Seismic Safety at Auburn Dam: An Evaluation of Geotechnical Studies

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I. Introduction

A. Forward

Following the Richter magnitude 5.7 earthquake near Oroville on August 1, 1975, construction of the thin arch concrete dam at Auburn was halted. Located only 45 miles north of Auburn and on the same fault system as the Auburn dam, the earthquake forced re–evaluation of seismic safety of a 685–foot high dam poised above Sacramento: a metropolitan area with nearly 1 million residents in the path of a potential failure–induced catastrophic flood.

The Auburn Dam project has been embroiled in controversy since its inception, even before it was authorized by Congress in 1965. Seismic safety is only one of the issues that have been debated at length. After years of geotechnical investigations following the earthquake, the U.S. Bureau of Reclamation abandoned the thin arch design in 1980, advocating instead a concrete gravity dam that they asserted would meet requirements for seismic safety. The geotechnical evaluation that led to the new seismic safety specifications, however, left many questions unanswered. Controversy about seismic safety has been muted since 1980, though, because economic issues have dominated the debate. Now, as the flood control imperative revives the possibility that a dam will be built at the Auburn site, the unresolved concerns about seismic safety must be aired.

All of the alternative designs so far proposed for a multipurpose dam at Auburn present a great risk to the vast number of residents in the path of the flood from a potential earthquake–induced dam failure. The California Seismic Safety Commission (Scott, 1981, p. 14) emphasizes that no structure can be made completely safe:

> "Of course, we necessarily 'gamble,' with lives in the design and construction of any critical facility, since 100 percent safety is never possible. Perhaps further public education is in order on this point. Moreover the public needs to be involved in decisions as to the appropriate level of safety to be sought, and of the level of risk that should be considered acceptable. Failure to meet such agreed–upon safety levels would constitute undue 'gambling.' But it is important to acknowledge that there is some chance of failure in all projects."

It is most important that those at risk understand their level of exposure so they can make informed decisions about how, or whether to proceed. My report is written in the spirit of involving the public in decisions about the levels of safety and risk relevant to building a dam at the Auburn site, and with the conviction that errors in risk assessment and safety design have been made. The issues are technical, but not so complex that they cannot be appreciated by people who lack a geotechnical background. All that is needed is a translation of the already–available documents from technical jargon to less arcane terminology. I have attempted to do so, but there is so much necessary background information and there are so many areas of controversy that this document has grown beyond a length that invites easy reading. When I have had to make a choice between easy reading and detailed documentation, I have chosen the latter.

To get a quick idea of the contents of this report, read Section VI: Summary and Conclusions. Those who are familiar with the issues and want to get right into the geotechnical material may want to skim quickly through to Section IV – Seismic Safety Design Parameters for Auburn Damsite. Each controversial topic (designation of the maximum credible earthquake, evaluation of fault activity, estimation of surface fault displacements, specification of ground motions, and significance of reservoir–induced seismicity) are discussed at length so that the reader can form his or her own judgments about the controversial issues. The closing paragraphs of each topic or sub–topic usually contain a summary. All the figures may be found together at the end of the text.

B. The Controversy

As a result of an extensive geotechnical study of the potential for a damaging earthquake at the damsite and adverse publicity surrounding failure of their newlybuilt Teton Dam in 1976, the United States Bureau of Reclamation (USBR) abandoned the concrete thin–arch dam being built at Auburn and proposed a more earthquake–resistant concrete gravity design for the same site (USBR, 1980, Supplement No. 2 to Final Environmental Statement, Auburn Dam). Other possibilities have arisen since then, including a "dry" dam aimed at flood control alone with or without provisions for future expansion to a multipurpose facility, "stageable" designs, and multipurpose dams of various sizes (Auburn Dam Alternative Study, USBR, 1987; Information Paper on Alternatives, American River Watershed, California, U.S Army Corps of Engineers, 1989).

Most parties presently involved in the Auburn Dam controversy evidently believe that seismic safety is no longer a concern. However, a major professional disagreement among earth scientists and engineers involved in the re–evaluation of the design of the proposed Auburn Dam for seismic safety was never resolved and the observations and conclusions of those calling for more stringent safety design parameters were largely ignored.

A very thorough, well–reasoned review by the U.S. Geological Survey (USGS) of the work of Woodward–Clyde Consultants (WCC), done for the USBR, criticized some aspects of the geotechnical investigations and values chosen for the seismic safety design parameters. The California Division of Mines and Geology (CDMG) represented the interests of the State of California. There was surprisingly wide variance in the conclusions reached by the USBR, WCC, USGS, and CDMG. Most of the questions raised by the USGS and CDMG, and even some uncovered by WCC, were never subsequently discussed by the USBR or incorporated into their own assessments. The USGS report was never widely distributed and none of the many detailed criticisms were answered in any public forum or in documents, technical or otherwise, that are accessible to the public. The technical nature of the USGS report (and most other documents relevant to seismic safety) renders public assessment of the safety issues difficult. My purpose in this report is to present the most important geotechnical analyses and seismic safety design parameters for the proposed Auburn Dam in non–technical terms so that a wider cross–section of people can participate in evaluation of the never–resolved conflicts in seismic safety specifications.

C. A Brief History of the Auburn Dam Controversy

The USBR seismic safety study at the Auburn damsite was carried out by USBR personnel, who concentrated on evaluating the activity of faults in and near the dam foundation. In 1977 they produced a three–volume Project Geology Report, which will be referred to as USBR (1977). Following receipt of the WCC report, the USBR issued a six–volume Supplement to Project Geology Report in 1978, which will be referred to as USBR (1978). The geotechnical consulting firm of WoodwardClyde Consultants of San Francisco was hired by USBR and produced in 1977 an eight volume report (WCC, 1977).

Five authorities on geology, seismology, and dam design (the "USBR Consultants") were retained by the USBR to follow and review the work done by the USBR and WCC. On 10 January 1978 the USBR Consultants were each asked to submit individual reports concerned solely with the seismic loading characteristics of the damsite, and each did so in July 1978 (Allen, 1978; Clough, 1978; Jahns, 1978; Johnson, 1978; Serafim, 1978). The U.S. Geological Survey was asked to review the work of WCC in February of 1978 and submitted their report to USBR on 30 December 1978 (USGS, 1978).

Following the Oroville earthquake and the failure of the Teton Dam, concerns about the seismic safety of the Auburn Dam were high enough that the Seismic Safety Commission of the State of California became involved and, in March 1977, formally called on the State of California to "conduct a thorough, expeditious, independent review of the proposed dam's seismic safety" (Scott, 1981, p. 23).

> "The upshot was that, after a good deal of pulling–and–hauling, negotiating, letter writing by the Commission as well as by top state officials, and several Commission hearings, a thorough, independent state review of Auburn Dam was carried out, principally by the Division of Safety of Dams and Division of Mines and Geology, and with the assistance and cooperation of the Bureau of Reclamation" (Scott, 1981, p. 25).

Under the state Department of Water Resources (DWR), the State of California established a six member Consulting Board for Earthquake Analysis for Auburn Dam (the "DWR Consulting Board") to review all work performed by USBR and its consultants and the USGS, as well as studies by the CDMG, DWR, the state Department of Conservation, and the state Division of Safety of Dams. With inputs from all these state activities and the recommendation of the State Geologist, the Resources Agency of California adopted the recommendations of the DWR Consulting Board for seismic safety design parameters for the Auburn damsite. The USBR was notified on March 5, 1979 by Huey D. Johnson, Secretary of Resources for the State of California, of the state requirements for seismic safety of the Auburn Dam, and that the state would oppose construction of any dam at the site which did not comply with the state design criteria. Copies of these letters stating the State position, as well as the report on CDMG studies, are published in Special Publication 54 (CDMG, 1979).

The Secretary of the Interior, based on USBR recommendations, adopted parameters for seismic safety design of the Auburn Dam in July 1979. The parameters and discussions related to their selection were made public in 1980 by the USBR (temporarily renamed the Water and Power Resources Service during the Carter administration) in two documents: USBR Supplement (1980, p. S–4 and S–5) and a Special Report to the Secretary of the Interior (referred to hereafter as USBR Special Report, 1980). These seismic safety design parameters, still in effect for all present designs for dams at the Auburn site, are:

- A maximum credible earthquake of M 6.5 close to the damsite.

- A foundation fault displacement of 5 inches, but a "desired design capability" of withstanding 9 inches. (Note that there is no requirement that the dam be designed to withstand 9 inches of surface displacement).

- Maximum ground acceleration at a vibration period of 1.0 seconds of 0.5 g (i.e., 50% of the acceleration of gravity). Maximum ground accelerations at other vibration periods are scaled to the value at one second using ground motion response spectra recorded during historical earthquakes.

D. The Present Seismic Safety Specifications Are Inadequate

Overview of Seismic Safety Specifications

The findings of all parties involved in developing or reviewing the seismic safety design parameters were summarized in Table C–1 of the USBR Supplement (1980). There was general agreement that an earthquake near or in the foundation of the dam as large as M 6.5 is credible (the USGS considered earthquakes as large as M 7.0 to be credible) and that any dam must be designed to withstand forces generated by such an earthquake.

A major professional disagreement exists, however, between geologists of the U.S. Geological Survey on the one hand and USBR, WCC, the five USBR Consultants, the DWR Consulting Board, and the State Geologist on the other hand, with regard to the amount of surface fault displacement that could take place in the dam foundation and how intense the ground shaking could be. The USGS argued that a dam at Auburn must be capable of withstanding 3 feet of surface displacement in the foundation during an earthquake, as well as ground accelerations in the critical 1.0second vibration period of 1.1 g (i.e., 1.1 times the acceleration of gravity).

The other parties specify much smaller surface displacement parameters of about 1 inch (USBR and its consultants), or 5 inches (DWR Consulting Board), or up to 9 inches (WCC and the State Geologist). Ground accelerations in the 1.0–second vibration period of 0.29 to 0.5 g, less than half the USGS number, were also specified.

The CDMG noted (1979, p. 1) that Dr. Clarence Allen, one of the five USBR Consultants, testified in response to a question posed at the May 17, 1979 hearing of the USBR in Sacramento on Auburn Dam seismic parameters that he would be more comfortable with a design that would withstand on the order of 6 inches of surface fault displacement. See Section V–D: Bias in Technical Judgments, for relevant comments by Dr. Allen on that topic.

Evolution of the State Specification for Displacement

Interestingly, in its preliminary conclusions presented to the DWR Consulting Board in November 1978, "CDMG had concluded that a surface faulting displacement of 1 to 2 feet within the dam foundation rock might be associated with the design earthquake if it were to occur in the vicinity of the proposed structure" (letter from James F. Davis, State Geologist, to Priscilla C. Grew, Director of the State Department of Conservation, 23 February 1979, reproduced in CDMG (1979, p. ix). The CDMG conclusion was changed to "CDMG does not recommend a surface faulting displacement parameter below 0.75 feet" (CDMG Special Publication 54, 1979, p. 17) in the May 1979 Special Publication. In the letter from the State Geologist referred to above, the specification became "a surface displacement of up to three quarters (3/4) of one foot, or nine (9) inches, should be considered as the design parameter...".

Note the change in emphasis with respect to the 9 inch specification. The CDMG clearly intended that displacement values less than 9 inches should not be used. The State Geologist, however, changed the meaning to allow values smaller than 9 inches and exclude larger values, giving no justification. The State Consulting Board finally recommended a value of up to 5 inches (CDMG 1979, p. xiii–xviii).

The U.S. Bureau of Reclamation and the USGS Review

In choosing 5 inches (9 inches desirable) as the surface faulting design parameter, the USBR ignored the USGS review and seismic safety design parameters without addressing any of the very detailed, technically and scientifically reasoned arguments presented by the USGS in their 143 page review of seismic safety at the

Auburn damsite. The detail of the evaluation presented in the USGS report far exceeds that in the reports prepared by the USBR Consultants and the DWR Consulting Board that were accepted by the USBR.

The USGS review is the combined work of 10 professional geologists in the employ of the well–respected U.S. Geological Survey, who were chosen for their special expertise related to the Auburn seismic safety issue. Nine other USGS earth scientists contributed to the report, either by reviewing selected parts of the WCC report or by providing data or interpretations from their own research. The expertise of the 19 USGS reviewers cannot be dismissed:

> "Most members of the review group are engaged in relevant geologic or geophysical research on the west slope of the Sierra Nevada, or in topical research such as studies of ground motion caused by earthquakes" (USGS, 1978, p.21).

All members of the USGS review group visited the Auburn damsite and some examined many of the exploration localities described in the WCC (1977) and USBR (1977) reports. The USGS report was endorsed by the Acting Director of the U.S. Geological Survey via a letter dated 13 July 1978 which accompanied transmittal of the USGS report to the USBR. The Acting Director closed the letter with a caution to USBR that the data base, the methods of estimating the maximum credible earthquake, and the analyses of ground motions for earthquakes over M 6.5 are at the limits of the state–of–the–art, requiring a conservative engineering approach. In late 1987 Robert Brown, co–chairman of the USGS (1978) study, said that no new information had surfaced in the intervening years to discredit the original findings of the USGS (Jim Mayer, The Sacramento Bee, 5 November 1987, p. A1). On 4 March 4 1988 Dallas L. Peck, Director of the U.S. Geological Survey, wrote to U.S. Representative Vic Fazio that USGS conclusions with respect to faulting at the Auburn damsite remain unchanged.

The USGS was given the opportunity to review a draft of the USBR Supplement (1980). H. William Menard, then Director of the U.S. Geological Survey wrote (letter appended to USBR Supplement, 1980): "the environmental statement does not present the Survey's position adequately." Referring to differences in interpretations by USBR, WCC, CDMG, and USGS, Menard says:

> "<u>These differences in interpretation are significant because they show the range of uncertainty surrounding the seismic design parameters at this site</u>. This message should be conveyed in the environmental statement; it is of major importance and interest to a non–technical reader."

The emphasis by underlining is Menard's. Such uncertainty reinforces the need for prudent, conservative performance specifications and design measures.

The differences in seismic safety specifications among the involved parties are critical, not just because so many lives may be put at risk, but also for economic reasons. A dam capable of withstanding larger earthquake forces than specified by the USBR is probably too expensive and may not be possible. A multipurpose dam at Auburn is feasible only if the less stringent seismic safety specifications can be justified. In light of the fact that failure of a large dam at Auburn presents a life–ordeath situation for as many as 1 million residents in the flood path (see Section II–B), the USBR should be required to respond publicly and in detail to the conflicts of their geologic interpretations and seismic safety design parameters with those of the USGS and others.

The following section describes general aspects of dam safety, followed by a description of what is presently known about the consequences of a dam failure at the Auburn site.

II. Safety of Dams

A. General Aspects of Dam Safety

A number of recent incidents led to the establishment in 1984 of a Committee on Safety Criteria for Dams under the auspices of the National Research Council to undertake a study of dam safety and make recommendations for improving the safety of new and existing dams in the United States. Some of the developments that led to the establishment of the Committee are (NRC, 1985, p. 6, 7):

1) The occurrence of several disastrous incidents in the preceding two decades that led to uncontrolled releases of reservoir waters {e.g., Vaiont in Italy (2,600 dead), Malpasset in France (421 dead), Machha in India (2,000+ dead), and in the United States such dams as Buffalo Creek (125 dead), Bear Wallow, Teton (11 dead, 25,000 homeless, $1 billion damages), Toccoa Falls, and Laurel Run}, plus several cases of severe damage and near failures from earthquake {e.g., Koyna Dam in India and the Upper and Lower Van Norman (San Fernando) Dams in southern California}.

2) The results of the National Dam Inspection Program conducted by the U.S. Army Corps of Engineers, in which it was found that one–third of the approximately 9,000 high–hazard dams inspected were probably unsafe.

3) The finding, based on investigation of existing projects by the USBR and the Army Corps of Engineers in light of current concepts of the effects of earthquakes on dams, that some of those projects must be altered to assure acceptable safety during earthquakes.

The failure of a dam is ample cause for concern. According to NRC (1985, p. 75–76):

> "... dam failures represent a relatively low chance but great impact type risk to people and property."

and:

> "... the maximum number of people who could be killed in a worst event is probably greater for dam failures than most any other kinds of hazards. Only a few hazards (principally those related to nuclear and war activities) are indicated to have potential for killing more people in a single event."

In the preface to the same National Research Council report:

> "On the average, about 10 significant dam failures have occurred somewhere in the world in each decade, and many more damaging near–failures have occurred. Some of these events have resulted from incorrect decisions made during the design and construction process, whereas others have been the consequence of inadequate maintenance or operational mismanagement. Many have resulted from unanticipated large floods, and a few have resulted from intense earthquake shaking. The water retained in a large reservoir has enormous potential energy that can cause extensive loss of life and damage to property. In fact, few activities of man pose greater potential for destruction. Accordingly, engineers tend to take a very conservative approach in designing dams; however, the more conservative the design, the greater the cost of safety. Also, relatively few dams will experience the extreme events for which they are designed, but the location and magnitude of these events cannot be predicted and, therefore, conservative designs generally are provided at most dams to avoid catastrophic failures at a few."

The United States has not been immune from truly terrible loss of life from dam failures. The collapse of the South Fork dam in Johnstown, Pennsylvania in 1889 killed 2,209 people (Jansen, 1980, p. 95). St. Francis Dam, the key facility of the Los Angeles Bureau of Water Works and Supply failed suddenly and completely in 1928, killing 450 people (Jansen, 1980, p. 171). The 1971 San Fernando earthquake severely damaged the two Van Norman Dams, causing the emergency evacuation of 80,000 people. As described by Jansen (1980, p. 222):

> "There is no question that, if conditions had been just fractionally more adverse, this event would have been recorded as one of the worst disasters in history."

Dam failures have generally resulted from design, construction, or site inadequacies, or from storm floods or earthquakes that exceeded design criteria. Mark and StuartAlexander (1977) performed a statistical analysis of dam failures and found that, on average, each dam has a probability of failure of about 0.0001 each year. In other words, in 100 years (the life expectancy of many dams before they are filled with sediment and become useless) the average dam faces a 1% risk of failure. For large dams in the United States the failure rate declined during the first forty years of the twentieth century, but since then has fluctuated between 1% and 2% per 100 years for the average dam. The decline in failure rate at the beginning of the century probably came from improvements in dam technology, but since then the greater safety from design improvements has been counterbalanced by the need to build on more difficult damsites as the "good" sites have been used up.

B. Risk At and Below the Auburn Damsite

The State of California requires that, for any new large dam project, maps be prepared showing the areas that would be inundated if the dam should collapse when full. The maps are for use by local authorities for emergency evacuation and control of the population in the areas that would be affected in the event of a dam failure. The USBR response to the requirement is limited to a single page of text (USBR Supplement, 1980, p. 38–39) and an inundation map (Plate 6), which was also supplied to the State Office of Emergency Services. The inundation map is reproduced here as Figure 1.

The complete collapse of Auburn Dam would cause failure of both Folsom and Nimbus Dams. The USBR presents a table (USBR Supplement, 1980, p. 39), reproduced below, which shows how long it would take for the flood wave from collapse of the Auburn Dam to reach selected localities, how long it would take for the peak of the flood to arrive, and how deep that peak flood would be.

Location	Initial Arrival	Peak Arrival	Maximum Depth
Folsom Dam	5 minutes	1 hr. 10 min.	12 feet
Nimbus Dam	25 minutes	2 hr. 30 min.	70 feet
Federal Building, Cottage Way	1 hr. 40 min.	5 hr. 15 min.	46 feet
State Capitol	2 hr. 6 min.	6 hr. 37 min.	40 feet
Clarksburg	3 hr. 55 min.	9 hr. 10 min.	6 feet

The area inundated following failure of Auburn Dam (Figure 1) is greater even than that submerged by a 400–year storm flood (Figure 2, reproduced from Plate 4, Army Corps, 1989). The dam–failure flood would extend farther east, beyond the Sacramento River levees. Only the Yolo Bypass would protect Woodland and Davis. The eastern margins of the flood would pass through Mather Air Force Base, then Elk Grove, and extend south through and beyond Walnut Grove. According the the USBR Supplement (1980, p. 39):

> "This inundation area has a population of 672,000 people based on the 1975 special census. If the hypothetical failure were to occur during the daylight hours of a weekday (Monday through Friday), the influx of workers to Sacramento from areas, principally in Yolo County which could not be inundated, would increase the number of people in the area of inundation to about 681,000 people. If the hypothetical failure were to occur at night or on weekends or holidays, the number of people in the area of inundation would be about 672,000 people."

Since 1975 the Sacramento area has experienced remarkable growth. Referring to the area that would be flooded if Folsom Dam (which impounds far less water than the proposed Auburn Dam) failed, journalist B.J. Bashin (The Sacramento Bee, March 2, 1986) suggested that one million people would be affected. Even when considered apart from the greater area flooded, collapse of the Auburn Dam would be far more destructive than a storm flood because of the extremely rapid rise of water and unusually turbulent flow. The table shows that downtown Sacramento would have 2 hours or less to evacuate before the initial arrival of the flood waters.

The magnitude of the disaster that would result from an Auburn Dam failure is reinforced by a report by Ayyaswamy and others (1974) in which it was concluded that 260,000 people would be drowned if Folsom Dam failed. Donald C. Rose, a member of the Association of Engineering Geologists Seismic Hazards Committee, wrote a letter on 22 March 1976 to Gordon Oakeshott, chairman of that committee, in which he said:

> "If Auburn Dam should fail and release some or all of its 2.3 million acre–ft reservoir downstream into Folsom Dam's smaller reservoir, the Folsom Dam's earthfill flanks could then be overtopped. All told, several million acre–feet of water would then be released into the American River and head toward Sacramento in a wave about 100' high."

Notice that complete failure of Auburn Dam is not required to activate this disaster scenario, nor does Auburn Dam need to be full at the time of failure. All that is needed is uncontrolled release at a rate great enough that the earthfill flanks of Folsom Dam are overtopped.

The USBR states (Supplement, 1980, p. 38) that failure of the Auburn Dam "is an event with such an extremely remote probability of occurring, that it is not credible." The USBR experience at Teton Dam and other sites, together with statistics of dam failures in the United States and elsewhere, suggest otherwise. If the proposed Auburn Dam should fail, the death and havoc wreaked downstream would ensure Sacramento of an unwanted place in history as the site of the worst self–induced disaster ever to befall humanity. Clearly, great conservatism must be applied to the design of any dam built at the Auburn site.

III. Geologic Setting of the Auburn Damsite

In this section the general features of the geology in the western foothills of the Sierra Nevada and in the vicinity of the Auburn Dam foundation will be described, to provide a basis for later examination of earthquake hazards. Many faults are present, but the questions of whether and which faults may be presently active will be deferred for discussion in Section IV–C: Activity of Faults in the Vicinity of the Dam Foundation.

A. Regional Geology

The Auburn damsite is located in the western foothills of the Sierra Nevada. The rocks in this region are mostly volcanic rocks and sediments that, after deposition, were heated and changed ("metamorphosed") into relatively hard, strong rock. These rocks are quite old, mostly older than 160 million years (m.y.). In some places, younger magmas intruded into the metamorphic rocks and crystallized to form igneous rock bodies. In the western foothills, the youngest of these igneous rocks are about 130 to 140 m.y. old.

Of most importance to the Auburn Dam project is the structural geology of the western foothills. Structural geology is concerned with deformation of rocks, both by bending (folding) and by breaking (faulting). The rocks of the foothills have been tilted on a regional scale so that originally–horizontal layers within them tend to dip (i.e., are inclined into the ground) steeply to the east. The trends of the tilted rock layers where they intersect the approximately horizontal erosion surface (the "strike") of the rock layers is generally northwest–southeast, but in many areas the rocks are also folded in a more complex way.

Besides being tilted and folded, the rocks of the western Sierran foothills have been extensively faulted. These faults are referred to collectively as the Foothills fault system, and are shown in Figure 3 (taken from CDMG, 1979, p. 3). The eastern–most faults are called the Melones fault system and the western–most faults are called the Bear Mountain fault system. Both of these, in turn, are composed of numerous smaller branches, and many additional faults are located between the two. From Sonora the Foothills fault extends north about 190 miles. It connects southward to other faults which extend for another considerable distance.

The Auburn damsite is located within the Bear Mountain fault zone. Width of the Bear Mountain fault zone in the Auburn area is about 2 miles and includes, as major elements with regional extent, the DeWitt–Salt Creek Lineament zones on the east and the Pilot Hill–Maidu–Deadman Lineament zones on the west (Figure 4, taken from CDMG, 1979, p. 11). Viewed in a regional context, the Bear Mountain fault zone exhibits a complex pattern: the regional–scale, major elements serve as bounding zones, but cross–cutting faults extend between the bounding zones (CDMG, 1979, p. 7). This is the pattern in and near the Auburn damsite, where the cross–cutting faults are represented by the F–0 and F–1 faults. Figure 5, taken from WCC (1977, v. 2, p. 121) shows the larger F–zones and other structures in the vicinity of the dam foundation. These F–zones will be discussed in the Section III–B: Damsite Geology.

Most of the activity on the Foothills fault system took place prior to about 140 m.y. ago during a time when the entire region was being compressed by plate tectonic forces. In response to the compression, blocks of rock rode up over adjacent blocks along steeply–inclined faults that make up the Foothills fault system. This type of faulting is called "reverse", or "thrust" faulting. The compressive forces died off as the jostling of the tectonic plates diminished, and active faulting ended until about 10 million years ago. At that time the rocks of the western Sierra Nevada began to experience tension (i.e., began to be pulled apart). Many of the faults of the foothills were reactivated, but with opposite motion across them: blocks of rock began to slide down off of adjacent blocks along the steeply–dipping faults. This type of faulting is called "normal" faulting, and continues to this day. There is some horizontal ("strike–slip") motion across these faults, too. A fault with both normal and strike–slip components to its motion is called a "normal–oblique" fault.

When construction of the Auburn Dam began the Foothills fault system was considered inactive and incapable of producing a damaging earthquake. That assumption was proven wrong when the M 5.7 Oroville earthquake struck on 1 August 1975 on a northerly branch of the Bear Mountain fault zone called the Cleveland Hill fault. Damaging earthquakes also occurred in the Foothills fault system in the Melones fault zone near Downieville in 1888 and 1909 (Cramer and others, 1978). Seismicity of the western Sierra Nevada is low compared to other regions in earthquake–prone California (WCC, 1977, v. 5), but microearthquakes, occasional larger earthquakes, and vertical crustal movements in the order of one to several inches in 10 year periods (Bennett, 1978), centered on faults near Auburn, demonstrate that the Foothills fault zone must be considered active.

B. Damsite Geology

Bedrock

The bedrock at the Auburn damsite is composed mostly of a hard, strong metamorphic rock called amphibolite. The amphibolite is layered and tilted, reflecting the regional structural trend discussed in the previous section, with the layers striking northwest and dipping steeply to the east. This rock, however, is cut by numerous thin planar zones, called talc zones or T–zones, which contain abundant talc, chlorite, and serpentine, three minerals which are very weak. Hence the T–zones, which are oriented the same way as layers within the amphibolite, are generally zones of weakness within and adjacent to the dam foundation. Much of the more than $200 million spent on building the foundation for the Auburn dam was directed at excavating and strengthening these T–zones.

F–Zones

The major structural element in and near the foundation is a system of faults, called F–zones, that are oriented at an angle to the T–zones and the layering in the bedrock (Figure 5). There are at least 37 F–zone faults at the Auburn damsite, 19 of which traverse the dam foundation (WCC, 1978, v. 2, p. 94). Where F–zones intersect Tzones, the T–zones are offset, clearly showing that fault movements on F–zones are younger than the rocks of the T–zones. The F–zones do not offset faults within T zones, however (WCC, 1977, v. 2, p. 120, 130–132; see Section IV–C). The longest and most pronounced F–zones at the damsite are labeled F–0 and F–1 (see Figure 5).

The dominant fault exposed in the foundation excavation is F–1. It shows evidence of 120 feet of offset, but most of this displacement is older than 130 to 140 million years (USBR, 1977, v. 1, p. 19). It has a sinuous trace and traverses most of the left abutment. In midstream it intersects a T–zone called T–10 and turns abruptly upstream to follow it. In the upstream (northwest) direction, F–1 splays out in several small faults and appears to die out. The USBR showed the fault terminating at its southeast end in a body of serpentinite, and calculated a total length of 4,500 feet (USBR, 1977, V. 1, p. 19). The CDMG, however, believed that F–1 merges with F0 within the serpentinite body and connects with another fault that extends at least another 8,000 feet to the southeast (CDMG, 1979, p. 10). These relations are shown in Figure 6, taken from CDMG (1979, p. 9). The lengths of the F–zone faults and their geometrical relationships to other structural elements are extremely important in interpreting associated seismic hazards; see Section IV–C: Activity of Faults in the Vicinity of the Dam Foundation.

The other major F–zone, F–0, passes within 120 feet of the left abutment of the foundation (Figure 5). The amount and timing of displacements across this fault are uncertain because of ambiguities in cross–cutting relationships with other geologic features. It was thought by the USBR (1977, v. 1, p. 20) to be the longest of the F–zone faults, about 6,600 feet long but, as described above for F–1, CDMG suggested that F–0 connects at its southeast end to the 8,000 foot fault. CDMG (1979, p. 10) further suggested that F–0 continues to the northwest at least 3000 feet beyond the limit mapped by USBR and that it may form a complete linking fault across the entire Bear Mountain fault zone. If true, then F–0 is a much more important fault than thought by USBR. See the discussion in Section IV–C, below. CDMG noted that additional field work is needed to test this hypothesis, but none has been done.

T–Zones

Twenty–six T–zones have been mapped at the damsite (Figure 5). Most of them are 1 to 20 feet thick and are commonly sheared at their borders (WCC, 1978, v. 2, p.113). It is important to remember that T–zones are rock units and are not necessarily associated with faulting. Many T–zones, however, contain shear zones within them, and some of these T–zone faults displace other rock units by up to several feet (WCC, 1978, v. 2, p. 118). Deformation observed within both T–zones and F–zones is very similar, suggesting that both may have formed at the same time (WCC, 1978, v. 2, p. 120). The USBR suggested that some of the T–zones in the dam foundation might be considered small splays off branches of the Bear Mountain fault zone, but emphasized their belief that many T–zones are simply layers of different rock types within the more–abundant amphibolite bedrock (USBR, 1977, v. 1, p. 19).

The Maidu East Shear Zone

The Maidu East fault zone has taken on special significance because it passes within 200 feet of the dam foundation (see Figure 5) and has caused vertical separation of as much as 18 feet in the Mehrten Formation, (USBR, 1977, v. 1, p. 37). The Mehrten Formation is a sedimentary rock composed largely of volcanic fragments that were deposited from 4 or 5 to 20 million years ago. The shear zone occurs within a Tzone called T–26, which is known to extend about 1.5 miles to the south of the foundation and about 1 mile to the north. Displacement across the fault appears to diminish to zero towards the north, and there is some speculation that the displacement may jump to adjacent T–zones. Much effort was expended to find sediments younger than 100,000 years in the shear zone so that its activity could be assessed, but results were ambiguous.

IV. Seismic Safety Design Parameters for Auburn Damsite

The important engineering parameters that must be specified for Auburn Dam are: (1) magnitude of ground motions, and (2) surface fault displacements that the structure must withstand without uncontrolled release of impounded waters. To make these specifications, one must first estimate: (1) the magnitude of the greatest plausible earthquake that might shake the dam, and (2) the minimum plausible distance from the epicenter to the dam.

There is general agreement that moderate earthquakes close to the Auburn damsite present a much larger threat than larger earthquakes located on distant faults, so these estimates for Auburn depend upon evaluation of activity of faults in proximity to the damsite. Unfortunately, there are few of the geological features needed to unambiguously evaluate the activity of faults in the damsite vicinity, so it is necessary to use information acquired from study of more distant faults within the Foothills fault system. Then, professional judgment must be used to extrapolate results to the actual damsite. Factors other than the technical considerations for which engineers and scientists are trained become important, for example, judgment as to what constitutes acceptable risk. Most of the disagreements evident in this section derive from such unquantifiable judgments.

A. Seismic Safety Design Parameters

During an earthquake a dam is subjected to vibratory ground motions that are characterized by their "particle velocity" and acceleration over a range of vibratory frequencies. Particle velocity is simply the speed and direction that each tiny particle of rock moves at any instant during the earthquake. The dam structure must be designed to withstand these ground motions without failing in a way that leads to uncontrolled release of impounded water. Special attention must be paid to natural vibrational frequencies of structures which, if they are similar to ground shaking frequencies, can cause enhanced sympathetic vibrations that can tear the structure apart. Such a coincidence of vibrational frequencies probably contributed to the collapse of the I–880 freeway in Oakland during the October 1989 earthquake in the San Francisco bay area (Hough and others, 1989).

If potentially active faults are present in the dam foundation, as is the case for the Auburn damsite, the structure could be subjected to shear stresses as the underlying foundation rock moves in opposite directions on either side of the fault. In this case, the dam must be designed to resist the shearing, or to seal against water loss even if the structure is itself sheared.

Consequently, there are two basic design parameters that must be specified for seismic safety of a dam when potentially active faults are present in or near the foundation:

1) the magnitude of expected ground motions, and
2) the amount of displacement that can occur across a foundation fault.

To arrive at such specifications, it is necessary to determine the size of, and distance from, the largest earthquake likely to affect the structure. The word "likely" is important because it implies a question of judgment that can't be easily quantified. The concept of "maximum credible earthquake", commonly abbreviated as "MCE", has evolved to inject the required conservatism and reduce the arbitrary nature of the specification of the design earthquake. As stated in WCC (1977, v. 7, p. 1):

> "A maximum credible earthquake is the largest earthquake that appears capable of occurring under given geologic conditions. It is a rational and believable event that is in accord with present knowledge. In estimating the maximum credible earthquake, there is little regard to its probability of occurrence, except that its likelihood of occurrence is great enough to be of concern."

Once the size of the MCE and its proximity to the dam foundation has been determined, then estimates can be made of the maximum ground motion and the maximum surface displacement that the structure must withstand without catastrophic failure.

B. Maximum Credible Earthquake for the Auburn Damsite

The way in which a specific site is investigated to determine a maximum credible earthquake is explained by WCC (1977, v. 7, p. 7):

> "Estimates of the maximum credible earthquake that can occur along a given fault are based on the following factors: 1) geologic evaluation of the regional tectonic framework; 2) the historical seismicity along the fault and in the

> surrounding region; 3) the geologic history of slip along the fault; 4) the relationship between earthquake magnitude and fault rupture length; and 5) the relationship between earthquake magnitude and amount of slip."

All of the parties involved in evaluating the seismic potential of the Auburn damsite agreed that an earthquake at or near the damsite poses a far greater hazard to the dam than larger earthquakes on more distant faults. Using the evaluation methods described above, most parties felt that a M 6.0 to 6.5 earthquake on a fault located within 0.5 miles of the damsite is credible, although some felt that it is very unlikely. The USGS preferred a value of M 6.5 to 7.0. These estimates of the MCE overlap at M 6.5 and this intermediate value was adopted as a design parameter by the USBR.

Although the difference between M 6.5 and 7.0 does not seem great, it must be remembered that the Richter magnitude scale is logarithmic. That is, each greater whole number on the scale signifies an earthquake with 10 times the amount (i.e., wave amplitude) of ground motion. Because of the logarithmic nature of the magnitude scale, a M 7.0 earthquake generates ground motion 3.2 times greater than a M 6.5 earthquake.

The differences in estimates for the MCE arise mostly from two factors: (1) disparate estimates of displacements that have taken place in the past on faults in or near the damsite; and (2) application of statistics theory to mathematical relationships between earthquake magnitude and parameters such as surface displacement or fault length (USGS, 1977, p. 80–84). Adoption of different values for the MCE will affect the estimates of maximum ground motion and surface fault displacement expected at the damsite. Other factors (see below) contribute more strongly than a difference of 0.5 in magnitude of the MCE to the large disagreements about ground motion and surface displacement, so evaluation of the MCE will be discussed no further.

C. Activity of Faults in the Vicinity of the Dam Foundation

Whether faults in and near the foundation of the proposed Auburn Dam are active is the crucial question and, as it turns out, the most difficult question to answer. Estimates of ground shaking and especially surface fault displacement that a dam must withstand require a knowledge of fault activity. The criteria used for classifying fault activity are explained in the following subsection, followed by a description of problems in making such classifications that are specific to the Auburn damsite. A summary of the positions of the different parties is given next. Following that are detailed comparisons of the data and interpretations of each party which led to their fault activity classifications.

The observations and arguments presented in this section can be long and detailed, but they are not complex. They are presented here, not to convince the reader of the validity of any particular argument, but rather to show how much difference there can be in "professional judgment" rendered by different investigators working on the same problem when the data are inconclusive. As you will see below, all four major organizations who rendered opinions on fault activity at the Auburn damsite recognized that there was not definitive evidence one way or the other. In keeping with the requirements for prudent, conservative engineering of high risk structures, WCC, CDMG, and USGS all concluded that, in the absence of certainty that all foundation faults are inactive, they must be considered active. Only the USBR designated all foundation faults as inactive despite the lack of conclusive evidence.

Classification of Fault Activity

The USBR (1977, v. 2, Appendix 2) defined as <u>active</u> a fault which has experienced relative displacement during the last 100,000 years. An <u>inactive</u> fault has not experienced relative displacement for the last 100,000 years. An <u>indeterminate</u> fault is a fault for which definite evidence has not been established concerning its activity during the last 100,000 years.

Acceptable evidence for active faulting includes: (1) an accurately determined epicenter from a historic earthquake; (2) direct evidence of displacement on the fault in deposits that are 100,000 years old or younger (e.g., surface rupture, cut or displaced deposits); and (3) indirect evidence of displacement on the fault on or in deposits that are 100,000 years old or younger (e.g., stream offsets, sag ponds, fault scarps).

A fault can be classified as inactive only if there is direct evidence which shows the fault has not experienced relative displacement in the last 100,000 years. For example, if a fault is covered by a sedimentary rock containing fossils known to be greater than 100,000 years old, and the fault does not cut the sedimentary rock, then the fault is inactive by USBR criteria.

In the USBR classification scheme, an indeterminate fault can be classified as <u>indeterminate (active)</u> or <u>indeterminate (inactive)</u> if inconclusive evidence is available which allows the geologist to make a judgment one way or the other. These two subclassifications indicate uncertainty in the classification which should be taken into account when decisions that affect safety are made.

If 100,000 years seems like an inordinately long time, keep in mind that geologic processes span periods far longer than human lifetimes. One–hundred thousand years is a geological eye–blink. Using that time interval as a criterion for judging fault activity is appropriately prudent and conservative when considering construction of hazardous structures such as large dams and nuclear power plants. See Section V–C for additional discussion of geologic time and recurrence intervals for earthquakes.

There are few deposits or rock units in the damsite area that are 100,000 years old or less and would therefore allow definitive classification of these faults. The youngest rock unit is the Mehrten Formation, composed of volcanic rocks that range in age from 4 or 5 to 20 million years old. If a fault cuts this unit, all that can be said about the fault is that it is younger than 4 to 20 m.y., which isn't much use for classification of fault activity. If, on the other hand, a fault in older rock is overlain by the Mehrten Formation and does not cut it, then the fault must be older than 4 to 20 m.y. and can be classified as inactive.

Elsewhere in the Foothills fault system there are two types of deposits that are fairly widespread and can be used to help classify fault activity: paleosols and colluvium. These are defined and described as follows:

<u>Colluvium</u> is a loose, incoherent deposit of weathered rock fragments and finegrained soil–like material usually found on slopes. Being loose, it tends to creep very slowly down the slopes, which would tend to wipe out evidence of faulting. Therefore, a fault that cuts colluvium must be very young and certainly active.

<u>Paleosols</u> are ancient soils. They are commonly buried under colluvium or other, younger soils. The paleosols contain layers with different clay mineral contents, so evidence of faulting can be seen when the layers are offset. Offset of the bedrockpaleosol contact is also evidence for faulting. The most widespread and useful paleosol is called the "paleo B horizon." The ages of paleosols were not known at the start of the investigations, but WCC (1977, v. 4) attempted to correlate them with paleosols of known age in the central valley and other locations and assigned an age of 100,000 years to the paleo–B horizon. Therefore, the paleo–B horizon was useful for testing activity of those faults with which it is in contact. A similar effort by another consultant under contract to USBR resulted in age estimates for colluvium in the Maidu East shear zone of at least 50,000 to 70,000 years, perhaps in excess of 100,000 years (USBR, 1978, v. 3, p. 41).

After the Auburn Dam seismic studies were done, Borchardt and others (1980) showed that previous soil and colluvium age assignments were probably wrong, and that the paleosol was probably an active soil until about 9,000 years ago. Regardless of which age is used, a fault which cut the paleo–B horizon would be classified as active. Using the new, younger age, however, the fault would be assigned a much younger age (less than 9,000 years instead of less than 100,000 years), which would imply a much higher rate of fault activity than inferred by WCC, USBR, and USGS. Any fault which was classified as inactive because it was overlain by a paleo–B horizon or colluvium without cutting it, however, can no longer be classified as inactive because all that is known using the new age of the paleosol is that the fault is older than 9,000 years. This latter point is especially important, because it suggests that the USBR classification of the Maidu East shear zone (see below) as inactive is incorrect.

In the vicinity of the damsite there are very few young deposits for dating T–zone faults, F–zone faults, and the Maidu East shear zone. The investigators, chiefly WCC, were forced to look at more distant faults where deposits of appropriate age were present to try to find more information on activity of faults in the Foothills fault system.

Summary of Activity Classifications of Damsite Faults

The USBR has consistently argued against the possibility that foundation faults are active (1977, v. 1, p. 6, p. 41; 1978, v. 1, p. 39; Supplement, 1980, Table C–1). They rated the Maidu East fault zone as inactive and regarded the possibility of movement along T–zones as "not credible". In Table C–1 of USBR Supplement (1980) they rated the group of all faults in the foundation as "indeterminate (inactive)". The assumption that foundation faults are inactive in the absence of direct evidence should be closely examined in the light of the potential extreme hazard posed by the proposed Auburn Dam.

Woodward–Clyde Consultants did not find definitive evidence for activity or inactivity of any of the foundation faults. Because similar faults elsewhere in the Foothills fault system are known to be active, and because many of the faults in the foundation showed small–scale features on the fault surfaces that are identical to those on related active faults (Figure 4, portions of faults marked by heavy dots), WCC classified the foundation faults (T–zones faults and F–zones) as indeterminate (active) (1977, v. 2, p. 126). WCC estimated the probability of faults in the foundation being active as 1 to 10 percent.

The USGS (1978, p. 24) concurred with the WCC judgment that foundation faults must be considered active, even in the absence of conclusive evidence. They were, however, unable to confirm the WCC activity probability assessment because the probability estimate is a subjective judgment (USGS, 1978, p. 30).

CDMG (1977, p. 7) also agreed that foundations faults must be considered active, but presented additional evidence to support the hypothesis that F–0 and F–1 may be part of a major crosslinking fault system within the Bear Mountain fault zone that is capable of producing the maximum credible earthquake (M 6.5).

All parties agreed that there is not definitive evidence for deciding whether foundation faults are active or inactive. In the absence of such definitive evidence professional judgment had to be applied and that is where the parties disagree. In the professional judgment of WCC, the USGS, and the CDMG, faults in the Auburn damsite must be considered active. Only the USBR decided that the foundation faults may be safely judged inactive.

The USBR (1977, v. 1, p. 26–34) argued that the F–zones are old, showing major displacements more than 140 million years ago. Only much smaller displacements have taken place since dikes were intruded into rocks in the vicinity of the damsite at least 130 million years ago. USBR analysis of offsets of two dikes in the foundation by F–1 and F–0 showed about 6 feet of net slip on F–1 since emplacement of the dikes. This value reduced to about 3 feet when account was taken of the possibility that intrusion of the hot magma that cooled into the dike rock may have wedged apart and moved the basement rock on either side of the fault.

The displacements across the F–zone faults could have taken place anytime from the age of the dikes to the present. The lack of young deposits in contact with these faults precludes definitive determination of whether they have been active in the past 100,000 years. The USBR made three arguments that post–dike faulting on Fzones is old and the F–zones are inactive.

First, the USBR argued (1977, v. 1, p. 28) that the post–dike displacements must have taken place when the damsite rocks were still deep in the earth, before uplift and erosion brought them to their present position at the surface, because the F–1 fault surface is sinuous. According to this hypothesis, if the post–dike faulting took place under low pressure near the surface, chunks of wall rock would have been broken off as the irregular rock masses on either side of the fault tried to slide by each other, forming a crushed zone known as a "fault breccia". A fault breccia is not present, so the post–dike faulting must have taken place at great depth where the pressure would prevent formation of a breccia. Hence, the USBR argued, the post–dike faulting must have taken place before uplift, more than 100,000 years ago. Consequently, the F–zone faults are probably inactive.
This argument about the effect of pressure on breccia formation is it is invalidated by the USBR's own observation (1977, v. 1, p. 19) that the average thickness of sheared material surrounding F–1 is 3 feet, and by the WCC observation (1977, v. 2, p. 95) that the zone of deformation associated with F–1 varies from 3 feet to more than 30 feet thick. F–0 is bounded by a 3 to 10 foot zone of disturbed rock. The presence of these shear zones can be used to argue the opposite of the USBR position: that the post–dike faulting took place so close to the surface that wide shear zones could form; therefore post–dike faulting is young and must be considered active. Furthermore, a study of mineralization along the surface of F–1 by R.R. Compton (USBR, 1978, v. 4, Appendix C, p. 4) showed that clays that formed on the fault surface during late–stage movements on the fault could have done so only at shallow depth when temperatures and confining depths were low.

I am not actually making the argument that F–1 is a demonstrably active fault. This example should be taken as illustrative of the uncertainties involved in applying professional judgment to the question of fault activity in the Auburn damsite. In many cases it is possible to make arguments for either side of a case; which argument is made can depend on the bias of the person making the argument.

The second argument made by USBR to support their hypothesis that F–zone faults are inactive came from studies of post–dike movements on F–1 and F–0. Four special study areas were investigated in the foundation where dikes and faults intersect. The geologic relations were ambiguous in each case (USBR , 1977, v. 1, p. 30–34), but the observations of displacements were used, along with the assumption that the sinuous F–1 fault could be approximated as a plane and that there was no rotation during fault movement across the plane, to calculate that F–1 behaved as a reverse fault during post–dike displacement. Reverse faulting is usually associated with compression in a region. It is known that the western Sierra Nevada were subjected to compression prior to 130–140 million years ago, changing to tension from about 10 million years ago (Section III: Geologic Setting of the Auburn Damsite). Hence, the USBR concluded that it is highly likely that post–dike motions on the F–zone faults took place during the period of compression 130–140 million years ago, so that Fzone faults are inactive.

From the geologic data it is possible that post–dike reverse motion on F–1 took place during the 130–140 m.y. period of compression. However, reverse faulting in one small locality cannot be taken as evidence for regional scale compression as required by the USBR argument; the post–dike reverse motion on F–1 could have resulted from local variation in the regional stress field. Therefore, the second USBR argument for inactivity of F–zone faults is inconclusive.

In a third argument, USBR described four F–zones structures in basement rocks that were encountered in one trench in the 4–20 million year old Mehrten Formation. These four faults did not displace the Mehrten rocks, demonstrating that they are older than the Mehrten and therefore inactive. USBR (1977, v. 1, p. 28) further argued for the antiquity of F–zone faulting because they found no F–zone faults in any trenching of the Mehrten Formation. This can be taken as conclusive evidence, however, only for the four faults seen to be overlain by Mehrten rocks.

All of the arguments made by USBR that F–zone faults are inactive are inconclusive. WCC (1977, v. 2) observed many of the same F–zone features, but further noted that distinctive details of deformation seen on fault surfaces of F–1 and F–0 (see Figure 5; locations are indicated by heavy dots) are the same as those identified on known active faults elsewhere within the Foothills fault system. All fault surfaces showing these features are not necessarily active faults (WCC, v. 2, p. 94), but WCC followed the prudent, conservative route in judging that F–zones could be active (WCC, v. 2, p. 133).

The USGS (1978, p. 30–31) confirmed the WCC findings and their rating of fault activity. The USGS (1978, p. 33) noted that, even if F–zones and T–zones are older structures, they may be capable of renewed fault slip if reservoir loading and invasion of fault zones by water change the effective strength of the rock. This possibility is discussed further in Section IV–F: Reservoir–Induced Seismicity.

Independent of the issue of activity of F–zone faults, USBR suggested that F–zones are not deep–rooted structures capable of producing earthquakes, but rather are reverse faults associated with the emplacement of the nearby Rocklin and Penryn granitic rocks 130–140 million years ago (USBR, 1977, v. 1, p. 21, and their Figures 4 and 5). This hypothesis is based on a postulated spatial relationship of the faults with the two rock bodies. The cited figures lend little support to the hypothesis and no more substantial arguments are made.

Instead, the CDMG (1979, p. 7) made the case that the F–zone faults, especially F–0, may be part of a major oblique cross–cutting element of the Bear Mountain fault system, a zone capable of producing the maximum credible earthquake of M 6.5 in the immediate vicinity of the damsite (see Section III–A: Regional Geology). This hypothesis is based upon identification of an 8000 foot extension of F–0 to the southeast of the damsite (Figure 6), along an unnamed fault which both the USBR and WCC (1977, v. 2, p. 109) failed to associate with F–0; and the alignment of F–0 with other lineaments to the northwest. With these extensions, F–0 connects across the entire Bear Mountain fault system between the Salt Creek – Dewitt Lineaments on the east and the Pilot Hill – Maidu – Deadman Lineaments on the west (Figure 4). The CDMG hypothesis is not proven, but certainly supports the use of prudence and caution before declaring the F–zones inactive.

In summary, there is no definitive evidence that F–zone faults are active or inactive. There is evidence suggestive of activity. The USBR arguments for inactivity are weak or invalid. By USBR criteria, F–zone faults should be rated as indeterminate, with the preponderance of evidence supporting a designation as indeterminate (active). The possibility that F–zones could generate the maximum credible earthquake of M 6.5 should be considered in designing seismic safety criteria.

T–Zone Faults: Professional Judgments About Activity

The USBR studies revealed that the larger F–zone faults offset T–zones when they intersect, so they suggested that fault motions on the F–zones are younger than on the T–zones (USBR, 1977, v. 1, p. 26). Some F–zones, however, "deflect" along Tzones, obscuring the crosscutting relationship. A few T–zones that offset minor Fzones are in turn offset by other F–zones. These conflicting offset relationships are interpreted to be the expression of widespread adjustments which occurred prior to or contemporaneously with the last major movements on F–1. The USBR concluded that the F–zones represent the youngest faulting in the dam foundation, and therefore that the T–zones are inactive (USBR, 1977, v. 1, p. 27).

WCC (1977, v. 2, p. 120, 130–132) disagreed. They pointed out that T–zones are mainly rock units. The types of rocks within them are weaker than the amphibolite in surrounding basement rock, so faulting tends to be concentrated within the Tzones. The zones of shearing occur along segments of T–zones, but not usually along entire T–zones. Although F–zones, specifically F–1 and F–0, truncate all T zones they encounter, WCC noticed that the F–zones do not truncate the zones of shearing that occur along segments of some T–zones. Therefore, truncation of foundation T–zones by F–1 is not direct evidence for inactivity of faults along Tzones. Active faulting may occur along T–zones and die out or transfer to other zones before reaching F–1 or F–0. Furthermore, as for F–zones, WCC noticed small scale features on fault surfaces within some T–zones that are identical to those seen on other strands of the Foothills fault system that are known to be active (indicated by heavy dots in Figure 5).

A significant observation about T–zone faults made by WCC (v. 2, p. 118–119) and evidently missed by USBR, is that some T–zone faults (at least three) have offset dikes within the foundation by several feet. Although the geometrical and geological relationships at the intersections of T–zones and dikes can be complicated, there is no doubt that some T–zone faults have displaced the dikes. Therefore, some T–zone faulting post–dates dike emplacement, just as is the case for F–zone faults, and by similar amounts. This observation casts further doubt on the USBR conclusion that all T–zone faults are older than F–zone faults and can be considered inactive.

WCC (1977, v. 2, p. 119–120) noted that F–zones and the sheared segments of T–zones exhibit the same style of deformation. Within the fault surfaces the rock is deformed into a distinctive style called "crenulation cleavage". The only real distinction between F–zones and T–zone faults is their regional orientation: the Tzones trend north to northwest and are inclined (dip) steeply to the east, whereas the F–zones have more variable trends and moderate dips to the west or southwest. Similar pairs of fault types with different orientations, which formed in metamorphic rocks during the same period of deformation, are seen elsewhere in the western Sierra Nevada. Therefore, WCC suggested that F–zones and T–zones may have formed at the same time and may be the result of the same deformational pulse.

The WCC hypothesis explains the USBR observation (above) that minor F–zones and T–zones offset each other. The hypothesis explains the additional observations made by WCC and does not conflict with any observations made by USBR. The most significant consequence to the question of active faulting in the foundation is that the F–zones cannot be dismissed as minor faults related to intrusion of the granitic bodies to the south. They must be considered as part of the overall regional faulting picture involving major offsets before 130–140 million years ago, with reactivation in more recent times.

For all these reasons, WCC included T–zone faults with the F–zones in their assessment that foundation faults are indeterminate (active).

The USGS said little about T–zones, beyond noting that reservoir loading and infiltration of water along them can weaken them and cause renewed fault slip (1977, p. 33). This possibility is discussed in Section IV–F: Reservoir–Induced

Seismicity. CDMG comments were focussed on the Maidu East fault zone, which is discussed next.

T–zone faults were rated as inactive by USBR solely on the basis of truncation by Fzones. Inasmuch as the USBR did not definitively rule out activity of F–zones within the past 100,000 years (USBR criterion for fault activity), it is not logical to infer that T–zone faults could not have slipped in the past 100,000 years. On this basis alone, USBR should have rated T–zone faults as indeterminate. The USBR evidently did not notice the places where T–zone faults offset dikes, nor did they make the observation that F–zones, even though they truncate all T–zones encountered, do not truncate T–zone faults.

WCC correctly rated the T–zones as indeterminate (active), an action that was implicitly approved by the USGS and CDMG. In reports that post–date the WCC report, the USBR should have either updated their activity rating to agree with WCC, or explicitly shown why the WCC rating is incorrect. They did not do so.

The Maidu East Shear Zone: Professional Judgments About Activity

The westernmost T–zone in the area, T–26, passes within 200 feet of the right foundation abutment (see Figure 5) and presents a special case (USBR, 1977, v. 1, p. 36–39). T–26 ranges in width from less than 20 feet to more than 300 feet and extends for a distance of at least 2.5 miles. It is overlain in places by the Mehrten Formation, composed of volcanic rocks that range in age from 4 million years to 20 million years. Associated with T–26 is a shear zone, the Maidu East shear zone, which offsets the Mehrten Formation with as much as 18 feet of apparent vertical displacement at a location 2500 feet southwest of the dam foundation. Hence, this fault has been active since the 4–20 million year age of the Mehrten Formation. The amount of offset, however, appears to diminish northward along the fault and decreases to zero about 450 feet southwest of the foundation right abutment. The extension of T26 and a branch of it called T–25, continue north to where, about 4000 feet north of the foundation, they are offset by F–0, confirming that the shearing has died out. The possibility remains, however, that shearing has transferred to an adjacent Tzone (CDMG 1979, p. 7).

Colluvium and soils overlie the Maidu East shear zone in places. The USBR examined exposures of them in three trenches to determine whether there has been any faulting activity younger than the age of the deposits. There is no definitive way to date these young units. The USBR (1977, v. 3, Appendix 5) inferred an age of at least 50,000 to 70,000 years, perhaps in excess of 100,000 years, based on local geomorphology (shapes of land forms) and interpretation of climatic changes associated with glacial epochs in the Sierra Nevada. In work that post–dated the Auburn damsite studies, however, Borchardt and others (1980) showed that paleosols were probably active soils during the period from 9,000 to 130,000 years ago. Certain fault–induced features in paleosols, such as slickensides, would be destroyed during active soil formation. Hence, presence of such features, particularly in the upper layers of the paleosol, may indicate faulting more recently than 9,000 years ago rather than 50,000 to 70,000 (or 100,000) years ago.

In two closely–spaced trenches, BHT–53 and BHT–64, USBR (1977, v. 1, p. 40, and v. 3, Appendix 6) observed no offset bedding. Slickensides (polished and scratched surfaces that usually result from friction along a fault plane) were present, but slickensides also form in soils that have clays which expand and contract with changes in soil moisture, such as those present in the trenches. Thus, as interpreted by the USBR, the last movement on the Maidu East shear zone occurred at least 50,000 to 70,000 years ago (USBR, 1977, v. 3, Appendix 6, p. 4).

In trench ST–65, the USBR found undisturbed soils and colluvium overlying the Maidu East shear zone. These units were interpreted to be more than 100,000 years old, indicating that faulting on the Maidu East fault zone had to be greater than 100,000 years old. Consequently, USBR rated this fault zone as inactive (USBR, 1977, v. 1, p. 41).

Borchard and others (1980) examined the same trench and concurred that the undisturbed paleosol units were probably at least 75,000 years old. They pointed out, however (p. 27), that the Mehrten Formation is not present in this trench; the paleosol rests directly on top of the much older basement rock. Therefore, it is possible that the shears underlying the paleosol do not represent the entirety of the Maidu East fault zone as seen elsewhere in the Mehrten Formation. Splays of the fault zone that were not observed in the trench could be present elsewhere, and they could possibly be active.

WCC (1977, p. 132) described, in trenches BHT–53, BHT–64, and GT–1, distinct steps in the contact between colluvium and underlying Mehrten Formation across traces of the Maidu East fault zone. In trench GT–1, a clay soil on the downthrown side of the Maidu East fault ends abruptly against the fault plane and slickensides with similar orientations to ones in the fault where it passes through underlying basement rock were observed in the colluvium. These features could be caused by soil processes, but WCC suggested that they also could be caused by faulting within the colluvium since it was formed. They classify the Maidu East fault system as indeterminate (active).

The USBR (1978, p. 13–20) described bedrock steps in trenches removed from known strands of the Maidu East fault, and suggested that they can form in ways other than faulting and should not be regarded as evidence for fault activity. Consequently, the USBR did not change their classification of the fault as inactive.

The USGS (1978, p. 32–33), which probably did not see the USBR (1978) Supplement to Project Geology Report, agreed with all of WCC's observations and the judgment that the Maidu East fault zone should be classified as indeterminate (active). They pointed out that there is doubtful significance to the appearance that the fault dies out to the north: most fault zones, especially for normal faults, exhibit complex patterns of stepped or "en echelon" strands, each of which may terminate only to be succeeded by another strand which may be hundreds of feet away.

The CDMG (1979, p. 7) echoed the USGS theme, citing the branching, braided pattern formed by strands of the fault in the vicinity of trenches ST–68 and BHT–64. Such a pattern is typical of normal faults in the western foothills, with displacement being taken up on many smaller shears as it steps laterally to another, parallel shear. Although they felt the evidence is ambiguous, the CDMG recognized that active faulting cannot be ruled out and judged the Maidu East fault zone as indeterminate (active).

The evidence that the Maidu East fault zone may be active is more ambiguous than for F–zones and T–zone faults. Because of this ambiguity, the degree of certainty implied by the USBR rating is not justified. WCC, the USGS, and the CDMG rating of indeterminate (active) is prudent and appropriately conservative, considering the risk involved.

<u>D. Surface Fault Displacement</u>

The greatest seismic safety–related issue for the Auburn Dam is the specification of the surface fault displacement parameter, as outlined in Section I–D. There are basically two ways to estimate surface displacement. One method is derived from the evaluation of fault activity (Section IV–C) and direct observation of displacement on the fault in question or on other faults thought to exhibit similar characteristics. The second method utilizes the estimate of maximum credible earthquake (Section IV–B) together with an observed correlation between earthquake magnitudes and fault displacements for real earthquakes.

The USBR did not formally estimate a surface fault displacement parameter for Auburn Dam, but listed 1 inch as the estimated displacement per event in the foundation (USBR Supplement, 1980, Table C–1). This number is consistent with the USBR evaluation that foundation faults are inactive (Section IV–C).

WCC used the field observation method to estimate the surface fault displacement parameter as 0.8 feet (WCC, 1977, v. 7, p. 20–27). <u>The USGS (1978) review of this work strongly criticized the WCC methods and re–estimated the displacement parameter as 3 feet</u>. The CDMG (1979, p. 13) used both methods and arrived at values in the order of 2 to 3 feet with each. Even though they explicitly recognized the weaknesses in the WCC estimation (1979, p. 13), the CDMG assumed that WCC was correct (1979, p. 14) and "tempered" their initial estimates to a value of 0.75 feet. Hence, the USGS criticism of the WCC method applies to the CDMG estimate as well.

Faults in the dam foundation could not be used to estimate displacement per earthquake because of the lack of usable young deposits for identifying whether displacements are recent. WCC dug trenches in likely places to find active faults elsewhere in the Foothills fault system and observed a maximum vertical separation across a fault that displaced the paleo–B soil horizon of 2.0 feet. If there was horizontal movement in addition to vertical movement on the fault, then the net slip would be greater than the vertical separation. Making an estimate of the amount of horizontal movement, WCC calculated that the maximum net slip was 2.3 feet (1977, v. 7, p. 23). For many reasons (see Section IV–C) it was assumed that this value was appropriate for faults in the dam foundation as well.

The active faults revealed by the trenches commonly showed "steps" in the fault surface at the bedrock–soil interface. The vertical separations observed for individual steps ranged from 0.4 to 1.0 feet, for equivalent net slip (taking into account that some of the motion was horizontal) of 0.46 to 1.15 feet. WCC assumed that each step represents a single earthquake, so an earthquake in the dam foundation would produce displacement less than the 2.3 feet of maximum net slip. To estimate the maximum amount of slip that would be expected per earthquake, WCC used the formula:

slip per event	=	recurrence interval	x	rate of slip
(feet per event)		(years per event)		(feet per year)

Assuming that the paleo–B soil horizon is 100,000 years old, and noting that several bedrock steps were seen in active faults at the bedrock–soil interface, WCC decided that the recurrence interval should be in the vicinity of 10,000 to 30,000 years. They note, however, that the recurrence interval could be as low as hundreds of years (WCC 1977, v. 7, p. 25), so there is much uncertainty in this estimate.

Parenthetically, it might seem that recurrence intervals in this range render the probability of an earthquake occurring at the Auburn damsite during the lifetime of the dam a remote possibility. Such is not the case, especially when the fact that reservoir impoundment can induce an earthquake sooner than its "natural" recurrence time is considered. See Section IV–F for information on reservoirinduced seismicity and Section V–C for a discussion of recurrence intervals.

Rates of slip were calculated for different active faults of the Foothills fault system by dividing the values of total net slip on faults exhumed in various trenches by the assumed 100,000 year age of the paleo–B soil horizon. The numbers ranged from 0.000005 to 0.00002 feet per year.
Using the equation above, the maximum net slip per event was calculated at 0.7 feet. A slightly different method gave 0.8 feet per event. The average of these two values is the same as 9 inches, which eventually became the official "desired" specification

for the surface fault displacement parameter for the Auburn Dam.

Because there is so much uncertainty in knowledge of parameters like the recurrence interval and age of paleosols, different, equally valid values for recurrence interval and slip rate could have been arbitrarily picked without violating the (poorly) known facts about faulting in the western Sierra Nevada. Thus different, equally valid estimates of the displacement parameter are possible. The USGS (1978, p. 34), using the same data from the WCC report, calculated that the displacement for a single earthquake could range from a fraction of an inch to more than 3 feet. They went on to say:

> "The geologic data provide little basis for deciding which is most likely, but as is discussed elsewhere in this review, to evaluate risk or to estimate the maximum credible earthquake a 3 foot displacement is considered a prudent estimate."

A second flaw in the WCC method is failure to use their own observation of a single step (hence a single earthquake by their logic) with net slip of 1.15 feet (13.8 inches) at one of the active faults. Furthermore, there is every reason to believe that, in the limited number of trenches WCC dug across active faults in the Foothills fault system, the largest net slip for a single earthquake was not observed. In other words, single earthquakes on active faults in the Foothills fault system are capable of causing surface displacement in excess of 13.8 inches. This flaw was also pointed out in the USGS report (1978, p. 77).

A further weakness of the WCC estimate of surface displacement lies in the assumption that multiple steps in a fault imply multiple earthquake events. The USGS (1978, P. 77) pointed out that multiple bedrock steps do not necessarily imply multiple events Normal faults, such as those responsible for present activity in the western Sierra Nevada, are capable of producing multiple breaks near the surface in single earthquakes. It is possible, therefore, that an earthquake in the Foothills fault system could produce surface displacement in excess of the observed maximum total net slip of 2.3 feet.

The USGS (1977, p. 75–77) presented additional reasons to suspect that even greater single–event surface displacements are possible. Most importantly, there is evidence for more of a strike–slip component to the motion on many faults than used by WCC in calculating net slip from observed vertical separation. Recalculated according to this evidence, the USGS found that a vertical separation of 2.0 feet corresponded to net slip of 3.4 feet rather than 2.3 feet.

The CDMG (1979, p. 13) agreed with the USGS that geological evidence does not preclude the possibility that the entire observed maximum vertical separation could have taken place in a single event, regardless of the presence of bedrock steps. They also agreed that it is unlikely that the maximum displacement was observed in the limited number of WCC trenches:

> "The 2.4 feet figure for net slip is assumed by WCC to have occurred in 3 distinct events or episodes so that the maximum slip per event is 0.8 feet. The evidence does not preclude the possibility that the entire amount of 2.4 feet could have occurred in a single event. Similarly it is possible that the observed 2 feet vertical offset associated with Quaternary movements on faults in the Foothills area does not represent the maximum displacement."

The CDMG also used the Magnitude vs. Displacement method to show that displacements of more than 3 feet are expected from M 6.5 earthquakes (discussed in the next section). Despite these observations, the CDMG (1979, p. 14) reversed itself when it specified the surface fault displacement parameter:

> "CDMG has assumed that the displacement range of between 0.4 and 1.0 feet in paleo–B bedrock steps and in the stone line separating colluvial units (Woodward–Clyde Consultants, v. 7, p. 24) represents individual seismic events, the occurrence of which is more probable than the MCE. With these caveats in mind, the CDMG estimates that a reasonable design parameter can be based on a net slip of three–quarters (.75) of a foot per event."

The two foregoing statements in the same report are difficult to reconcile on a scientific basis. In light of the evolution of the surface fault displacement parameter as specified by the State of California (see Section I–D) it could be interpreted that factors other than scientific observation and deduction were involved.

The Magnitude vs. Displacement Method

It has been found that a plot of magnitudes of natural earthquakes versus the logarithm of the observed surface displacement forms a straight line. Slemmons (1977) assembled a set of data for earthquakes which occurred on different types of faults and in different regions of the world and plotted them. In Figure 7 I have plotted Slemmons' data for earthquakes on normal and normal–oblique faults. A solid line is plotted through the middle of the trend defined by the data points. By selecting a value of magnitude on the vertical axis that corresponds to the maximum credible earthquake for the Auburn damsite, then moving horizontally to the right until the solid line is encountered, then moving down vertically until the horizontal axis is reached, the expected value of the surface displacement can be determined. For a maximum credible earthquake of M 6.5 for the Auburn damsite, it can be seen that 2 feet of surface displacement would be expected in the dam foundation. This value is far higher than the 5 inch (9 inches desirable) value that the different versions of the dam have been designed to withstand.

The situation is even worse than it appears. As pointed out by the USGS (1978, p. 7980) in their review of the WCC report, and by Bonilla and others (1984), the line drawn down the middle of the data points in Figure 7 represents the <u>average</u> value of displacement that would be expected for each value of magnitude. Notice, however, that the M 6.5 earthquakes plotted in Figure 7 have produced observed surface displacements ranging from about 1 foot to almost 10 feet. From statistics theory, 50 percent of M 6.5 earthquakes would produce surface displacements of less than 2 feet, and 50 percent would cause surface displacements of greater than 2 feet. The dashed line in Figure 7 is plotted at a position such that one–third of the displacements observed for earthquakes of any particular magnitude fall on the high side of the line. One–third of the M 6.5 earthquakes, for example, would be accompanied by surface displacement in excess of 5 feet.

More formalized and accurate methods for calculating and expressing probabilities of occurrence of surface displacements and earthquake magnitudes are given in papers by Mark (1977) and Bonilla and others (1984). For the M 6.5 earthquake thought to be credible at the Auburn damsite, the predictions of displacements are nearly the same as the older estimates.

Using the Slemmons (1977) data for normal, normal–oblique, and strike–slip earthquakes, the CDMG (1979, p. 13, Table 2) found that a M 6.4 earthquake at Auburn would produce an average surface displacement of 1.3 to 2.4 feet, depending on which type of faulting is assumed. One–third of those earthquakes would cause more than 3.4 to 6.7 feet of displacement, again depending on which type of faulting is thought to occur. CDMG discounted these numbers, however, because of the low rate of recurrence for M 6.4–6.5 earthquakes inferred for the Foothills fault system. This argument is discussed in the next section.

Discussion of Surface Fault Displacement Estimates

From the correlation of earthquake magnitude with displacement and their discussion of the WCC single–event displacements, CDMG showed that large displacements during a M 6.4–6.5 earthquake are plausible. CDMG specified the surface faulting displacement parameter at 0.75 feet, however, seemingly contradicting their own assessment (see above). The only reason cited by CDMG to justify contradicting the evidence that surface displacements in the order of 3 feet are expected for the maximum credible earthquake at the Auburn damsite, however, was that "geologic, geomorphic and soils evidence in the field in the Foothills region, do not tend to support the maximum surface displacement values that can be obtained through use of published curves..." (CDMG, 1979, p. 14). The only support given for this statement was the fact that 3–foot fault scarps had not yet been located by geologic mapping.

Fault scarps in the western Sierra Nevada may be difficult to see, considering the discontinuous nature of surface breaks that accompany earthquakes on normal faults, as exemplified by the Oroville earthquake and others (WCC, v. 2, p. 78–87). Soil creep and erosion on slopes where faults are likely to be found further diminishes their prominence. This kind of negative evidence is insubstantial and certainly too weak to contradict the plausibility of 3–foot displacements occurring at the Auburn damsite.

The CDMG also implied that a low recurrence interval for M 6.5 earthquakes in the

Foothills fault system somehow argues against the possibility of large displacements at the Auburn damsite (CDMG, 1979, p. 14–15). The recurrence interval suggested by CDMG is comparable to the that derived by WCC, in the vicinity of 30,000 years, in the field observation method described above.

Despite a long exploration of recurrence intervals, however, CDMG gave no further rationale for lowering the surface faulting displacement parameter. Recurrence intervals may actually be much shorter than estimated (see Section V–C).

A long recurrence interval does not reduce the surface displacement produced when the earthquake finally strikes. Nor is their any way of knowing where the Bear Mountain fault zone at the Auburn damsite is in its recurrence cycle. There is direct evidence that stress has accumulated on the fault in the immediate vicinity of the damsite (see Section IV–F: Reservoir–Induced Seismicity), so the damsite could be due for an earthquake much sooner than suggested by the length of the recurrence interval.

The USGS (1978, p. 72–73) maintained that, because faults in the foundation are judged to be indeterminate (active), they must be considered to be capable of producing the maximum credible earthquake and sustaining the maximum credible slip. The CDMG suggested that the F–zones represent major oblique cross–cutting elements within the Bear Mountain fault zone that may be associated with the maximum credible earthquake (1979, p. 7), which supports the USGS assessment. Both the field observation and the magnitude–displacement methods of estimating single–event surface faulting displacement for the maximum credible earthquake yield estimates in the range of 3 feet and higher. The arguments employed by WCC and CDMG to "temper" these estimates are not convincing. Because of the great potential hazard of the proposed Auburn Dam, the surface faulting displacement parameter of 3 feet, as advocated by the USGS, is appropriately prudent and conservative. The 5 inch (9 inch desirable) parameter used by the USBR to design the dam is far too low for adequate safety.

E. Ground Motions

Analysis showed that even very large earthquakes on distant faults would not generate ground motions at the Auburn damsite nearly as great as the moderate maximum credible earthquake of M 6.5 located near the damsite. Therefore, WCC (1977, v. 8) focussed attention on the M 6.5 earthquake.

Development of Response Spectra

Earthquakes cause the ground to vibrate at many different frequencies simultaneously. Vibrations are described in terms of vibration periods: the length of time for a single back–and–forth motion to be completed. The seismic safety specification for ground motions is expressed in terms of a response spectrum, which relates the amount of ground acceleration to vibration period. Response spectra measured in earthquakes of similar magnitude to the design earthquake are used to model the ground motion expected. The response spectrum derived by WCC (1977, v. 8, p. 19) for the Auburn damsite is illustrated in Figure 8.

The vertical axis in the response spectrum is labeled "spectral acceleration" and represents the acceleration experienced at each particular vibration period. In the example shown in Figure 8, the spectral acceleration reaches a maximum of between 1.8 and 1.9 g at a period of about 0.175 seconds. One g is equal to the acceleration of gravity. If an object experienced more than 1 g of acceleration during an earthquake, it would speed up faster than if it was in free–fall after being dropped from an airplane. The object would not achieve the same high speed during an earthquake, however, because the vibration of an earthquake reverses the acceleration twice in every period, so the motion of the object reverses.

The response spectrum obtained by averaging spectra from multiple historical earthquakes is an average spectrum. Consequently, the acceleration values would be expected to be exceeded by one–half of all M 6.5 earthquakes. To introduce conservatism into the design of nuclear power plants and dams, values of accelerations that are higher than 84 percent of expected earthquakes are commonly used, so that only 16 percent of expected earthquakes would exceed the design accelerations. The response spectrum in Figure 8 is the 84th percentile spectrum for an M 6.5 earthquake at the Auburn damsite.

Scaling of Response Spectra

Because response spectra are measured at different distances from the earthquake epicenters, a scaling factor must be introduced to correct the amount of acceleration to what would be expected for the design earthquake at a specified distance from the dam. The main disagreements between groups working on the Auburn damsite arise from specification of the scaling factor. The scaling factor is derived from plots of ground acceleration vs. distance of the recording station from the earthquake epicenter. The plot used by WCC (1977, v. 8, p. 15) is shown in Figure 9. Sometimes, ground velocity or some similar parameter is used instead of acceleration.

A curve is drawn through the data points and extrapolated to the distance value for the design earthquake. Then the equivalent value of acceleration is read from the plot, and the response spectrum is scaled to that value. Different groups can arrive at different scaling factors depending upon selection of data for the acceleration vs. distance plot and upon the way that a curve is fit to the data. Scaling to velocity or some other parameter can lead to somewhat different values as well.

Comparison of Response Spectra for Auburn Damsite

The scaling process, including selection of data points in Figure 9, is the crux of a problem identified by the USGS (1978, p. 89–94) with the WCC estimate of the response spectrum. The final values obtained for design accelerations at the dam site are proportional to the value chosen for the scaling parameter. The USGS thinks the value of 0.55 g obtained by WCC is too low because:

1) The large acceleration values recorded at Pacoima Dam during the M 6.4 earthquake in San Fernando in 1971 were ignored, but should have been used. The Pacoima Dam acceleration values are the two solid dots plotted between 1.00 and 1.20 g at the left side of Figure 9.

2) The Parkfield earthquake (two triangle symbols that plot at 12 kilometers in Figure 9) was closer to M 5.6 than M 6.5 and shouldn't be used.

3) The distance to the Helena earthquake (triangle with a slash through it in Figure 9) was actually significantly greater than the value plotted, although the exact distance is not known.

4) The basic physics of the acceleration vs. distance problem should follow a power law rather than a straight line. That is, the curve drawn through the data should rise sharply as the distance value gets smaller. This would result in a much higher estimate of the peak acceleration at 1 kilometer distance than the straight line method used by WCC.

5) For structures with natural vibrational periods in the vicinity of 1 second, such as large dams, peak particle velocity is likely to give more accurate scaling than acceleration.

The Pacoima Dam record was rejected by WCC (and USBR as well) because the local topography evidently amplified the ground motion beyond that normally expected for a M 6.4 earthquake. This selection resulted in a smaller scaling factor, hence smaller accelerations for the response spectrum for the Auburn damsite. The Pacoima Dam record is particularly important because it is one of the few ever recorded as close to the epicenter of an earthquake as the Auburn Dam might one day be.

The USGS included the controversial point, scaled according to velocity rather than acceleration, and extrapolated their curve somewhat differently, and concluded that the spectral accelerations should be a factor of 2 to 3 times higher than the WCC values. CDMG also incorporated the controversial point after it was first corrected for the topography effect, and obtained spectral accelerations that were higher than the WCC values by a factor of about 1.27.

The CDMG (1979, p. 12) summarized the values of spectral acceleration, choosing two important vibration periods, as follows:

	0.15 second	1.0 second
USBR	1.27 g	0.29 g
WCC	1.84	0.45
USGS	———	0.72–1.08
CDMG	2.34	0.57
Dam Specification	1.65	0.50

The CDMG ground motion parameters are higher than those specified for the redesigned Auburn Dam, especially for shorter periods. The USGS parameters are much higher. In support of the USGS position, the Director of the U.S. Geological Survey, Dallas L. Peck, in a letter to U.S. Representative Vic Fazio dated 4 March 1988, wrote that new data support the conclusion that the scaling used for the proposed Auburn Dam is too low, but perhaps not by as large a factor as 2 or 3. He noted, in addition, that the 1979 Coyote Lake earthquake produced peak velocities that exceeded equivalent velocities from the Auburn Dam response spectra derived by WCC, even though that earthquake was only M 5.8 instead of M 6.5.

The Coyote Lake earthquake data indicates that the ground motion parameters for the Auburn damsite should be higher than those presently specified, but how much higher is uncertain. Use of the 84th percentile response spectrum already introduces a certain amount of conservatism into the specification; the disagreement among the 4 groups may suggest that there is not as much of a safety factor as the 84th percentile is normally taken to imply.

Perhaps the most important point to be made from this discussion is that the uncertainties surrounding specification of earthquake ground motion parameters are great. Because of this, and the risk associated with building a very large dam above a populous metropolitan area, prudence and conservative design principles call for adoption of values at the high end of the range. The underestimation of the surface fault displacement specification is probably much more serious than the underestimation of the ground motion parameters, however.

F. Reservoir–Induced Seismicity

Factors Conducive to Reservoir–Induced Seismicity

The reality of reservoir–induced seismicity (RIS) is difficult to prove because many dams are built in areas that are already seismically active, and there are no known distinctive signatures that distinguish between reservoir–induced and other earthquakes. The best evidence for RIS comes from reservoirs impounded in regions of low seismicity, where the onset and frequency of earthquakes correlates with filling of the reservoir and with reservoir level.

The National Research Council (1985, p. 71), cited in Section II in reference to other aspects of dam safety, gave the following example:

> "The reservoir behind the 300–foot–high Koyna gravity dam in India started filling in 1962, and in 1963 a number of small–magnitude earthquakes occurred in the vicinity of the dam. As the depth of the water in the reservoir increased in following years, the frequency of occurrence and the magnitudes of these local shocks increased. In 1967, six earthquakes of M 5.5–6.2 occurred, and on December 12, 1967, a damaging M 6.5 earthquake occurred within 3 kilometers

> of the dam. The strong shaking caused horizontal cracks at about two–thirds the height with slight traces of water leakage visible on the downstream face of the dam. The dam was located in a region of low historical seismicity ..., so that the correlation of frequency of occurrence and magnitude with reservoir filling indicated a cause and effect relationship: the filling of the reservoir presumably triggered stress failures (earthquakes) in a prestressed body of rock."

James & Kiersch (1988, p. 747) summarized the most important findings about RIS up to 1988:

1) Induced seismicity appears to be a transient phenomenon, with seismic activity decreasing with time. None of the largest induced earthquakes have occurred more than 10 years after the reservoir was first filled.

2) A deep reservoir in a steep–walled, V–type canyon of reasonable young age with associated fault zones is a "prototype setting" for RIS.

3) RIS can occur when less than 164 feet of water is impounded, but stronger seismic activity occurs when the water depth is over 328 feet.

4) The weight of the water alone on the crustal rocks does not cause RIS. However, the infiltration of reservoir water downward through the rock can increase hydrostatic pressures in the rock mass and thereby increase pore pressures along a pre–existing fault surface that is already experiencing critical stresses.

5) The addition of water pressure to a critically–stressed fault plane may decrease the shear–friction values of the fault enough to trigger an earthquake.

6) The evidence for reservoir–induced earthquakes of M 6.0 or greater is circumstantial, but not definitive.

7) There is no unique signature that distinguishes a reservoir–induced earthquake from a naturally–occurring seismic event.

8) Statistical techniques can identify significant changes in seismicity coincident with reservoir impoundment, but statistics alone is not enough to understand the physical processes taking place.

Statistical analyses by Stuart–Alexander and Mark (1976) and Stuart–Alexander (1981), show that the percentage of reservoirs that have induced, or probably induced earthquakes increases with the depth of the reservoir. Reservoir–induced earthquakes have occurred at 20 percent of reservoirs deeper than 150 meters (492 feet), a group which Auburn would join if built. The probability of RIS was also found to increase with increasing volume of the reservoir. No correlation was found between the occurrence of RIS and either presence of faults or fault activity. RIS was correlated weakly with metamorphic rock types, such as are present in the Auburn damsite, but not with sedimentary or igneous rock types.

Note that the Auburn Dam would create a deep reservoir in a "prototype setting" for RIS. Furthermore, the Koyna gravity dam and reservoir is universally accepted as having induced an earthquake of the same magnitude as the maximum credible earthquake specified for the Auburn damsite. The Koyna region was characterized by low seismicity prior to dam construction, just like the Auburn region.

It is generally felt that reservoirs cannot cause an earthquake by themselves. Instead, they serve to trigger earthquakes in regions where crustal stresses have already accumulated. The main effect of RIS, then, is to interrupt the earthquake recurrence cycle, bringing on an earthquake sooner that otherwise expected. As will be shown after the next section, there is evidence that crustal stresses at the Auburn damsite are presently high enough that reservoir impoundment can trigger an earthquake, increasing the probability well beyond that expected from natural recurrence intervals on the Foothills fault system.

Was the Oroville Earthquake Induced by the Reservoir?

The possibility that the Oroville earthquake was triggered by reservoir impoundment is especially significant to the Auburn Dam issue for two reasons: (1) the earthquake was located in the same fault system as the proposed Auburn Dam, and (2) the WCC estimate of the probability that a reservoir at Auburn would cause an earthquake is much higher if the Oroville earthquake was reservoir–induced.

There is no agreement among earth scientists that the Oroville earthquake is an example of RIS. As factors supporting the hypothesis, Toppozada and Morrison (1982) note the following:

1) Lake Oroville is very deep and large.
2) The earthquake was located close to the reservoir.
3) The fault that caused the earthquake extends into the reservoir, providing an avenue for water under pressures as high as 20 bars (about 20 times atmospheric pressure, or 290 pounds per square inch) to infiltrate and weaken the fault.
4) The earthquake followed an unprecedented fluctuation in the level of the lake caused by the need to repair the intakes to the power plant. The M 6.5 earthquake at Koyna Dam in India followed the largest seasonal fluctuation in that lake.

According to Toppozada and Morrison (1982), the occurrence of strong earthquakes following the largest seasonal drawdown and refilling of a reservoir has been observed at at least 4 reservoirs besides Oroville. At Lake Oroville, other, smaller earthquakes have accompanied other, smaller fluctuations in lake level. It is probably the drawdown, rather than the refilling, that is responsible for triggering earthquakes, because the drawdown reduces the weight on the fault that normally keeps it "stuck" at the same time that pore pressure from water infiltration has reduced the strength of the fault. The mechanism explains why RIS tends to happen a few years after initial filling rather than when the reservoir is first filled. It takes time for reservoir water to infiltrate and weaken the fault.

If Oroville really represents a case of RIS it has strong implications for Auburn. First, as described below, WCC greatly increases their judgment of the possibility of RIS at Auburn if the Oroville earthquake was caused by reservoir impoundment.

Second, the wide fluctuation anticipated in water levels at Auburn reservoir will promote the possibility of a reservoir–induced earthquake.

Judgments About Reservoir–Induced Seismicity at the Auburn Damsite

The probability of RIS at the Auburn damsite was evaluated by WCC (1977, v. 6) using statistical methods. Of 55 reported cases of RIS, WCC classified 16 as accepted cases, 35 as indeterminate (they used the term "questionable"), and 4 as not being reservoir related. WCC evaluated the data for the 16 accepted and 35 indeterminate cases of RIS and concluded that, as water depth and reservoir volume increase, there is an increase in the occurrence of RIS. Other factors thought to increase the probability of RIS were:

1) presence of active faults;
2) extensional tectonic regime; and
3) predominance of sedimentary strata.

WCC (1977, v. 6, p. 11) listed factors in favor of RIS at the Auburn damsite:

1) the reservoir will be very deep,
2) it will be large in volume,
3) it will be located in an extensional tectonic regime, and
4) active faults are present.

WCC applied professional judgment to conclude (1977, v. 6, p. 12) that the probability of the Auburn reservoir inducing an earthquake of M 5.7 or larger is 2 to 5 percent. If, however, the 1975 Oroville earthquake was caused by the reservoir behind Oroville Dam, then WCC estimated that there is a 30% chance of a reservoirinduced earthquake of equal or greater magnitude at Auburn.

These likelihoods are judgmental and the method used by WCC in deriving them was not given, so the USGS (1978, p. 70) couldn't evaluate them. The USGS (1978, p. 59–71) agreed with WCC that greater depth and volume of reservoirs both promote RIS, but they found that there are too few data to statistically justify the correlation with fault activity, extensional tectonic regime, and sedimentary rocks. They made several additional observations that have relevance to the Auburn damsite:

1) Laboratory experiments show that increasing pore pressure, such as happens in the bedrock as reservoir water infiltrates, can lead to fault creep (1978, p. 63). Reservoir–induced fault creep could cause damaging fault slippage under the dam foundation without earthquakes.

2) If rock stresses in the vicinity of a reservoir are near the critical value to produce active faulting on a zone of weakness, the impoundment of a reservoir could cause instability and fault movement. Under these conditions the strengths of inactive faults near the reservoir could become less than the strengths of more distant, active faults (1978, p. 69). The USGS concluded (1978, p. 18):

"Both theory and field evidence support the view that inactive faults can be rejuvenated by the physical processes that accompany reservoir impoundment. Until more evidence is produced, a prudent assumption is that large, very deep reservoirs may reactivate faults."

This possibility may render the uncertainties in judging activity of foundation faults at Auburn irrelevant. Even if all foundation faults could by shown to be inactive by USBR standards, impoundment of the reservoir could reactivate them. This fact is especially important in light of the evidence that crustal stresses sufficient to induce seismicity and deformation are present in the immediate vicinity of the damsite (discussed below).

The CDMG concluded that there is reason for concern about RIS at Auburn (1979, p. 15–16):

"It is quite possible that the presence of a reservoir can trigger a large earthquake prior to the time when an earthquake might otherwise be expected... Because there is no way of reliably predicting where the Auburn segment of the Foothills fault system is in its recurrence cycle, a near MCE induced event (M 6.0 – 6.5) must be considered in risk evaluation at Auburn."

This statement becomes more ominous in light of evidence for accumulation of stress in the immediate vicinity of the Auburn damsite. CDMG (1979, p. 7) notes that both they and the USGS have detected low level seismic activity near the northeast border of the Rocklin Pluton, a body of granitic rock several miles west of the damsite. The microearthquakes are centered about 6 miles west of the damsite and indicate normal faulting, down to the east, on fault surfaces oriented the same as the regional fault trend of the Foothills fault system (Cramer and others, 1978).

Furthermore, Bennett (1978) has analyzed level line data, measured at intervals between 1912 and 1978, to show that crustal stresses are presently causing elevation changes in the order of 1 to 3 inches over ten–year periods within the Bear Mountain fault system. The maximum point of inflection of the crustal deformation is coincident with the northward projection of the Maidu East, F–1 and F–0 structures. According to CDMG (1979, p.12):

"Measurable movement that can be correlated with a known fault feature is conclusive evidence of either displacement along an active fault or of strain accumulation along the fault."

In their closing paragraph, the CDMG (1979, p. 17) admonished:

"Reservoir Induced Seismicity is of extreme importance for the Auburn site because a large earthquake could be triggered by the presence of the reservoir prior to the time when an earthquake might normally occur. Conditions known to be necessary for RIS are, or will be, present at the Auburn site, including preexisting faults and fissures, an existing state of stress sufficient for earthquake

> activity, faults with possible Quaternary offsets beneath the reservoir, and a very deep reservoir. All of these factors argue in favor of a design sufficient to withstand offset that appears geologically probable for the Foothills fault system."

Observations of crustal deformation and seismicity within the Foothills fault system in the immediate vicinity of the Auburn damsite suggest that the fault may be approaching the next earthquake in its recurrence cycle, even though the recurrence interval may be long. Impoundment of a reservoir may trigger these accumulated crustal stresses.

The USBR evaluation of RIS is contained in the Supplement No. 2 to Final Environmental Statement (1980, p. D–46 and D–47). They summarized the WCC results, emphasizing the rarity of unquestioned examples of RIS and the judgment that reservoirs may act as triggering mechanisms that alter the time of occurrence of an earthquake, but are not capable of inducing significant earthquakes without the presence of active faults. The USBR stated that "it is not possible to predict the location or magnitude of an earthquake, if any, which might be induced by Auburn Reservoir." All of the other geotechnical studies at Auburn damsite had been finished by this time, but the USBR did not discuss them.

Reservoir–Induced Earthquakes and Nearby Communities

One additional aspect of RIS bears mentioning. An earthquake of M 6.0–6.5 in the vicinity of the Auburn damsite, even if it does not cause failure of the dam, would severely damage the city of Auburn and other nearby foothill communities. If the earthquake is induced by the reservoir, the USBR will be exposed to legal liability for damages, just as for failure of Teton Dam. Regardless of whether such an earthquake is "due" anyway or is induced by reservoir impoundment, the reservoir will be blamed for damages in the communities.

The M 6.4 San Fernando earthquake of 1971 killed 64 people and caused hundreds of millions of dollars of property damage. An earthquake near the Auburn damsite could be of similar magnitude and is also close to population centers, so similar casualties and damage would be expected. The probability of this kind of disaster to Auburn and other foothill communities should be taken into account in any decision about building a dam at Auburn.

V. Other Seismic Safety Issues

A. Slope Failure in the Dam Foundation

The USGS (1978, p. 23, 29, 111) found a feature of the F–1 fault surface that impacts potential safety of the dam and had not been noticed or discussed by anyone else.

Some of the striations and slickensides on the F–1 fault surface indicate movement of the higher rock mass downslope toward the present river channel (see Figure 5, the rock mass is located between F–1 and F–0). This direction of motion is different from the direction of net slip that was determined from analysis of displaced dikes. The downslope motion therefore indicates that a small amount of gravity sliding has occurred along the F–1 surface and raises the possibility that slope failure could occur. Water from reservoir impoundment would further weaken the rock across the F–1 surface and could trigger a landslide. An earthquake near the damsite could do the same. The USGS called on the USBR to initiate a geotechnical investigation to evaluate the landslide threat.

The foundation for the left abutment of the original thin–arch concrete dam design is crossed by F–1. Thin arch concrete dams are especially dependent upon very strong, stable foundation rock for safety and would be especially threatened by a landslide in the foundation abutment. A group called Protect American River Canyons brought this safety problem to the attention of U.S. Representative George Miller in 1985, who forwarded the concerns to the Secretary of the Interior. The Department of the Interior responded to Miller in a letter dated 25 October 1985, denying a threat to the dam's structure from gravity–induced sliding. The undulations in the F–1 fault surface were cited as a factor that would prevent gravitysliding. They suggested that the placement of a dam (at this point the design called for a concrete gravity dam) would buttress any slide mass related to F–1 by both confining the toe of any postulated slide mass and increasing the slide resistance along the F–1 fault plane.

In geotechnical remediation work, rock bolts, buttresses and toe stabilization are used to mitigate landslides. A massive concrete gravity dam would probably do the same at the Auburn damsite. The great potential hazard of a dam at Auburn, however, requires a more formal resolution of this question.

B. Faulting in Other Foundation Locations for the Proposed Dam

All versions of a dam for Auburn that are presently being considered are located at the Mile 20 site where the foundation work for the thin arch concrete dam was completed. The USBR (Secretarial Issue Document, Auburn Dam, U.S. Department of the Interior, 17 December 1980, p. 7) designed their CG–3 concrete gravity design to utilize the original foundation. The U.S. Army Corps of Engineers (1989) studied options for five different dams at the Mile 20 site, ranging from flood–control–only dams to a large multipurpose dam as originally specified by the USBR. Figure 10 shows the location of the foundation of one of the Army Corps designs relative to the original USBR dam foundation (Army Corps, 1989, Plate 9). No other foundation maps were shown, so it is assumed that this one is representative of all Army Corps designs.

The F–1 fault was considered to be the major geotechnical problem with the USBR design because it traversed the entire left half of the foundation. By moving the foundation slightly downstream and removing the curvature, the Army Corps was able to minimize the length of F–1 in the foundation, but it still crosses the far left abutment. The situation is improved, but as discussed in Section IV–C, other faults in the foundation must be considered active as well. Comparison of Figure 10 to Figure 5 reveals that both F–zones and T–zone faults, some of which display fault surface features identical to those seen on active faults, lie in the proposed foundation for the Army Corps dams. Any dam built at the Mile 20 site will be subjected to all of the same seismic hazards as have been enumerated in this report.

Another site, at Mile 19, has been investigated by the USBR, and recommended in a study by Bechtel Corporation (1985). A shift of the dam location to that site would require a major new geotechnical study, with no guarantees that it would prove safer than the Mile 20 site. The resultant delay in implementing a flood control solution for Sacramento probably eliminates the Mile 19 site from further consideration.

C. Recurrence Interval for Earthquakes at the Auburn Damsite

Both WCC (1977, v. 7, p. 25) and CDMG (1979, p. 14–15) have estimated recurrence intervals in the range of 7,500 to 75,000 years, acknowledging that these estimates are very uncertain. The age of the paleo–B soil horizons is critical for some of the techniques used to estimate recurrence intervals. WCC assumed an age of 100,000 years, but Borchardt and others (1980) showed that paleosol formation was probably taking place through most of the time interval from 130,000 to 9,000 years ago. Hence, evidence for displacements of paleo–B horizons older than 9,000 years could be erased by soil activity. Such erasures could eliminate evidence for up to 90 percent of the fault offsets generated in the past 100,000 years, causing the recurrence interval to be calculated as too long by a factor of up to 10. Even such a factor, however, appears to be in the range of uncertainty already acknowledged for recurrence interval estimates (CDMG 1979, p. 15).

Such long recurrence intervals might be taken to discount the possibility of a damaging earthquake in the foundation of the proposed Auburn dam. Such is not the case, for several reasons.

First, failure of the dam anytime during its service life would be catastrophic and is unacceptable. If the recurrence interval for the maximum credible earthquake in the dam foundation is taken to be in the order of 10,000 to 20,000 years and the service life of the dam is 100 to 200 years, then the probability of a threatening earthquake during the life of the dam is about 1 percent. Given the extreme damage and number of casualties that would be caused by an earthquake–induced dam failure, 1 percent probability requires highly conservative design of the dam for seismic safety.

Second, we do not know where in its recurrence cycle the Auburn damsite is presently. Evidence from seismicity and land leveling studies, cited in Section IV–F in the discussion of reservoir–induced seismicity, indicates that significant stress has already built up on the Bear Mountain fault system in the immediate vicinity of the Auburn damsite. Thus, the probability of a damaging earthquake during the lifetime of the proposed Auburn dam may be substantially higher than 1 percent.

Third, although reservoir impoundment probably does not induce earthquakes in regions where stress is not already available, it does act to trigger earthquakes before their "natural" time (see Section IV–F). The Auburn damsite is acknowledged by WCC, the USGS, and the CDMG as a prime location for reservoir–induced earthquakes. WCC (1977, v. 6, p. 12) regards the likelihood of a reservoir–induced earthquake near the damsite that would be more powerful than that at Oroville to be 2 to 5 percent. If the Oroville earthquake is considered to be reservoir–induced, then the probability at Auburn increases to 30 percent.

With the potential for disaster posed by a dam at Auburn, and the relatively high probabilities for damaging earthquakes near the damsite as just discussed, it is clear that seismic safety is a critical issue that requires very conservative design.

D. Bias in Technical Judgments

In each of the technical judgments made with regard to seismic safety at the Auburn damsite, WCC, the USGS, and the CDMG have been more conservative than the USBR. Woodward–Clyde Consultants, under contract to USBR to study seismic issues at the damsite, were closest to the USBR position, but even they differed strongly with USBR conclusions about activity of faults in and near the foundation. Despite the flaws that have been pointed out throughout my report, the USBR position was ratified by the five USBR consultants who were hired at serve as an independent review panel. The USBR maintains that their seismic safety parameters, having survived independent review, are correct.

The State of California position was achieved through interaction of the DWR Consulting Board, also intended to be independent reviewers, with CDMG and other State personnel. The CDMG (1979) report and associated letters indicate that the surface fault displacement parameter may have been reduced without appropriate scientific justification.

Independent safety review panels are intended to minimize the chances that biases will compromise safety. If so many questions about seismic safety at the Auburn damsite remain, how were the USBR seismic safety parameters ratified by independent reviewers? I have no answers to that question. All I can offer for insight is a few comments from a study on independent review of critical facilities, especially dams, issued by the State of California Seismic Safety Commission (Scott, 1981). The need for independent review of designs was emphasized in this report, and human factors that can introduce unconscious bias were discussed.

Even members of review panels can become unconsciously biased to less safe professional judgments because they are usually consultants who are paid by the agency that wants to build the structure, and they commonly work closely with employees of the agency for a long time so they can become infected with the employees' enthusiasm for the project.

Clarence Allen, who served as one of the USBR Consultants, wrote in a letter to the State Seismic Safety Commission dated 12 June 1980 and cited by Scott (1981, p. 9) about how unconscious biases not related to the fact that the consultant is paid by an agency with a vested interest in the outcome can creep in to the consultant's evaluation. Three of the possible biases described by Allen are:

1) "Team spirit" may affect panel members who, by constant association, can become convinced that they are right, and discount the position taken by the "opposition." There may be pressures to arrive at a consensus, resulting in failure to give adequate weight to the opinions of individuals on the review board.

2) Psychological biases exist among consultants as for any other group of people. Some individuals advertise their individuality by consistently taking minority positions. Others may be inclined to go along with members of a group, perhaps to avoid risk of losing friends. Another factor is false pride and unwillingness to admit or accept changes.

3) The engineer–scientist on a review board finds himself or herself in the position of having to make a "safety" evaluation that involves both technical considerations and judgment as to what constitutes acceptable risk. Thus social and policy judgments enter into an engineering–technical decision, and an expert's personal view of appropriate risk levels is likely to influence what purports to be a purely technical judgment.

Most of the disagreements among the various parties involved in seismic safety evaluation of the Auburn site derive from differences in professional judgment. Differences in perceived risk lead to differences in level of conservatism used in making the judgments. This is where biases can creep in. As discussed in Section IA, no structure can be made absolutely safe. Because judgment calls are involved there will generally be disagreement.

I am a scientist and am subject to unconscious biases like anyone else. As a scientist I strive to keep biases from affecting my scientific judgment. I am very aware of one strong bias, however. The greater the magnitude of the potential disaster of a structure, the more conservative that design must be. I have tried to present this information as even–handedly as possible, but that 685 foot high dam has loomed in my mind and driven me toward a very conservative position. With this information now in hand, it is your turn to develop a position.

VI. Summary and Conclusions

Surface fault displacements in the dam foundation that are much larger than those espoused in the USBR specification, on the order of 3 feet, are plausible and no effective argument has been presented to indicate otherwise. Ground motions from the maximum credible earthquake at the damsite also are likely to exceed those specified by the USBR. Conditions favorable to reservoir–induced seismicity are present at the damsite. Crustal stresses are high enough in the immediate vicinity of the damsite to trigger microearthquakes and cause crustal deformation centered close to the foundation area, thereby increasing the probability that a reservoir at Auburn will trigger a damaging earthquake. The present seismic safety specifications are inadequate to ensure reasonable protection for the one million residents downstream of the proposed dam.

The experts don't know everything, a fact that is especially obvious with respect to the Auburn Dam seismic safety issue. The USBR has minimized the amount of professional disagreement that exists among geologists who have studied seismic safety at the Auburn damsite. They have not responded to the many specific geotechnical questions that have been raised by the USGS and CDMG studies, or even the studies of their own consultants.

The real message of this review is not that one group was right and another was wrong, but rather that there is too much uncertainty about the geologic conditions at the damsite to assure safety at an acceptable level unless the worst–case effects of a damsite earthquake are assumed for design of the dam. More geotechnical studies are unlikely to resolve the issue. That damsite has already been studied far more extensively than any other in history. The reason it has been studied so much is that <u>the answers aren't there</u>. The geologic conditions preclude finding a definitive answer to the safety question.

In light of the large number of safety–related questions left unanswered even after the extensive geotechnical investigations, in view of the apparent reluctance of the USBR to specifically discuss any of the criticisms and alternative hypotheses, and keeping in mind the potential for unprecedented disaster posed by the proposed Auburn Dam, the prudent course is to reject any dam at Auburn that would impound water for a significant time. Such a dam could be justified only if it was designed to provide much higher resistance to seismic forces. It may be possible to justify a flood–control–only dam built to present seismic safety specifications because it is unlikely to be filled when an earthquake strikes. A dam that could later be expanded into a multipurpose dam, but built to present seismic safety standards, makes no sense – the passage of time will not improve the safety of the Auburn damsite.

A. Safety of Dams

Dam failures have generally resulted from design, construction, or site inadequacies, or from storm floods or earthquakes that exceeded design criteria. Within the United States and worldwide, the average dam has a probability of failure of 1 to 2 percent per 100 years. Site–specific factors can change that probability. In the first 40 years of the twentieth century the failure rate declined in the United States because of improved technology, but has not declined since then, probably because the good damsites have been used up. Casualties and property damage from dam failures can be very high, so prudent, conservative design of dams is mandatory.

The complete collapse of a dam at Auburn would inundate an area greater than a 400 year storm flood, in which a million people reside. The flood would arrive at the State Capitol in about 2 hours, cresting at 40 feet in about 6 1/2 hours. More than 250,000 casualties could be expected. A concrete gravity dam, as presently proposed at Auburn, is less likely to fail so catastrophically, but the consequences would be nearly as great if the rate of uncontrolled release exceeded the capacity of Folsom Dam, causing its earthfill flanks to fail.

As unlikely as these scenarios are, they are possible. The proposed Auburn Dam poses a greater threat than probably any other dam in the United States. Highly conservative design principles are required.

B. Geologic Setting of the Auburn Damsite

The Auburn damsite is located within the Bear Mountain fault zone, part of the Foothills fault system in the western Sierra Nevada. A M 5.7 earthquake occurred on August 1, 1975 about 45 miles north of the damsite on another branch of the Foothills fault system, suggesting that faults in the damsite might also be active.

Most of the activity in the Foothills fault system took place prior to about 140 million years ago when the entire region was being compressed by plate tectonic forces. The compression forced blocks of rocks to ride up over each other along the faults, in a style called reverse faulting. When the tectonic forces subsided, so did active faulting. About 10 million years ago tectonic forces started to slowly pull the region apart, causing extension in the region. Many of the ancient faults of the Foothills fault system were reactivated, but now with the opposite sense of motion: blocks of rock began to slide down off of each other in a style called normal faulting. This type of faulting continues today, but at a much lower rate of activity than along the California coast or east of the Sierra Nevada.

The damsite is composed of a hard, strong metamorphic rock called amphibolite. Irregular layers of weaker rocks containing abundant talc, called T–zones, run northwest–southeast. Some of the T–zones contain faults which were probably active during the period of compression in the western Sierra Nevada. Some were reactivated in the present period of extension and are possibly active today.

The damsite is cut at an angle to the T–zone layers by faults called F–zones. Like the T–zone faults, these were active during the period of compression, then reactivated in the present period of extension and could possibly be active today. The F–zones may represent major cross–cutting structural elements within the Bear Mountain fault system, capable of generating the maximum credible earthquake for the site.

C. Maximum Credible Earthquake

All groups investigating seismic hazards at Auburn except the USGS decided that the maximum credible earthquake should be M 6.0 to 6.5, centered within about 0.6 miles of the damsite. The USGS considered M 6.5 to 7.0 to be credible. The estimates of the MCE overlap at M 6.5 and this intermediate value was adopted as a design parameter by the USBR, with approval by the State of California.

A magnitude 7.0 earthquake causes ground motions 3.2 times greater than a M 6.5 tremor, which is significant, but probably not as important as the underestimates of of other seismic safety design parameters. The main effect of the USGS–preferred MCE of M 7.0 would be to increase the ground motion parameters.

D. Activity of Faults In and Near the Foundation

Woodward–Clyde Consultants, the USGS, and the CDMG all found insufficient geologic evidence to allow a definitive judgment that faults in and near the foundation are active or inactive. All three groups presented evidence supporting the possibility that foundation faults are active and made the prudent, conservative judgment that the dam must be designed to withstand significant surface fault displacement from a potential earthquake.

The USBR, on the other hand, classified the T–zone faults and the associated Maidu East fault zone as definitely inactive. They, too, recognized that the geologic evidence does not permit such a certain classification of the F–zones as inactive, but they made three arguments supporting inactivity. These arguments were shown to be inconclusive in Section IV–C. The USBR missed critical observations that require them, by their own criteria, to rank T–zones as indeterminate (active). Furthermore, the USBR did not use or acknowledge the observations about T–zone faults that were made by their own consultants (WCC) in any subsequent documents.

The five USBR Consultants concurred with the USBR judgments although one of them, as discussed in Section I–C, had subsequent misgivings about the surface fault displacement parameter. The DWR Consulting Board, however, implicitly required that foundation faults be considered active when they specified that the dam be designed to withstand significant surface fault displacement.

E. Surface Fault Displacements

The USBR judged that foundation faults are indeterminate (inactive), so they specified no surface fault displacement. WCC used field observations of active strands of the Foothills faults system to determine that maximum cumulative net slip is 2.4 feet. They argued that bedrock steps at the interface with soil horizons in the faults signify multiple seismic events and calculated that maximum singleevent net slip is 0.8 feet.

The USGS pointed out that single steps with as much as 1.2 feet net slip have been observed, and that larger strike–slip components are present on the faults than assumed by WCC for calculation of net slip from observed vertical displacements. Therefore, the maximum observed single–step net slip is closer to 1.7 feet. The USGS argued further that the assumption that each step represents a single earthquake is erroneous, so that the 2.4 foot total net slip (recalculated to a higher value of 3.4 feet to account for strike–slip motion on the fault) is appropriate for single–event net slip. They pointed out that WCC almost certainly did not encounter the maximum net slip in the limited number of trenches across faults that they examined, so the USGS argued that 3 feet is a more prudent estimate of the surface faulting parameter.

The CDMG supported the USGS arguments. Furthermore, they used a plot of magnitudes vs. surface displacements to show that net slips in the order of 2 to 3 feet are expected from average M 6.5 earthquakes. About 1/3 of such earthquakes could produce earthquakes of greater than 3 feet net slip. CDMG "tempered" their specification of the surface fault displacement parameter to 0.75 feet, based mostly on calculated low recurrence rates for faulting in the Auburn damsite vicinity and lack of evidence for fault scarps in the order of 3 feet high in the western foothills.

The USBR Consultants generally agreed with the USBR that significant slips in the dam foundation are unlikely. The DWR Consulting Board specified 5 inches, a value accepted by USBR as the required surface fault displacement parameter. The State of California adopted the CDMG value of 0.75 feet (9 inches). The final specification for the Auburn Dam design was for 5 inches (9 inches desired) of net slip.

The "tempering" of the net slip specification by CDMG is unjustified because recurrence interval is unrelated to how much slip takes place when an earthquake, even in a region where the recurrence interval is long, finally happens. The "untempered" CDMG estimates obtained by both field observations and the magnitude vs. displacement correlation agree with the USGS figure. Both CDMG and USGS presented reasonable arguments that faults in the foundation could generate the maximum credible earthquake of M 6.5. Therefore, the single–event surface fault displacement parameter should be 3 feet, much higher than the 5 inch (9 inch desirable) parameter used in present dam designs.

F. Ground Motions

The ground motions that a structure must survive during an earthquake are specified as values of acceleration for different periods of vibration. These accelerations are modeled after those measured during historical earthquakes. The differences in values estimated by different groups arose from different estimates of the scaling factors used to adjust for distance to the earthquake epicenter. Part of the controversy centered around how much weight to assign to the value of acceleration measured at Pacoima Dam during the 1971 San Fernando earthquake. The acceleration was unusually high, and was rejected by the USBR and WCC because it was probably amplified by local topography and was not representative of most earthquake accelerations. The USGS and the CDMG used the Pacoima acceleration values after correction for topography effects. In addition, the USGS used a somewhat different method for scaling than the others.

Representative values obtained by the different groups, and those officially adopted as seismic safety design parameters by the USBR are listed in the following table:

	0.15 second	1.0 second
USBR	1.27 g	0.29 g
WCC	1.84	0.45
USGS	———	0.72–1.08
CDMG	2.34	0.57
Dam Specification	1.65	0.50

It is difficult to evaluate the validity of these different specifications. It would seem that the Pacoima Dam record, corrected for topography, is valid and should be used, favoring the CDMG and USGS specification over the others. The difference between the CDMG and USGS values may be related more to professional judgment in drawing lines through scattered data points than anything else.

A record obtained from the M 5.8 Coyote Lake earthquake of 1979, which occurred after these analyses, showed greater ground motion than the specification for a M 6.5 design earthquake at the Auburn damsite, so the seismic safety design parameter for Auburn damsite is definitely too low.

G. Reservoir–Induced Seismicity

Known and suspected cases of reservoir–induced seismicity were analyzed statistically by WCC to identify important factors. They concluded that the occurrence of RIS increases with both depth and volume of the reservoir. Other factors thought to increase the probability of RIS were: presence of active faults, extensional tectonic regime, and predominance of sedimentary strata. Factors that favor RIS at the proposed Auburn reservoir are: the reservoir will be very deep, it will be large in volume, it will be located in an extensional environment, and active faults are present. WCC estimated that there is a 2 to 5 percent chance that the reservoir will induce an earthquake of M 5.7 or greater at Auburn. If the Oroville earthquake was induced by the nearby reservoir, an issue which is still controversial, then WCC would increase their estimate to 30 percent.

The USBR relied on the WCC study for information on RIS at the Auburn damsite. They emphasized the rarity of unquestioned examples of RIS and pointed to the WCC conclusion that active faults are required for RIS to occur. Inasmuch as the USBR does not believe that faults near the foundation are active, the implication is that RIS is unlikely in that area.

The USGS agreed that conditions would be present at the Auburn site for RIS because 20 percent of large, deep reservoirs like that proposed at Auburn have induced earthquakes. They claimed that there are too few data to lend statistical validity of the WCC correlations of other factors with RIS. They made several other important observations: (1) RIS can, in theory, cause fault creep, so that the dam can be damaged even if there is no earthquake, and (2) RIS can reactivate inactive faults. The latter point is particularly relevant to the Auburn damsite because it implies that the inability to prove that foundation faults are active or inactive is irrelevant: infiltration of reservoir water can activate them.

The CDMG considered the possibility of RIS at Auburn to be of "extreme importance" because a large earthquake could be triggered by the presence of the reservoir prior to the time when an earthquake might normally occur. In addition to the conditions mentioned above that favor RIS, the CDMG cited evidence that crustal stresses are building up within the Bear Mountain fault system in the immediate vicinity of the damsite: seismicity centered 6 miles west of the damsite, and crustal deformation indicated by level line data and centered on the northward projection of the Maidu East, F–1, and F–0 foundation area faults.

RIS is thought to trigger earthquakes in areas where crustal stress has already accumulated. Despite the low natural recurrence rate for earthquakes in the Foothills fault system, seismicity and crustal deformation so close to the damsite, coupled with the other conditions known to favor RIS, suggests a high probability that reservoir impoundment at Auburn will trigger a damaging earthquake. Perhaps the WCC estimate of a 30 percent probability is reasonable.

A magnitude 6.0 – 6.5 earthquake at the damsite would cause casualties and heavy damage to Auburn and surrounding communities. If the earthquake is induced by the reservoir, then the USBR will be viewed as liable for damages. Earthquake damage to nearby communities is much more likely than the catastrophe of a dam failure and should be taken into account in considering construction of a dam at

Auburn.

H. Other Seismic Safety Issues

The USGS suggested that latest motions on the F–1 fault are downslope, implying the possibility of gravity sliding (landsliding) in the left abutment of the proposed Auburn Dam. This would have been an intolerable situation with the original thin arch dam, which is completely dependent on the strength of its abutments for support. The concrete gravity dam presently proposed for the site is much less dependent on abutment support, and might even stabilize the abutment against a gravity slide. Because the proposed Auburn Dam poses a potential hazard to so many people, further geotechnical investigation of the possibility of slope failure in the vicinity of the dam foundation is justified.

Some of the proposed dam designs move the foundation just downstream of the original foundation. The F–1 fault clears most of the foundation if this is done, but many other F–zones and T–zone faults still cross it and they must be considered active. No significant seismic safety advantage is realized by moving the foundation slightly downstream.

Recurrence intervals for M 6.5 earthquakes in the vicinity of the Auburn damsite are not known very well but are probably long, on the order of 7,500 to 75,000 years. Recent findings that ancient soils in the western Sierra Nevada are younger than originally thought suggests that the actual recurrence interval is closer to the low end of the range. Despite the long recurrence interval, the probability of a nearby maximum credible earthquake occurring during the lifetime of the dam is on the order of 1 percent. Active crustal deformation centered on the northward extension of the F–0, F–1, and Maidu East fault zones is conclusive evidence of either displacement along an active fault or of strain accumulation along the fault. Seismicity centered 6 miles from the damsite further suggests that the Auburn damsite may be closer to the end of a recurrence interval than the beginning. The crustal strain accumulation may enhance the probability of an earthquake induced by reservoir impoundment.

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Figure 1. Potential areas of inundation if a 2.3 million acre–foot dam at Auburn suddenly failed. This figure is taken from USBR Supplement (1980), Plate 6.

Figure 2. Potential areas of inundation for a 100–year storm flood and a 400–year storm flood. This figure is taken from Army Corps (1989), Plate 4.

Figure 3. A map showing elements of the Foothills faults system. This figure is taken from CDMG (1979), p. 3, Figure 1).

Figure 4. Lineament zones associated with the Bear Mountain fault system in the vicinity of the Auburn damsite. This figure is taken from CDMG (1979), p. 11, Figure 5.

Figure 5. T–zones, T–zone faults, and F–zone faults in the immediate vicinity of the Auburn damsite. Portions of faults that show surface features identical to those seen on active faults elsewhere in the Foothills fault system are indicated by heavy dots. This figure was taken from WCC (1977), v. 2, p. 121, Figure 54.

Figure 6. A map showing major F–zone faults in the vicinity of the Auburn damsite, and their extension to the southeast. This figure was taken from CDMG (1976), p. 9, Figure 4B.

Figure 7. A plot of maximum surface fault displacements observed after earthquakes of various magnitudes. Notice that the displacement scale is logarithmic. The data are for normal faults and normal–oblique faults, as listed by Slemmons (1977). The inclined solid line is the "best fit" to the data, drawn so that 50 percent of the surface displacements observed for earthquakes of any particular magnitude plot at higher values. The dashed line is drawn so that 33 percent of the observed surface displacements plot at higher values. The horizontal line labeled "Max. Credible Earthquake" is located at M 6.5, the MCE for the Auburn damsite. The vertical line labeled "MCE" shows that 50 percent of the M 6.5 earthquakes would cause displacements of 2 feet or higher. The unlabeled line shows that 33 percent of M 6.5 earthquakes would cause displacements greater than 6 feet. The lines labeled "USBR" indicate that the 5–inch displacement specification corresponds, on the average, to a M 5.6 earthquake. The lines labeled "State" show that the 9–inch displacement specification corresponds, on the average, to a M 6.0 earthquake.

Figure 8. Response spectrum for the ground motions at the Auburn damsite. These are the 84th percentile spectra determined by Woodward–Clyde Consultants (1977, v. 8, p. 19, Figure 4). The jagged curve was computed directly from response spectra recorded for several earthquakes. The smooth curve was drawn to eliminate the jaggedness.

Figure 9. The correlation of peak ground acceleration with distance of the measuring station from the earthquake, from Woodward–Clyde Consultants (1977, v. 8, p. 15, Figure 1). The disputed data points, from the Pacoima Dam record of the 1971 San Fernando earthquake, are the solid dots that plot between 1.00 and 1.20 g at the left side of the diagram. The point labeled "(Boore, 1973)" is the Pacoima Dam acceleration value after correction for amplification caused by local topography.

Figure 10. Plan view of foundation locations for different versions of the proposed Auburn dam. This figure is taken from Army Corps (1989), Plate 9.