influence on activity and the degree of adaptation to human activities.
The results from this study show that the compensatory response to sleep loss can be recorded without measuring the EEG. Night-time immobility has been used as an index of sleep quality in drug studies[2]. The same method was applied in the present study to measure the duration of sleep or rest. In dogs REMS is often accompanied by bouts of motor activity e.g. running activity and barking[7]. In the same study, frequent body movements were also reported during episodes of drowsiness. Our pilot study involving time-lapse video recordings confirmed this observation. Therefore, we arbitrarily allowed up to 5 counts for a rest episode in order not to include such 'agitated' sleep episodes. This measure proved not only appropriate for quantifying the effectiveness of SD but also to describe the effect of SD during recovery. Recovery from SD was less evident from the reduction of motor activity than from the enhanced number of rest episodes. It has been previously demonstrated in the rat that the increase of slow-wave activity is not a consequence of locomotion but must be attributed to sleep loss[3,9]. Particular attention was given in this study to avoiding unnecessary activation of the dogs during the deprivation. It is therefore not probable that the compensation after SD was only a consequence of enhanced motor activity.
The use of motor activity as a measure for compensatory processes after SD has formerly been applied in animal species where EEG measures are difficult or impossible to obtain. Thus rest deprivation in fish brought about by exposure to light prolonged rest during recovery[20]. In cockroaches, rest deprivation by mechanical stimulation was also followed by a short period of enhanced rest[18]. The present results are consistent with the proposition that the reduction of motor activity after sleep loss reflects a homeostatic process of sleep regulation.

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Luminous phenomena and earthquakes in southern Washington

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Summary. Luminous phenomena, mostly nocturnal lights, are associated with very small earthquakes in southern Washington state. The phenomena seem to be electrical in nature, related to earthquake lights, and tend to occur when the locus of earthquake activity moves across an active fault in an area of compressional stress.
Key words. Luminous phenomena; earthquake lights; nocturnal lights; earthquakes; Yakima Indian Reservation; Toppenish Ridge; Washington; seismicity; tectonic stress; geomagnetism; exoelectron; piezoelectric.

Introduction

Variable luminous events that occur during or just before some earthquakes have been reported for centuries[10,16]. Spherical, discrete sources of light of various colors and odd kinetics have also been paired with seismic activity[11,15,42]. Statistical analyses suggest that large numbers of similar luminosities may be reported weeks to months before an increase in the number of low intensity ($\leqslant$ V) earthquakes[27,30]. Several multivariate studies have shown conversely that temporal patterns of earthquakes within a region can accurately forecast reports of these odd phenomena[28,31,32]. Recently, miniature luminosities have been generated in laboratory experiments immediately before rock fractures. Rocks under uniaxial pressure produce light of 1–15 μs duration from exoelectron emission, independent of rock type and with a spectrum that of the ambient atmosphere[6,20]. All of these results are consistent with the hypothesis that many of these luminosities are correlated with the accumulation and release of tectonic strain within the earth's crust[25,26,38].

We suspect that earthquake lights (EQL) and luminous phenomena (LP) are related, and suggest the following working definitions: earthquake lights are the luminous phenomena that occur at the same time as an earthquake and are observed in direct association with a fault or the epicentral area. If there is no simultaneity, LP cannot be directly linked to a specific earthquake. If the LP remain unidentified after diligent investigation, then they would seem to be natural in origin. Our data suggest that LP may result from small rock fractures as tectonic strain accumulates over a large region, whereas EQL are the result of the release of that strain in the immediate area of the epicenter and along any fault breakage. Stated another way, LP may be effects of the accumulation of small strains over a large, future epicentral region, indicating the accumulation of stress, whereas EQL are effects of local strain release. Thus, we suggest the possibility that LP are actually EQL for very small quakes, with earthquake magnitude (M) $\leqslant 1.0$.

The capabilities for recording and identifying earthquakes are vastly greater than those for LP, so one must expect discrepancies in comparing these types of data. However, even the earthquake data do not reach a low enough threshold for direct comparisons. Because the LP data base is certainly contaminated and both LP and earthquake data bases are incomplete, we use the techniques of multivariate analysis to test for various correlations. We expect to have either no LP sighting data or incorrect identification of LP in many instances, and a fragmentary seismic data base for low M which becomes essentially complete at $M \geq 2.5$.

Toppenish seismicity and luminous phenomena

There are many reports[1,5,39] of natural luminous events on or near the ground in the vicinity of Toppenish Ridge within the Yakima fold belt in south-central Washington. This volume of data led to its selection as an area to test the hypothesis that luminous phenomena are related to regional strain. The Satus Peak anticline, the middle of three segments of the Toppenish Ridge structure, is similar in structure and topography to more than 50 other segments within the Yakima fold system[8]. However, quite unlike the other segments, the Toppenish Ridge fold is still undergoing compressional deformation, as revealed by a 32-km-long zone of nearly 100 surface ruptures and by shallow-focus seismic events[8].

Figures 1 and 2 are photographs of typical nocturnal lights (NL) seen from the vicinity of Toppenish[1]. Both luminosities occurred below the ridge line in areas accessible only by foot. Cited distances to the lights assume they were at or near ground level. The locations, durations, kinetics, and luminous characteristics of the sightings are such that conventional explanations seem improbable. Studies of the original slide for figure 2 indicate a source having tens of watts of radiant power, based on experiments with comparable film[2]. If generated by an isotropic incandescent lightbulb, it would have required approximately 1000 W input. If generated by a car or motorcycle headlight (35–60 W), it would have to have been pointed directly at the camera, with a filter, and the image would have been even brighter[2]. If the image diameter is representative of the source size, it would have been approximately 4 m in diameter, which is probably an upper limit. Accounting for exposure time

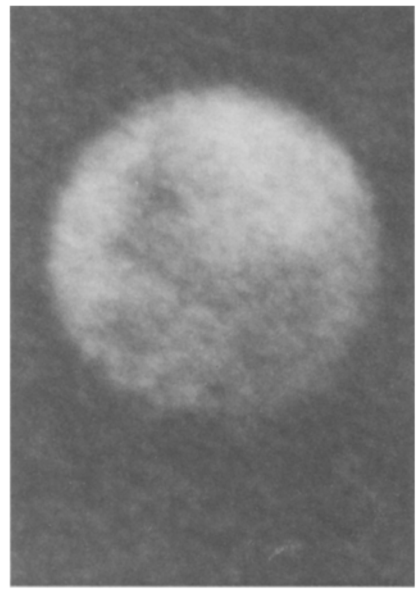

Figure 1. Nocturnal light seen on the lower third of Toppenish Ridge, north side, taken from a point about 6 miles due north at about 20.00 h local time, in January 1973. Exact date unknown. HS Ektachrome film, ASA 200, 150 mm lens, shutter speed probably 1/60 s, f-stop unknown. Object was stationary, well below the horizon. The area is very steep and accessible only by foot. (Photo by William J. Vogel.)

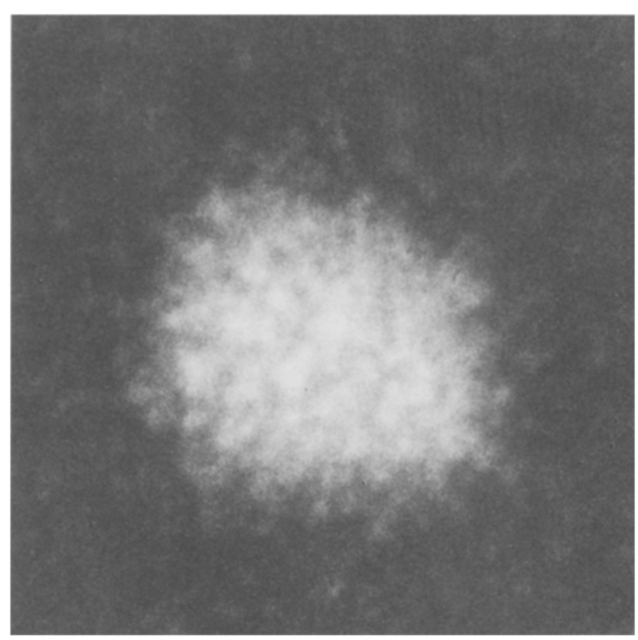

Figure 2. Nocturnal light seen north of Hunt Creek, Yakima Indian Reservation, Washington, below the ridge line. Picture taken from the vicinity of Toppenish, 19 miles east of the NL, on August 19, 1972, 21.38 h, with a 500 mm f/8 lens, Kodak High-Speed Ektachrome film, ASA 125, 1/4 s exposure. Weather at the time was high broken to overcast, visibility more than 40 miles, temperature about 65 °F, wind NW 0–5 mph. Four pictures were taken during the 55 min sighting. (Photo by David W. Akers.)

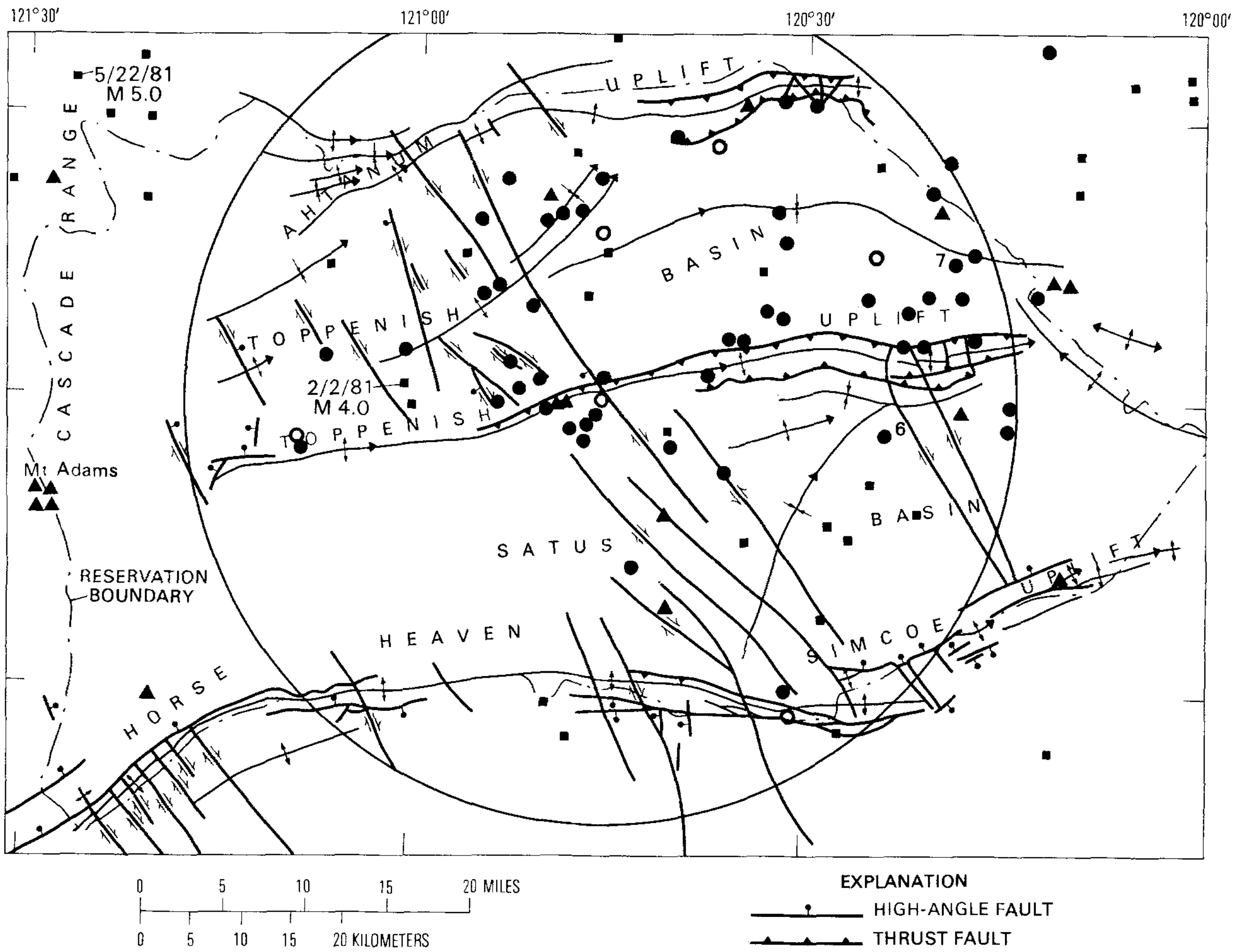

Figure 3. Yakima Indian Reservation, Washington, showing mapped tectonic features, principal fire lookouts and other observation points (open circles), approximate locations of LP to the extent known (closed circles where accurate to the nearest section, 1 sq mi; solid triangles where accurate only to within a certain township, 36 sq mi),[15] and all earthquakes (solid squares) from 1970 through January 1983. A number beside a closed circle indicates sightings on different occasions in approximately the same location. Large circle is a 40 km radius of Satus Peak.

causing probable growth of image size on the film, its diameter is most likely to be about 1 m^2.

Eighty-two reports of LP were obtained from a relatively homogeneous collection period between July 1972 and April 1977. An additional 21 reports extend the data base through July 1981, but are not complete and were not available to us initially, and so are used only later as a separate test of our hypotheses. Most (78%) of the reports are classified as nocturnal lights. Other reports involved unclassified events and episodes where observers were close enough to discern specific details of the lights. Seven of the reports involved daylight observations or overly elaborate descriptions and were not included in the analyses because they appear to belong to the class of sightings we have called 'exotic cases'[36]. Including these in the analysis, however, produced no significant change in the result.

Figure 3 shows the major tectonic features of the Yakima Indian Reservation[8] with the locations of known LP sightings between June 1972 and October 1977. The seismicity in this area during the period of the sightings was very low: no earthquakes greater than M 2.0 were recorded (fig. 4). Therefore, we have shown on figure 3 all recorded earthquakes (solid squares) over the 13 years period, 1970–1982, to help in looking for trends. There was one quake of M 5.0 with an aftershock sequence at the far western edge of the reservation, shown here by only one symbol, and one quake of M 4.0 near Toppenish

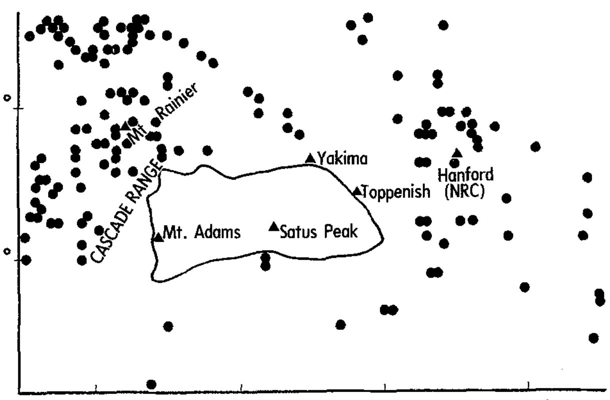

Figure 4. Epicenters in the vicinity of Toppenish, Washington, July 1972, through June 1977, $M \geq 2.0$.[19]

Ridge. All other quakes are of M less than 3.0 and most less than 2.0, and almost all have focal depths less than 5 km. (All M figures are coda length magnitudes).
If seismicity in this area is similar to that in the Hanford area to the east, which has been studied in greater detail[23], one would expect swarms of small, shallow-focus events of M generally less than 2.0 and depths less than 2 km. Because of the complete absence of seismograph stations in the area of the LP sightings, we cannot rule out the possibility of simultaneous, very small earthquakes. The observers reported that they never felt any earthquakes or heard any noises at the time of a sighting, although unusual sounds possibly related to earthquakes have been reported at other times. These sounds are described as like a heavy truck climbing the hill to the fire lookout, or like a large turbine, but no machinery ever was found to explain the phenomena. Such sounds are consistent with microearthquakes, e.g. those recorded near Moodus, Connecticut, in 1982, ranging in M from 2.3 down to − 0.9[13], and there is ample evidence that unfelt earthquakes can be heard[40,41]. Given the uncertainty in the locations of the sightings, most of which are in the vicinity of the ridges, it is possible that the LP are related to continuing deformation on the Toppenish and Ahtanum uplifts. In particular, there is a distinct cluster of LP around Satus Peak, the general area of the surface ruptures, sounds, and the M 4.0 earthquake.
Most of the observations were recorded in log books by the regular fire lookouts at their stations atop the ridges during the fire season (generally May through September). These lookouts provide regular coverage of the area during daylight and evening hours, and irregular coverage during the night. Random observations by other observers, including law-enforcement personnel from various jurisdictions, supplement the data base. Additional observations were provided by a team of scientists and engineers who came to the towers specifically to observe and photograph the LP. Their observations are included in figure 3. The fire lookouts are in radio contact with each other, and are skilled at triangulation for locating fires. Many of the LP were observed simultaneously by more than one person and so noted in real time by radio communication between them. The observers' experience should minimize, if not eliminate, the inclusion of lightning, aurorae, and artificial light sources in this set of observations. The LP certainly bear a strong resemblance to ball lightning, although the weather conditions at the times of the sightings would tend to rule out this explanation. The following sighting was given by the Sopelia lookout: 'A very strong white light about the size of a (baseball) was floating along just north of me down the slope from east to west, north of the trees on the deep canyon side about 6 to 10 feet below the tallest trees. I watched it as it went by between the trees. Really looked like someone *could* have been out for an evening stroll with a light in their hand. But nothing to stroll on but air. So this light must have been floating along. No noise at all. All quiet.'[39]. This report is evidence for the hypothesis that short-duration (less than 1 min) LP seem to behave the same way ball lightning does: once formed, the assumed plasmas seem to have a life of their own, apparently with no more energy input required. Their paths would seem to be determined by the ambient electromagnetic fields. LP of much longer duration, however, almost certainly require a continual energy input.
An alternate explanation has been offered for LP in the 1960s in the Uinta Basin, Utah, and might partially explain this particular sighting. This luminosity could have been caused by spruce budworms or other insects flying in an intense electric field, causing them to glow by stimulated emission similar to St. Elmo's fire[7]. The location and motion would seem consistent here, but the weather was clear, so there is no apparent source of atmospheric electricity. Thus, we still need to look to the Earth for the energetic source. Most of the other Toppenish LP are not subject to explanation by the spruce budworm hypothesis because of their perfect sphericity, intensity, motion, or other factors inconsistent with the kinetics of a swarm of insects.
LP are observed in the Yakima Indian Reservation because the lookouts are there, and they are there because the area is dry and prone to fires. Most of the earthquakes in southern Washington are grouped generally in the Cascade Mountains to the West for tectonic and volcanic reasons. The mountains tend to trap precipitation, making the earthquake area also cloudy and wet. Because of the apparent similarity to ball lightning, we assume that LP are electrical in nature, and any electric charge would be likely to dissipate more rapidly in the wetter areas. Also, LP would be more likely to be obscured by clouds in the Cascades. Thus, if the LP are associated with Cascade quakes, it is possible for whatever the causal mechanism might be to be uniform about the center of earthquake activity, but the *observations* of LP would still be skewed to the drier area to the east. If the LP are associated with very small, local quakes, however, this explanation is not required. One way to check the hypothesis that the Toppenish LP are associated with very small quakes would be to install a seismometer near Satus Peak and perhaps other locations of frequent LP reports. This possibility is presently being pursued by other investigators.

Statistical analyses

Data on earthquake hypocenters and magnitudes for Washington State were obtained from the University of Washington[3]. The Yakima Indian Reservation lies between two independent seismic networks, so the threshold for complete coverage has been higher than for other locations in the state. For 1970 through mid 1978, the threshold was M 2.5 to 3.0. From then on, it drops to M 2.0 or better. To maintain homogeneity of coverage, only those seismic events with magnitudes greater than 2.0 were used in the first stage of this analysis. The second stage involved the use of magnitudes less than 2.0 as well within an area surrounding and including the Yakima Reservation. If LP are generated by earthquakes smaller than M 2.0, then the seismic history is marginally adequate for temporal analyses. However, the spatial distribution of earthquakes should be fairly representative.
The first procedure was simply to determine if any gross correspondence existed in time between earthquakes and the LP. We selected one-month increments of analyses for both theoretical and technical reasons[29,35,38]. Because the major clusters of earthquakes tended to occur near

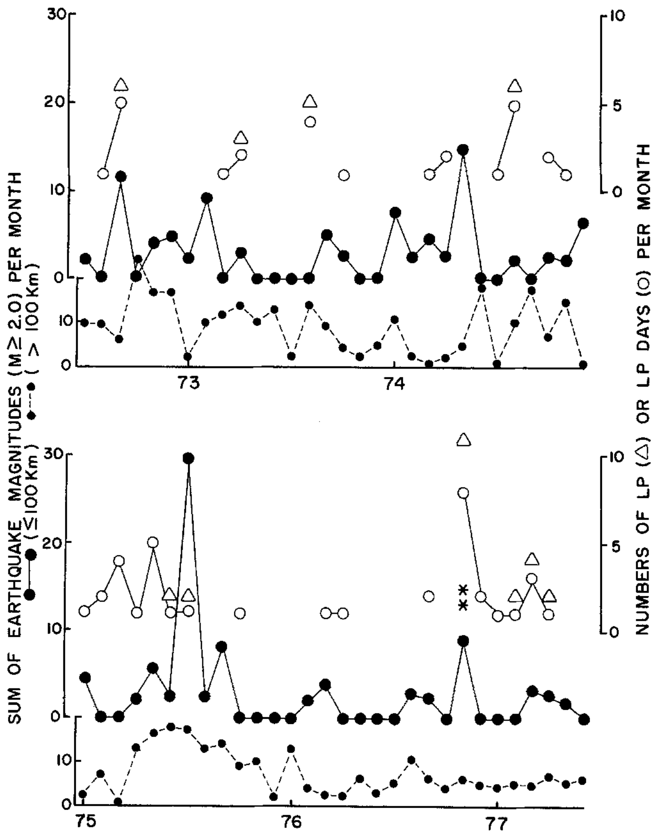

Figure 5. Time sequence of LP and earthquakes from figures 3 and 4. Open circles indicate numbers of days per monthly increment in which LP were reported, and open triangles give the total numbers of LP reported per month between July 1972, and May 1977. Large closed circles (solid lines) indicate the sum of earthquake magnitudes for $M \geq 2.0$ events within a radius of 100 km from Satus Peak; smaller closed circles (dashed lines) indicate the same measures for distances between 100 and 200 km. Asterisks refer to events that occurred within a radius of 40 km from Satus Peak.

the end of the month, the monthly increments were defined as from the middle (15th) of one month to the middle (14th) of the next. The first increment was June 15 to July 14, 1972 and the final increment was March 15 to April 14, 1977 (n = 58 months). Two measures of LP were calculated: the total numbers of LP per month and the numbers of LP days per month. The latter measure was calculated in order to attenuate the excessive effects from days that contained multiple observations.

We assumed that if the LP were associated with seismic events, then the occurrence of the LP would be functionally related to the local magnitude M and distance Δ of the quakes. We would expect to find a correlation between the numbers of LP and earthquake energy release. Our primary measure was calculated as the monthly sum of the log of the earthquake energy,

$$I_1 = \Sigma \log E \propto \Sigma M$$

for all seismic events with $M \geq 2.0$. Another monthly index,

$$I_2 = \log \Sigma E \propto \log \Sigma 10^{1.5M},$$

was also calculated because our primary measure was heavily weighted by the numbers of different seismic events rather than the energy of a particular large event. Other measures entailed dividing I_1 and I_2 by the square of the distance from Satus Peak. Because the extra indices did not yield appreciably different information, the rest of the analyses will involve the primary measure, I_1.

Figure 5 shows the monthly values for the numbers of LP, LP days, and earthquake energy within 100 km of Satus Peak for earthquakes with $M \geq 2.0$. The more distant seismic activity was included as a control for the contribution of general seismicity and clearly does not correlate. The occurrence of LP during the same month as increases in nearby seismic activity was not always apparent, although increases in seismic activity ($\Delta \leq 100$ km) during July–August 1972 and October–November 1976 were associated with the largest numbers of LP days, and, interestingly, the longest successive report of LP occurred during the 7-month period that preceded the unusually large release of seismic energy ($\Delta \leq 100$ km) during June-July 1975. Note that LP occur each month during which there is measurable earthquake activity over the last two years of this figure.

To determine quantitatively the relationship in time between the LP and earthquake energy, lag/lead correlations were computed between LP 1, 2, or 3 months before; during; or 1, 2, or 3 months after monthly values of the earthquake measures for July 1972 to April 1977 (n = 58 months). The analyses were completed separately for seismic events within 100 km and greater than 100 km from Satus Peak. Because both the LP and earthquake

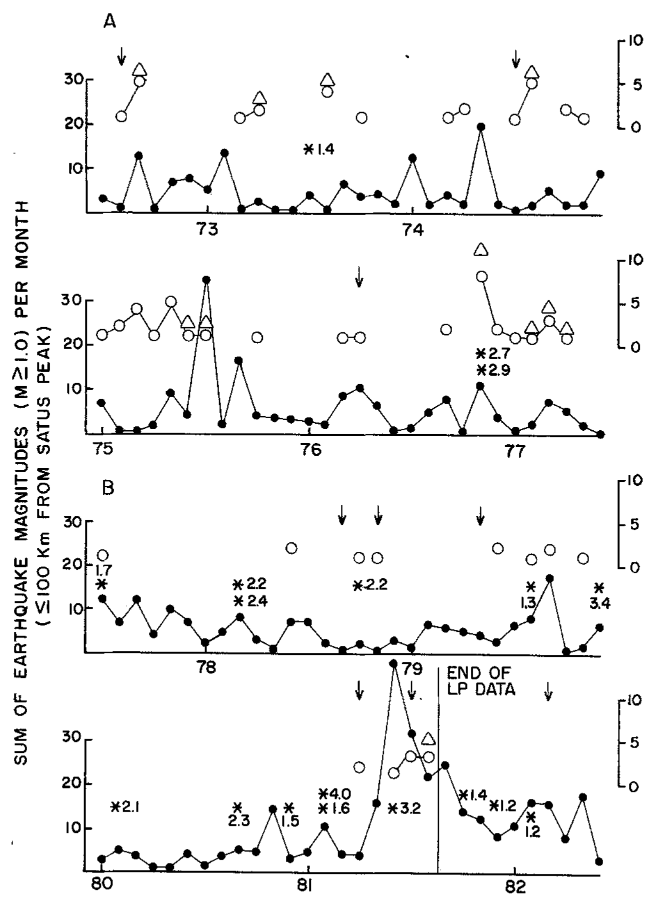

Figure 6. *A* Time sequence of LP and earthquakes as in figure 5, but for all events with $M \geq 1.0$ and distances only within 100 km of Satus Peak. Arrows indicate months in which the Ap index (geomagnetic activity) on at least one day exceeded 100. Arabic numbers indicate magnitudes of the earthquakes. *B* Continuation of the fig. 6a for the years after the major sampling, with additional fragmentary LP data.

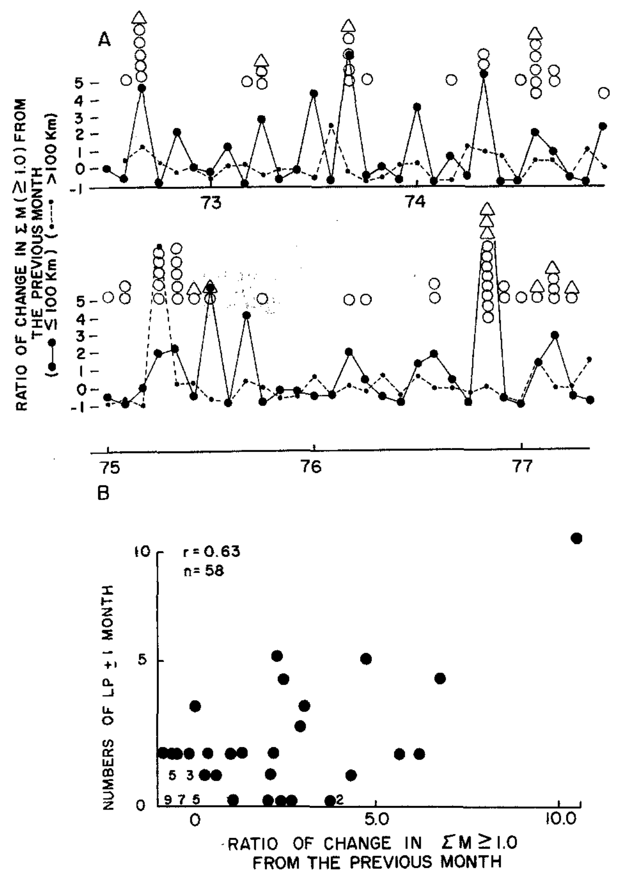

Figure 7. *A* Ratio of the change in the monthly sum of earthquake magnitudes with respect to the previous month for all earthquakes ($M \geq 1.0$) within a radius of 100 km from Satus Peak (large, closed circles), and for earthquakes between 100 and 200 km from the Peak (small circles, dashed lines). Open circles refer to the number of LP per month that occurred with ± 30 days of the major cluster of earthquakes in that month. Open triangles indicate the total numbers of LP and include multiple reports on the same days. The LP data have no vertical scale: each symbol represents one datum. *B* Scattergram between the total numbers of LP within ± 30 days of the major cluster of earthquakes per month (open circles in part A) and the ratio of the change in the sum of earthquake magnitudes per month from the previous month (large closed circles in part A) for July 1972, to May 1977. Numbers indicate multiple dots at the same location.

measures tended to be skewed, Pearson r and Spearman rho correlations were completed in this and all subsequent analyses. The non-parametric (rho) or rank order procedure was included in order to detect any misleading results that may have been caused by one or two outliers in the data base. Neither set of correlational analyses indicated any statistically significant relations between LP and the earthquake measures for the entire data period.

Because most epicenters ($M \geq 2.0$) within 100 km of Satus Peak were farther than 80 km away, we suspected that any potential relationship between the occurrence of LP and earthquakes might have been masked by the sum of these distant events. We looked for a period in which earthquakes occurred less than 50 km from the peak. Only one month (October–November 1976) met this criterion. During this increment, two seismic events with magnitudes of 2.7 and 2.9 occurred within approximately 40 km of the peak, just south of the reservation. This month was also associated with the largest numbers of LP or LP days that had ever been reported in the area. The relationship between the magnitude of I_1 and the occurrence and numbers of LP this month is clearly evident in figure 5, suggesting a closer look at this period. Quantitative analyses for the last 18 months of the data period (November 1975 to April 1977) indicated statistically significant ($p < 0.01$) correlations between the numbers of LP ($r = 0.85$; $rho = 0.59$) or the numbers of LP days ($r = 0.84$; $rho = 0.58$) and the sum of earthquake magnitudes during the same month within 100 km of Satus Peak. For the more distant events between 100 km and 200 km away, there were no statistically significant ($p > 0.05$) correlations between LP ($rs < 0.10$; $rhos \leq 0.10$) and earthquake measures. Similarly, LP were not correlated significantly with either the seismic activity the month before or the month after their occurrence. There were weak positive but nonsignificant ($p > 0.05$) correlations ($r = 0.12$; $rho = 0.18$) between I_1 for seismic events within 100 km and seismic events at greater distances.

Additional analyses of the final 12-month interval (May 1976 to April 1977) around the October-November 1976 episode indicated that the significant correlations between LP and I_1 were not artifacts of the quiet periods during early 1976. Earthquake measures were correlated significantly ($p \leq 0.01$) with the total numbers of LP per month ($r = 0.88$; $rho = 0.62$) and LP days ($r = 0.87$; $rho = 0.58$). The discrepancies in the magnitudes of two correlation coefficients r and rho were due primarily to the extreme values for both earthquake activity and LP during October–November 1976. Again, neither correlations between LP and distant quake measures nor correlations between LP and earthquake activity either the

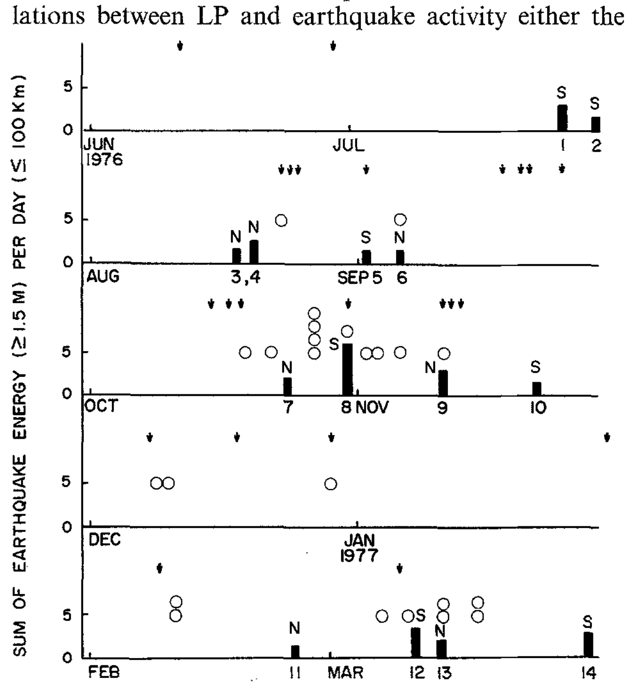

Figure 8. Daily occurrence of LP (open circles) and the release of seismic energy (closed bars) for events ($M \geq 1.5$ per day) from June 1976, to April 1977. The arabic number under each bar refers to the temporal sequence of epicenters. Arrows indicate days in which the Ap values were greater than 2 standard deviations (≥ 23) above the mean for that 8-month period. N and S indicate that the earthquake occurred north or south, respectively, of the area of the LP sightings. Note that LP occurred during clusters of earthquakes and/or during increased geomagnetic disturbances during this period.

month before or after their occurrence were statistically significant. We also tested the LP data for seasonal or other periodic correlations which might indicate non-random observations of LP. These might be associated with more people looking in the summer or during fire season, for example. No periodicity was found, however, indicating a surprising uniformity in the LP data base.

The first analyses ignored the contribution from small magnitude events within the Toppenish region. We decided to incorporate these weaker events ($1.0 \leqslant m < 2.0$) within our analyses, even though some occurrences may have escaped detection, to see if there might be a clear relationship between LP and small, local earthquakes within 100 km of Satus Peak. The monthly values of I_t for $1.0 \leqslant M < 2.0$ were not significantly correlated with LP for the entire period and only weakly correlated (rhos $\leqslant 0.40$; $p \leqslant 0.05$) with LP for the last 18 months. However, the monthly values of I_t for all seismic events $M \geqslant 1.0$ enhanced a more systematic relationship between LP and seismic activity within 100 km of Satus Peak. Figure 6a shows this clear temporal relationship between monthly LP and I_t for the last 18 months of the record. The correlations were: I_t and total LP ($r = 0.58$; rho = 0.57; $p < 0.001$); I_t and LP days ($r = 0.62$; rho = 0.61; $p < 0.01$). Similarly, LP days and the earthquake measures were highly correlated ($r = 0.69$; rho = 0.62) for the 12-month interval around the month of the strong nearby seismic activity.

Some of our previous studies[30,33,35] have indicated that *relative change* in seismicity over time appears to be correlated with LP. To determine if this relationship occurred within the present data base, the ratio of the monthly change in I_t for $M \geqslant 1.0$ was calculated for the interval ($n = 58$ months). (Because some months contained no detected events, a 1 was added to all months to prevent 0 in the denominator.) This value, called the ratio of change in I_t, was determined for seismic events within 100 km from Satus Peak and separately for further events for comparison. The number of LP within ± 30 days of the major cluster of earthquakes each month were determined for each of the two distances.

The results are shown in figure 7a. Quite clearly, LP tend to occur within ± 30 days of increases in seismic energy release within 100 km of Satus Peak; the correlations between the ratio of the change in I_t from the previous month and the occurrence of LP were $r = +0.63$, and rho = +0.40 ($p \leqslant 0.001$). On the other hand, there were no significant ($p > 0.05$) correlations between changes in seismic measures at distances greater than 100 km ($r = 0.07$; rho = 0.03). As a control for possible statistical artifacts, correlations were completed between LP and the ratios for the month before and the month after LP; they were not statistically significant. A scattergram between numbers of LP within ± 30 days of the change in seismic energy release is shown in figure 7b.

Although the correlations between the relative change in seismicity and LP were interesting, we felt that any clear relationship between LP and seismicity must be tied to specific earthquakes or clusters of earthquakes. All the previous analyses had been based upon the implicit assumption that all earthquakes within 100 km of Satus Peak contributed 'equally' to LP. Very recent analyses[36] indicate that shifts in the spatial distributions of epicenters with respect to the LP area are a key factor. In the Uinta Basin, Utah, for example, events that were very similar to LP occurred in the interval between two successive, nearby earthquakes most frequently when their epicenters were on opposite sides of the LP area.

The daily record of the occurrence of earthquake activity and LP is shown in figure 8. The numbers under the bars refer to the temporal order of epicenters for earthquakes with $M \geqslant 1.5$/day. It is visually apparent that most LP clustered during periods of earthquake activity, although only four LP occurred on the same days as earthquakes. This is fairly representative of LP and seismicity on a daily basis. LP occurred between December 1976 and February 1977 when no quakes ($M \geqslant 1.5$) were detected. This pattern would be more consistent if undetected seismic events very near the observations occurred between epicenters 10 and 11.

The direction of the tectonic stress in the Toppenish area is north-south compression with an active fault running east-west through the middle of the area of LP sightings. Therefore, we have noted by each earthquake bar numbered in figure 8 whether the quake was north or south of the area of the sightings. In the time period covered by this figure there were 11 earthquake-LP cycles. Eight of the LP episodes occurred in time intervals between epicenters located north and south of the sightings. Two more episodes occurred on the same day as a north-south shift. Only one time interval does not show this pattern. A similar, one-dimensional analysis in the Uinta Basin, where the direction of tectonic compression is also north-south, shows seven similar earthquake-LP cycles in 1967[33]. Six of these cycles show this same pattern of LP occurring when groups of epicenters shift from north of the sighting area to south. This type of analysis in two dimensions in the Toppenish area seems to suggest that most of the LP occurred when nearby epicenters moved from one general area to another; however, the data are not uniform enough to warrant conclusions.

Discussion

Even the intermediate strength correlations between LP and seismic activity may be sufficient to allow some general forecasts within monthly increments. If we extrapolate the relations between LP and seismicity ($M \geqslant 1.0$) within 100 km of Satus Peak during 1972 through May 1977 to later intervals, then LP should have occurred when there was a sudden increase in seismicity, following relatively little activity or during larger relative increases in absolute seismicity. LP should have been even more likely during these periods if epicenters were detected within 40 km of Satus Peak. According to figure 6b, LP should have occurred during June–July 1977, March–April 1978, May-June 1978, September–October 1978, July to September 1979, and November–December 1979. During 1980, there should have been LP during January–February, August–September, and October through December 15. Although LP should have been prominent during January–February 1981, by far the most robust display of LP should have occurred in mid-1981, particularly during the massively enhanced seismicity that followed the M 5.0 Goat Rocks earthquake of May 28, 1981, just northwest of the reservation.

Unfortunately, whatever uniformity the LP data base might have had from 1972 through April 1977 is lost from that time on. What LP data do exist from May 1977 through July 1981, however, are generally compatible with these forecasts. As can be seen in figure 6b, LP occurred during all of the expected months except March 1978; in addition two LP occurred two months before the July–September 1979 period. Despite the absence of LP that should have occurred during 1980, the greatest number of LP since 1976 occurred during the heavy seismicity between May and August of 1981. January–February 1982 would have been an expected LP month, but not even fragmentary LP data are available after August 1981.

The present analyses confirm the importance of some factor correlated with geomagnetic activity (as represented by the Ap index) in the occurrence of luminosities. The daily Ap is a relative international index of magnetic activity, a measure of the maximum deviation in 3-h intervals from the seasonal quiet day curve, averaged over the entire planet. We use the Ap index because it is one of the most widely used measures of solar activity. Figure 6 also shows those months (indicated by an arrow) in which at least one day displayed an Ap value of greater than 100[4]. The contribution from geomagnetic activity (or the many geophysical phenomena that are correlated with it) has been weak but persistent in our analyses of LP, even for daily analyses (fig. 8). Some studies[34] have indicated that LP tend to increase during months of large geomagnetic storms ($Ap \geqslant 100$) if tectonic stress, as indicated by later earthquake activity within the area, is increasing. During the major analysis period, there were three months in which the daily Ap value exceeded 100; each event was followed by LP within 30 days. For the period depicted in figure 6b, Ap values exceeded 100 on at least one day during each of only five months before the end of the LP data. All five Ap maxima preceded the LP, three occurring in the same monthly increment and the other two occurring the month before. Thus, the peak Ap values consistently precede LP; however, the precise role of geomagnetic factors in LP or in relevant earthquake processes (if any) remains to be established.

The LP data base indicates that the total number of sightings has decreased since the Mt. St. Helens eruption. If confirmed, this trend would suggest that the increase in LP during the decade before the eruption might be significant. This statement is compatible with the persistent contribution of very intense distant quakes in both the monthly and daily analyses. We are led to speculate that LP might then be taken as a symptom of strain accumulation and might be related to an impending large earthquake or volcanic eruption.

Although the geophysical mechanisms are not clear at this time, this analysis suggests a relationship between LP, seismic activity, and geomagnetic activity, even from simple graphs. These results are compatible with a variety of other analyses performed on less homogeneous samples of luminous reports from other parts of the USA and Europe[28,31,32]. Collectively, they suggest that luminous events, especially those following intense geomagnetic activity, may be useful in forecasting earthquakes within certain areas. We are not suggesting that geomagnetic activity might be a causative factor in triggering earthquakes. Rather, we consider it possible that earthquakes and geomagnetic activity are independent processes which, when they happen to be in a certain phase relationship with each other, may locally enhance conditions for producing LP.

The low quality of the LP data base and the absence of very local seismic stations would seem to preclude associating specific earthquakes with these sightings at this time, if indeed this can be done, although the most logical association with energy ($10^{1.5\ M}$) seems to be established. We have been strongly motivated to find correlations between individual earthquakes and individual reports of LP, hoping to find a direct cause and effect relationship. Close scrutiny of the spatial distribution and temporal sequence of LP and earthquake epicenters suggests that not all seismic events within 100 km may have contributed to the occurrence of LP. LP tended to occur when there was a shift in the location of the closest earthquake activity, particularly if they moved across the observation area, which essentially coincides with the Yakima Indian Reservation. If this analysis is valid, the data suggest to us that the spatial-temporal pattern may reflect some process associated with changing tectonic stresses across the reservation. LP would be natural phenomena coupled to these local stresses, which are almost invariably compressional[43] wherever these apparent geophysical luminosities have been observed in the US. This hypothesis is also consistent with the possibility that LP are caused directly by very small quakes below the threshold for location.

All work in this area suggests that EQL should be associated with some sort of fracture mechanism, which would be consistent with two other hypotheses. One of these is the linear relationship between M and R, the radius of visibility of earthquake lights: the greater the magnitude, the greater the distance to which EQL are seen[18]. The other is that EQL may be chemical luminescence due to gas eruptions from the soil or the deep interior of the earth[17,19,24]. If EQL are more likely to be generated by either larger or deeper quakes, then we might have several mechanisms at work. For large, shallow events, one might consider the frictional heating hypothesis of Lockner et al.[21], and the piezoelectric hypothesis[14], although laboratory tests involving pressing rocks to failure consistently have not demonstrated this latter effect[6], and theoretical studies show it to be unlikely[12]. In either case, we would expect the EQL to be very local to the source of faulting.

For earthquakes in the deep crust or upper mantle, EQL might be caused by gas eruption, either luminous or burning. This mechanism would permit observations of LP at greater distances from the epicenter and also produce some time lead or lag. LP after the main event could be explained by the time required for gas to leak along cracks formed by the quake, whereas LP before quakes might be due to gas moving along lines of weakness as they begin to open. This explanation is also consistent with the proposed enhanced electrostatic field mechanism caused by exhalation of positive ions[22]. EQL and LP may also be caused by exoelectron bombardment if a fracture reaches the surface of the ground or the sea floor, in which case they could be independent of magnitude[6,20]. This latter mechanism seems the most consistent with the

Toppenish reports which are evidently spherical, plasma-like occurrences, although there are definite problems in scaling the laboratory work up to the size of phenomena in the field. More important, the laboratory luminosities are definitely not plasmas, as evidenced by the lack of microwave emissions[6]. This suggests that any field observation equipment designed to capture LP or EQL should include a broadband radio receiver as well as an optical spectrum analyzer.

Another potential mechanism involving the semiconductor properties of polymetallic ore bodies has been proposed by Demin et al.[9]. Their idea involves electrical discharges from cracks which are amplified by unusual occurrences of semiconducting minerals. These minerals would then become transistor amplifiers or thyristors in the bodies, with high-frequency stress waves producing piezoelectric polarized p and n junctions. This theory entails the generation of ultrasonic waves and electron emission, in addition to luminescence, and suggests that LP might be associated with polymetallic ore bodies near the surface.

Our present study suggests that EQL and LP are multi-mechanism, related phenomena, caused by changing stresses in the crust. If it can be shown that LP are caused by very small quakes, $M \leqslant 1.0$, then at least some LP would simply be EQL for very small earthquakes. However, considerable theoretical, experimental, and observational work remains to be done to elucidate these phenomena.

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Short Communications

Articular cartilage canals – a new pathogenetic mechanism in infectious arthritis

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Summary. In experimentally-induced erysipelas polyarthritis, preexisting cartilage canals in articular cartilage play a crucial role during the very onset of the disease. This observation might have some implications for the pathogenesis of other infectious arthritides in young animals or even rheumatoid arthritis in man.
Key words. Cartilage canals; erysipelas arthritis; rheumatoid arthritis.

When investigating the etiology and pathogenesis of any type of arthritis, one cannot avoid a basic study of the morphology and physiology of the joints. Generally, cartilage is considered to be free of nerves, blood vessels and lymphatics. The fact, however, that fetal mammalian cartilage is vascularized and that vascular channels, known as cartilage canals, course through the hyaline