TSUNAMI ANOMALIES AND PRECURSORY PHENOMENA HAVING POTENTIAL VALUE AS PREDICTORS

by

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ABSTRACT

The tsunamis generated within 600 kilometers of the northeast coast of the island of Honshu, Japan, are studied with respect to the frequency-magnitude relationship. Improvements in the definition of tsunami magnitude are found to be desirable, so new definitions are developed. For a logarithmically linear definition of tsunami magnitude, with correction for spherical spreading, an energy gap of more than one order is found. This is for a data base spanning one thousand years. Peculiar phenomena, both physical and biological, have occurred prior to some of the tsunamigenic earthquakes. These phenomena have potential predictive value. Additional instrumentation and field instrumentation is required.

BACKGROUND

A catalog of tsunamis for the vicinity of Japan has been compiled and published.[1] These data have also been subjected to statistical correlation methods.[2] To a first approximation, using the usual practice, the frequency versus size may be considered linear for that data base. However, on the basis of other data for other regions, a case for non-linearity has been proposed.[3]

On the occasion of the Third Meeting of the International Coordinating Group of the Intergovernmental Oceanographic Commission for Tsunami Warning Systems in the Pacific Basin, a field trip to the Tokoku coast on the northeast coast of the island of Honshu was arranged for the participants. This prompted an investigation of the frequency-magnitude relationship appropriate for tsunamis in that area.

IMPROVED DEFINITION OF TSUNAMI MAGNITUDE

For the historical tsunamis due to sources within 600 km and perpendicular to the Sanriku coast, as reported by the tsunami "grade-magnitude" method, a revised scale seems appropriate. The "grade-magnitude" is not linear with respect to energy, even after a logarithmic transformation. Therefore, a definition of tsunami magnitude is used that does have the desirable feature of being linearly related to energy after taking the logarithm of the appropriate run-up--i.e., that extrapolated to 1000 kilometers. Thus the definition used here, and proposed for universal

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use, is the logarithm to the base two of the run-up expected at 1000 km from the epicenter. This definition of the tsunami magnitude, designated the logarithmically linear scale, is significantly better than that proposed and used in the "Preliminary Catalog of Tsunamis in the Pacific Ocean."[4] Namely, data are reduced to a fixed epicentral distance even if not observed there. This is simply the introduction of a correction for geometrical spreading, but this is very important when analyzing tsunami data from some regions, e.g., the Sanriku coast. There the small tsunamis are generated relatively nearshore, whereas the large tsunamis are generated about two to three times farther offshore, almost in the Japan Trench. This correction of four to nine on the amplitude is considered significant.

In the course of this work, the desirability of upgrading the grade-magnitude of the 1896 tsunami became apparent. This is consistent with the summary statement by the Director of the Earthquake Research Institute, made in the Preface to the Special volume devoted to the 1933 tsunami and earthquake, dated March, 1934, that, ".... they were about the same." He is comparing the 1896 tsunami with the 1933 tsunami. (see Fig. 1)

NON-TRIVIAL FREQUENCY-MAGNITUDE RELATIONSHIP FOR TSUNAMIS

Although the tsunami data for all Japan display a linear relation between log frequency and tsunami grade-magnitude, the tsunami data for the Sanriku coast do not.[5] Instead, there is a hiatus on the energy scale, almost two orders of magnitude, for which no historical tsunamis have been observed. This large hiatus will be considered to cover "forbidden states" of the tectonic environment in that area. Although the spatial distribution of the tsunamis generated in the Sanriku area had previously been noted, relatively small inshore and relatively large offshore, the existence of an energy gap has not previously been noted. While of interest to tectonophysicists and other scientists involved with the basic science of the Earth, this observation and the corresponding hypothesis have immediate implications for tsunami prediction in the Sanriku coastal zone. (see Fig. 2)

Because of the rarity of tsunamis, even more rare than earthquakes since only a small percentage of earthquakes give rise to tsunamis, the statistical significance of the hypothesis of a tsunami energy gap was immediately questioned. Therefore, a study of the statistical signifcance was conducted, using the chi-squared test.[6] The results, subject to the limitations attendant in the use of the chi-squared test for significance,[7] indicate that the observed gap is significant at the 0.05 level. Hence the existence of the tsunami energy gap for tsunamis generated off the Sanriku coast is accepted as a working hypothesis.

PHENOMENA PRECEDING THE LARGER HISTORICAL TSUNAMIS ON THE SANRIKU COAST

In addition to the spatial and size anomalies already discussed for the tsunamis generated offshore from the Sanriku coast, there is claim for temporal variation of activity.[8] Imamura also documents observations of extraordinary large secondary undulations of the water in the ria coasts a few hours prior to the arrival of the major tsunami (and hence prior to its generation!). This was noted for the very large tsunamis of 1896 and 1933 and also for the small tsunami of 1894--but not for other tsunamis.

There have been numerous reports on "lights" accompanying earthquakes. Since these reported lights were usually observed concomitant with the earthquakes, they are of no predictive value.

In the case of tsunamis, the light seems to often occur from the direction of the sea. One possible explanation is that the light is generated by luminescent plankton excited by the tsunami. If this explanation is correct, then the light provides a natural signal of the impending tsunami.[9] Time should be sufficient for an active person to run to high ground if unimpeded by paraphenalia. The explanation appears reasonable since, in a separate incident, a wave generated by a landslide was the source of light.[10] Other observers of light associated with a tsunami attributed it to luminescence of the animals on the sea-bottom, exposed during ebbing of the tsunami. This would be of value to a warning system only if the tsunami began as a withdrawal.

PRIMARY PHYSICAL PREDICTORS OF EARTHQUAKES AND TSUNAMIS

Extensive efforts, ranging over several fields of geophysics, have been made to record physical phenomena prior to an earthquake that would be useful for predicting the earthquake in time and location. In Japan, such efforts were industriously begun in the 1930's. Recent studies in Japan have concentrated on statistical analyses,[11] measuring strain,[12,13] electrical conductivity,[14] or temporal changes in seismic velocities.[15] Successful long-range forecasting of the occurrence of earthquakes having magnitudes greater than six has sometimes been possible. Much remains to be done before an earthquake warning system, sufficiently reliable for public operation, can be instituted with assurance of voluntary compliance.

SECONDARY BIOLOGICAL PREDICTORS

There are many reports of certain animals, such as carp, birds, cats, and dogs, behaving in a peculiarly disturbed manner a few moments before an earthquake was noticed by humans. The peculiar behavior of fishes just before an earthquake has been reported by Musya. The catfish has been the subject of a special study by Hatai.[16]

The 1933 tsunami-earthquake pair exhibited anomalous behavior of fishes several hours before the event. Two such peculiarities occurred. First, on the evening prior to the day of the earthquake, and thus about eight hours before the event occurred, the stomachs of *Sardina melanostica* were found to be gorged to almost five times normal weight on species of diatoms such as *Synedra* and *Fragilaria*, which usually adhere to the bottom of the sea.[10] The diatoms probably appeared in the upper layer of the sea where the fish were caught by a purse seine. An analogous relationship between fish and the Kwanto earthquake of 1923 has been reported by Togo.[17]

The second observation is also reported by Musya. A specimen of Nemichtys avocetta, a rare deep-sea fish normally found at depths greater than 500 m, was caught on the coast at 7 a.m. on 3 March 1933, only about four hours after the earthquake-tsunami event. The fish could not have reached the coastline by swimming, if it left a depth of 500 m at the time of the earthquake. Hence, it must have been prompted to leave the depths several hours before the earthquke occurred.

A careful review of several such documented reports has convinced this writer that there is some unresolved associated phenomenon. Some scientists have argued that modern instrumentation is so greatly improved as regards sensitivity and dynamic range, etc., that surely the causative field can be measured. Although this is probably true, the fact remains that which field to measure, when to measure it, and with what instrumental characteristics remains unknown. Even if some field were observed to be disturbed shortly before an earthquake, such would not prove it to be the causative field. A controlled experiment in a seismic area is definitely desirable and feasible using the current technology of videotape recording.

IMPROVED DEFINITION OF TSUNAMI MAGNITUDE

An improved definition of tsunami magnitude has already been given in this paper. That definition, as well as the earlier, cited definitions, has the defect of being dependent on the number of observations made. Thus, if a potion of coastline is subjected to meticulous scrutiny, the extreme run-up is likely to be greater than if only a cursory examination is made. Here, each observation is considered to be a sample drawn from the "population" of run-ups occurring on that coastline.

This effect has not passed unnoticed. Cox used the upper decile value to represent the run-up at Hilo, Hawaii, for the 1960 value.[18] This choice was based on intuition.

That the effect is theoretically important can be seen by considering the log-normal distribution, sometimes used for modeling tsunami run-up. Since the basic distribution is unlimited in range, the extreme will increase towards infinity with increased sampling.

To remove this difficulty of the index value of run-up being dependent on the thoroughness of monitoring, a revised definition is suggested. Consider the distribution of run-ups to be $f(x)$, with the cumulative probability $F(x)$. The probability of a value equal or greater than x is $[1 - F(x)]$; so in n observations, $n [1 - F(x)]$ values are expected to be equal or greater than x .

For n observations, there is some number for which the expected exceedance is one. This number is defined by $u_n = F^{-1}(1 - 1/n)$. Call this the characteristic largest value.[19] The characteristic nth extreme can be defined in an analogous fashion as

$$F(u_m) = 1 - m/n \quad \text{with} \quad u_m \equiv u_m(n) .$$

This definition does not achieve the ideal of making the index run-up independent of n ; the characteristic largest value usually depends on n . However, this index has the value of drawing attention to the dependence of the index on n . This is only achieved, however, at the requirement that the distribution of the source population be specified.

An improved definition for tsunami run-up consists of the characteristic largest value for a fixed n ; here the value 10 is proposed, with observations made for other n being appropriately adjusted.

SYNOPSIS

The rarity of tsunamis, even relative to large earthquakes, makes the prediction and understanding of tsunamis difficult. Most statistical studies of tsunamis have combined data for earthquakes in many tectonic provinces. Although this practice allows simple estimation of the variance by using large sample-size theory, it also incorporates the variance due to "between tectonic provinces". By limiting study to one active tectonic province, it is possible to obtain results having a variance dominated by the "within-tectonic province" effects. The present study has concentrated on the tsunamis generated within 600 kilometers of the northeast coast of the island of Honshu in Japan. These tsunamis do not display a quasi-linear relation between frequency of occurrence and tsunami size, such as is characteristic of earthquakes, even when a logarithmically linear definition of tsunami magnitude is used. Indeed, there is an energy gap of more than one order of magnitude for which no tsunamis have been documented in the past one thousand years.

Of most practical importance are the peculiar phenomena observed prior to those tsunamis greater than grade magnitude 2. For such large tsunamis, both physical phenomena, such as seiching in the harbors of the ria coastline, and biological phenomena, such as surface fish feeding on ocean-bottom diatoms and migration of deep-water fish, have often been observed several hours in advance of the tsunamigenic earthquakes. Routine monitoring of such on-going phenomena provides a relatively inexpensive way of reducing the risk to life and movable property due to tsunamis.

Ocean-bottom measurements of strain should ultimately permit long-term forecasting of tsunamigenic earthquakes with an accuracy that would be useful to owners of real property in tsunami-prone areas and to public officials responsible for formulating building regulations for such areas. Time-dependent building regulations for tsunami-prone areas should be feasible if adequate submarine instrumentation is installed and the data monitored, analyzed, and evaluated. The one offshore seismograph that existed in the subject area was limited to observation of particle motion.

Tsunami magnitude has been defined as the extreme of a set of extremes; thus the variance is larger than an alternative definition in terms of the average of the set of extremes. Furthermore, geometrical spreading is only crudely considered in the existing definitions but digital ray-tracing techniques now permit a refined correction for such energy variation. A definition of tsunami magnitude, improved from the standpoint of having reduced variance, is given.

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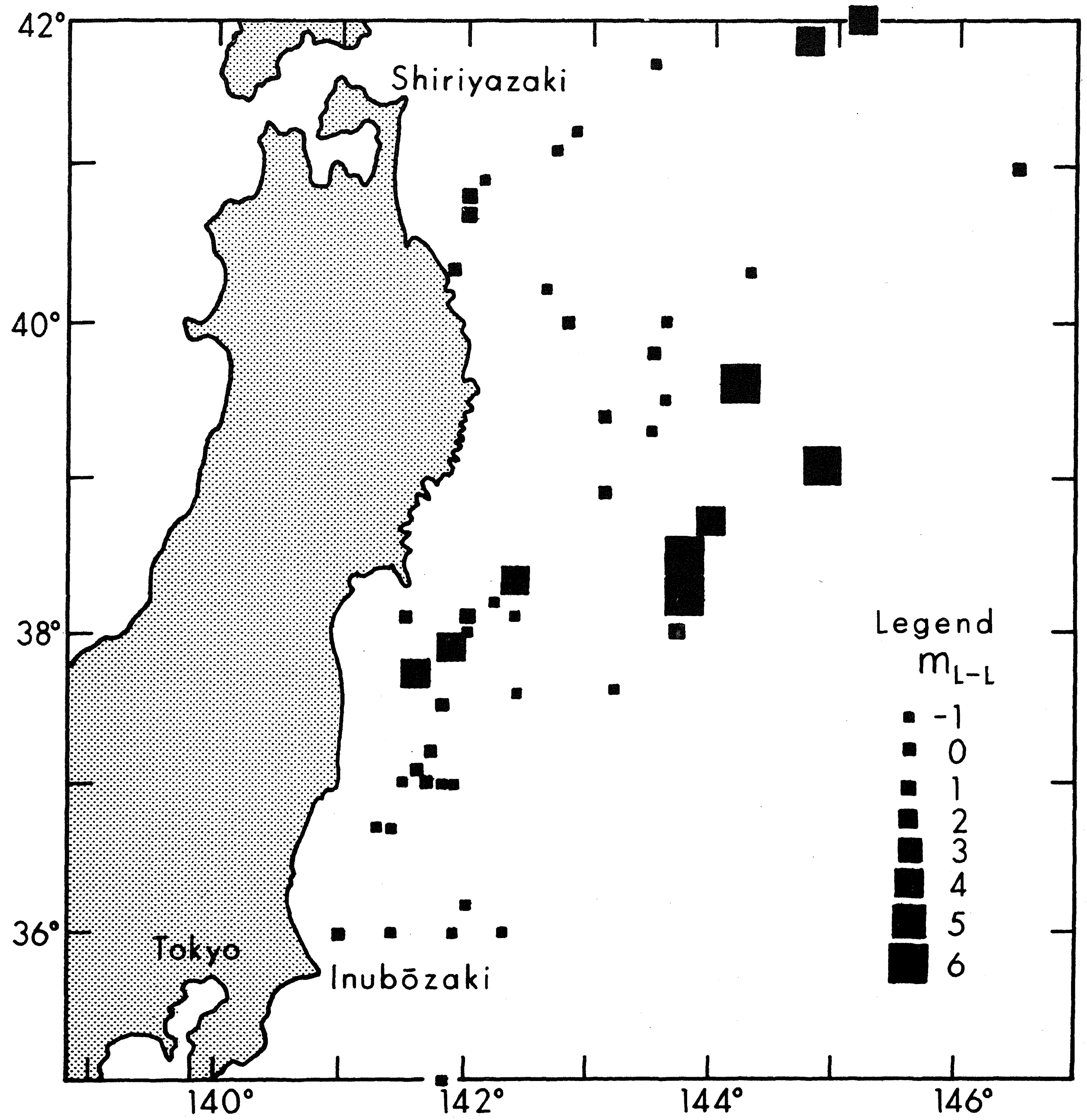

FIG. 1. A MAP SHOWING THE DISTRIBUTION OF THE EPICENTERS OF TSUNAMIGENIC EARTHQUAKES OFFSHORE FROM THE TOHOKU COAST.

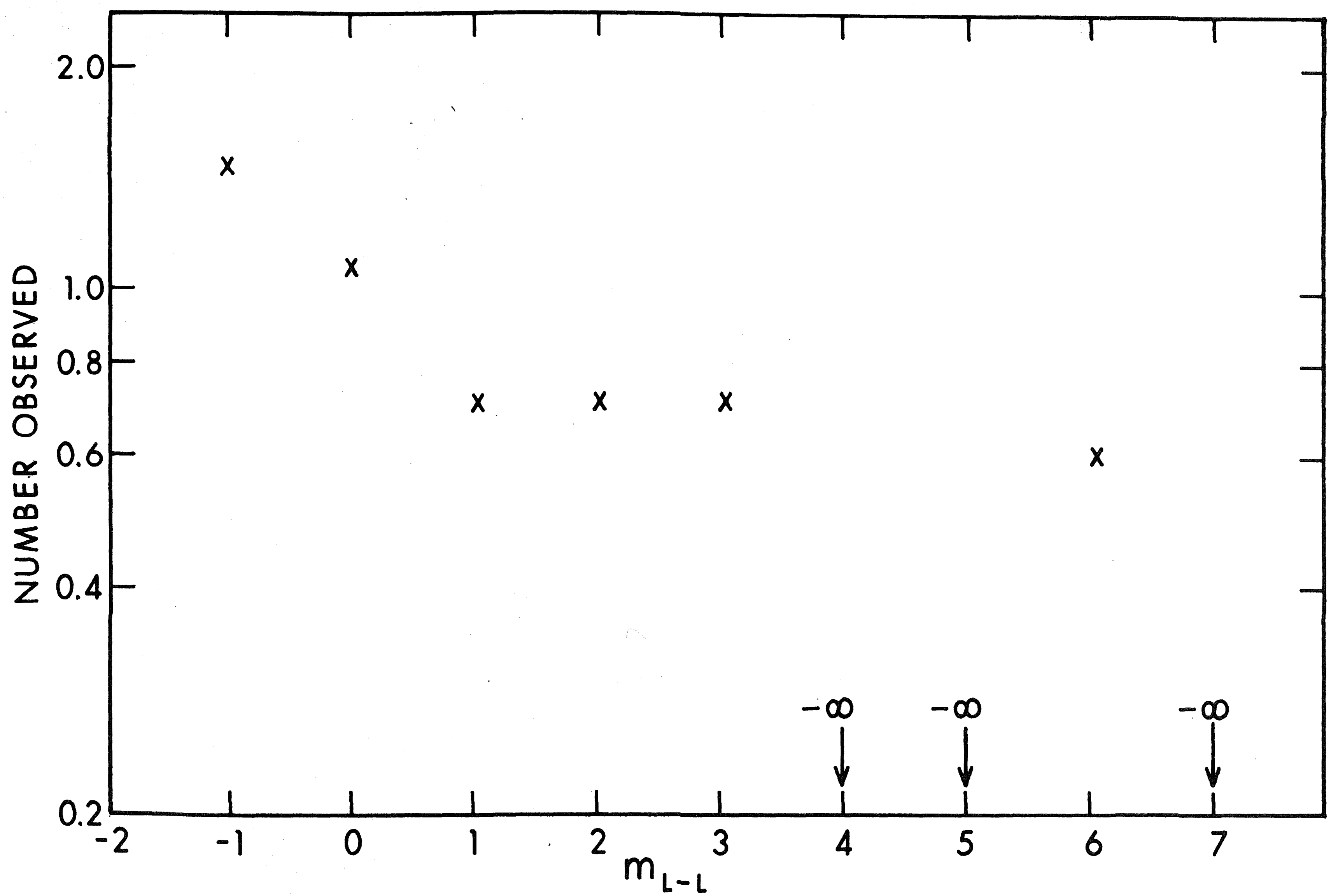

FIG. 2. A GRAPH OF THE LOG-FREQUENCY VERSUS THE LOGARITHMICALLY LINEAR TSUNAMI MAGNITUDE SCALE, WITH A CRUDE CORRECTION FOR SPHERICAL SPREADING (RAY TRACING HAS NOT BEEN USED).