Tektites Are Terrestrial

Age determinations link the origin of some tektites to specific impact craters on the earth's surface.

Henry Faul

To anyone who has worked with them, tektites are probably the most frustrating stones ever found on earth. For almost 200 years these glassy objects have been scientifically collected, studied, and subjected to every conceivable kind of analysis. A vast amount of data has been accumulated, but one still can draw only a very crude outline of the physical and chemical processes that formed the tektites. It has been established that tektite-like glass is produced in hypervelocity impacts on rocks; that tektites formed and cooled enough to be rigid before they entered (or reentered) the earth's atmosphere; and that aerodynamic ablation partly melted them again on their passage through the atmosphere. The exact process of tektite formation remains largely a mystery, but age measurements are beginning to show *where* this formation occurred. The violent controversy over a terrestrial versus an extraterrestrial origin for tektites is nearing its end.

The age of a tektite can be measured in several different ways. One may determine the amount of Ar^{40} that has accumulated from the decay of K^{40}, or one may develop and count the tracks left in the tektite glass by the spontaneous fission of U^{238}, or one may determine the present-day Sr^{87}/Sr^{86} and Rb^{87}/Sr^{86} ratios in the glass and extrapolate to the initial Sr^{87}/Sr^{86} ratio, drawing the strontium isochron. These three ages have different meanings. The potassium-argon method dates the time when argon diffusion in the glass became negligible compared to the rate of its generation from potassium decay. The fission-track method establishes the time of last cooling to a temperature where the tracks in the glass remain stable with time. If a tektite has been through a grass fire, for example, the fission tracks will date the fire. That is one reason why ages measured by the fission-track technique are occasionally lower than ages determined by the potassium-argon method. The Sr^{87}/Sr^{86} and Rb^{87}/Sr^{86} ratios are not altered by melting, hence the strontium isochron age of tektites refers primarily to their parent material. If that was a crystalline rock, then the isochron dates the time when this rock was derived from the earth's mantle, directly or indirectly. If it was a sediment, then the isochron age is an average of the ages of the primary rocks from which the sediment was derived.

Tektite Fields

There are basically four groups of tektites, undoubtedly formed in four separate events. The largest and youngest tektite field is in the southwest Pacific area, where tektites are found in the southern part of Australia and in Indochina, China, the Philippine Islands, and Indonesia (*1*). Australasian tektites differ slightly in physical and chemical properties from area to area; they are uniformly dark brown in transmitted light, and their ages, measured by the potassium-argon and fission-track methods, are about 700,000 years (*2*). The Australasian field is by far the largest known tektite field. It is so large, when its possible extension into the Indian and Pacific oceans is taken into account, that geographic arguments for a terrestrial origin of tektites hardly apply to it, as we shall see.

The next older tektites are found in the Ivory Coast Republic (Fig. 1). They occur in a relatively unexplored region and are rare. Both potassium-argon and fission-track dating methods give their age as about 1.5 million years (*2*). They are also dark brown.

Moldavites, the Czechoslovakian tektites named after the Moldau (the German name for the river Vltava), are next in age. They occur in a small area (about 50 kilometers long) in southern Bohemia and in an even smaller district in southern Moravia (Fig. 2). Again, there are slight differences in color and chemical composition (*3*). Bohemian moldavites are light green and Moravian ones are olive green or brownish, but both the potassium-argon and the fission-track dating methods yield ages close to 14.8 million years for all of them (*2*). The extent of the moldavite fields (*4*) is better known than the extent of any other tektite area, and a wealth of geologic detail (*5*) is available.

The oldest tektites are in America, in east-central Texas and south-central Georgia (Fig. 3). The Texas tektites (called bediasites after the Bedias or Bidai Indians) are generally brown, and the Georgia tektites are greenish and lighter in color, but ages of about 34 million years have been obtained for all of them. A single tektite was found on Martha's Vineyard in Massachusetts, but this solitary stone is indistinguishable from Georgia tektites and of exactly the same age. One cannot ignore the implication that it was brought to the island by man (*6*). The geology of Martha's Vineyard has been studied meticulously, and the area has been combed in search of another tektite, without success.

Geology

Tektites are always found on the surface or in sediments much younger than the measured age of the tektite glass (*7*). I am not aware of any valid report of a tektite's having been found in sediments of the same age. Bediasites are found in young gravels on the surface of the Jackson group of formations, usually considered to be of Late Eocene age. In Grimes County, Texas, they are found along the middle and lower parts of the Jack-

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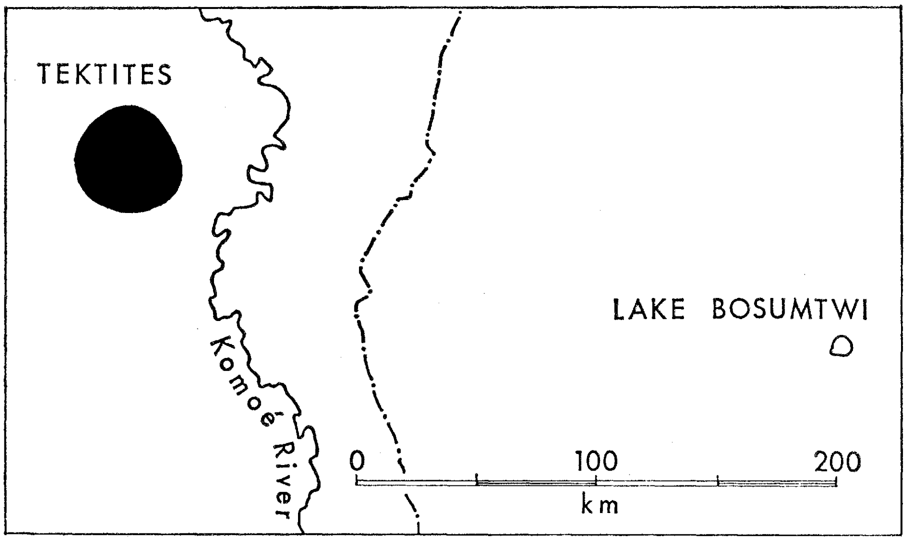

Fig. 1. The Bosumtwi crater in Ghana and (solid area) the approximate area where the Ivory Coast tektites are found.

son group, in Fayette County they occur along the upper part of the group, and elsewhere they lie in between. In view of the rarity of tektite-making events in general and the uniformity of bediasites in particular, one could hardly assume that more than one bediasite shower had occurred. The area now underlain by the Jackson group has undergone extensive uplift and erosion in post-Jackson time, as well as some warping, as shown by the relatively high dips of the Early Pleistocene Citronelle formation (*8*). Thus it appears probable that bediasites now found on the surface of the Jackson group have been moved by water.

Bediasites are now weathering out of the Jackson formations. If one accepts the view that the Jackson group belongs to the Late Eocene (about 40 to 45 million years ago), then one says, in effect, that Jackson time had ended more than 5 million years before the bediasites fell. That time interval is too large to be ascribed to errors in the age determination for the bediasites or to inadequacies of the Cenozoic time scale. Either Jackson rocks were exposed at the time of the bediasite fall, or else Jackson time extended well into the Oligocene.

Georgia tektites are exceedingly rare. They are found on the surface of young (Pliocene-to-Pleistocene) gravels that unconformably overlie Eocene, Oligocene, and Miocene rocks. They could have been reworked from any of them (*9*).

Moldavites had been thought to be Middle Miocene in age (*10*) long before their age was measured by the potassium-argon method. When this method gave an age of 14.8 million years, the result was hailed as confirming the stratigraphic correlation (*2*). It was even suggested that moldavites could be used as a tie point for the Helvetian stage in the Cenozoic time scale. Detailed geologic survey of the Moravian moldavite field, together with a study of the distribution of unusual and characteristic minerals of restricted provenance in the moldavite gravels (*5*), has shown that the earlier stratigraphic correlation is invalid. Moldavite gravels are all very young, Late Pliocene or younger. All known moldavites have been transported by water, even though the distances cannot have been very great (*4*).

Ivory Coast tektites are found in recent gravels on an ancient (2000-million-years-old) crystalline basement (*11*). Australasian tektites also occur on the surface or in strata generally younger than the tektites themselves, but occasionally there is room for doubt in correlating Pleistocene sediments. Hence the argument from stratigraphy carries less weight for these fields than for the older tektite fields.

The Age Paradox

It should not be surprising that tektites are not found where they landed. They are, first of all, geologically rare, even in places where they are most "abundant." In the tektite areas outside Asia it takes a trained man hours to find one.

Even in the Australasian field there are only a few places where tektites are sufficiently numerous to be picked up by the handful.

Being in the size range of gravel, tektites are readily concentrated by running water, especially by the intermittent water of streams in flood. Thus it is obvious why tektites occur in gravels. Furthermore, there is good evidence that tektites dissolve rapidly in pelitic sediments, especially where the *p*H is high. The Besednice brick pit occurrence in Bohemia is a good example. The tektites found in the white calcareous clay there are often corroded to mere slivers, yet the clay is quite young and the tektites were probably washed into it. There is no evidence that they fell there.

Hence the supposed paradox of stratigraphic versus radiometric age for tektites seems to be largely imaginary. A tektite is much more likely to have been transported than to lie where it fell. An analogy is the common occurrence of placer gold in stream gravels as opposed to the rarity of "mother lodes" upstream.

The Flight

It is an established fact that tektites fell from the sky. Aerodynamic ablation experiments with tektite glass (*12*) have gone a long way toward explaining how tektites entered the earth's atmosphere and how they interacted with it. Comparison of synthetically produced ablation forms with the morphology of some well-preserved australites has shown that australites entered the atmosphere at velocities around 10 kilometers per second, and at low angles. Strictly speaking, these results apply only to Australasian tektites, but it has been shown that at least one bediasite and one moldavite also have the flattening that is characteristic of aerodynamic ablation (*13*), and one may accept the conclusion that the entry of the less-well-preserved groups of tektites was not very different from the flight of the australites.

But what happened before the tektites entered the atmosphere? The lack of any evidence of cosmic-ray interaction with the tektite glass (*14*) shows that tektites were not long in space. They could not have come from far away, astronomically speaking. An object in the mass range of even the largest tektites will be slowed down to a halt after only a few kilometers' flight

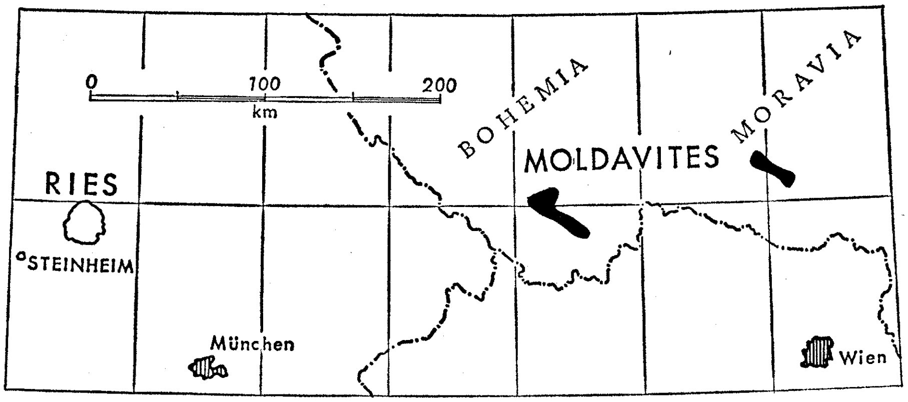

Fig. 2. The Ries and Steinheim craters in Germany and (solid areas) the tektite fields in Czechoslovakia.

in air at atmospheric pressure, no matter how great its initial velocity may have been. Thus we are left with two alternatives. If tektites originated on earth, then they had to fly up through an atmosphere that either moved along with them or was temporarily greatly rarefied, presumably by the event that produced the tektites (*15*). Alternatively, the tektites could have come from outside the earth's atmosphere, presumably from the moon.

Possibility of a Lunar Origin

There is much that motivates theorizing that tektites came from the moon. Both the composition and the morphology of tektites could be more easily understood if one could assume that the glass was made in a vacuum. Some tektites have bubbles in them, and many of these bubbles preserve a more or less high vacuum (*16*). Tektite glass contains an extremely small amount of water, 10 to 100 times less than man-made glass and 1000 times less than obsidian (*17*). The spherical and drop shapes of well-preserved tektites indicate some kind of splash of the molten glass and an absence of any strong forces acting on the still-molten particles. Solidification of molten tektite requires from a fraction of a minute to a few minutes, depending largely on its size. During this interval, surface tension seems to have been the dominant force in the shaping of the tektites. These processes can be most readily imagined as occurring in a vacuum. The lunar vacuum would seem to be ready-made for such purposes.

Furthermore, if it could be assumed that tektites are thermally altered samples of the lunar surface, then it would follow that the moon has a highly siliceous crust, with all the attendant implications of internal melting, magmatic differentiation, and an internal structure analogous to that of the earth. The tektite evidence then could be used to sweep aside the alternative hypothesis of a cold undifferentiated moon composed essentially of material similar to stony meteorites. A whole class of hypotheses concerning the origin and early history of the earth then could be dismissed.

One fatal objection has long stood in the way of the lunar origin hypothesis: the lack of any focusing mechanism that would keep the hypothetical tektite swarm together on its long journey from the moon. Only the Australasian tektite field is large enough to be attributable to a fall from an extraterrestrial source (*18*), and even there one would have to postulate very little mixing within the tektite swarm en route in order to account for the small but real differences observed in Australasian tektites from place to place.

No mechanism is known that would permit transportation of ejecta from some lunar crater into a target area as small as the tektite fields in Bohemia and Moravia or on the Ivory Coast. The various proposed mechanisms in-

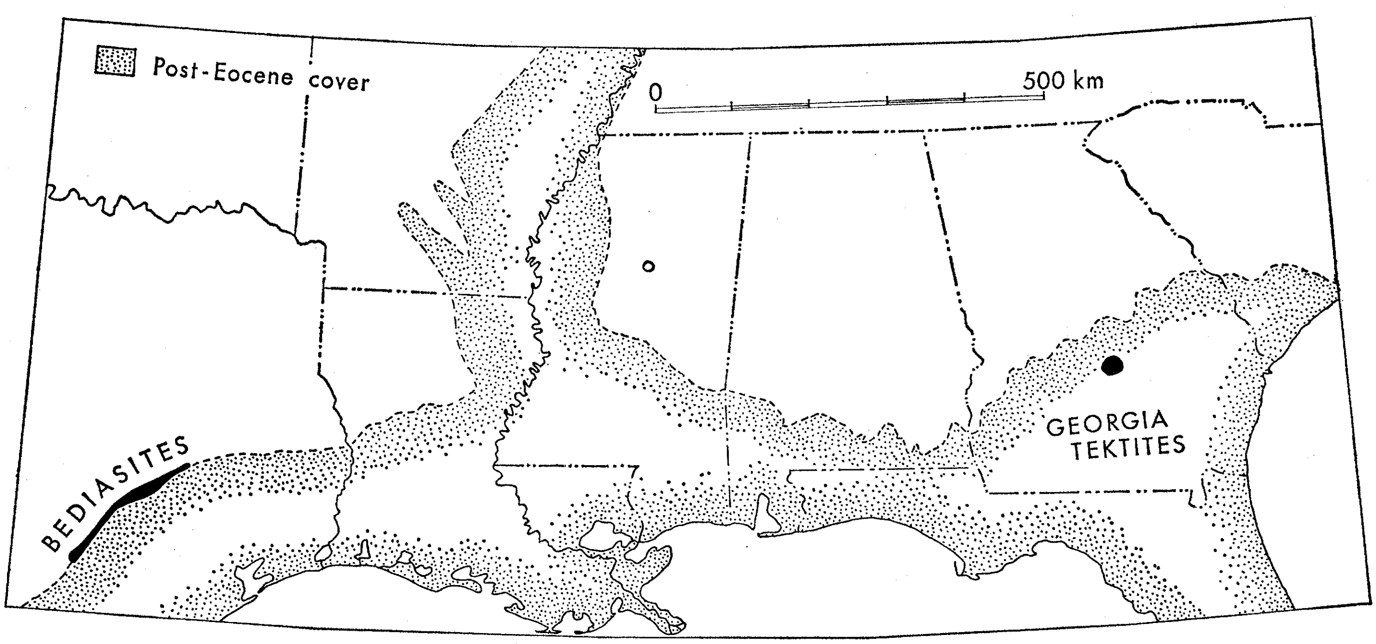

Fig. 3. (Solid areas) Regions where tektites are found in Texas and in Georgia. (Stippled areas) Regions covered by sediments deposited after the tektites fell. (Open circle) The Kilmichael crater in Mississippi.

volving intermediate parent bodies (*19*) also would produce strewn fields much too large to fit the facts. Theoretical analysis of the phenomena following the impact of a large body on the earth indicates that tektites could be formed in such an event (*15*). A body such as a comet with a geocentric velocity of several tens of kilometers per second, a density of the order of 0.1 gram per cubic centimeter, and a mass greater than about 5×10^{17} grams, colliding with the earth, would have sufficient energy to blow a momentary "bubble" in the earth's atmosphere and thus produce, for a moment, an environment suitable for the production and ejection of tektites from a terrestrial crater (see *15*).

Tektites and Craters

The proposal that moldavites are associated with the crater called Nördlinger Ries, in south-central Germany, was made even before it was known that impact glass from the Ries had the same age as the moldavites (*20*), which are found roughly 300 kilometers to the east. There were uncertainties about the validity of the first age measurements because of difficulties in completely extracting the radiogenic argon from the viscous tektite melt, but these technical problems have been resolved, and the age measured by the potassium-argon method has now been confirmed by the altogether independent method of fission-track counting. Within the limits of experimental error, the age of the moldavites and of the crater has been established, by these two independent methods, as 14.8 million years (*2*).

The glass in the debris around the Ries crater and the moldavites are of the same age, but their chemical compositions are different. The crater glass is chemically similar to granitic gneiss. Such gneisses are exposed in the Black Forest, a little more than 100 kilometers west of the Ries, and externally similar but severely shocked and altered rock fragments are common in the crater debris. The moldavites, like all tektites, have chemical and isotopic compositions reminiscent of weathered crystalline rocks or the sediments derived from them. In the Ries area, the crystalline basement rocks are overlain by sediments about 500 meters thick. The crater glass and the moldavites could not have come from the same melt but could have been produced by the melting of different rocks during separate phases of the same explosive event.

Another tektite field has a crater nearby. The Ivory Coast tektite area lies roughly 300 kilometers west of Lake Bosumtwi (in Ghana), an undoubted impact crater. Here again the two dating methods give the same result for glass from the impact area and for the tektite glass—about 1.3 million years (*2*). Again, there are some uncertainties about the results, but in this case the uncertainties stem mostly from the obvious fact that an age of 1.3 million years is more difficult to measure than one of 15 million years. As repeated measurements are made, the experimental error is reduced and it becomes clearer and clearer (*21*) that Lake Bosumtwi and the Ivory Coast tektites were formed at the same time.

The American tektites are not clearly associated with any known impact structure. The Gulf coastal plain region is geologically a poor place to look for an Oligocene crater. The geologic history of the coastal region makes for a vanishingly small probability that any trace of such a crater could be seen there today, had one existed. Further northward, the Kilmichael, Mississippi, structure is large enough and possibly old enough to be considered a possible source of bediasites and Georgia tektites, but it is a difficult one to study. For glass from the Clearwater Lake crater in northern Quebec, the fission-track dating method yields an age of 33.5 ± 4.5 million years (*2*), roughly in agreement with the age of the American tektites. This age has not been confirmed by potassium-argon dating. The rocks in the vicinity of Clearwater Lake are very ancient, and American tektites could not have been made from them. The strange glass found in great quantity in the Sand Sea of the Libyan Desert also has a similar age (*2*), but it is difficult to imagine what physical connection this glass could have with American tektites.

The size and geography of the Australasian tektite fields strain the imagination in considering a possible association of tektites and craters. The tektites might have come from more than one crater, and hypothetical locations in Antarctica and Indochina have been proposed (*22*). The craters would not have formed in the deep sea, but might have formed in the large areas of shallow water. Of the several known dry-land craters in Australasia, none seems to fit.

The Place

Ages yielded by the potassium-argon and fission-track methods link tektites with craters in terms of time but not necessarily in terms of place. The strontium isochron method, however, has the potential for showing *where* tektites were made.

Whatever the exact process of tektite formation may have been, it could not alter the average Sr^{87}/Sr^{86} ratio of the material, and it could only slightly reduce the Rb^{87}/Sr^{86} ratio by fractional volatilization of the silicates. Hence it is possible to make age determinations on tektites by the whole-rock strontium method. When plotted on an isochron diagram, the ages obtained in this way for American, Australasian, and Czechoslovakian tektites all fall roughly on the same line with a zero intercept (the initial Sr^{87}/Sr^{86} ratio) of about 0.705 (*11*). The slope of the line corresponds to an age of about 400 million years. If allowance were made for a rubidium loss of, say, 25 percent, the age would be correspondingly lower, or roughly 300 million years.

This curious agreement for the three groups of tektites could be interpreted in two entirely different ways. Either (i) these three kinds of tektites were formed from a common source material now 300 to 400 million years old, or (ii), in the case of the moldavites, this age would reflect the 300-million-year age of crystalline rocks of the German crystalline basement north of the Alps (*23*) but the apparent agreement of the American and Australasian tektite isochrons with the moldavite isochron would be, for the moment, unexplained.

For some time, the first interpretation seemed the more likely. It would favor the hypothesis of an extraterrestrial origin of tektites, in view of the difficulty of explaining how rocks at three regions on earth, "picked" effectively at random by the impacting bodies, could have the same strontium isochron age.

As it turns out, however, the second interpretation is probably correct. The crucial argument comes from recent age measurements, by the whole-rock strontium isochron technique, for the Ivory Coast tektites and for a suite of rocks from the vicinity of Lake Bosumtwi (*11*). The lake is located in a region of metasedimentary and granitic rocks with hardly any sedimentary cover. The rocks give a clearcut isochron with a slope equivalent to 2000 million years, and both the Ivory Coast tektite glass and the impact glass from Lake Bosumtwi fall convincingly on the same isochron, or a little to the left of it, as would be expected had there been a slight loss of rubidium. There can be little doubt that Ivory Coast tektites were made from rocks 2000 million years old, and that such rocks once lay on the spot now covered by Lake Bosumtwi.

Origin of Tektites

The accumulating geochronologic evidence indicates more and more convincingly that tektites were formed from terrestrial rocks in large meteoritic impacts on the earth. Ivory Coast tektites were formed about 1.3 million years ago, simultaneously with the Bosumtwi crater, and from rocks 2000 million years old. The rocks around the crater are of the same age. Moldavites were formed 14.8 million years ago, simultaneously with the Ries crater, and from rocks now roughly 300 million years old. Crystalline rocks throughout Germany north of the Alps are about 300 million years old. North American tektites were formed 35 million years ago, but no crater is known to be associated with them. Their age, as determined by the strontium isochron method, would be compatible with an origin from Appalachian granites, volcanic rock, or sediments derived from them.

Not much can be said about a parent rock for the Australasian tektites, except that it would be roughly 200 to 400 million years old. The principle of simplicity suggests that one might more profitably look for large concealed craters in that vast region than postulate an extraterrestrial origin for the tektites.

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24. This article is contribution No. 29 from the Geosciences Division of the Southwest Center for Advanced Studies of the Graduate Research Center of the Southwest.

Radiation-Induced Mutations and Their Repair

Bacteria reduce the mutagenic effects of ultraviolet light by repairing DNA damaged by the radiation.

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Ultraviolet light kills bacteria, and it also induces mutations among the survivors. For many years, radiobiologists have suspected that both effects start with photochemical changes in the nucleic acids of the exposed cells (*1*). Recently, they have succeeded in identifying specific photoproducts, formed in the DNA of irradiated bacteria, that contribute to the bactericidal effect of ultraviolet light, and have begun to understand how bacteria sometimes repair potentially lethal radiation damage (for recent reviews, see *2–4*). This article explores the roles played by newly discovered products of ultraviolet irradiation and by the mechanisms whereby such damage is repaired in the induction of mutations.

The first photochemical lesion found in the DNA of irradiated bacteria was the thymine dimer (*5*). Ultraviolet light produces thymine dimers mainly by linking adjacent thymine bases in the same strand of DNA, via carbon-to-carbon bonds. (Normally, of course, the purine and pyrimidine bases in a single strand of DNA are connected only to the sugar-phosphate "backbone," and not to each other.) Other pyrimidine dimers (cytosine-cytosine and cytosine-thymine) are also formed in irradiated DNA, but probably less efficiently than dimers of thymine (*2, 6, 4*). Dimers containing thymine block DNA replication in vitro (*7*) and in vivo (*8*) and are responsible for an important fraction of the lethal effects of low doses of ultraviolet light in some strains of bacteria (*8*).

Pyrimidine dimers are subject to repair in the bacterium *Escherichia coli*. They may be eliminated from the DNA of irradiated cells in one of two known ways. The first requires exposure, after irradiation, to an intense source of visible light (the most effective wavelengths being those around 4000 angstroms), a treatment known to reverse or "photoreactivate" many of the biological effects of ultraviolet light (*9*). In one kind of photoreactivation, pyrim-

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