Airview shows the trace of the San Andreas fault in Carrizo Plain, west of Bakersfield, California. The elongate scarp in the foreground and the linear break in the field beyond show the line of displacement during the great 1857 earthquake, which followed the same path as previous breaks in the recent geologic past.

EARTHQUAKES, FAULTING, AND NUCLEAR REACTORS

by Clarence R. Allen

Most of the recent controversy concerning seismic hazards to proposed nuclear facilities in California has centered not on the usual problems of earthquake-resistant design but instead on the possible hazards associated with ground displacements by faulting through the foundation of a nuclear plant. In addition, there has been much difference of opinion as to the maximum credible earthquake that should be specified for any given area.

A large proportion of the public opposition to specific sites has centered on the problem of safety, because many individuals have apparently felt—rightly or wrongly—that this was the only effective political means by which they could oppose the development. The government has made it very clear that exceptionally stringent safety requirements must be satisfied before plants will be licensed. Within the field of safety, arguments have tended to focus on geological aspects of the seismic hazard, partly because this field is admittedly less quantitative and less thoroughly understood than engineering aspects, and thus more open to debate.

Nevertheless, some very legitimate geological-seismological questions have been raised in these controversies, and some proponents of specific sites have tended to underestimate these factors in the over-all evaluation of safety. Furthermore, it has become abundantly clear that more research is needed in this field if we are to be fully confident that our seismic design and siting criteria are adequate to ensure public safety.

Much evidence has accumulated in recent years to indicate that most earthquakes are caused by faulting. During large earthquakes this faulting may start at some depth in the earth's crust and extend to the surface where it abruptly displaces the ground by as much as 11 meters vertically (India, 1897) and 9 meters horizontally (Mongolia, 1957). Even very small earthquakes are occasionally accompanied by surface faulting if the focus is unusually shallow; a recent shock of magnitude 3.6 in the Imperial Valley of California, where it was only locally felt, was associated with a 1.5-cm horizontal displacement at the surface along the Imperial fault.

Continuous gradual slippage (or "creep") along

"Earthquakes, Faulting, and Nuclear Reactors" has been adapted from a talk given to the International Association of Atomic Energy panel meeting on Aseismic Design and Testing of Nuclear Facilities in Tokyo, June 1967.

Gradual horizontal slippage, or "creep," has been taking place for several years along a branch of the San Andreas fault in Hollister, distorting this wall and damaging a number of houses along the fault trace.

faults, without accompanying earthquakes, is being observed at an increasing number of localities in California. It now appears that this is a much more common phenomenon than we thought only a few years ago. Slippage along the San Andreas fault near Hollister averages about 1.7 cm/yr, and slippage along the same fault near Parkfield continues at about 0.1 mm/day even one year after the magnitude 5.6 earthquake that started this particular "episode."

Slippage may well have occurred episodically along virtually all active faults in California, and this is an additional reason for avoiding such faults in locating major engineering structures—a reason that is not being fully appreciated in numerous current housing developments in California. Particularly in the San Francisco and San Bernardino areas, many houses have recently been built squarely astride the most recent trace of the San Andreas fault in areas where it could have and should have been clearly recognized and taken into consideration.

Vertical aerial photograph of the northern part of San Bernardino, taken in the late 1920's. The dark line crossing the picture delineates the most active trace of the San Andreas fault, which dams ground-water and thus controls vegetation. This line is barely visible on more recent photographs because much of the area is now covered by houses—many of them straddling the fault trace.

The white line along this mountain front is the 1915 earthquake scarp south of Winnemuca, Nevada. Despite the predominance of vertical displacement, the scarp is a single, relatively simple break along most of its 35-km length.

Although small earthquakes occur in nearly all parts of California, almost all large earthquakes have occurred in close association with major faults that had been or could have been mapped by geologists prior to the earthquakes. Likewise, future large earthquakes will probably be limited to areas of active faulting, and most active faults in this region can be recognized by physiographic features of the disturbed ground surface, such as recent scarps, elongate closed depressions, rift-like valleys, and displaced stream channels.

Indeed, the geologist is generally in a better position to delineate these areas of possible large earthquakes than is the seismologist, who must necessarily work with a relatively short history of instrumental records. Despite a very complete 34-year instrumental record of detailed seismicity in southern California by the Caltech Seismological Laboratory, there are many reasons for believing that this record is not a statistically adequate sample for extrapolating into the future. In fact, a seismic energy-release map for the past 34 years probably gives a partially *reversed* picture for the next 34 years, and extreme caution must be used in extrapolating historic seismicity data into the future unless many hundreds of years of data are available.

Similarly, a recent Caltech study of micro-earthquakes at more than 60 sites along the San Andreas fault system indicates that micro-earthquakes share the same statistical distribution as the larger shocks and are probably no better indicators of future activity. Parts of the San Andreas fault that have broken during great earthquakes as recently as 1857 and are prime candidates for future great earthquakes, nevertheless show a virtual absence of micro-earthquakes today. Segments of active faults characterized by occasional very large earthquakes may, in the intervening periods, be characterized by extremely low seismicity, possibly due to some "locking mechanism;" segments of faults characterized by the absence of very large earthquakes may, in turn, be characterized by more-or-less continuous seismic activity on a smaller scale. In any given area it will take the close cooperation of geologists and seismologists to give the best evaluation of potential seismicity, and engineers must recognize that a precise evaluation is an impossibility at the present state of the science.

Although California's San Andreas fault and associated earthquakes were once thought to be unique and unusual, recent studies indicate that the geological and seismological characteristics of California are shared by many other circum-Pacific areas. Regional throughgoing faults similar to the San Andreas have now been recognized in Alaska, Canada, Mexico, Venezuela, Chile, New Zealand, Sumatra, the Philippines, and Taiwan, in addition to far-removed areas such as Turkey. Nevertheless, not all areas of high seismicity appear to be tectonically dominated by similar throughgoing fault systems; Japan, for example, appears to be geologically very different from California, and it is important that we try to understand the reasons for these differences.

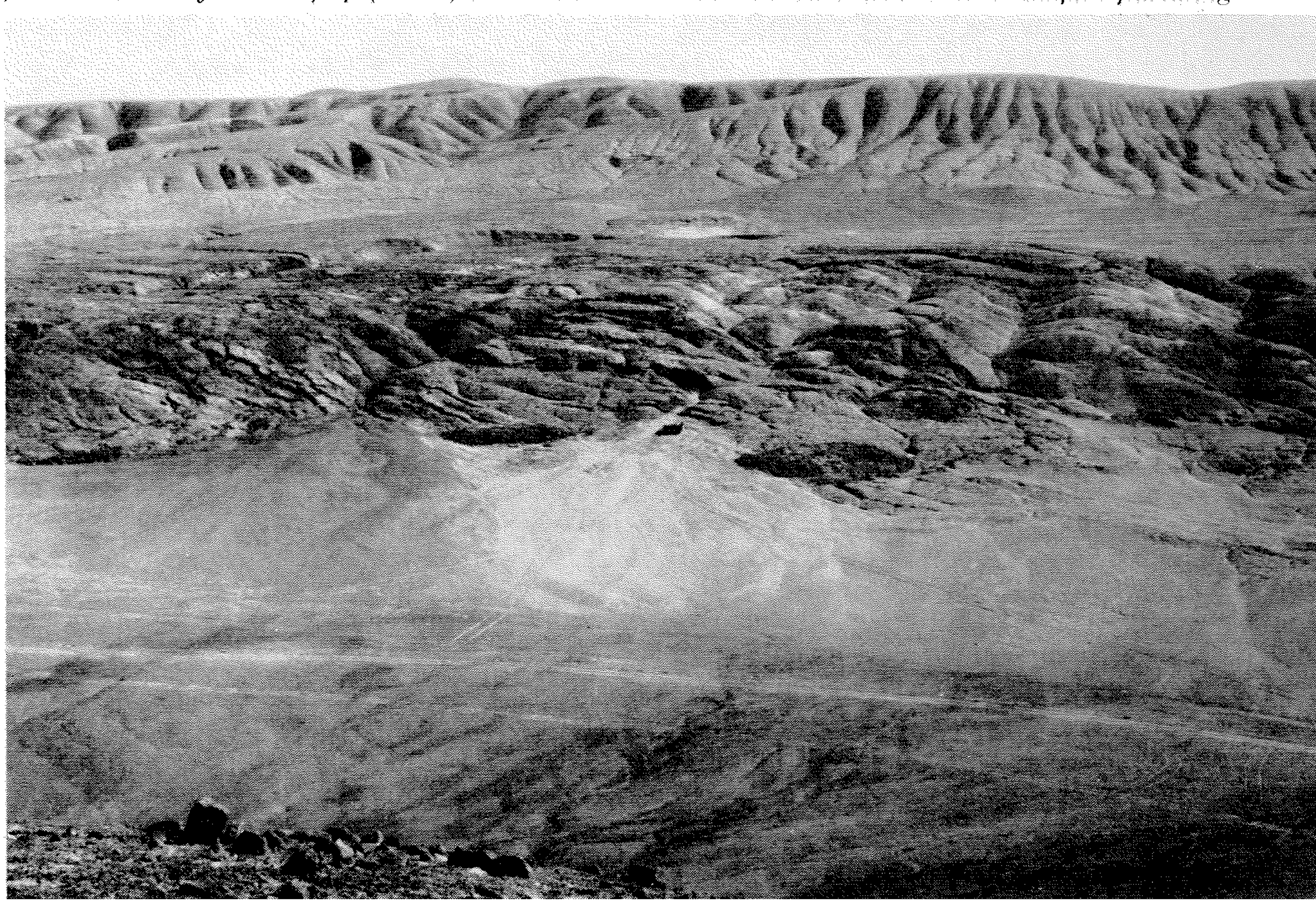
In California and many other parts of the world the largest earthquakes have been associated with the longest faults. Thus, the length and continuity of nearby faults have been major considerations in attempting to specify the maximum credible earthquake for a given locality. This generalization appears to be particularly valid for strike-slip faults (those with a history of horizontal rather than vertical displacements) as are common throughout most of California. Despite the many geological problems in trying to apply this type of criterion for establishing the maximum credible earthquake, it certainly has more justification in most areas than merely assuming that the largest nearby earthquake in the historic past is representative of the largest possible event in the future.

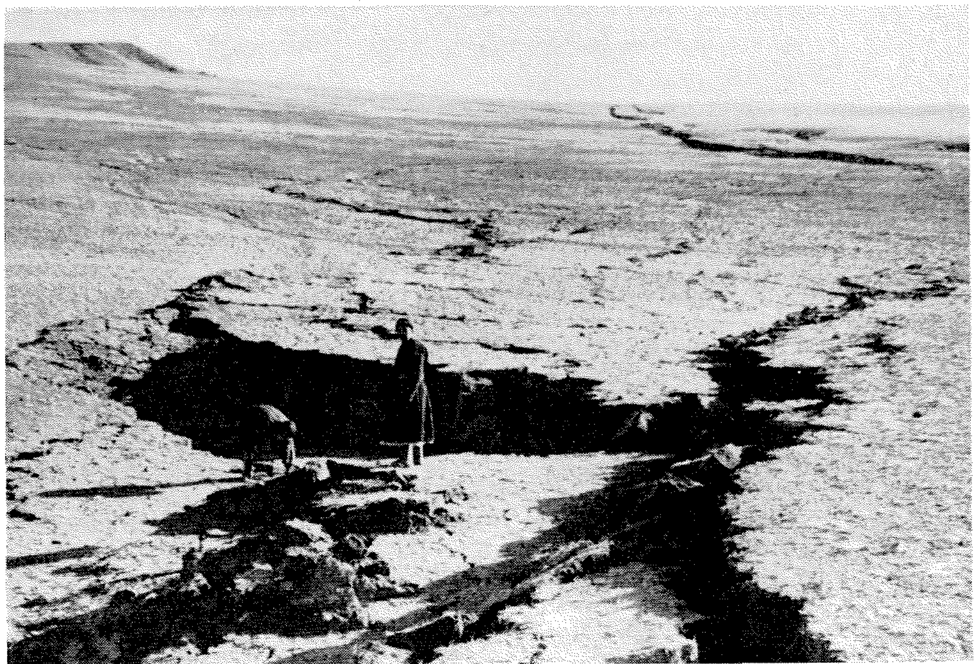
In the case of nuclear reactors, the specification of the maximum credible earthquake for which public safety must be assured demands extreme conservatism for two principal reasons: (1) the consequences of some types of serious failure in a nuclear facility must be guarded against even if their likelihood is exceedingly remote; and (2) the historic record of earthquake occurrences is so short that it cannot encompass the entire spectrum of possible events.

Almost every large earthquake that has occurred in California has proved to be surprising in terms of what would have been expected by geologists, seismologists, and engineers at the time. The recent unexpected events associated with the relatively small 1966 Parkfield-Cholame earthquake emphasize once again how little we know about what constitutes an "average"or "likely" earthquake. For this reason the present state of knowledge demands an unusually conservative approach to the specification of seismic siting and design criteria for structures such as nuclear reactors and dams that are critical to public safety. Perhaps we can become less conservative as we learn more from research studies and from experiences during major earthquakes in the future.

In those few areas where large earthquakes are not clearly related to surficial geological structures, such as in the eastern United States, the problem of assigning the maximum credible earthquake is a particularly difficult one to which there are presently no very satisfactory answers. Two of the largest and most disastrous earthquake occurrences in American history were in Missouri (1812) and South Carolina (1886), regions otherwise characterized by relatively infrequent shocks. Not only is this a perplexing problem for geologists, who are as yet unable to relate these events to obvious geologic

Complex zone of surface fracturing along a branch of the Atacama fault in northern Chile. The width of the fissured zone beyond the jeep (center) is at least 100 meters. The last major earthquake here was prehistoric, but the next large earthquake will probably again be associated with similar complex fracturing.





Complex faulting in alluvium associated with the great 1957 Mongolian earthquake is shown at the left. The 280-km-long fault zone was very complicated in places, although in the area of greatest horizontal displacement—8.85 meters (below)—the trace was relatively simple. (Photographs by V. Solonenko)

causes, but engineers are put in the very difficult position of having to decide whether these two areas are really any more hazardous than other parts of the eastern United States that do not happen to have recorded a similar great earthquake within the relatively short historic record. Could a great earthquake such as hit Charleston in 1886 just as well hit Washington, D.C., tomorrow?

This problem will probably never be solved until we gain a much more thorough understanding of how and why earthquakes occur. In the meantime, it may well be that nuclear reactors built in California will be seismically *safer* than those built on the East Coast, simply because we will have a better understanding—however incomplete—of what the seismic hazard is in California that must be designed against.

Particularly in the case of strike-slip faults, fracturing at the surface during a large earthquake is likely to be confined to a single well-defined fault plane without a myriad of auxiliary branching faults. Nevertheless, complicated zones of surface breakage do sometimes form, and this problem of branch or "splinter" faulting has been one of the greatest sources of difficulty in the recent California controversies. No one has knowingly contemplated building a reactor directly astride the most obvious break of a major active fault zone, but how far away from this line must one be to avoid possible branch or splinter fractures? This is a particularly difficult problem when it is considered that almost no location in California is very far from a fault that might be considered active by someone's criteria. Auxiliary faulting is not as random in occurrence as some people have implied, and the geologist can make several constructive contributions to the problem:

(1) Although auxiliary fractures have sometimes been observed during earthquakes several tens of kilometers away from the master fault (e.g., Mongolia, 1957), these breaks have usually occurred on or in close association with pre-existing faults that could have been recognized by geologists prior to the earthquake. Completely new fractures at such distances are rare, particularly in bedrock.

(2) Segments of fault zones in which complex surface fracturing tends to be uniformly distributed over a width of perhaps several hnudred meters can usually be recognized by evidence from previous earthquakes.

(3) Particularly with vertical displacements, complex surface fissuring is more likely in areas of thick alluvium than in bedrock. Strike-slip faults often have relatively simple surface expression even in areas of thick alluvium, and the straighter the fault trace, the less likelihood of auxiliary faulting.

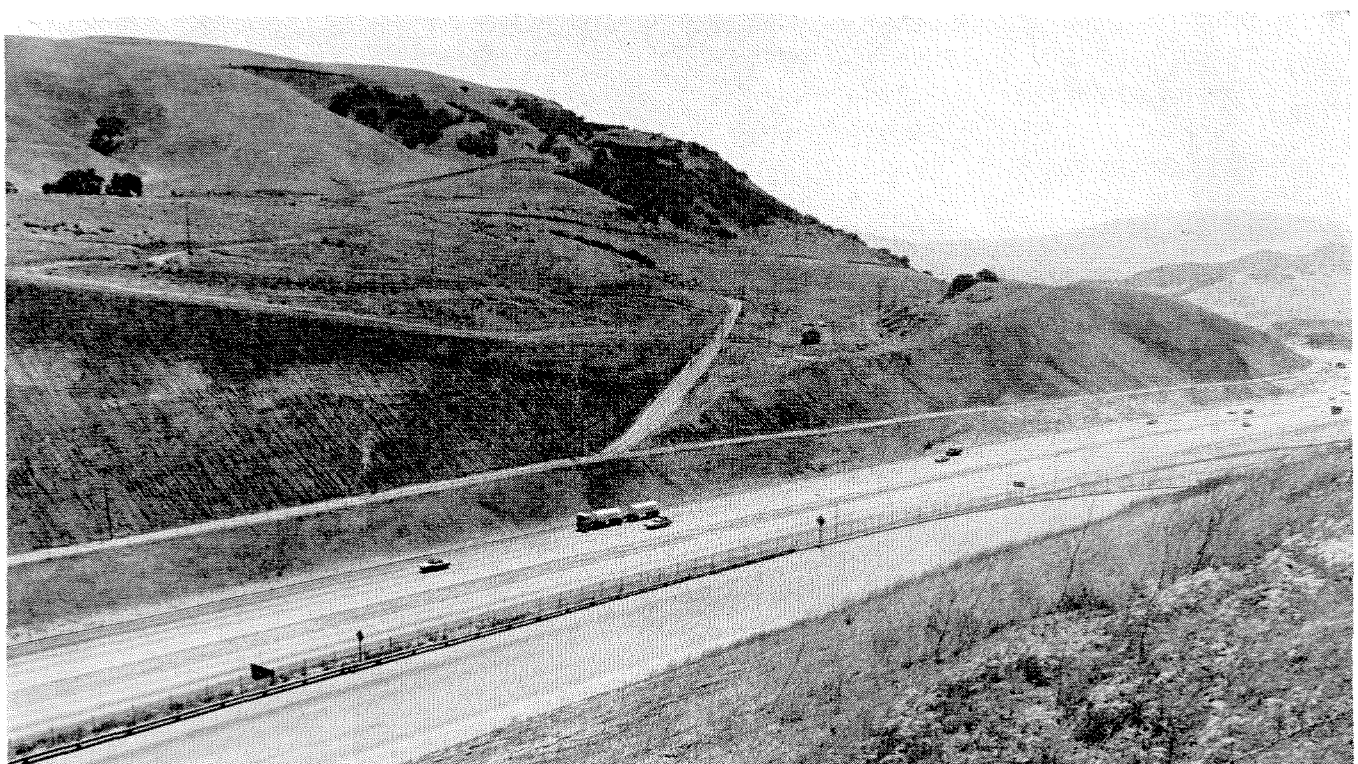
(4) Fault displacements on branch faults are generally only a fraction of those on the master fractures, and thus more easily accommodated in engineering design.

(5) Many features that have been called branch faults in the past were in reality the results of massive landsliding, and hazardous landslide areas can usually be avoided by judicious planning.

(6) Both descriptions and photographs of past large earthquakes associated with faulting have seemingly given undue emphasis to areas of complex surface fissuring as compared with the less spectacular, but often much more extensive, areas of relatively simple faulting.

It must be emphasized that it is often possible for the geologist to say with some degree of confidence exactly where within the width of a wide fault zone the next displacement is likely to take place. This is because the physiographic evidence of recent faulting indicates in many cases that all of the most recent breaks, for perhaps the last few thousand years, have taken place along the same plane within the fault zone, so the next break will probably follow the same path. Thus, despite the fact that many major fault zones are several kilometers wide, with broken and crushed rock exhibited over a broad area, the seismic hazard from faulting in the foreseeable future is usually limited to one or two major planes within the zone. For example, two earthquakes on the San Andreas fault in 1966 were associated with surface faulting along the exact line of earlier breaks, and despite the great width of the fault zone, geologists could have (and indeed *had*) delimited these potential lines of dislocation within one or two meters.

On a broader scale it must be recognized that within tectonically active areas such as California



Despite the great width of pulverized rocks exposed in this new freeway cut through the San Andreas fault at Tejon Pass near Gorman, geologists expect the next displacement to occur along a line passing through the dark zone behind the truck because this is where displacements have occurred in the recent geologic past.

and Japan, almost all rocks—and particularly those of greater geologic age—will show some degree of faulting and fracturing. A completely unbroken block the size of a nuclear facility is virtually impossible to find. But by concentrating his attention on those rocks that have been broken most recently, the geologist can usually specify where the most active and where the most quiescent areas are at the present time.

Whereas the local geology is all-important in attempting to decide whether a given site is subject to possible fault displacement during an earthquake, the assignment of seismic hazard due to shaking is a very different problem. Many studies indicate that heavy shaking during a great earthquake is distributed over a very wide region. In much of coastal California it appears that local soil conditions are more important in establishing the hazard from seismic shaking than is the proximity to the San Andreas or other major active faults. One should not forget that the city of Anchorage, which suffered major damage during the 1964 Alaskan earthquake, was about 130 kilometers from the epicenter—more than twice as far as is the center of Los Angeles from the San Andreas fault.

Clearly there are many needs that must be met if we are to succeed in establishing adequate geological and seismological criteria for the siting of nuclear facilities, both in terms of present practice and in terms of research for the future. Even at the present time, for example, there needs to be an increased understanding of the necessity for thorough geological and geophysical investigations before the commitment is made to build a nuclear facility at a particular site.

Too often in the past, far more time and talent have been expended in defending particular sites than in choosing them. But unless we rapidly gain more basic information about the nature of earthquakes and their geologic effects, it is clear that the geological-seismological field will increasingly become the stumbling block in the construction of nuclear facilities in seismic areas, regardless of how much is known of the geological details at the particular site; this has already been amply demonstrated in the California controversies.

The engineer now appears to be in a much better position to design adequately for any specified seismic event than is the geologist or seismologist prepared to tell him just what that specified event should be! This state of affairs points up the need for vigorous research in a number of closely related fields:

(1) We know very little about the recent geologic histories of major fault zones, yet it is obvious that these histories must be understood if we are to be able to say how *old* a fault is, how *recently* and how *frequently* it has slipped in the past, and how *likely* it is to slip again. Imaginative efforts must be made to use geochemical techniques of absolute age determination and quantitative geomorphology to establish the chronology of events on major active faults, as well as any other techniques that will lead to a better understanding of the mechanics and sequence of events in surface faulting.

(2) We need better documentation of what actually happens at the earth's surface along faults during major earthquakes, particularly with regard to the problem of auxiliary or branch faulting. This demands careful mapping of surface fractures associated with major earthquakes anywhere in the world.

(3) Good earthquake statistics are available for many parts of the world, but we have little idea of how to interpret these in terms of future expectancy. Aside from the statistical problem itself, a major stumbling block is our lack of understanding as to earthquake *mechanics*. Field, theoretical, or laboratory studies bearing on this question will hopefully enable us better to evaluate future probabilities.

(4) The relationship between seismicity and geologic structure obviously varies from one part of the world to another, and it is important that we try to understand these differences and the reasons for them, particularly if we are to be able to plan adequate nuclear programs in developing areas where the historic seismic record is limited.

(5) Earthquake prediction is a long-range goal that obviously has great import to society. Large national programs in this field are now under way in several countries, and they deserve the vigorous support of the engineering and scientific professions.

(6) In a more philosophic vein, both the engineer and the geologist-seismologist need a better understanding, or a better statement, of what risks society is willing to accept with facilities such as nuclear reactors. It should not be up to the geologist, for example, to have to define "safety" and to prescribe an acceptable level of risk for a given site, yet this problem has been at the core of much of the argument in the recent California hearings. All human endeavors involve some element of risk, and we must be prepared to accept this with nuclear installations. It is neither fair nor proper, however, to ask the scientific and engineering professions to take the sole responsibility for establishing and defending this level of risk.