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THE CORRELATION OF THE MADISON LIMESTONE

BY THE THERMOLUMINESCENCE METHOD

A Final Report

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INTRODUCTION:

Thermoluminescence is simply the omission of light by crystals when the crystals are heated. A crystal does not give off its light at a constant rate; neither will it give off light indefinitely. Rather, as the temperature of the crystal rises, the light may be observed to wax and wane several times before it finally disappears entirely or is masked by the light of incandescence. The various maxima of light emission are termed peaks, and the pattern formed by the peaks and the saddles between them constitutes the glow curve.

Although the phenomenon of thermoluminescence has been known for many years, only recently have attempts been made to put it to work as a tool in the correlation of rock strata. Saunders' preliminary work (1953) indicates that both glow curve shape and amount of thermoluminescence might be useful in the correlation of limestones. Parks (1953), working with limestone samples from well cuttings and cores of Chesteran age, also indicates that the method has promise, as did Bergstrom (1953) in his work on the Pennsylvanian. All these earlier efforts bore results which were positive enough to encourage further work on delimiting the usefulness of thermoluminescence.

The purpose of this paper, then, is to test further the thermoluminescence method of limestone correlation, and also to shed some light on the problem of the relative ages of the various sections of the Madison limestone and its equivalents which were studied. In order to test the thermoluminescence method it might be considered desirable to choose a limestone sequence wherein the age relationships are more perfectly known than in the Madison. However, it was believed that the internal consistency of the data, or the lack of it, would serve as a good check on any correlations made. Furthermore, it seemed desirable to determine whether or not thermoluminescence could solve correlation problems which have not yielded completely to other methods.

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The writer is also indebted to Dr. D. F. Saunders, Dr. J. M. Parks, and Dr. R. E. Bergstrom. Without their previous work on thermoluminescence correlations the present study would have been much more difficult.

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PREVIOUS WORK ON THERMOLUMINESCENCE CORRELATIONS:

The first published account of correlation by the thermoluminescence method is by Saunders (1953). He made the preliminary investigations of correlation by both curve shape and amplitude of a given peak. A 25-foot outcrop samples were used for correlation and sections in the Silurian, Mississippian, and Pennsylvanian were studied. In the thick sections of the Silurian and Mississippian glow curve shape was found to be best for correlation. The thinner limestones of the Pennsylvanian showed less consistency in glow curve shape but seemed to be distinguishable on the basis of glow-curve intensity.

Parks (1953) made a study of the correlation of the Chester Series of Illinois, Indiana, and Kentucky by the thermoluminescence method. He used both surface and subsurface samples for this work. A great deal of variation in curve shape was found within a single formation, suggesting that correlation on the basis of curve shape alone was impractical in these beds. The results which were obtained did indicate that the pattern of variation in thermoluminescence through a vertical section might be consistent laterally and therefore useful for correlation purposes.

Parks characterized his method of representing the vertical variations in thermoluminescence through a section as the "double curve of variation". This method made use of both the amplitude of the high temperature peak and the ratio between the high temperature peak and the next lowest temperature peak.

Bergstrom (1953) used a combination of glow curve shape and the double curve of variation in his work on the Pennsylvanian limestones of the mid-continent area. He concluded that the best correlations could be expected from the use of the double curve of variation in conjunction with certain distinctive marker glow curves when these exist. As was the case with Parks, Bergstrom found that some limestone units yielded much better correlations by the thermoluminescence method than did others. In general, the limestones which produced the best correlations were those which persisted for long distances without marked changes in lithology. Perhaps the most revealing aspect of Bergstrom's work was the discovery that limestones of similar placement in the Pennsylvanian cyclothems also seemed to have similar thermoluminescence characteristics. This appeared to be inferential evidence that glow curve shape is at least partially controlled by the chemistry of the seas at the time of deposition.

PROCEDURE:

The procedure followed in making thermoluminescence correlations properly begins with the sampling in the field. The frequency of sampling is something which must rest with the collector's discretion. It is determined as much by practical considerations as by any other factor. There appears to be no evidence that sampling in great detail produces conspicuously superior results, but this will be discussed in greater detail later on. The one thing which must be attended with considerable care in the field is the choice of the sample. The sample must be unweathered, and as free as possible from contamination by secondary calcite, silica, or other minerals.

The laboratory work consists of a number of steps. First the samples are crushed to a reasonably small size by the use of a hammer or with an electrically-driven jaw crusher. It may be preferable to use a hammer, because this permits the elimination of any altered fragments which were not excluded in the field. Next, the samples are put in a pulverator and ground to a powder. The powder is sieved into plus 80, 80 - 100, and 100 - 200 mesh fragments (Tyler scale). Before sieving, however, it is sometimes necessary to pass a magnet through the sample to remove fragments of iron which have been worn off the wheels of the pulverator. In the case of very hard limestones, the amount of iron in the ground-up samples occasionally is found to exceed the amount of limestone.

If the quantity of thermoluminescence, as opposed to the ratio between peaks, is to be used in correlation, it is necessary to make insoluble residue studies of all the limestone samples in order that the thermoluminescence may be corrected to 100 percent carbonate. In the present study the amount of thermoluminescence was found to be unreliable for correlation purposes.

Previous workers on thermoluminescence have introduced an additional transparency correction which has been described by Bergstrom. In the present study this procedure was not followed, because it is believed that the correction factor may introduce greater inaccuracies than those which it is intended to overcome. Furthermore, when ratios between peaks are used as the basis for correlation, as in the case in the greater part of this paper, corrections of this type are not needed.

The 100 - 200 mesh fractions of the samples were placed in gelatin capsules and irradiated in the five curie cobalt 60 gamma source for 72 hours. The time of irradiation was based on Bergstrom's time of saturation experiments. When irradiation was completed, the samples were immediately put in a freezer to prevent the draining of the low temperature peak which takes place quickly at room temperature.

The apparatus for running the glow curves has been described fully by Bergstrom. The procedure used here essentially is the same as his, but with a single exception. In the present study the samples were placed in a desiccator which was kept at dry ice temperature until the glow curves were actually run. In this way the full low temperature peaks were thought to have been preserved. Previous workers have expressed a lack of confidence in the low temperature peak and have made scant use of it in their correlation work. With this additional safeguard, however, the peak has been found to be reproducible, and hence is considered as reliable as the other peaks.

THE TETON PASS SECTION: ITS BEARING ON CORRELATION TECHNIQUES:

As a result of an interruption in the first measurement of the Teton Pass section, it was necessary to re-measure and re-sample the entire section. By comparing the sequences of peak heights and ratios in the two measured sections it was possible to determine which correlation techniques worked best. Any correlations made could be checked for accuracy, because, of course, the relationships of the two sections, each measured at the same place on the same mountain, were known. Furthermore, it became possible to determine how much variation in a glow curve sequence could be expected because of simple sampling errors. To put it differently, it became possible to determine whether or not there were systematic variations which were independent of bed by bed

variations. In a section as thick as the one at Teton Pass (660 feet) it is obviously impractical to take a sample from each bed, and unless each bed is sampled, it is impossible to be sure that in measuring the same section twice the same beds will be sampled both times. No such attempt was made, and since lateral variations in thermoluminescence may be completely ruled out in this case, any difficulties in correlating by thermoluminescence may be blamed directly on the fact that different beds were sampled in the two measurements. Difficulties of this kind will always appear wherever thermoluminescence correlations are attempted on a practical basis. Hence, the correlation of the Teton Pass sections is regarded as the best correlation to be expected under ordinary sampling conditions.

There is the possibility that if samples were collected at very small vertical intervals, say an interval of one foot, better correlations might be obtained; but collecting in this kind of detail is not only impractical from the point of view of the field geologist but also from the standpoint of the laboratory worker. The amount of work involved in preparing and running 660 samples is so great that the method would seldom be used.

The tendency among previous workers on correlation by thermoluminescence has been to emphasize the need for closely spaced vertical samples in the limestone formations being correlated. The present study indicates that this is not the case in the correlation of the Madison limestone and its equivalents. It is, of course, true that in any given section the closer the sampling interval, the more accurate will be the picture of the variations in thermoluminescence in that particular section. However, it is here suggested that the variations in thermoluminescence which are of limited persistence vertically - and these are the variations that close sampling brings out - are also of very limited lateral persistence. Knowing all the details of variation in one section is of little value if those details are not reproduced in other sections with which correlation is being attempted.

In correlating very thick limestones, it would seem that the things which should be brought out are the long-ranging, systematic variations in thermoluminescence. To do this a very close sampling interval is not needed. Indeed, when the samples are very close together, the minor variations tend to obscure the systematic variations which seem to be most useful.

A number of methods were tried in an effort to secure the best possible correlations. Most of these techniques are illustrated in this paper. The first method, and the only one which for practical reasons was not illustrated, was simply to lay out all the glow curves on a table in stratigraphic order and to compare the sequences of curve shapes in the two sections. This method is considered to have been highly successful, and the tentative correlations were substantiated by known field relations. However, to illustrate each glow curve would take up entirely too much space, and furthermore the actual examination of sequences of great numbers of glow curves may become a rather unwieldy process. It became obvious, therefore, that measurements of the various peak heights would have to be used in an attempt to put thermoluminescent glow curves on a quantitative basis which would permit their representation in graphical form.

Plate 1 shows the numbering of the peaks of a typical glow curve, peak 1, peak 2, and peak 3 being respectively the low, middle, and high temperature peaks. The plate shows the derivation of some of the ratios used later in this paper for correlation.

The first attempts at graphical representation produced the curves of the heights of the several peaks shown in Plate 2, Plate 3, and Plate 4. The solid line represents the complete section, the dashed line the partial section. Both were measured at Teton Pass. As is quite obvious from the plates, this method was not attended with any noteworthy success. Correlations might be made from the plots of peak amplitude, but in view of the wide fluctuations in all the curves, no correlation would seem to be wholly convincing. When two curves have as many peaks and saddles as these do, many possible correlations may be noted, but no unique correlation presents itself. Apparently then, the variations in intensity of thermoluminescence are not sufficiently systematic to overcome the inevitable sampling errors.

Next it was decided to graph the ratios between peaks 1 and 2 and between peaks 2 and 3. These graphs, which are illustrated in Plates 5 and 6, express in a rather crude way the shape of parts of the glow curves; thus they are considerably closer to the successful method of comparing glow curve shape. As might be expected, the results were considerably better than those based on intensity, particularly so in the case of the ratio of peak 2 to peak 3 (Plate 6). Correct correlations might be made by this method.

However, both of these ratios express only part of the glow curve; one ratio leaves out peak 1, and the other omits peak 3. In an effort to correct this situation a double-ratio was used, that is, a combination of the two previously used. The ratio is $1/2$ divided by $2/3$, which reduces to $1 \times 3/2^2$. The numbers refers to the peaks. Because a value of less than one was often obtained by this method, and because the values between zero and one were considered quite significant, the values were plotted on semi-logarithmic paper (Plate 7).

The results using the double-ratio method were considered superior to those obtained with other methods, but minor variations still tended to obscure the general trends of rise and fall of the curve. Often a single sample would deviate sharply from a trend established by a sequence of several other samples, and when graphed, these one-sample variations tended to assume a prominence out of proportion to their real significance. To remove, or at least to de-emphasize, these variations a "three point moving average" was used. The results of this technique are illustrated by Plate 8. When the three point moving average is used, the value for sample two is obtained by averaging the values of samples one, two, and three; sample three is given the value of the average of samples two, three, and four, and so on. In this way rapid changes in the ratio are not fully expressed unless the change persists through three samples. Occasionally a very significant single glow curve might be overlooked by the use of this method, but the advantage of the method, namely, the clear representation of systematic changes in glow curve shape, far outweighs the disadvantage. The correlation shown in Plate 8 is considered to be far superior to any of the others.

SHORT RANGE CORRELATIONS - CONFUSION RANGE

The Confusion Range in Millard County, west-central Utah, was chosen as the location for detailed studies of the correlation of the lower Mississippian limestones over short distances for the following reasons. First, it is an area where the stratigraphy was quite familiar to the writer. Secondly, exposures are very good indeed, it being possible in some instances to check the validity of the correlations by simply walking the outcrop between two sections. Finally, and this is the most important reason, the area seems to have been tectonically active during at least part of Mississippian time with the result

that these limestones pinch out entirely a few miles from the point where they reach their maximum thickness of 230 feet. It was hoped that thermoluminescence might show where and how the thinning has occurred.

The Confusion Range was mentioned in early reports, but the first detailed work in the area was published by Bacon (1948), who discussed the stratigraphy, paleontology, and structure of the area. He used the new name Midridge limestone for the Madison equivalent in the area and indicated that it ranged in thickness from 200 to 500 feet. Christiansen et al. (1951) included a detailed discussion of the geology of the Confusion Range. In this publication much of Spencer's (1917) terminology of the Ely, Nevada, area was employed. Here the Madison equivalent is called the Joana limestone. In the same year Ogden (1951) published a discussion of the Carboniferous stratigraphy of the area, and used Bacon's term Midridge limestone.

Zeller (1951) includes several sections measured in the Confusion Range in his Ph.D. thesis at the University of Wisconsin. He was the first to attempt to separate the Mississippian limestone into several units on the basis of fossils and to trace those units laterally in an effort to see precisely where and how the thinning of the section takes place. Zeller used endothyroid foraminifera in his breakdown of the formation. His thickest section of some 160 feet was measured about half way between Skunk and Conger Springs. He found that this section could be divided into a lower Granuliferella zone about 80 feet thick and an upper Plectogyra tumula zone of equal thickness. Zeller also measured two sections further north where considerable thinning has occurred. These sections, one on the crest of the Bishop Springs Anticline and the other at North Granite Mountain, bear only the lower Granuliferella zone. This suggests that the northward thinning is due primarily to either erosion or non-deposition of the upper portion of the limestone. There is further evidence that there was a positive area to the north in late Mississippian and/or Pennsylvanian time. Ogden states that the 1900 feet of rocks immediately overlying the Midridge limestone at Conger Spring thins to 1100 feet at Skunk Spring just a few miles to the north. Ogden refers these rocks to the lower Pennsylvanian, but others consider them to be in part upper Mississippian in age. Miller, Youngquist and Nielsen (1952) have examined a cephalopod fauna from a locality about 450 feet above the top of the Midridge in the Skunk Spring area, and they consider it to be of about the same age as rocks in other areas commonly assigned to Meramecian and Chesteran time.

In the present study four sections of the Mississippian limestone were measured and collected. A section 182 feet thick was measured at Skunk Spring about three and one-half miles south of old U. S. Highway 6, which crosses the range at Cowboy Pass. The thickest section (223 feet) is located about two miles east of Conger Spring. It is listed as stop 6 in the guidebook of the 1951 field trip of the Intermountain Association of Petroleum Geologists. Two much thinner sections were measured further north. One, at the crest of the Bishop Spring Anticline about five miles east of the Foote Ranch, measured 31 feet; the other, at North Granite Mountain, ten miles east of Partoun, was 69 feet thick.

The peak heights and ratios for the various sections have been plotted in graph form and are illustrated in Plates 9 to 15. As was the case in the sections at Teton Pass, the graphs based on amplitude of a single peak seem to show very little correlation.

In Plate 9, where peak 1 is graphed, the Conger and Skunk Springs sections are characterized by wide fluctuations in thermoluminescence. The maxima in these two sections do occur at about the same level, but a correlation based on a single pair of maxima is not very convincing, particularly when the

possible sampling error is considered. In the same plate the relation of the North Granite Mountain section to the others is not at all clear.

Approximately the same comments can be applied to Plate 10, which shows the variations in peak 2. The fact that the maxima occur at about the same level as in Plate 9 might seem to corroborate a correlation of the maxima in Plate 9. However, a rise of one peak in a glow curve is usually accompanied by a rise in other peaks as well; hence, the verification of the correlation is apparent, not real. The above remarks also apply to Plate 11 and the graph of peak 3.

The graphs of peak 1/peak 2 and peak 2/peak 3 (Plates 12 and 13) were very disappointing. They show less apparent correlation than do the graphs of pure peak height previously discussed. However, when the double-ratio is plotted (Plate 14), the true relationships begin to appear. All sections show a general higher level of the curve in the area between 50 and 130 feet on the footage scale, but as was the case in the Teton Pass sections, the systematic changes are sometimes obscured by large fluctuations between adjacent samples.

Plate 15 shows this same double-ratio with the three point moving average applied. It is felt that the relationships shown by these curves are real and that the correlations made from these data are correct.

The indicated correlations are shown in Plate 16. The zones W, X, Y, and Z are defined as follows: the lower zone W includes that part of the curve before the point where a pronounced upward trend sets in; zone X begins where W ends, continues through the crest of the curve, and ends where a pronounced downward trend begins; zone Y includes the sharply descending part of the curve; and zone Z is made up of the relatively level platform in the curve in the upper part of the section.

These correlations, although not fully corroborated by the field relations, at least do not conflict with them. Furthermore, the correlations are in general agreement with Zeller's zonation of the formation on the basis of endothyroid foraminifera.

The Skunk Spring locality is about five miles north of the Conger Spring section, and it is not surprising that corresponding zones in the two sections agree closely in thickness. The greater overall thickness of the Conger Spring section is gained almost exclusively in zone W at the bottom of the section, apparently indicating that deposition began somewhat earlier or proceeded at a somewhat faster rate in its early stages at Conger Spring. Zones X, Y, and Z are almost exactly equivalent in thickness in the two sections.

At North Granite Mountain zone W is absent from the base; zone X is of nearly the same thickness as at Skunk and Conger Springs; the upper zones, Y and Z, are almost entirely lacking. The thinning of this section, then, has occurred at both top and bottom.

A section was also measured at the crest of Bishop Springs Anticline. However, here, only 31 feet of section is present. This did not prove to be enough section to establish which part of the curve was involved; hence, the Bishop Spring section is not included in the plates.

The logical interpretation of these correlations would seem to be as follows: the sea entered the area from the south as is shown by the absence of the lower beds to the north. The missing upper beds in the North Granite Mountain section were either cut out by erosion or they were not deposited in the first

place. Evidence indicates that they were removed by erosion. The uppermost, fully-developed zone at North Granite Mountain, zone X, is approximately as thick as it is further south; one would expect any cessation of deposition in zone Y to be preceded by a slowing down of deposition in the zone below it, and such is not the case. Furthermore, the entire Mississippian limestone section wedges out less than one-half mile from the place where the section was measured.

LOCALITIES USED FOR LONG DISTANCE CORRELATION:

Willow Creek Section. The section was measured in a small canyon traversed by a road about four miles north of the town of Willow Creek, Jefferson County, Montana. It is about five miles west of Three Forks.

Peale (1893) was the first worker to assign definite stratigraphic names to the rocks present in the Three Forks area. It was Peale who first named the Madison limestone and established its type locality in the vicinity of Logan, Montana. He stated that it is overlain by the Quadrant formation (Pennsylvanian) and underlain by the Three Forks shale (Devonian). Peale's measured section of the Madison totaled 1250 feet. He divided it into three zones, a lower laminated zone of 350 feet, a middle massive zone of 325 feet, and an upper jaspery zone of 575 feet.

Weed (1899) assigned the name Paine shale to the lower laminated beds, Woodhurst limestone to the massive beds, and Castle limestone to the upper jaspery beds.

Cathcart and Collier (1922), working on the Madison of the Little Rocky Mountains, divided it into a lower thin-bedded part which they called the Lodgepole limestone and an upper massive part which was called the Mission Canyon limestone. This last terminology was applied to rocks in the Three Forks area by Sloss and Hamblin (1942) who concluded that the Lodgepole of Cathcart and Collier corresponds to the Paine and Woodhurst of Weed and that the Mission Canyon corresponds to Weed's Castle limestone. Sloss and Hamblin measured 1643 feet of strata at the Madison type section, 731 feet in the Lodgepole, and 912 feet in the Mission Canyon.

Berry (1943) described the Willow Creek section some nine miles west of Logan, Montana, as consisting of 1800 feet of strata. His section contains a lower unit of laminated and massive beds about 1200 feet thick, and an upper jaspery zone of about 600 feet in thickness. He stated that the Madison is overlain by the Amsden in this area. Sloss and Moritz (1951), however, reached the conclusion that the sandy beds immediately overlying the Madison belong to the Kibbey formation of the Big Snowy group.

Holland (1952) measured 584 feet, 6 inches, of Lodgepole limestone at the type locality of the Madison, but he gave no total thickness for the Mission Canyon.

Considerable difficulty was experienced in determining the contact between the thin-bedded Lodgepole and the massive Mission Canyon in the section at Willow Creek. This difficulty is apparently a familiar one, since the figures for the thicknesses of the Lodgepole by Sloss and Hamblin on the one hand and Holland on the other are 731 feet and 584 and 1/2 feet, respectively. Both measurements were made at the type locality. The writer's section at Willow Creek

totaled 1398 feet of strata, of which the lower 723 feet are assigned to the Lodgepole and the upper 675 feet are assigned to the Mission Canyon, the dividing line being admittedly quite arbitrary. Measurement was begun at the top of the Sappington, and ended, again quite arbitrarily, where the sandstones of the Amsden or the Kibbey begin.

Uinta Section. The section in the Uinta Mountains was measured on the cliffs along the west side of the Duchesne River about one and one-half miles north of the Stockmore Ranger Station in the western Uinta Mountains, Utah. This area has been described by a number of authors and is thought to contain the best Carboniferous exposures in the whole mountain range.

Early workers in the canyon of the Duchesne were Berkey (1904), Emmons (1907), and Weeks (1907). All these writers recognized the prominent cliff-forming limestones as Mississippian in age, but they used names different from those now in use. Berkey and Emmons used the term "Wasatch limestone", but this had to be abandoned because of the priority of the Eocene beds which carry that name. Weeks simply used the term Mississippian limestone. Forrester (1937) wrote on the structure of the area in his treatment of the range as a whole. The most detailed published work on the Carboniferous of the Duchesne River section is by Williams (1943).

In this area the Madison limestone is underlain by the Pine Valley quartzite of Cambrian age. According to Williams, the Madison itself is 1115 feet thick and is overlain by the Brazer. However, in the Uinta Mountains the Madison, which is typically a pure limestone in most areas, gives way, particularly in the upper part, to fine clastics. Because reasonably pure limestones are required for thermoluminescence determinations, only a part of the section referred to the Madison by Williams could be used. The writer's section of 568 feet of fairly pure limestone corresponds approximately to Williams' units 2 and 3 and the lower 400 feet of his unit 4. The part of the section used was not exclusively limestone, there being some intercalated clastics as well. However, at the 568 foot level the amount of clastics present became so great that further sampling seemed useless.

Leatham Hollow Section. This section was measured on the north wall of Leatham Hollow, a canyon tributary to Blacksmith Fork Canyon, in the Bear River Range, about eight miles southeast of Logan, Utah.

The first detailed work on the Mississippian of the area was by Richardson (1913). He divided the Mississippian into several units, which was the Brazer, a name currently in use.

More recently, Williams (1943), (1948) has done extensive work on all the Paleozoic rocks of the area, with especial attention being given to the Carboniferous.

Holland (1952), working in Leatham Hollow, separated the basal 76 feet of the Madison of earlier workers into a new formation, the Leatham. Holland correlates the shales and impure limestones of the Leatham formation with the Sappington of Montana.

In the present study, measurement and sampling were begun at the point where the basal shales still assigned to the Madison give way to good limestones and ended at the basal sands of the Brazer.

Teton Pass Section. The Teton Pass sections were measured on the south slopes of Glory Mountain on the north side of Teton Pass. The section is reached from Wyoming Highway 22 at the summit of the pass.

Early workers gave general descriptions of the rocks in the Teton area. St. John (1879), who did the preliminary work in the Wyoming-Idaho area noted that the lower Carboniferous was represented by limestones varying from 1000 to 2000 feet in thickness. He did no detailed work in the Teton Pass area but observed that lower Carboniferous rocks do occur there.

Blackwelder (1911) measured the 1300 foot Mississippian section in the northwestern part of Yellowstone Park and noted the presence of these strata in the Teton Range; he published no detailed sections there, however.

The first detailed work on the Carboniferous of the Teton Pass area was by Horberg (1938). He referred the Mississippian limestones of the area to the Madison and Brazer formations and assigned them a combined thickness of 850 to 1000 feet. In his work Horberg did not differentiate the Madison from the Brazer and suggested that the contact would be difficult to pick. He assigned the beds below the Madison to the Darby formation of Devonian age and those above to the Pennsylvanian Wells formation.

A section of Mississippian limestone of 663 feet was measured from the top of the Darby formation to the point where the first red siltstones of the Amsden begin. None of the large solitary corals or colonies of Lithostrotionella which are so common in the Brazer at many localities were noted in this section. This fact, plus the lack of an unconformity or appreciable change in lithology, would seem to indicate that no Brazer is present in the area.

RESULTS OF LONG DISTANCE CORRELATIONS:

In the long range correlations a single peak in the double-ratio curve is taken as a zone or unit of correlation. Although its peaks are not particularly well defined, the Willow Creek section of the Madison is used as the standard for comparison with other sections, because Willow Creek is only slightly removed from the type section. Also the Willow Creek section is the thickest section measured and probably contains the equivalents of all beds present in the thinner sections further south.

Unit A is defined as including the first peak in the curve at the Willow Creek section (Plates 17 and 18); unit B includes the second peak, which in this section is quite low; and unit C encompasses the third peak. Unit D includes the plateau-like area in the curve to the right of unit C.

The Lodgepole - Mission Canyon contact does not coincide with any of the unit boundaries as defined above. The contact was placed at the 723 foot level at Willow Creek; this is fairly close to the boundary between zones C and D. It is interesting to note that the double-ratio has a consistently low value in all the rocks assigned to the Mission Canyon. Values this low are encountered in none of the other sections, suggesting that, at least for the most part, the sections to the south are Lodgepole equivalents. This idea is in general agreement with those of other workers (Holland, 1952).

A comparison of the standard section with the one at Leatham Hollow (Plates 19 and 20) shows the three peaks with different relative amplitudes, but there is fair agreement between the thicknesses of the several units, except in the case of unit C which is incompletely developed at Leatham Hollow.

The amplitudes of all peaks in the Teton Pass section (Plates 7 and 8) are greater than in the aforementioned localities. However, the three units are discernible, and the thickness of the one completely developed unit, unit B, is in fair agreement with that of the same unit at Leatham Hollow.

Progressing to the Uinta section (Plates 21 and 22), we see a curve which in many respects is similar to the curve of the Teton Pass section, particularly in the right hand part of the graph, which represents the upper part of the section. In the Uinta section, however, unit A is much thicker, and unit B is markedly thinner than in the other sections discussed.

Farther south in the relatively thin Confusion Range sections the bulk of the beds are involved in the prominent single peak which is here interpreted as unit B. However, this interpretation is admittedly open to question. The zonation of the Confusion Range sections is shown in Plates 14 and 15.

Criticism. As might be anticipated the results of the long distance correlations, which are summarized in Plate 23, are not as clear-cut as those obtained in the short range correlations. These long distance correlations are open to two main criticisms, both of which are justified.

In the first place no correlation based upon the matching of two curves, each with several maxima and minima, can be a unique correlation. There are always several different ways in which the maxima and minima may be matched, and the selection of the correct one among the several alternatives must come from other geological evidence. For example, a very different correlation between the Leatham Hollow and Willow Creek sections might have been made were there not paleontological evidence that the Leatham Hollow section is Lodgepole in age.

The second criticism is that the thermoluminescence zones are not necessarily time zones. Glow curve shape apparently is controlled at least partly by the impurities in the limestones. Thus thermoluminescence may be considered as a kind of chemical facies correlation technique. In restricted areas these chemical facies may correspond to time lines for all practical purposes. Over long distances, however, it would be extremely surprising if this were so. Whether or not the thermoluminescence zones in the Madison limestone cross time lines to a significant extent is a question which cannot now be answered.

CONCLUSIONS:

A. The Method.

1. In the sections studied very little advantage is to be gained by very detailed sampling because:

a. The variations of limited vertical persistence which detailed sampling brings out are often severely limited laterally as well. Therefore, they are thought to be of little value for correlation.

b. In cases where these variations are persistent laterally, they may be of little aid in correlating thick limestone units, because thick sections will contain a great number of maxima and minima which are similar to each other; hence, they do not present a unique correlation.

c. In thick limestones very detailed sampling is impractical from the point of view of the field and laboratory worker.

2. The correlation of thick limestone units requires the use of a method which will bring out the systematic variations.

3. The best method found so far for showing such systematic variations is the double-ratio in conjunction with a three point moving average.

4. Because impurities and conditions of deposition have a part in determining glow curve shape, and because these factors are likely to vary greatly over long distances, not too much should be expected from thermoluminescence correlations over long distances.

5. Thermoluminescence correlations are likely to be most valuable in restricted areas where the details of the thickening and thinning of formations are in doubt.

B. The Correlations.

1. The northward thinning of the Mississippian limestones in the Confusion Range is very likely due to two factors. There is a progressive thinning of the lowermost unit, unit W, from south to north, indicating that lime deposition probably began slightly earlier in the south. In the most northerly section the two highest units, Y and Z, are almost entirely lacking. They were probably removed by erosion.

2. Tentative correlations are made involving the Conger Spring section in the Confusion Range, the Teton Pass section, the Leatham Hollow section, the Uinta section, and the Willow Creek section, but it cannot be stated with certainty that these correlations are correct.

3. The consistently low value of the double-ratio in the Mission Canyon part of the Willow Creek section, coupled with the lack of such low values in other sections measured further south, suggests that these southerly sections are largely Lodgepole in age.

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ILLUSTRATIONS

15

PLATE

- 1 Typical glow curve showing derivation of quantities used in correlation.
- 2 Variations in amplitude of peak 1, Teton Pass section
- 3 Variations in amplitude of peak 2, Teton Pass section
- 4 Variations in amplitude of peak 3, Teton Pass section
- 5 Peak 1/peak 2, Teton Pass section
- 6 Peak 2/peak 3, Teton Pass section
- 7 Double-ratio, Teton Pass section
- 8 Double-ratio, three point moving average, Teton Pass section
- 9 Variations in amplitude of peak 1, Confusion Range sections
- 10 Variations in amplitude of peak 2, Confusion Range sections
- 11 Variations in amplitude of peak 3, Confusion Range sections
- 12 Peak 1/peak 2, Confusion Range sections
- 13 Peak 2/peak 3, Confusion Range sections
- 14 Double-ratio, Confusion Range sections
- 15 Double-ratio, three point moving average, Confusion Range sections
- 16 Summary of Confusion Range correlations
- 17 Double-ratio, Willow Creek section
- 18 Double-ratio, three point moving average, Willow Creek section
- 19 Double-ratio, Leatham Hollow section
- 20 Double-ratio, three point moving average, Leatham Hollow section
- 21 Double-ratio, Uinta section
- 22 Double-ratio, three point moving average, Uinta section
- 23 Long range correlations

NOTE: Plates 17 and 18 are represented together on number 18.

Typical glow curve showing derivation of quantities used in correlation

t.l.
mg.

18

Variations in amplitude of peak 2
Teton Pass section

6593 20

19
Variations in amplitude of peak 3
Teton Pass section

6593 21

Peak 1 / peak 2,
Teton Pass section

20

Peak 2 / peak 3
Teton Pass section

21

6593 23

22

$\frac{\text{Peak 1 / peak 2}}{\text{peak 2 / peak 3}}$

Teton Pass section

7

6593

24

23

8

6593

25

Variations in amplitude of peak I Confusion Range sections

24

—— CONGER SPRING
—— SKUNK SPRING
---- NORTH GRANITE MT.

6593 26

Variations in amplitude of peak 2 Confusion Range sections

25

Variations in amplitude of peak 3 Confusion Range sections

26

—— CONGER SPRING
—— SKUNK SPRING
----- NORTH GRANITE MT.

Peak 1/peak 2
Confusion Range sections

27

—— CONGER SPRING
—— SKUNK SPRING
----- NORTH GRANITE MT.

26

Peak 2 / peak 3 Confusion Range sections

—— CONGER SPRING
—— SKUNK SPRING
----- NORTH GRANITE MT.

6593 30

29

Peak 1 / peak 2
peak 2 / peak 3

Confusion Range sections

— CONGER SPRING
— SKUNK SPRING
- - - NORTH GRANITE MT.

14

6593 31

30

Peak 1/ peak 2
peak 2/ peak 3

Three point moving average

Confusion Range sections

— CONGER SPRING
— SKUNK SPRING
- - - NORTH GRANITE MT.

15

6593 32

Summary of Confusion Range correlations

31

Skunk
Spring

Conger
Spring

North
Granite Mt.

FT.

32

Peak 1 / peak 2
peak 2 / peak 3

Three point moving average
Willow Creek section

Plate 18

6593 34

Willow Creek section
Peak 1 / peak 2
peak 2 / peak 3

33

$\frac{\text{Peak 1 / peak 2}}{\text{peak 2 / peak 3}}$

Leatham Hollow section

19

6593

35

34

$\frac{\text{Peak 1 / peak 2}}{\text{peak 2 / peak 3}}$

Three point moving average

Leatham Hollow section

20

6593

36

35-

$\frac{\text{Peak 1 / peak 2}}{\text{peak 2 / peak 3}}$
Uinta section

16.

6593

37

36

Peak 1 / peak 2
peak 2 / peak 3

Three point moving average

Uinta section

22

6593

38

Long range correlations

TETON
PASS

UINTA

CONFUSION
RANGE

LEATHAM
HOLLOW

WILLOW
CREEK

FEET

I-II

1-37

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