1	13°	27°
Opcina, Northern Italy	0.13	0.97	13.4	14° ±	24° ±
Predazzo, Northern Italy	12.0	76	15.8	14° ±	24° ±
Rosenlaui, Switzerland, under glacier	12.2	39	31.3	<0°	<0°
Rosenlaui, Switzerland, in front of ice	11.0	39	28.2	>0°	>0°
Marble Point, Antarctica, elev 2± m	8.1	38	21.3	–17°	–3°
Marble Point, Antarctica, elev 10± m	41.4	82	50.5	–17°	–3°
Ward Hunt #1, Arctic Canada	0.70	1.15	60.9	<0°	0° ±
Ward Hunt #2, Arctic Canada	0.30	1.0	30.0	<0°	0° ±
Thule #1, Greenland	0.85	2.1	40.5	<0°	<0°
Thule #2, Greenland	4.53	7.4	61.2	<0°	<0°
Windy Gully, Antarctica	13.4	23	58.3	<0°	<0°
Taylor Dry Valley #1, Antarctica	14.4	20	72.0	<0°	<0°
Taylor Dry Valley #2, Antarctica	12.7	20	63.5	<0°	<0°
Tunnel Mountain, Banff, Canada	2.94	8 5	34.6	5° ±	15° ±

saturation point of the sample, that is, it is a function of the total number of traps actually present in the crystal lattice that are available for the production of the 230°C glow-curve peak. The number of traps present in the crystal lattice grows, probably asymptotically, through time because radiation damage is produced by the natural radioactive content. The unit of measure thus is not constant but could grow slowly with time in certain cases.

The equations of thermoluminescence indicate that an equilibrium position is asymptotically approached if the temperature is held constant. As long as this temperature remains constant, the equilibrium position will remain unchanged. However, by using the total number of traps as the unit of measure, we are in the unfortunate position of measuring a constant value with a lengthening yardstick. The seeming result is a decrease in the value for the equilibrium position. In summary, the limitations introduced by the normalization are:

1. Random errors because of differences in the trap-energy distribution. As previously discussed, this seems to be a minor effect.

2. The equations do not limit the amount of thermoluminescence a sample can show. However, the normalization process limits the amount of natural thermoluminescene to 100 percent of the plateau. This means that a sample could be at 100 percent of the plateau and still be out of equilibrium. In that case thermoluminescene would be growing as fast as new traps produced by radiation became available.

The numerical values for the constants must be calculated to give the value of the peak not in absolute units but in terms of the percentage of the saturation value.

The values for the Marble Point samples (Ronca, 1964) were:

$$\begin{aligned} \text{plateau value} &= 13 \times 10^{-6} \\ a_0 &= 755. \times 10^{-8} \\ m &= 4.80 \times 10^{-12} \\ b &= 52.8 \times 10^{-8} \\ e^{\mu} &= 92.7 \end{aligned}$$

Defining the normalized equilibrium position as A'_{eq}, it will be:

$$A'_{eq} = KA_{eq} \tag{6}$$

and using the value at the plateau:

$$\begin{aligned} 100 &= K \times 13 \times 10^{-6} \\ K &= 7.69 \times 10^{6} \end{aligned}$$

thus

$$A'_{eq} = K\left[a_0 e^{p\left(\frac{1}{T} - \frac{1}{T_0}\right)} m e^{\mu} - b\right]$$

$$K a_0 m e^{\mu} = a'_0 m' e^{\mu'} = 258.8 \times 10^{-10}$$

$$Kb = b' = 4.06$$

$$A'_{eq} = 258.8 \times 10^{-10} \times e^{p\left(\frac{1}{T} - \frac{1}{T_0}\right)} - 4.06 \tag{7}$$

Equation (7) gives the theoretical equilibrium position of the 230°C glow-curve peak as a percentage of the plateau. The equation is valid only for values between 0 and 100 percent, as explained before.

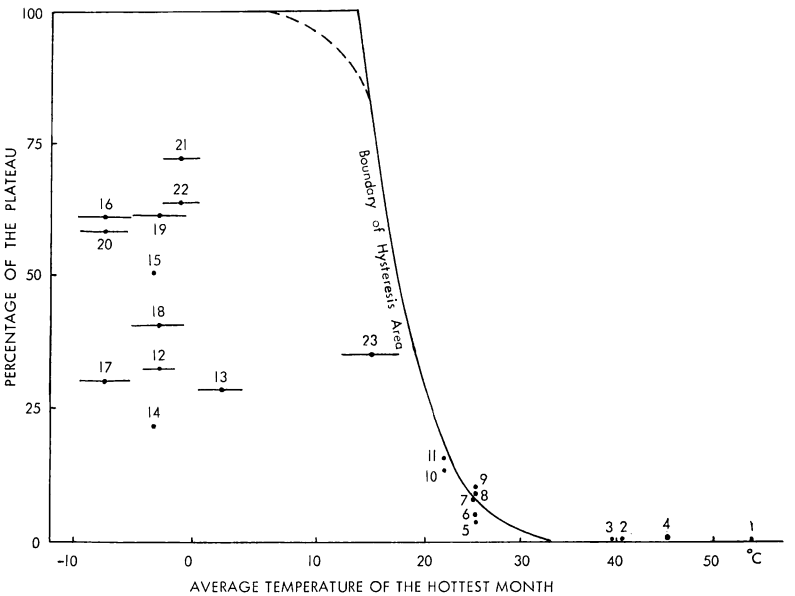

Fig. 4. Normalized natural amount of the 230°C glow-curve peak versus average temperature of the hottest month of the region of collection. The line represents the theoretical equilibrium position, the points represent the experimental values. Temperatures for the cold samples are approximate since reliable climatic data are not available. 1. Simplon Tunnel; 2. Sahara #1; 3. Sahara #2; 4. Death Valley; 5. Puerto Rico #2; 7. Malaya; 8. Kansas, Douglas County #1; 9. Kansas, Douglas County #2; 10. Opcina, Northern Italy; 11. Predazzo, Northern Italy; 12. Rosenlaui, under glacier; 13. Rosenlaui, in front of ice; 14. Marble Point, elev 2 m; 15. Marble Point, elev 10 m; 16. Ward Hunt #1; 17. Ward Hunt #2; 18. Thule #1; 19. Thule #2; 20. Windy Gully; 21. Taylor Dry Valley #1; 22. Taylor Dry Valley #2; 23. Banff, Canada.

Figure 4 shows the curve determined from the equation, arbitrarily rounded at 100 percent. The curve represents the value of the 230°C glow-curve peak that is produced by a sample kept at the corresponding temperature for an infinite length of time. The points represent the experimental values, plotted on the corresponding average temperature of the hottest month of the region of collection. Although this criterion for the choice of the temperature is not completely satisfactory, it yields good agreement between the theoretical curve and the experimental points except for the polar material.

Samples collected in the Arctic and the Antarctic have a percentage lower than the theoretical value. At present polar temperatures the equilibrium position would be 100 percent; however, to reach 100 percent saturation would require approximately 2.6 million years as shown by equation (8) given below. This indicates that the samples are not in equilibrium with the present polar climate and therefore are currently growing. It also establishes a time of 2.6 million years as a maximum limit for the length of the glaciations in Antarctica. Samples collected in temperate areas can be in equilibrium with the summer temperature, but those from polar areas cannot as the present frigid conditions have not been in existence for a sufficiently long time.

It is interesting that the curve of figure 4 looks like the right half of a hysteresis loop. Actually the relationship between the 230°C glow-curve peak and temperature is essentially a hysteresis phenomenon, that is, the amount of thermoluminescence depends on the history of the specimen.

It must be emphasized that thermal effects are not limited to climate. Geothermal heat, heat generated by tectonic activity, and hydrothermal sources may have a greater influence on the thermoluminescence of the sample than the climate of the area of collection. The nature of the research will necessarily dictate the type of sample that must be collected, and the area of collection must be carefully selected with respect to geology and geomorphology. If the primary objective is measurement of climatic effects, care must be taken to avoid samples that may have been recently uncovered from depth by rapid erosion. High rates of erosion can expose deeply buried material at the surface in lengths of time that are substantially shorter than the period required for the samples to reach their climatic equilibrium. Also care must be exercised to avoid the possibility of the sample being in a microclimatic environment substantially different from the regional climate. Under certain circumstances it might be possible to determine rates of erosion if the difference between the subsurface temperature and the climatic temperatures can be determined.

APPLICATIONS TO FRIGID CLIMATE

Previous work (Ronca, 1964) resulted in the estimation of a minimum time of 210,000 years for the duration of the glacial conditions at Marble Point, Victoria Land, Antarctica. This figure was obtained by assuming that the 230°C glow-curve peak was in equilibrium with a cold-temperate climate before the glacial conditions set in. The preglacial value was assumed to be the equilibrium position corresponding to 20°C, and it resulted in a value of 47 percent. The experimental values presented in table 2 show that this is probably much too high for a non-glaciated region. We are dealing with a hysteresis phenomenon, and positions on the boundary are improbable. A value of 20 percent is probably a maximum value for preglacial conditions. The use of a maximum value results in a minimum length of time for the glaciation. It has been pointed out (Ronca, 1964) that only minimum values can be determined in any case because of the effects of erosion. To solve for time we can apply equation (5), using the normalized values for the constants.

The constant m represents the asymptote of the slope of the growth of the 230°C peak at 0 K. For the Marble Point sample it was $m = 4.80 \times 10^{-12}$. We can calculate m′, the normalized value for m, in the following way.

$$m = \lim_{t \to \infty} \left(\frac{\Delta A}{\Delta t} \right)_{0°K} = 4.80 \times 10^{-12}$$

Arbitrarily let us choose $\Delta A = 13 \times 10^{-6}$. The corresponding Δt will be 2.71×10^{6} years. Using the normalizing factor K of equation (6)

$$\Delta A' = K\Delta A = 100$$

$$m' = \frac{100}{2.71 \times 10^{6}} = 36.90 \times 10^{-6}$$

From equation (7) it is possible to calculate the normalized values for the product $a_0 e^{\mu}$.

It was $$a'_0 m' e^{\mu'} = 258.8 \times 10^{-10}$$

Thus $$a'_0 e^{\mu'} = \frac{258.80 \times 10^{-10}}{36.90 \times 10^{-6}} = 7.01 \times 10^{-4}$$

and

$$\Delta t = \frac{A'_{now} - A'_0}{36.90 \times 10^{-6} - \frac{A'_{now} + 4.06}{7.01 \times 10^{-4} e^{p\left(\frac{1}{T} - \frac{1}{T_0}\right)}}} \qquad (8)$$

where A'_{now} is the present A normalized, A'_0 is the assumed normalized A at the time of the climatic change.

$$e^{p\left(\frac{1}{T} - \frac{1}{T_0}\right)} = 12.2 \times 10^{10}$$

At 0°C. which means that for temperatures of 0°C and below drainage is insignificant, the simple equation can be used:

$$\Delta t = \frac{A'_{now} - A'_0}{36.90 \times 10^{-6}} \text{years} \qquad (9)$$

Applying the equation to the Antarctic samples of table 1, the following values were obtained:

Marble Point, sealevel, Δt = 35,000 years
Marble Point, 10 meters above sealevel, Δt = 830.000 years
Taylor Dry Valley #1, Δt = 1,400,000 years
Taylor Dry Valley #2, Δt = 1,180,000 years
Windy Gully, Δt = 1,040,000 years

The samples from the Arctic gave:

Ward Hunt #1, Δt = 1,110,000 years
Ward Hunt #2, Δt = 270.000 years
Thule #1, Δt = 560,000 years
Thule #2, Δt = 1,120,000 years

The sample from Tunnel Mountain, Banff area, Canada gave Δt = 400,000 years. The differences between the values can be explained in the following way. The presence of marine terraces at Marble Point means that the area was under the thermostatic action of the ocean during the interglacial stages of the Northern Hemisphere. This explains the low values for those samples from localities near the sea.

Windy Gully is an area of active erosion. The surface was brought near the sample only after glaciations and exposed to low temperature. Mount Nussbaum in Taylor Dry Valley gives the oldest values. It is probably an area where erosion is less active than in other sample localities. It seems likely that some warming occurred at and near sealevel, probably because of drowning by relatively warm ocean water raised during the interglacial stages. At higher altitude the temperature remained cold even when other parts of the world were undergoing interglacial stages. Our current research indicates that for areas above sealevel a conservative estimate for a minimum length of time for

the frigid conditions is about one million years. Ericson, Ewing, and Wollin (1963) describe ice-rafted material found in an oceanic core that indicates that Antarctica had become glaciated some 250,000 years before the climate changes influenced oceanic waters. Their calculations would place the beginning of the glaciation in Antarctica as more than one million years ago. This value is in good agreement with the results obtained from thermoluminescence. Recent field work in Southern Victoria Land (Calkin, 1964, p. 14) failed to distinguish any true interglaciations such as have occured in the Northern Hemisphere.

Two of the four samples from the Arctic gave ages higher than one million years, thus indicating that the areas were not subjected to a warm climate since the beginning of the Pleistocene. The other two samples show warming more recently. Ward Hunt #1 was at an elevation of about 100 meters. It is possible that Ward Hunt #2 was heated by a higher level of the ocean. In the case of the samples from Thule, the sample that gave the lowest value (#1) was collected at a higher elevation than the other sample (#2). However, the area of collection of Thule #2 is in a valley that is filled by a glacier farther upstream. It is possible that Thule #2 was under the glacier until very recently. The sample collected at a higher elevation was probably exposed to the surface much earlier than the sample collected in the glacier-filled valley. Therefore, the higher-elevation sample has undergone more decay than the other and results thus in a shorter length of time.

In the case of the sample from Tunnel Mountain, Banff area, Canada, it is possible that the area has received little heating since the retreat of the Pleistocene glaciers, thus preserving an amount of thermoluminescence typical of that in polar samples.

In conclusion, no definite time for the length of the glaciations in Antarctica can be given at this stage, except to say that the region became cold more than one million years ago and that warming during interglacial stages was not to the point of changing the climate to temperate. During times of retreat of glaciers the region was probably similar to the present ice-free areas of Victoria Land, that is, unglaciated, but definitely not temperate. The results indicate that a thermoluminescence study of a systematic collection of samples may yield a thermal history of the area sampled.

ACKNOWLEDGMENTS

The authors are indebted to M. D. Turner for his initial comments. Economic assistance from the United States Atomic Energy Commission, contract number AT(11-1)-1057, and the National Science Foundation of the United States, contract number G 13503, is gratefully acknowledged.

REFERENCES

d'Albissin, Micheline, Fornaca-Rinaldi, Giuseppina, and Tongiorgi, Ezio, 1962, Modifications apportées aux courbes de thermoluminescence des roches calcaires par une pression orogénique: Acad. Sci. [Paris] Comptes rendus, v. 254, pt. 2, p. 2804-2806.

Barr, T. C., Jr., 1961, Caves of Tennessee: Tenn. Div. Geology Bull. 64, 25 p.

Calkin, P. E., 1964, Geomorphology and glacial geology of the Victoria Valley System, Southern Victoria Land, Antarctica: Ohio State Univ., Inst. Polar Studies, Rept. 10, 66 p.

Ericson, D. B., Ewing, Maurice, and Wollin, G. W., 1963, Pliocene-Pleistocene boundary in deep-sea sediments: Science, v. 139, p. 727-737.

Grossweiner, L. I., 1953, A note on analysis of first order glow-curves: Jour. Appl. Physics, v. 24, p. 1306-1507.

Johnson, N. M., 1963, Thermoluminescene in contact metamorphosed limestone: Jour. Geology, v. 71, p. 596-616.

Kikuchi, Takeo, 1958, The thermoluminescene of glasses: Phys. Soc. Japan Jour., v. 13, p. 526-531.

Levy, P. W., 1964, Use of color centers for the detection and measurement of defects: Am. Soc. for Testing and Materials, Spec. Tech. Pub. 359, p. 3-19.

Randall, J. T., and Wilkins, M. H. F., 1945, Phosphorescence and electron traps: Royal Soc. London Proc., v. 184, p. 365-407.

Ronca, L. B., 1964, Minimum length of frigid conditions in Antarctica as determined by thermoluminescence: Am. Jour. Sci., v. 262, p. 767-781.

Zeller, E. J., and Ronca, L. B., 1963a, Reversible and irreversible thermal effects on the thermoluminescence of limestone, *in* Geiss, J., and Goldberg, E. D., compilers, Earth Science and Meteoritics: Amsterdam, North Holland Pub. Co., p. 281-294.

———— 1963b, New developments in the thermoluminescence method of age determination, *in* Radioactive Dating: Internat. Atomic Agency Symposium, Athens 1963, Proc., p. 73-85.

Zeller, E. J., Wray, J. L., and Daniels, Farrington, 1957, Factors in age determination of carbonate sediments by thermoluminescence: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 121-129.