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TECHNICAL REPORT GL-90-11

GEOLOGICAL-SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS AT HARTWELL AND CLEMSON UPPER AND LOWER DAMS, SOUTH CAROLINA

by

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Seismic source zones have been developed for the southeastern United States that are based on the geology and historic seismicity. A floating earthquake was assigned to each source zone and earthquake motions were attenuated to Hartwell and Clemson Upper and Lower Dams. A maximum credible earthquake at each dam is a far field, MM VII (M = 5.5) earthquake.

Horizontal ground motions for this earthquake are as follows: acceleration 190 cm/sec^2, velocity 14 cm/sec, and duration 11 sec. Accelerograms and response spectra appropriate to these values were selected and are included. Where vertical motions are considered, they may be taken at two-thirds of the horizontal.

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PREFACE

The US Army Engineer District, Savannah, authorized the US Army Engineer Waterways Experiment Station (WES) to conduct a geological-seismological evaluation of Hartwell and Clemson Upper and Lower Dams, South Carolina, on 1 December 1987 under Department of the Army DA Form 2544, No. EN-GG-88-11.

Dr. E. L. Krinitzsky and Mr. J. B. Dunbar, Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory (GL), WES, performed the investigation and wrote the report. Mr. Dale Barefoot, EEGD, assisted with the preparation of illustrations. The project was under the general direction of Dr. A. G. Franklin, Chief, EEGD, and Dr. William F. Marcuson III, Chief, GL.

COL Larry B. Fulton, EN, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

CONTENTS

PART I: INTRODUCTION

Purpose and Scope

1. The purpose of this investigation is to define the maximum potential for earthquakes and to provide appropriate ground motions for earthquake shaking at Hartwell and Clemson Upper and Lower Dams. These dams are located in the Piedmont physiographic province (Figure 1) along the Georgia and South Carolina border. The proposed ground motions are for use in the engineering-seismic evaluation of these structures.

2. This investigation includes both a geological and seismological analysis and consists of the following parts: (a) an examination of the local and regional geology with an evaluation of faulting, (b) a review of the historical seismicity for the area under study, and (c) the determination of the maximum earthquake(s) that will effect these dams as well as the attenuated peak ground motions at each dam.

Study Area

3. The area covered by this study includes that portion of the southeastern United States in which earthquake activity can occur and has the potential to affect either Hartwell or Clemson Upper and Lower Dams. The study area includes portions of Georgia, South Carolina, North Carolina, and Tennessee.

4. The study area in general is limited to the region contained within a circle which has a radius of approximately 150 km with the reservoir formed by these dams at its center. Additionally, an earthquake source at Charleston, South Carolina is considered. The Charleston area is the location for a major historic earthquake which occurred in 1886 and was felt over much of the central and eastern United States. The area continues to be a seismic hotspot with many, very small earthquakes.

5. Hartwell Dam is a concrete and earth dam located on the Savannah River (see map, Figure 1). The Clemson Upper and Lower Dams are two earth dams located in South Carolina approximately 37 km north of Hartwell Dam. The Clemson Dams serve to prevent flooding to lands forming part of Clemson University. Hartwell and the Clemson Dams together form Hartwell Reservoir,

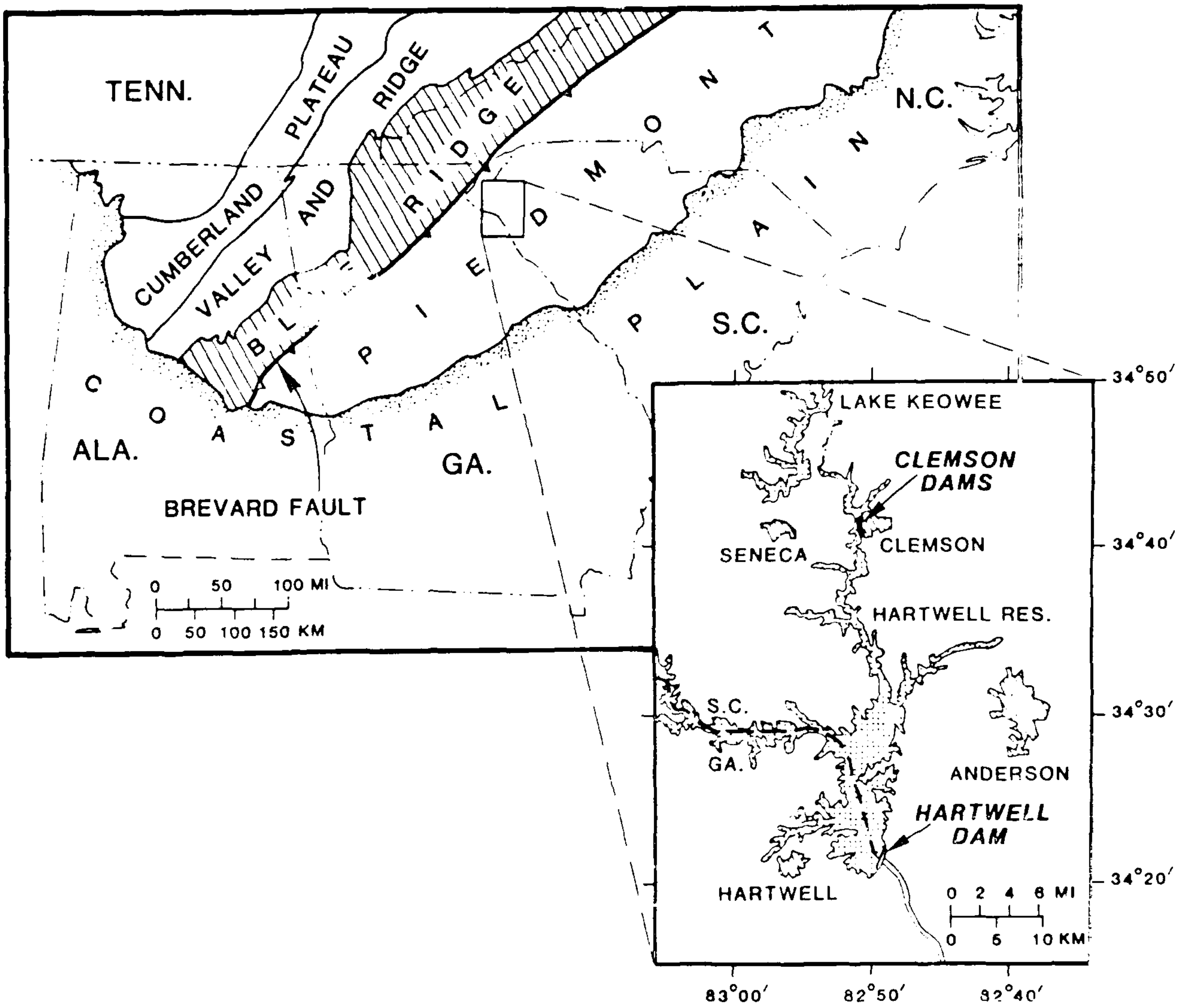


Figure 1. Physiographic subdivisions of the southeastern United States with the locations of Hartwell and Clemson Upper and Lower Dams

a 56,400 acre lake. Hartwell Reservoir is approximately 40 km long and ranges from 2 to 12 km in width.

6. Construction of Hartwell and the Clemson Dams was begun in 1957 and completed in 1963. Filling of the reservoir was begun in 1961. Primary benefits of the Hartwell Reservoir are hydroelectric power and recreation. The dams forming Hartwell Reservoir are operated by the U. S. Army Corps of Engineers, Savannah District.

PART II: GEOLOGY

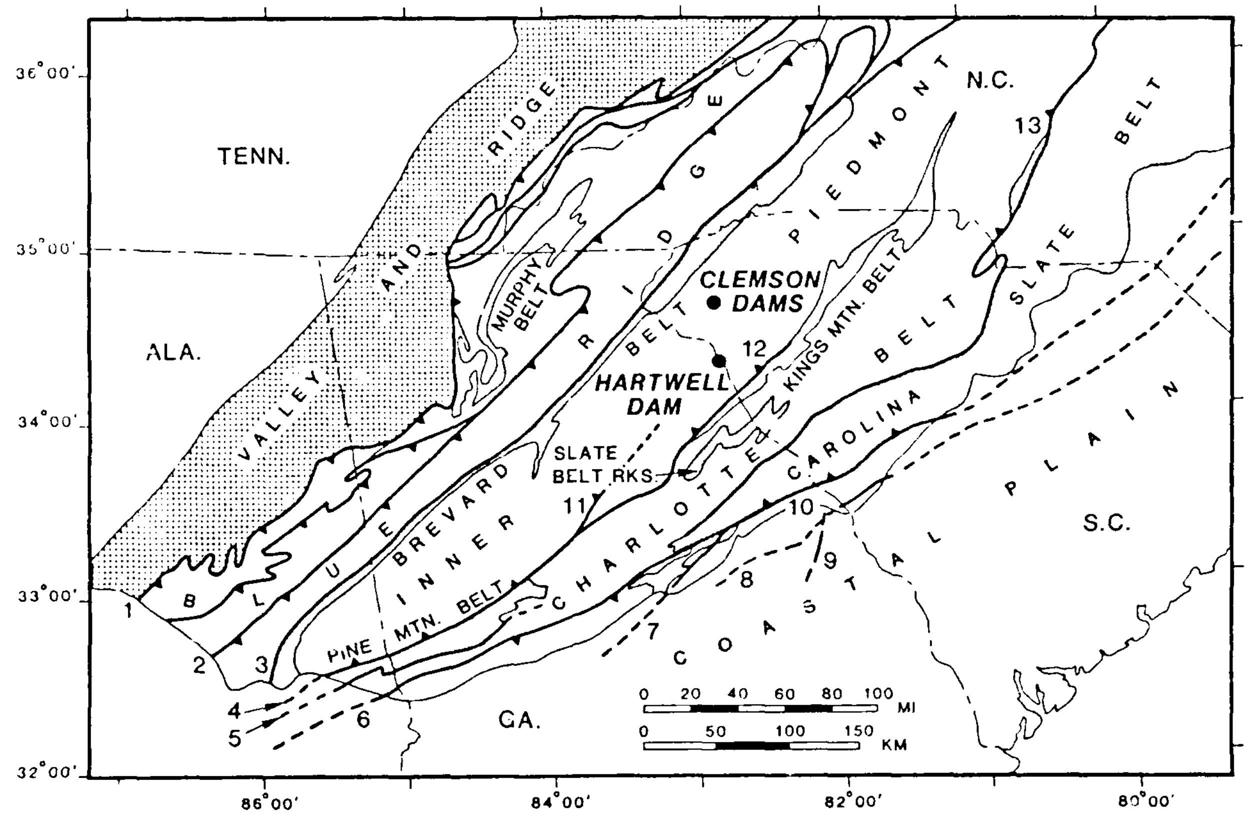
Tectonic History and Setting

7. The Southern Appalachians are dominated by intense folding, the presence of numerous thrust faults, and a vast variety of sedimentary, metamorphic and igneous rocks. The geology and structure of the region indicate multiple periods of deformation which have occurred during the past 600 million years (m.y.) of the earth's history. The history involves two collisions of Eastern North America with other crustal fragments and a third collision with the African continent during the Paleozoic Era, 600 to 250 m.y. ago (Hatcher, 1972 and 1978; Rankin, 1975; and Cook and others, 1979, 1981, and 1982). It has produced the geologic and tectonic features that are identified in Figure 2 (after Hatcher and Butler, 1979).

8. Large-scale thrust faulting and regional-wide metamorphism are the primary characteristics of the three collision events. Thrust faulting is responsible for creating the southern Appalachian Mountains. Figure 3 presents an idealized diagram of how the continental margin of the Eastern United States has been shaped by the various westward transported thrust sheets (from Oliver, 1982).

9. The beginning of the Mesozoic Era (250 to 65 m.y. ago) is the end of regional thrust faulting. Separation of North America from Africa began during this time by continental rifting and created the Atlantic Ocean. The separation of the two land masses represents a change in the tectonism of the region from compression to extension. Relaxation of crustal stresses produced Triassic basins (250 to 210 m.y. ago) that are bounded by normal faults and also produced the intrusion of numerous cross cutting, northwest-southeast trending dikes in the Piedmont region. Basin formation, normal faulting, and dike intrusion ended by the latter part of the Jurassic Period (210 to 145 m.y. ago).

10. The Cenozoic (65 m.y. ago to present) is in general a period of continental stability. The coastal plain was formed during this time as sediments were eroded from the uplifted Appalachian Mountains and deposited along the continental margin. The glacial advances in the Pleistocene (2 m.y. to 10,000 years) are the last major disturbances to have occurred in North America. The glaciers did not advance into the Southern Appalachian region.



FAULTS

1 BLUE RIDGE THRUST
2 HAYESVILLE FAULT
3 BREVARD FAULT
4 TOWALIGA FAULT
5 BARTLETT'S FERRY FAULT
6 GOAT ROCK FAULT
7 FLAT ROCK FAULT
8 AUGUSTA FAULT
9 BELAIR FAULT
10 MODOC FAULT
11 HARTWELL FAULT
12 MIDDLETON-LOWNDESVILLE FAULT
13 GOLD HILL FAULT

Figure 2. Tectonic map of the southeastern United States showing subdivisions of Piedmont Province and locations of major faults (after Hatcher and Butler, 1979; with data from Whitney, Elwood, and Stormer, 1980, and Prowell and others, 1975)

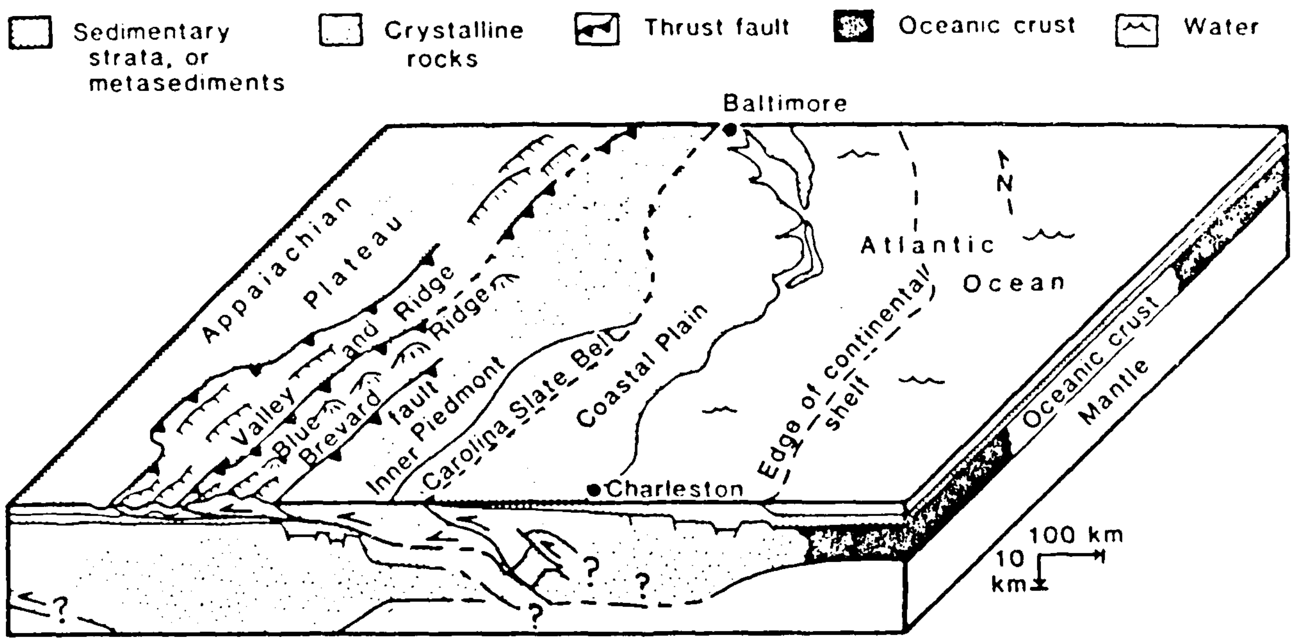


Figure 3. Generalized block diagram illustrating thrust faulting in the southeastern United States and how these thrust sheets overlie a former continental margin (from Oliver, 1981)

Regional Geology

Piedmont

11. The Piedmont is subdivided into several physiographic units or belts which are distinguished from each other by rock type and structure. These are the Brevard, Inner Piedmont, Kings Mountain, Charlotte, and Carolina Slate Belts. Hartwell and the Clemson Dams are all located in the Inner Piedmont. Only the Brevard, Inner Piedmont, and Kings Mountain Belts will be examined in detail as these are the belts in the immediate study area (see Figure 4).

Brevard Belt

12. The Brevard Belt derives its name from the Brevard Fault, a major topographic and structural feature. The Brevard Belt in Georgia and South Carolina is separated into the Brevard Fault, a narrow zone of cataclastic rock (rock containing angular fragments produced by crushing and fracturing from fault movements), and a much wider belt of low to medium grade metamorphic rocks (Griffin, 1974). The Brevard Fault is the boundary between the Blue Ridge and the Piedmont Provinces.

13. The rocks from the Brevard Fault zone are low to medium grade metamorphics. The most common types are phyllites and schists (chlorite, graphite, mica, and garnet), but also there are gneisses, amphibolite, quartzites, and carbonates (Roper and Justus, 1973). Detailed information on rock types in the Brevard Belt and other belts in the Piedmont is presented in a U.S. Geological Survey Report by Overstreet and Bell (1965). The age of the rocks in the Brevard Belt and the majority of rocks in the Inner Piedmont are mainly Paleozoic or older.

14. The area between the Brevard Fault zone and the Inner Piedmont is a noncataclastic, gradational zone or belt of low to medium grade metamorphic rocks. Hatcher and Butler (1979) identify it as a belt of low grade metavolcanics and metasediments. This zone is known as the non-migmatic belt by Griffin (1974), as the Chauga belt by Hatcher (1972 and 1978) and Hatcher and Butler (1979), or as the low rank belt. It has also been described as the Brevard-Poor Mountain-Henderson Belt after the various rock formations which form this zone (Griffin, 1974). This belt is distinct from the Brevard zone by the absence of cataclastic rock and from the Inner Piedmont by differences in metamorphic rock types. Hatcher (1978) interprets this belt as a

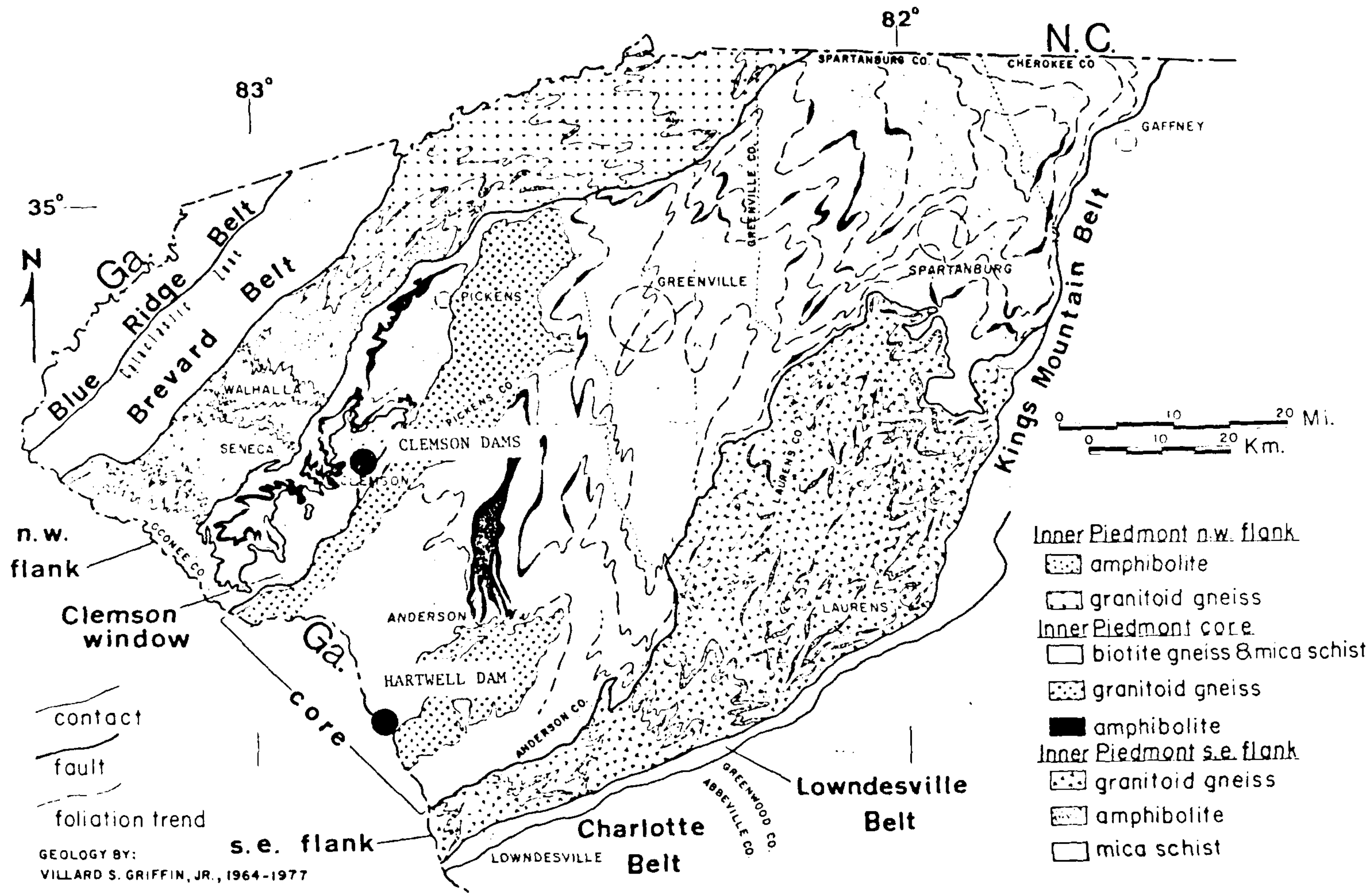


Figure 4. Generalized geologic map of South Carolina's Inner Piedmont (from Griffin, 1977)

metamorphic gradient between the higher grade rocks of the Inner Piedmont and the cataclastic Brevard Fault.

15. Many ideas have been expressed about the origin of the Brevard Fault; thrust fault, strike slip fault, root zone, normal fault, subduction zone, major fold zone, or various combinations. Roper and Justus (1973) regard the fault as having a polygenetic origin, involving repeated periods of deformation by folding, faulting, and extensive metamorphism. Hatcher and Butler (1979) characterize the Brevard Fault as experiencing a complex history of multiple ductile movement events followed by later multiple brittle events. Tectonic movements on the Brevard Fault ended by the Late Paleozoic.

Inner Piedmont

16. The Inner Piedmont is the area between the Brevard Fault zone and the Kings Mountain Belt. Rock types are predominantly metamorphic and are subdivided in South Carolina by Griffin (1971) into a central core bordered by a northwest and a southwest flank as shown in Figure 4 (from Griffin, 1977). The subdivision by Griffin is based on different metamorphic grades or degrees of metamorphism (identified by index minerals and certain key rock types; see Figure 4) and major structural boundaries within the Inner Piedmont. Hartwell Dam is located in the central core and the Clemson Dams are located in the northwest flank. A more detailed presentation of the site geology at each damsite is contained in Appendix A.

17. The general structure of the Inner Piedmont is complex; dominated by recumbent, reclined, and overturned isoclinal folds (both on a microscopic and macroscopic scale) and by northwestward directed nappes. Nappes are rock sequences that have been transported on nearly horizontal surfaces either by thrust faulting or recumbent folding. Griffin (1971, 1974, and 1977) identifies two major nappe sequences within the Inner Piedmont and has mapped these as the Walhalla and Six Mile Nappes. Griffin describes these nappes as forming primarily by recumbent folding and being rooted in or near the Inner Piedmont. A later interpretation about the tectonic structure of the Inner Piedmont is presented by Nelson and others (1985 and 1987). Their mapping indicates that thrust faults and thrust sheets are the primary tectonic structures. Their work combined with the results from reflection seismic profiling suggests that all the rocks of the Inner Piedmont were transported westward from an eastern source and are not rooted in place.

Kings Mountain Belt

18. Bordering the Inner Piedmont on the southeast is the Kings Mountain Belt, a narrow belt composed primarily of mica schists, various gneisses, and amphibolites with minor marble and quartzite (Griffin, 1974). Metamorphic rocks from the Kings Mountain Belt are generally at a lower metamorphic grade than adjacent rocks of the Inner Piedmont and Charlotte Belt. Metamorphic rocks of the Kings Mountain Belt are similar to those found in the Brevard Belt (Griffin, 1971). At its widest point near Kings Mountain, North Carolina, the belt is only 17 km wide.

19. The Kings Mountain Belt east of the Georgia and South Carolina state line merges with the Lowndesville Belt (named after rocks exposed at Lowndesville, South Carolina). At the state line, the characteristic rock types associated with this belt disappear, but the cataclastic zone continues to the southwest into Georgia as the Lowndesville Shear or Fault (Griffin, 1971; Hatcher, 1979; Horton, 1981; and Nelson, 1981).

20. Structures associated with this belt or zone include folds, mylonitic foliation and cleavages, as well as other structures attributed to both ductile and brittle deformation. Shear zone boundaries between the Inner Piedmont and the Charlotte Belt are gradational across this zone.

Lineaments and Faults

Lineaments

21. Personnel from the U.S. Army Engineer Waterways Experiment Station (WES), performed a detailed analysis of lineaments in the Piedmont region as part of the evaluation of earthquake hazards at the Richard B. Russell Dam in South Carolina (U.S. Army Corps of Engineers, 1977a). Richard B. Russell Damis located on the Savannah River, on the Georgia and South Carolina state line, approximately 90 km southeast of Hartwell Dam. Lineaments are straight features which extend for several kilometers and can be identified on topographic maps and aerial photographs. Recognition of lineaments from these sources of data can be important as they may often identify anomalous tectonism.

22. Lineaments were identified on over 175 topographic maps (mainly 7-1/2 minute maps) in the analysis for the Richard B. Russell Dam. The WES study encompassed portions of the Blue Ridge, the Piedmont, and the Coastal

Plain Provinces in Tennessee, Georgia, and South Carolina. The region examined included the area surrounding the Hartwell and Clemson Dams. The lineaments near Hartwell and Clemson Dams are presented on Figure 5 (after U.S. Army Corps of Engineers, 1977a).

23. The WES study concluded that two primary patterns stand out in the Piedmont. The first pattern is evenly dispersed and has two components at right angles. This pattern generally conforms with the structural grain of the region with a general strike at N55°E and a right angle component striking at N35°W. The primary lineament patterns probably reflect the orientation of folds and faults, major rock boundaries, dikes, or joints. Joint studies conducted in the eastern Piedmont at Richard B. Russell Dam and surrounding area indicate a close relationship with the two lineament trends identified above (U.S. Army Corps of Engineers, 1977b). Joints trend primarily in a northeast and northwest direction.

24. The second lineament pattern identified by the WES study consisted of narrow concentrated zones of lineaments extending considerable distances. This second pattern coincided with known shear zones and major faults.

Paleozoic Faults

25. The major faults in the Piedmont Province are shown in Figure 2. These faults are identified by Hatcher, Howell, and Talwani (1977) as forming the Eastern Piedmont fault system. The vast majority of these fault zones are thrust faults with strike-slip components. The four major fault zones are the Brevard, Towaliga-Middleton-Lowndesville-Kings Mountain, Goat Rock-Modoc, and the Augusta Faults. The above faults were formed and were mainly active during the Paleozoic Era.

26. Hartwell and the Upper and Lower Clemson Dams are situated between the Brevard and the Middleton-Lowndesville fault zones. Geologic mapping near both damsites by Nelson, Horton, and Clarke (1985 and 1987) and Nelson (1985) identifies a minimum of four (and perhaps even five) thrust sheets between the Brevard and Lowndesville Faults. These faults and associated thrust sheet are identified in Figure 6.

27. An unnamed fault, shown on the map by Nelson, Horton, and Clarke (1987), has been identified by Whitney, Ellwood, and Stormer (1980) as the Towaliga-Hartwell Fault. This fault is identified in Figure 6 as the Hartwell Fault. This fault splays from the main Towaliga Fault (see Figure 2), extends in a northeast direction, and ends less than 10 km southwest of Hartwell Dam.

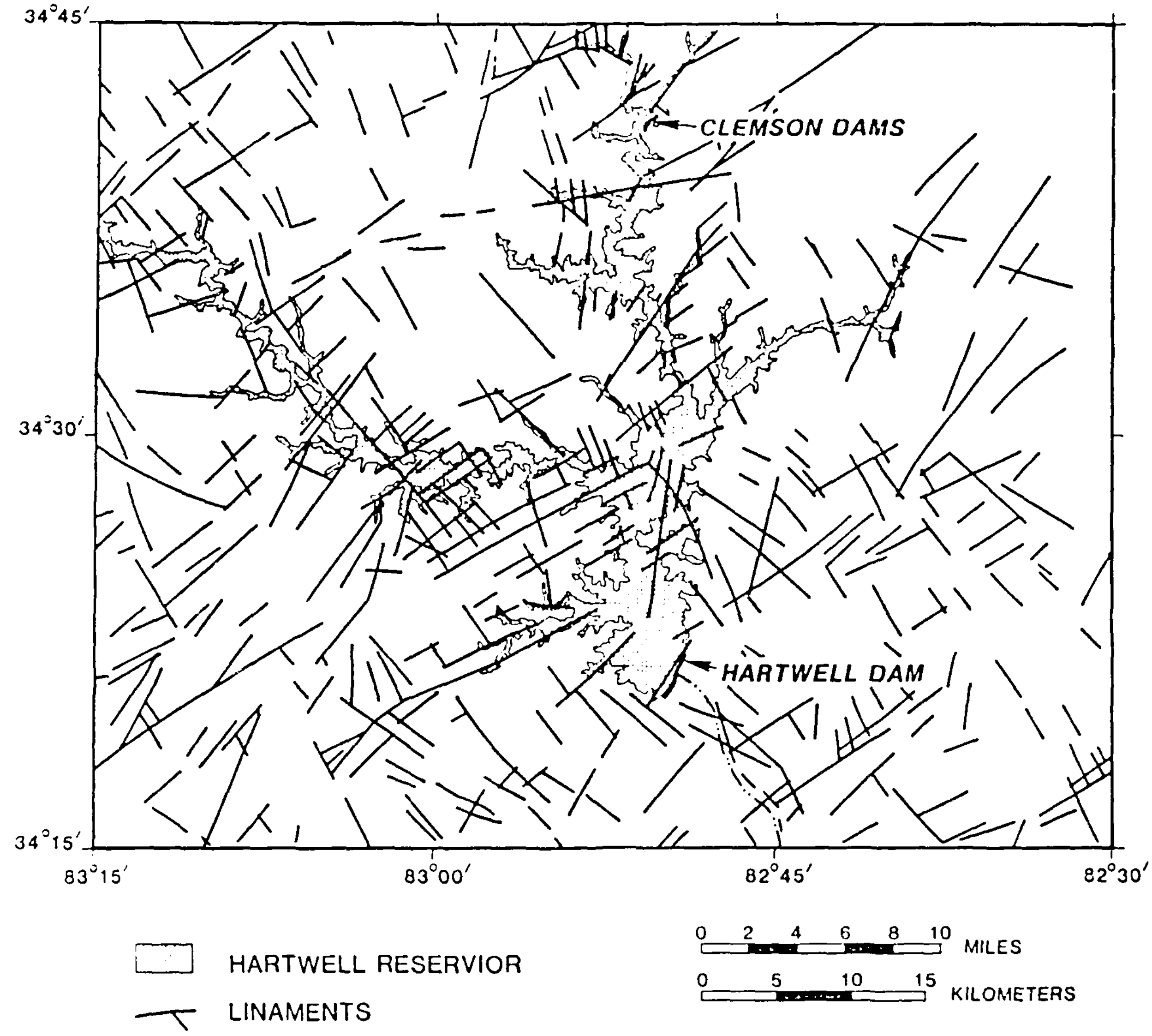


Figure 5. Lineaments near Hartwell and the Clemson Upper and Lower Dams (after U.S. Army Engineers, 1977a)

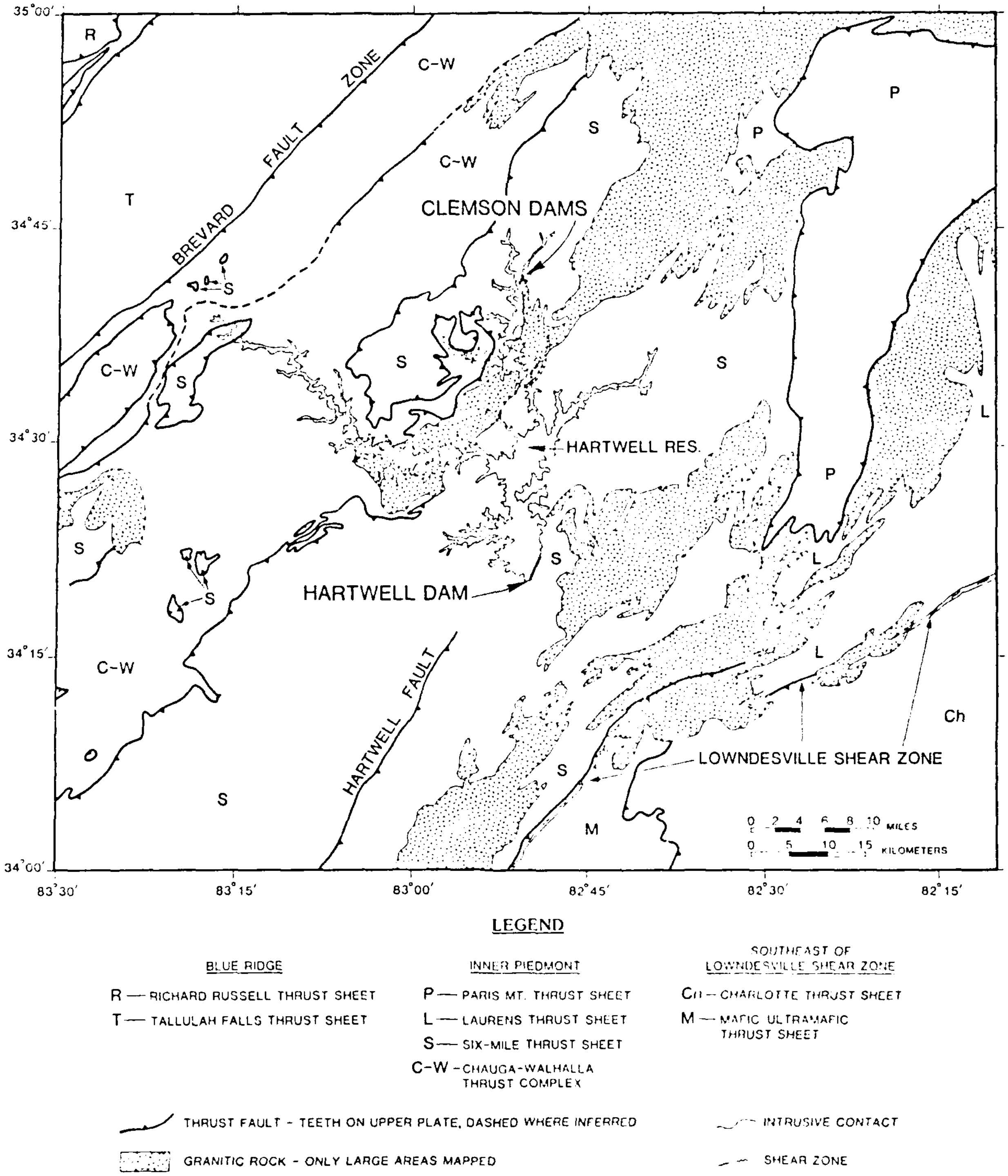


Figure 6. Thrust faults and associated thrust sheets near Hartwell and the Clemson Upper and Lower Dams (from Nelson, Horton, and Clarke, 1987)

The Geologic Map of Georgia (Pickering and Murray, 1976) also identifies this fault as a continuation of the main Towaliga Fault that extends toward and intersects Hartwell Dam. The Georgia State map also identifies a southern branch, named by Whitney, Ellwood, and Stormer (1980) as the Middleton-Lowndesville Fault (see Figure 2), which extends to the state line.

28. As part of the evaluation of earthquake hazards at the Richard B. Russell Dam, field investigations including limited geophysical surveys were conducted on the two branches of the Towaliga Fault near the state line (U.S. Army Corps of Engineers, 1977a). The existence of the Middleton-Lowndesville Fault and the "Hartwell Fault" were rejected when detailed examination utilizing field mapping and geophysical techniques failed to reveal evidence for either fault. Geophysical surveys were performed only on the southern fault and not on the northern Hartwell segment (U.S. Army Corps of Engineers, 1977h).

29. More recentdata has become available since the above study was published. Whitney, Wells, and Rozen (1980) describe the Hartwell extension of the Towaliga Fault as showing "...no cataclastic fabric in this area, and although it can be traced on aeromagnetic maps, its exact location is hard to pinpoint." They indicate that the northern extent of the Hartwell Fault is a brittle fault and at several points along the fault, it has been silicified by massive quartz which was deposited in a brecciated matrix.

30. Nelson (1981) identifies the Middleton-Lowndesville shear zone as a tectonic boundary that represents a polydeformed, 1 to 2 km wide zone of high strain. The extension of the Lowndesville Shear to the southwest and possibly connecting with the Towaliga Fault, and northeast along the western edge of the Kings Mountain Belt has been proposed (Griffin, 1971; Hatcher, 1972 and 1977; Hatcher and Butler, 1979; Nelson, 1981; and Whitney and others, 1980). The connection between the Towaliga Fault and Lowdensville Fault has been identified with an aeromagnetic anomaly and closely follows a gravity gradient (Nelson, 1981). If the Lowdensville Shear is continuous, as many believe, then it may form a major tectonic boundary that extends from Alabama to North Carolina and may be as extensive as the Brevard Fault.

31. The major thrust faults described above and identified on Figure 2 were all developed during the Paleozoic Era, prior to the opening of the present Atlantic Ocean. The opening and creation of the Atlantic Ocean during the Mesozoic marks an end to major thrust faulting in the Piedmont. These

faults are all east-dipping toward the coast. The thrust faults of the Piedmont may all converge at depth into a master detachment zone such as the Brevard Fault (Cook and others, 1979; and Edelman, Liu, and Hatcher, 1987).

Mesozoic Faults

32. The Mesozoic Era is characterized by extensional tectonism and the creation of large Triassic basins along the eastern edge of North America. The Mesozoic Era is the beginning for intrusion of numerous diabasic dikes into the crystalline rocks of the Piedmont. These dikes generally all strike northwest to southeast and are against the regional structure. Many of the major thrust faults are cut by these dikes. The latest movement on some thrusts faults in the Piedmont is established by these dikes.

33. The Triassic Basins are bounded by normal faults. The basins and associated normal faults are all buried beneath the coastal plain deposits in South Carolina. The nearest Triassic Basin, the Dunbarton Basin, is approximately 150 km south of Hartwell Dam on the Georgia and South Carolina state line (Marine and Siple, 1974).

34. Normal faults at the surface in the Southern Piedmont region are numerous and are related to regional uplift and extensional tectonism during the Mesozoic. The Patterson Branch Fault near Richard B. Russell Dam was identified as a Triassic Basin basement fault (U.S. Army Corps of Engineers, 1977f). Trenching was conducted on Tertiary and Pleistocene gravels that were overlying the trace of the fault. It was concluded that the fault was not active. Griffin (1981) also identifies numerous normal faults with displacements of less than one meter in the saprolite deposits covering the Inner Piedmont of South Carolina. These faults are related to regional uplift during the Mesozoic.

Cenozoic Faults

35. The U.S. Army Corps of Engineers, Savannah District, as part of the evaluation of earthquake hazards at Richard B. Russell Dam, performed detailed studies to detect active faults in the Southern Piedmont region. They examined aerial photography and satellite imagery for linears and faults, performed field investigations of known and suspected faults, and conducted several detailed studies on selected faults (U.S. Army Corps of Engineers, 1977a, 1977b, 1977c, 1977d, 1977e, 1977f, 1977g, and 1977h). The above studies also included an intensive field investigation in the area between Hartwell and Richard B. Russell Dams. It was determined that there are no

Cenozoic faults in the Southern Piedmont region except for the Belair Fault. Furthermore, there are no active faults in the Piedmont Province except for possibly the Belair Fault.

36. The Belair Fault is located at the Belair Clay Pits of a local brick company on the northern margin of the coastal plain near the Georgia and South Carolina state line (see Figure 2, Fault No. 9). It is approximately 125 km southeast of Hartwell Dam and is the first possible instance of Post-Tertiary fault displacement in the southeastern United States (Prowell, O'Connor, and Rubin, 1975; and O'Connor and Prowell, 1976).

37. Prowell, O'Connor, and Rubin (1975) trenched the fault and concluded that the Belair Fault is a 7.5 km long reverse fault which had moved approximately 2,450 years before the present. The displacement on the fault is interpreted to be approximately 1 meter. The principal basis for the age determination was made by radiocarbon dating of disseminated organic materials. The validity of the fault age has been questioned. The age was not generally accepted since contamination of the organic material was a possibility. The U.S. Geological Survey re-examined the age problem by conducting a follow-up study and trenching a second time across the fault zone (U.S. Army Corps of Engineers, 1977g). They concluded that the age was not reliable and that the organic material had been contaminated. The U.S. Geological Survey concluded that the age of latest movement on the Belair Fault is unknown, but it has moved within the last 50 million years or since Eocene time.

38. It is concluded that there are no active faults at or near either Hartwell or the Clemson Upper and Lower Dams. The basis for this determination is made from the available geologic data on the Piedmont region and from geologic site data (see References and Appendicies); from studies made by the U.S. Army Corps of Engineers, Savannah District; from discussions with government and university geologists and seismologists who are familar with this area; from the seismic record for this region; and from a brief analysis made during the study of the imagery from the Hartwell Reservoir area.

Relation of Seismicity and Geology

39. Geophysical studies are useful in identifying anomalous structures deep within the subsurface. Such structures are where tectonic stresses may become concentrated and serve as potential sources for earthquakes. Gravity and magnetic studies are two principal types of geophysical studies that are used to define these geological irregularities.

40. Figure 7 presents the results of a gravity survey over portions of South Carolina, Georgia, and Tennessee (from Long and others, 1976 and Long, 1979). A gravity map identifies density variations which in turn indicate differences in rock type and thickness. The gravity map generally corroborates with the major geologic boundaries in the Piedmont Province.

41. North of the Clemson Upper and Lower Dams, the contact between the Blue Ridge and the Inner Piedmont (i.e., the Brevard Fault) is marked by the -80 to -90 mgal contour. Long (1979) describes the characteristic negative anomalies associated with the Inner Piedmont as representing low density continental crustal rocks. These low density rocks are in general composed of granitic or metasedimentary rocks.

42. Southeast of Hartwell Dam, the boundary between the Inner Piedmont and the Lowndesville-Kings Mountain Belt is approximately defined by the -10 mgal contour. The boundary between the Inner Piedmont and the Lowndesville-Kings Mountain Belt is a generally linear zone separating lower density rocks of the Inner Piedmont from the more dense rocks of the Kings Mountain, Charlotte, and Carolina Belts. The positive gravity contours southeast of this zone identify rocks of different thickness and/or crustal composition as compared to rocks in the Inner Piedmont. Southeast of the Lowndesville-Kings Mountain Belt are several distinct linear and circular gravity highs. These highs are thought to correspond to the more dense, mafic to ultramafic rocks (amphibolite or basalts).

43. The boundary separating the Charlotte-Carolina Belt and the coastal plain deposits is approximately represented by the 0 mgal contour. Coastal plain sediments have buried the crystalline rocks and the Mesozoic age faulted basins. The Dunbarton Triassic Basin is a northeast trending low at 81.5 West Longitude and 33.0 North Latitude. This basin measures approximately 50 km long by 10 km wide.

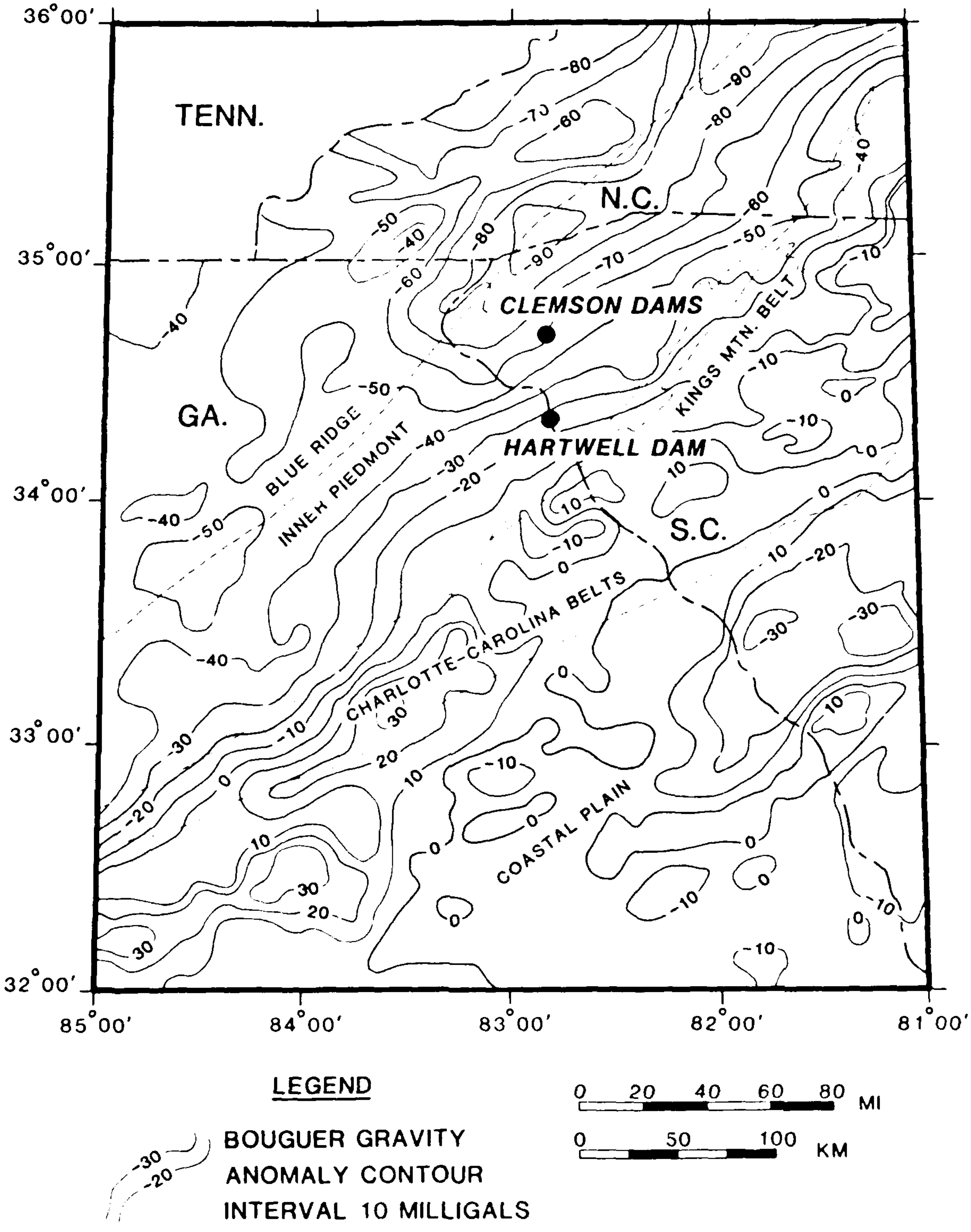


Figure 7. Gravity anomalies in Georgia and South Carolina (after Long, 1979)

44. An aeromagnetic map is presented in Figure 8 (from Zietz and Gilbert, 1980). The aeromagnetic map identifies areas having a susceptiability or remanant magnetization of sufficient magnitude to produce measureable distortion in the earth's magnetic field. Igneous rocks are the primary sources for magnetic minerals capable of producing variations in the magnetic field. The aeromagnetic map clearly shows the structural outline of the Inner Piedmont and surrounding areas. The aeromagnetic map corroborates the boundaries and other tectonic discontinuities identified by the gravity map.

45. Hartwell and the Clemson Upper and Lower Dams are bordered by an area of high magnetic intensity (1000-1200 gammas) as compared to the surrounding area. In general, the Inner Piedmont is a broad northeast trending zone ranging from 600-1000 gammas. In contrast, the Charlotte-Carolina Belt averages between 400 and 800 gammas. It is also a variable zone of magnetic highs and lows, ranging from a low of less than 200 gammas to a high of 1600 gammas. The highs identify areas where magnetic minerals are concentrated, generally represented by the more mafic rocks and probably corresponding to plutons. The basement rocks of the Coastal Plain increase in intensity as compared to the Charlotte-Carolina Belts. They generally average above 800 gammas. The Dunbarton Basin area (81.5 West Longitude and 33.0 North Latitude) is centered over a major high (2000 gammas) that is surrounded by a low (less than 400 gammas).

46. In summary, the gravity and aeromagnetic maps delineate the major structural and geologic boundaries in the Piedmont and Coastal Plain Provinces. These are areas where tectonic stresses can be concentrated and produce earthquakes. These areas include ancient faults, plutons, Triassic basins, or other major rock boundaries.

Distribution of Historic Earthquakes

47. The distribution of historic earthquakes of Modified Mercalli (MM) Intensity IV and greater in the study area is presented in Figure 9. Appendix B contains the catalogue of historic earthquakes for the study area and identifies the earthquakes shown in Figure 9. The catalogue is derived from the Earthquake Data Base of the National Geophysical Data Center, National Atmospheric and Oceanic Administration (NOAA), (from Rinehart, 1987). The

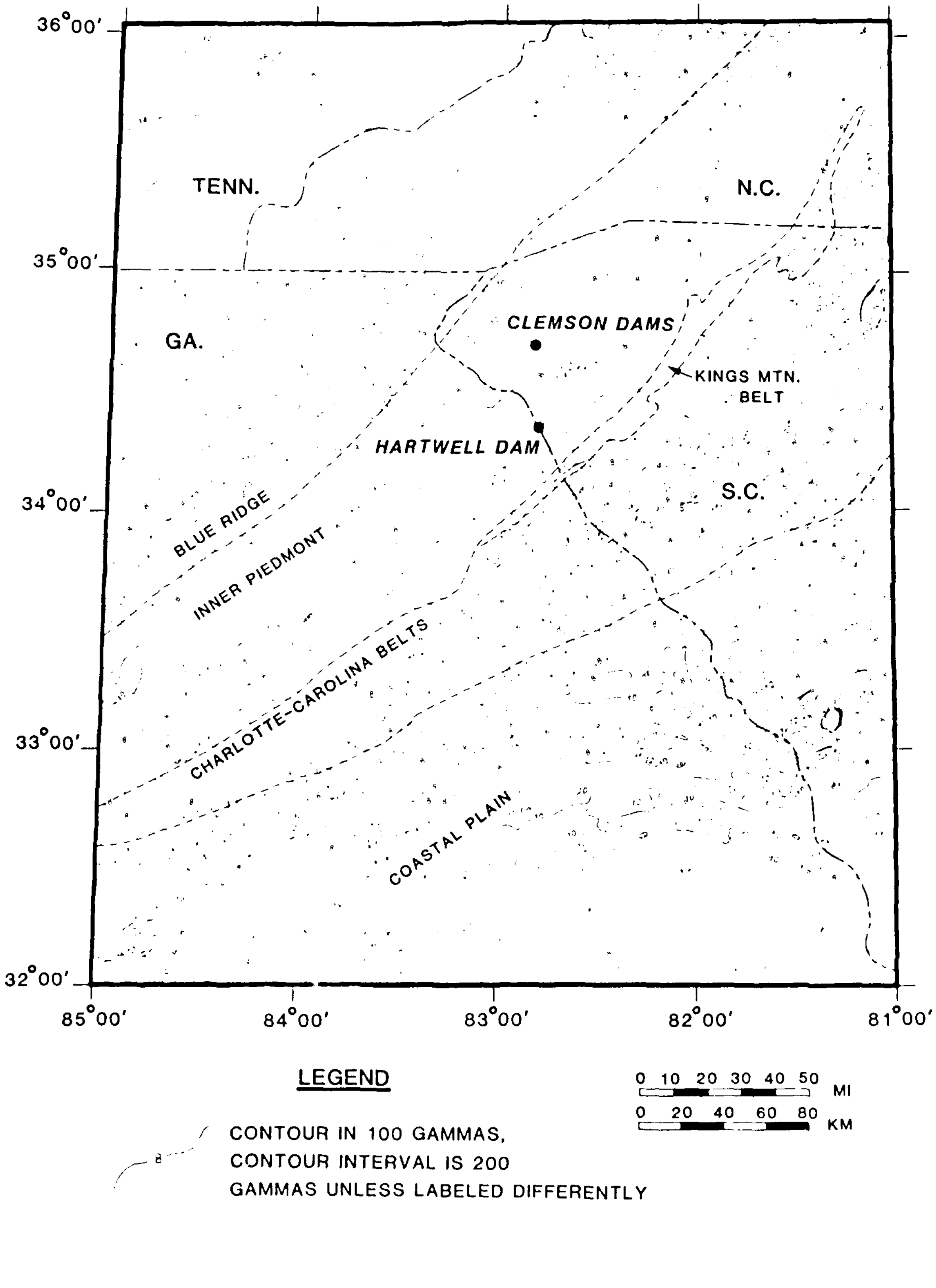


Figure 8. Aeromagnetic anomalies in Georgia and South Carolina (after Zeitz and Gilbert, 1980)

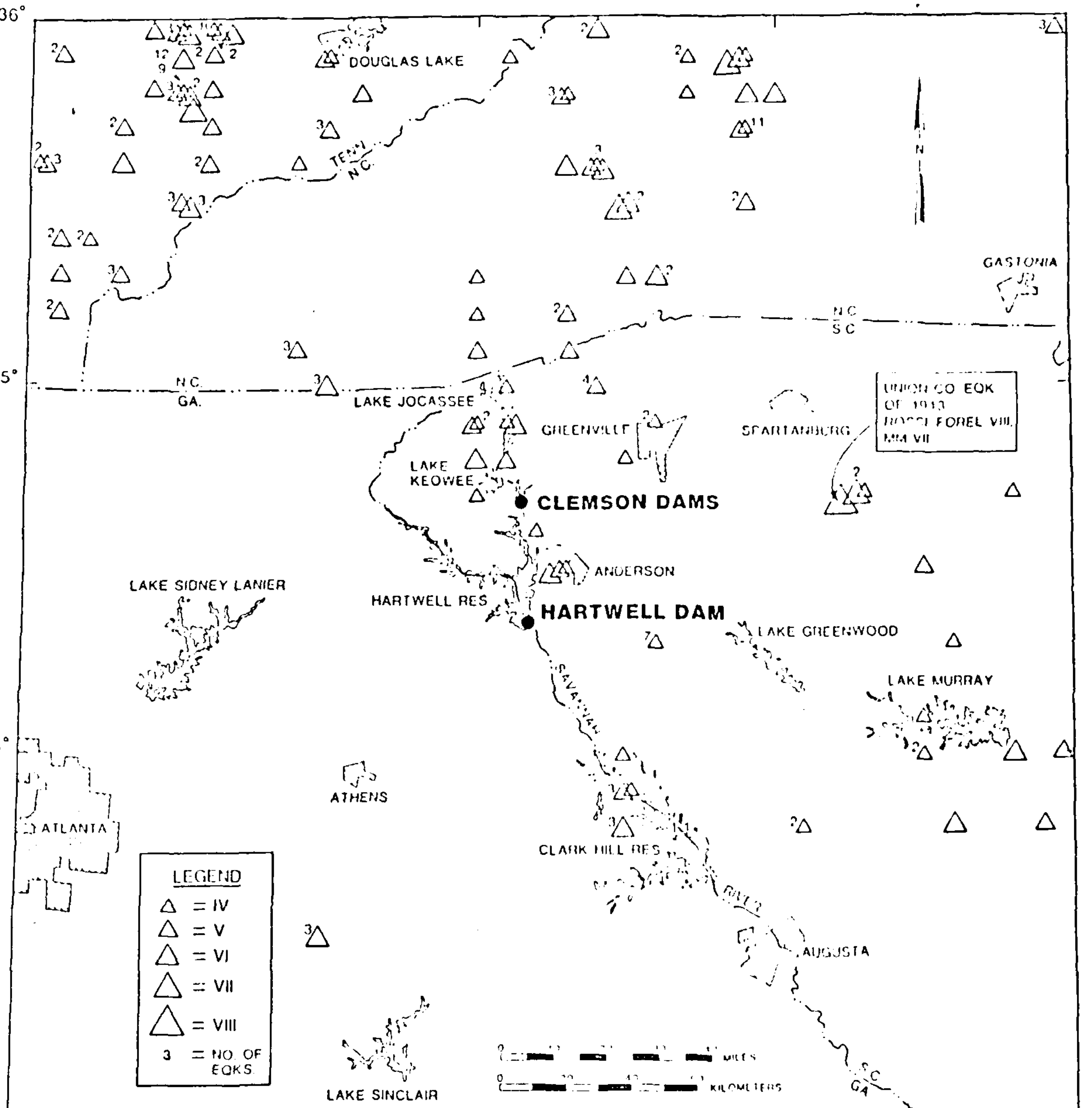


Figure 9. Distribution of historic earthquakes for region surrounding Hartwell and Clemson Upper and Lower Dams

list of historic earthquakes is arranged by date and time (Universal or Greenwich Time) and includes coordinate location of the epicenter, earthquake magnitude (m_b, M_L, and M_s), MM Intensity, and focal depth. A glossary of terms which describes the MM Intensity scale and the different instrumental or magnitude scales that are used is included at the end of this report (Appendix E).

48. The catalogue in Appendix B contains a listing of 413 events between the years 1776 and 1987. The catalogue identifies earthquakes which were barely felt to events as large as a MM VIII that appear to have been misinterpreted. The vast majority of earthquakes are less than MM IV. The distribution of historic earthquakes greater than MM IV is as follows: 83 earthquakes of MM IV, 68 earthquakes of MM V, 34 earthquakes of MM VI, 4 earthquakes of MM VII, and one earthquake that was identified as MM VIII and has since been reinterpreted as MM VII. This earthquake occurred on New Years day in 1913 at Union County, South Carolina. The reasons for reinterpreting and downgrading this earthquake are presented later in this section.

49. The catalogue also identifies possible duplicate listings. Duplicate listings occur when different interpretations of time, location, or MM intensity are made for an event, in which case each event has been listed and the source identified. The four MM VII earthquakes represent duplicate listings and/or alternative interpretations. Two MM VII earthquakes are reinterpreted values for the 1913 Union County earthquake. The remaining two MM VII events are alternative interpretations for two earthquakes which occurred in central North Carolina in 1916 and 1926. A detailed discussion of the larger earthquakes in the study area is presented later in this section.

50. Examination of Figure 9 indicates no general pattern or significant concentration of historic earthquakes. The highest concentration of earthquakes occur in Tennessee, to the northwest of Hartwell and Clemson Dams. The seismic record indicates that the region surrounding the damsites is characterized by low levels of seismic activity and by small earthquakes of MM intensities less than or equal to VI, a level that is too low to cause damage to properly engineered structures

Causes of Earthquakes

51. Earthquakes are produced when strain energy is suddenly released in the form of movements along faults. Strain energy is derived from concentrations of regional tectonic stresses. Sudden movement along a fault surface results in an elastic rebound. This elastic rebound produces vibrations in the earth's crust and these vibrations are felt as an earthquake. Large earthquakes require a large stress drop, signifying a large energy release, and usually can only be produced by fault movements originating within the crystalline basement rocks.

52. The causes of earthquakes both in the study area and in the southeastern United States are not well understood since there are no active faults that have been identified. There are six principal theories that may explain seismicity in the study area:

a. Focusing of regional stresses at heterogeneities, plutons or other discordant rock masses in the subsurface, and release of this stress by fault movements at depth.

b. Introduction of small-scale magmatic materials into the lower crust, producing stresses, and generating fault movements at depth.

c. Focusing and release of regional stresses along major tectonic discontinuities such as ancient rift zones or transform faults. A major transform fault has been proposed that passes through South Carolina and extends from the Blake Fracture Zone in the Atlantic Ocean to its proposed western extension in Eastern Tennessee (Sbar, and Sykes, 1973). This zone has been identified as passing through Georgia and South Carolina and is based in part on the pattern of historical seismicity. It is known as the Charleston-Cumberland trend.

d. Regional compression causing activation and slippage along pre-existing faults planes such as thrust faults (Tarr and Carver, 1976).

e. Regional extension producing movements along fault bounded coastal graben structures (Triassic Basins) or relaxation type movements on existing faults (Barosh, 1981; and Armbruster and Seeber, 1981).

f. Localized stress relief along joint planes or other near surface discontinuities (Long, see Appendix C; and Talwani, see Appendix D). Earthquakes are produced by fracturing in brittle rocks (granitic gneiss) at depths less than 2 km. These earthquakes are related to water table fluctuations and ground water movements.

53. Explanations a through e above can be interpreted as suggesting that a large earthquake can happen anywhere in the study area at a location where no historic earthquake has ever happened before. To project an earthquake into an area or a zone that has displayed no past seismicity, but is part of a major trend such as the Charleston-Cumberland trend or is near a major ancient fault, is not considered valid by the present authors unless there is some evidence in the seismicity. A key question must be asked in such an evaluation as this: "Is there a relation between the present tectonism and the existing geologic structures?" The evidence must be in the seismicity, including very small earthquakes. The folding and faulting that have been mapped (shown on Figures 2 and 6) are from ancient tectonism which is no longer active today. Present day tectonism is greatly different from the tectonism which formed these ancient structures. The present seismicity is related to the tectonism which is active today.

54. Explanation f above implies a very low upper bound on the maximum earthquake that can occur. The release of stress is near the surface and is unrelated to tectonic processes affecting major geologic structures. The cause is believed to be a triggering action resulting from ground-water movements through joints. Because such earthquakes are very shallow, a damaging earthquake (MMI ≥ VIII) is not expected to occur by this mechanism. However, if this mechanism is the primary cause of earthquakes in the southern Piedmont, then small earthquakes (MMI ≤ VII) may occur anywhere within the study area. This type of earthquake would be especially apt to occur near reservoirs. The mechanism for f is explored in Appendix C by Professor L. T. Long.

55. Long believes that the action of ground water on joints in the shallow subsurface, triggering stress releases at depths of generally less than 3 km, is the cause of the earthquakes that have occurred in the Piedmont. This mechanism is in agreement with field observations that have been made using seismometer arrays in this region over the years. The lack of surface rupture by these very shallow earthquakes reinforces the idea that there is an apparent dissipation of displacement at the surface by the spreading of displacements through joint sets. The effect is of a volume stress relief. The mechanism is consistent with the patterns seen in clusters of earthquakes where they have been induced at reservoirs in the Piedmont. Thus, the earthquakes can be inferred to have no necessary relation to major faults.

56. The hydrologic patterns in the region have been changed drastically in the last half century due to engineering and land usage. Thus, the concurrent earthquakes are not likely to be indicative of longer term recurrence patterns.

57. Long and Talwani both postulate that the 1913 Union County, South Carolina, earthquake of intensity VII may have been close to the maximum for the southern Piedmont. It does not follow, however, that the Union County maximum would occur everywhere. The historic seismicity is the only real guide for earthquake activity in the region, and the seismicity shows that the Union County experience is high for the region.

58. It must be assumed that the largest earthquakes which can occur in the area of the damsites are defined by the historic seismicity or by the presence of earthquake-producing faults. Such faults have not been found in this region and the historic seismicity is of a very low order, MMI ≤ VI. Also, the focal depths of these earthquakes are extremely shallow, thereby precluding potentials for large earthquakes. Thus, a floating earthquake with an upper bound at MM intensity VII, matching that of Union County, is assumed in this study to be a conservative maximum event.

Microearthquakes and Reservoir Induced Seismicity

59. Microearthquakes are earthquakes that are too small to be felt but are recorded by seismographic instruments. Microearthquakes are useful for defining areas where tectonic stresses are concentrated. These small earthquakes are helpful in determining focal depths, fault types and orientations, and where they are caused by tectonism, they aid in estimating rates of earthquake recurrence.

60. Microearthquake monitoring in the southern Piedmont has been concentrated at large reservoirs where reservoir induced seismicity was suspected. Monitoring has been performed on all of the principal reservoirs in the study area (see Figure 9 for locations). Earthquake activity has been associated with reservoir impoundments at Lake Jocassee, Lake Oconee, Monticello Reservoir, and Richard B. Russell Reservoir (Long, 1988 and Talwani, 1988). Earthquake monitoring was performed at Hartwell-Clarks Hill (J. Strom Thurmond) Reservoirs from 1979 to 1983 (Long, 1981; Long and Alexander, 1982 and 1983; and Long and Propes, 1984). The monitoring was

discontinued after 1983 as no apparent reservoir induced seismicity was detected. However, the monitoring was begun nearly 20 years after the reservoir was filled, after stress conditions had adjusted to reservoir loading. It is known that the reservoir since impoundment has not produced any earthquakes of $M \geq 2.5$. It is unknown what the microseismic characteristics were following the filling process until the time monitoring was begun. A detailed description and interpretation of reservoir induced seismicity in the Piedmont is presented by Long and Talwani in Appendices C and D, respectively.

61. The microseismic monitoring has indicated that Piedmont earthquakes have unique characteristics. These characteristics are their shallow depth (less than 2 km), swarm type of occurrence, high frequency spectral decay, correspondence between joint patterns and focal mechanisms, and their general association with reservoirs. These characteristics are described by Long in greater detail in Appendix C. The importance of microseismic monitoring programs is in determining if a correlation exists between ancient tectonic structures and present day seismic activity. There appears to be no correlation between ancient structures and present seismic activity.

Seismic Source Zones in the Southeastern United States

62. Earthquake source zones must be interpreted for the southeastern United States since there are no known active faults. These source zones are based on historic earthquakes. The seismic source zones interpreted for the southeastern United States are shown in Figure 10. The southeastern United States is in general a region of low level seismicity with areas of concentrated earthquake activity. These concentrated areas or zones are called "hotspots" and are potential sources for moderate to major earthquakes.

63. An earthquake zone as used in this report is an inclusive area over which a given maximum credible earthquake can occur. The latter is the largest earthquake that can reasonably be expected to occur. It can be moved anywhere in the zone and is thus a floating earthquake.

64. The criteria by which these seismic zones were developed are as follows:

a. Maximum sizes of earthquakes.

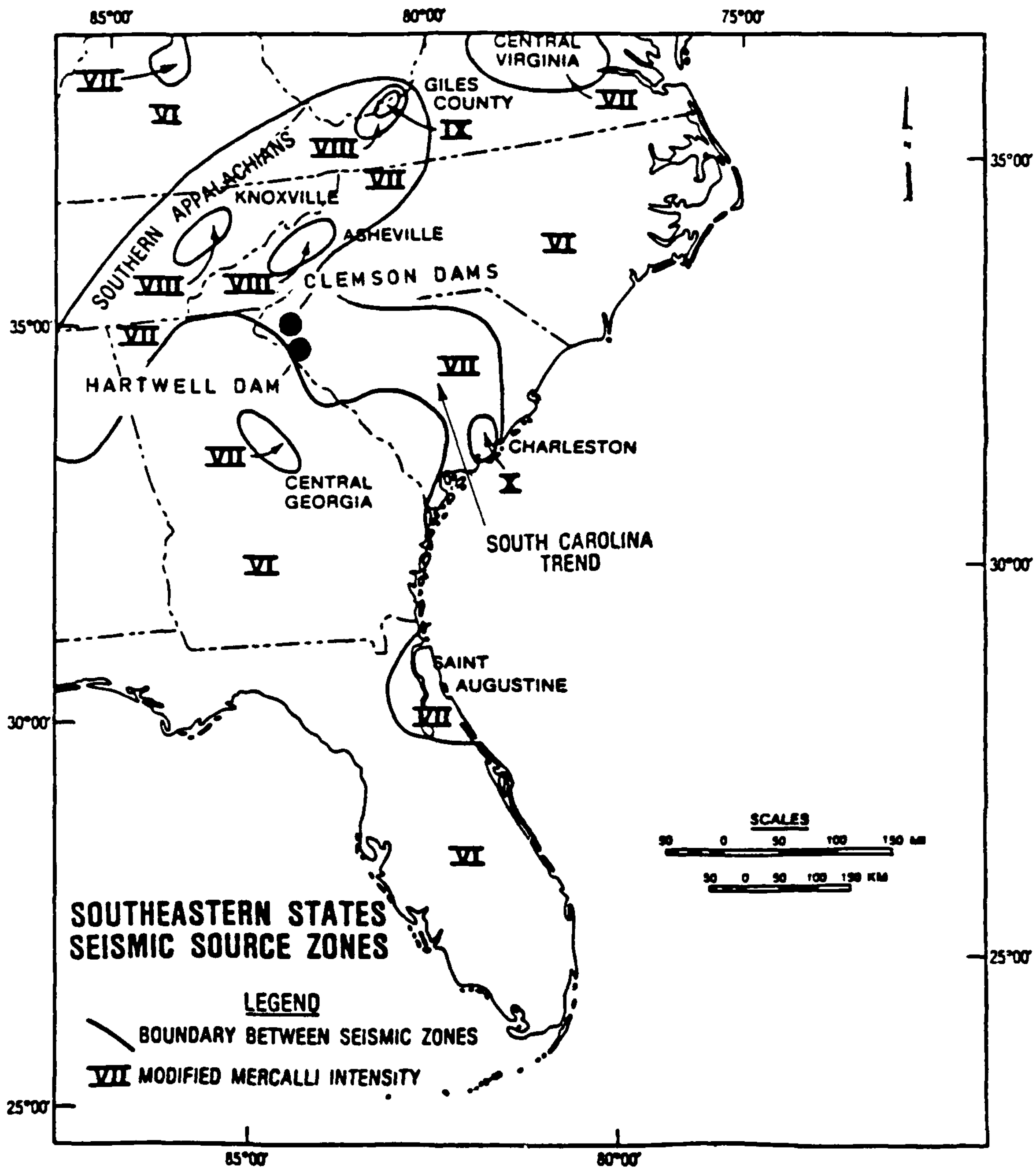


Figure 10. Seismic source zones in the southeastern United States

b. Density of earthquakes, using historic seismicity plus micro-seismic activity where available. A strong occurrence of both together identifies a seismic hotspot.

c. One earthquake will adjust a boundary but cannot create a zone.

d. Zones of greatest activity are generally as small as possible.

e. The maximum intensity of a zone cannot be smaller but may be equal to or greater than the maximum historic earthquake.

f. These zones are source areas. They do not necessarily represent the maximum intensity at every point since attenuations have to be taken into account.

65. The largest earthquake source zones in this portion of the United States are at Charleston, South Carolina and Giles County, Virginia. The Charleston area is shown as generating an earthquake of MM X. An intensity MM X earthquake occurred at Charleston in 1886. The Giles County area is shown as possibly generating an earthquake of MM IX. An intensity MM VIII earthquake occurred at Giles County in 1897 (Bollinger and Hooper, 1971).

66. Hartwell and Clemson Dams are located in the South Carolina Seismic trend or zone. This zone is a broad belt extending in a general southeast to northwest direction. The largest earthquake interpreted for the South Carolina zone is intensity MM VII.

67. The South Carolina zone is bordered on the northwest by the Southern Appalachian zone. The Southern Appalachian zone is identified as a broad northeast trending belt producing earthquakes of MM VII. Two hotspot areas are contained in this zone. These hotspots are approximately 50 and 100 km north of the Clemson Dams and are identified as producing earthquakes of MM VIII. The South Carolina zone is bordered to the southwest (Georgia) and northeast (North Carolina) by areas identified as producing earthquakes of MM VI.

Earthquake Recurrence

68. A deterministic approach was used in this report to specify earthquake ground motions. A deterministic approach is where a maximum earthquake is interpreted to occur regardless of time constraints and that earthquake is attenuated from its source to a site. The assumption is that

the structure must be able to withstand the predicted intensity of a maximum credible earthquake regardless of when it might occur.

69. A recurrence relation is useful for estimating the general return frequency for the maximum event to compare to the operating life of the structure. A recurrence relation is calculated from the seismic record and the basic Guttenburg-Richter relationship:

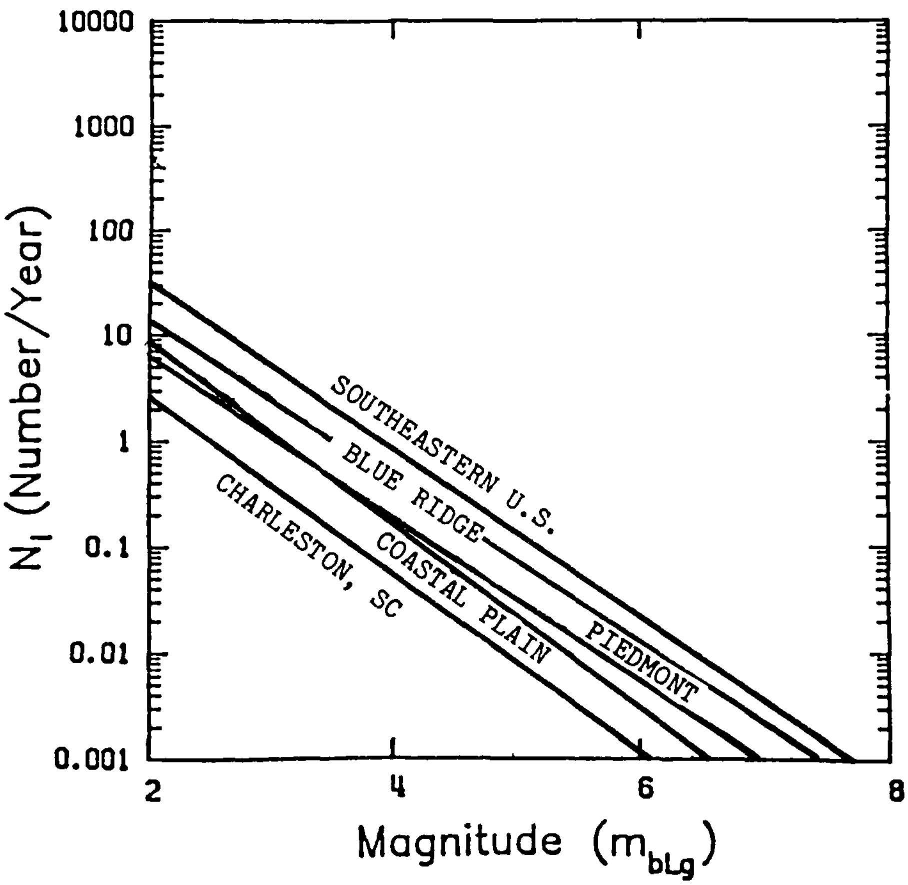
$$\log N = a - bM$$

where N is the number of events of magnitude M or greater per unit of time and a and b are constants. A characteristic recurrence is obtained for a given magnitude from the total number of events for the specified time interval.

70. A recurrence relation for the southeastern United States and its various subdivisions was developed by Bollinger and Davison (1987) and is presented in Figure 11. The basic equations are included on Figure 11 and are described by the authors as being subject to possible minor revisions. Their recurrence relations are based on both the historical and instrumental earthquake catalogues. The historical (intensity based) and instrumental (magnitude based) data sets were combined using relations defined by Sibol, Bollinger, and Birch (1987). The curves are based on the m_b (Lg) magnitude scale (see glossary for description). This scale is considered equal to the m_b scale between m_b 2 to 6.4. The correspondence between m_b and intensity for the Eastern United States is presented in Figure 12 (from Sibol, Bollinger, and Birch, 1987).

71. The mean recurrence for an MM VII earthquake in the Piedmont is about 40 years. For the Blue Ridge, Coastal Plain, and the Southeastern United States the mean recurrence for an MM VII earthquake is 9 years, 85 years, and 8 years respectively. The mean recurrence interval for an MM VII earthquake at Charleston, South Carolina, is about 90 years. The mean recurrence at Charleston for larger events (MM VIII to IX) ranges from 300 to 1000 years.

72. A recurrence relation for the Southern Piedmont is defined by Long in Appendix C (see Figures C13 and C14). The general relation in the Southern Piedmont for an MM VII earthquake is about 60 years and is comparable to results obtained by Bollinger and Davison described above. A recurrence estimate for Hartwell Reservoir based on a probabilistic approach and one that assumes a major event can occur is presented in Appendix C (see Figure C15).



SOUTHEASTERN U.S.	$\text{LOG } N_I = 3.25 \pm 0.11 - 0.86 \pm 0.030\ m_b\ (Lg)$
BLUE RIDGE	$\text{LOG } N_I = 2.51 \pm 0.11 - 0.76 \pm 0.034\ m_b\ (Lg)$
PIEDMONT	$\text{LOG } N_I = 2.02 \pm 0.15 - 0.72 \pm 0.048\ m_b\ (Lg)$
COASTAL PLAIN	$\text{LOG } N_I = 2.71 \pm 0.13 - 0.89 \pm 0.046\ m_b\ (Lg)$
CHARLESTON, SC	$\text{LOG } N_I = 2.69 \pm 0.16 - 0.88 \pm 0.049\ m_b\ (Lg)$

where N_I is number per year in $\pm$ 0.25 magnitude interval

Figure 11. Recurrence relations for the southeastern United States - preliminary results (from Bollinger and Davison, 1987)

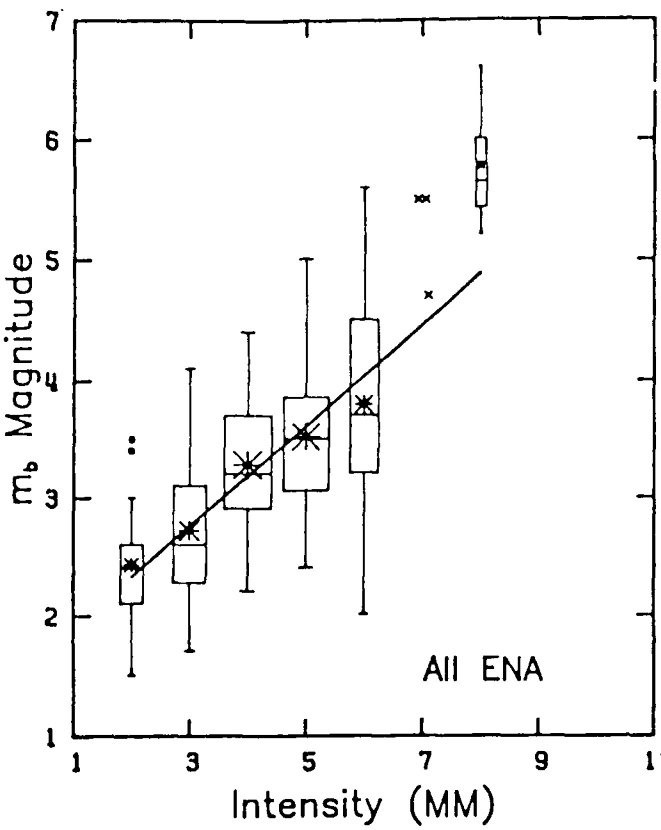


Figure 12. Relationship between m_b magnitude and MM Intensity for Eastern North America; range in data is defined by bar length and box plots: mean (asterisk), 25 and 75 quartiles (box ends), and median (center bar). From Sibol, Bollinger, and Birch, 1982

The rate of recurrence for an MM VI earthquake at Hartwell Reservoir is 6,000 to 8,000 years.

73. It should be noted that the recurrence estimates presented above are for the mean values. Because of the uncertainties in the recurrence equations and the assumptions that must be made, the range at each magnitude interval may extend over an entire log cycle. Because of this variability, the probabilistic approach was not used to specify maximum earthquake ground motions. The deterministic approach was used instead whereby the maximum credible earthquake for Hartwell and Clemson Dams was specified without regard to the probability of recurrence.

Felt Earthquakes at Hartwell and Clemson Dams

74. The southeastern region, with the exception of a small area near Charleston, South Carolina, is characterized by low level earthquake activity. Table 1 presents a list of MM VI or greater earthquakes that were judged to have been felt at Hartwell and Clemson Dams. The earthquake list was derived mainly from the catalogue in Appendix B. Included in Table 1 are events that occurred outside of the study area which are judged to have been felt at the three damsites (from Street and Nuttli, 1984; Bollinger, 1972 and 1975; Bollinger and Hooper, 1971; and Reagor, Stower, and Algermissen, 1980). Distances from the earthquake source areas to the Hartwell and Clemson Dams are identified in Table 1 along with the attenuated intensity.

75. The attenuation procedure selected for this study is based on the decrease of intensity with distance as determined from curves by Chandra (1979). His curves are shown in Figure 13 and the selected curve is that for the eastern province. The attenuation of MM intensity is determined by calculating the distance between the earthquake source and the damsites, selecting this distance on the horizontal axis of the attenuation curve, and then deriving the MM Intensity reduction factor. This reduction factor is subtracted from the intensity value at the source to arrive at the estimated felt intensity at the site.

76. The earthquakes in Table 1 span approximately 200 years and identify about 25 events that were large enough to have been felt. It is judged that the maximum earthquake felt at the Hartwell and Clemson Dams was MM VI as determined by the attenuation-distance procedure specified above.

Table 1

FELT EARTHQUAKES AT HARTWELL AND CLEMSON DAMS

INSIDE STUDY AREA BOUNDARY (See Appendix B)

Date	Lat. Degree	Long. Degree	Location	Distance (km) Hartwell	Distance (km) Clemson	MM (I_o)*	MM (I_s)* Hartwell	MM (I_s)* Clemson
2 Nov 1875	33.8	82.5	Lincolnton, GA	68	103	VI	IV	IV
5 Mar 1914	33.5	83.5	Godfrey, GA	110	142	VI	IV	IV
21 Feb 1916	35.5	82.5	Asheville, NC	138	105	VI-VII	IV-V	IV-V
8 Jul 1926	35.9	82.1	Spruce Pine, NC	182	150	VI-VII	III-IV	III-IV
3 May 1957	35.8	82.1	Woodlawn, NC	173	142	VI	III	IV
2 Jun 1957	35.6	82.7	near Asheville, NC	142	103	VI	IV	IV
24 Nov 1957	35.0	83.5	Macon County, NC	96	72	VI	IV	IV
5 May 1981	35.3	82.4	Hendersonville, NC	115	80	VI	IV	IV
20 May 1853	34.0	81.2	West Lexington, SC	150	165	VI	III	III
1 Jan 1913	34.7	81.7	Union, SC	110	105	VII	V	V
26 Jul 1945	33.8	81.4	near Pelion, SC	142	165	VI	IV	III
13 Jul 1971	34.8	83.0	Oconee County, SC	52	20	VI	V	VI
26 Aug 1979	34.9	82.9	Lake Jocassee, SC	60	22	VI	V	VI
28 Nov 1844	36.0	84.0	Knoxville, TN	218	180	VI	III	III
3 Nov 1928	36.0	82.6	Rocky Fork, TN	190	150	VI	III	III
30 Nov 1973	35.8	84.0	near Knoxville, TN	202	170	VI-VII	III-IV	III-IV
OUTSIDE STUDY AREA BOUNDARY								
16 Dec 1811	36.6	89.6	New Madrid, MO	640	640	XI	IV-V**	IV-V**
23 Jan 1812	36.6	89.6	New Madrid, MO	640	640	XI	IV-V**	IV-V**
7 Feb 1812	36.6	89.6	New Madrid, MO	640	640	XI	IV-V**	IV-V**
31 Aug 1886	32.9	80.0	Charleston, SC	310	330	IX-X	V-VI	V-VI
22 Oct 1886	32.9	80.0	Charleston, SC	310	330	VII	III	III
31 May 1897	37.3	80.7	Giles County, VA	385	350	VII	III	III
12 Jun 1912	33.0	80.2	Summerville, SC	280	305	VII	III	III
28 Mar 1913	36.2	83.7	Knoxville, TN	225	190	VII	IV	IV

*I_o - Intensity at origin *I_s - Intensity at site ** - Intensities interpreted from Street and Nuttli (1984)

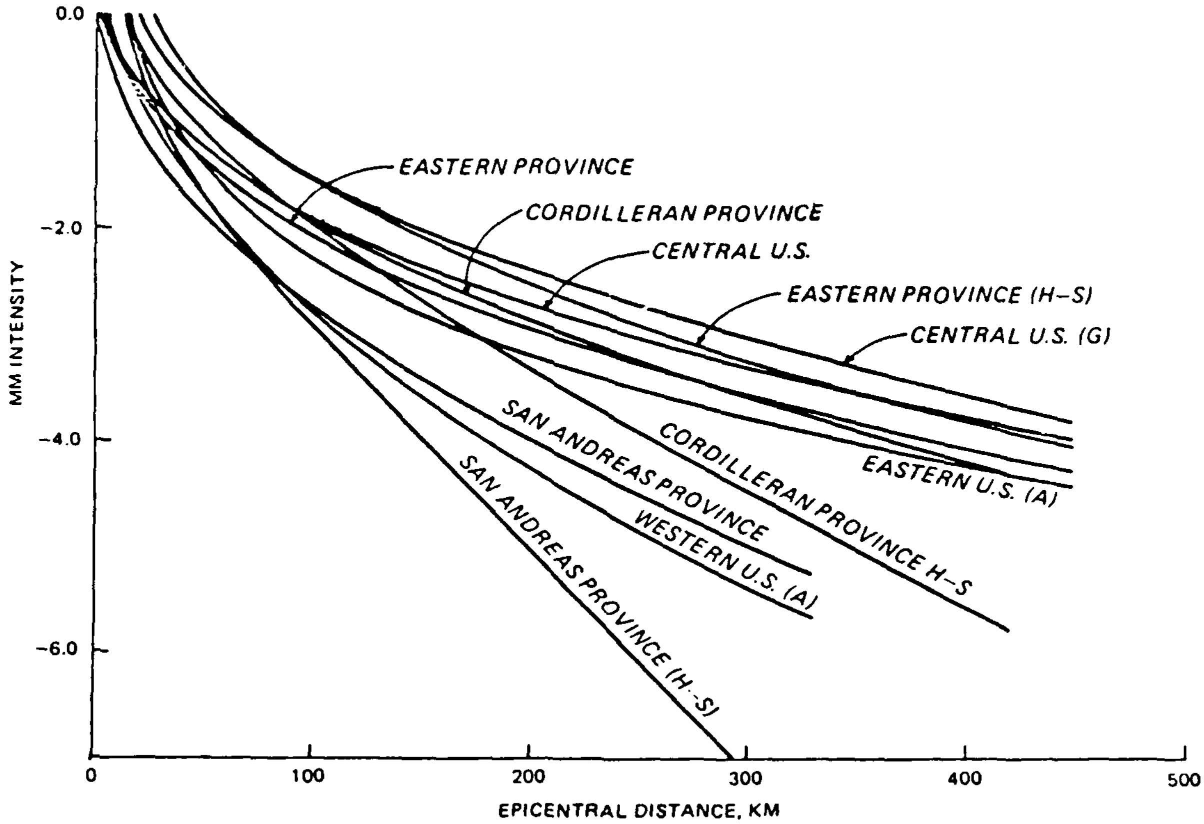


Figure 13. Attenuation of MM Intensity with distance (A = Anderson, G = Gupta. H-S = Howell and Schultz). From Chandra, 1979

Four MM VI intensities were felt at the Clemson Dams and two MM VI intensities at Hartwell Dam. The vast majority of earthquakes in Table 1 are estimated to have been felt at intensity levels of III to IV.

77. Figures 14 through 17 present isoseismals from the four largest earthquakes that were felt in the study area (from Visvanathan, 1980 and Talwani, Rastogi, and Stevenson, 1980). These earthquakes in order of occurrence are the Charleston earthquake (31 August 1886), Union County earthquake (1 January 1913), Oconee County earthquake (13 July 1971) and the Lake Jocassee earthquake (26 August 1979). All were in South Carolina. The Union County earthquake is contoured in the Rossi-Forel Intensity scale. Figure 18 presents the correlation between the Modified Mercalli and Rossi-Forel scales. The isoseismals define the intensities at the damsites as follows:

Earthquake	MM Intensity Hartwell	MM Intensity Clemson
1886, Charleston, SC	VI	VI
1913, Union County, SC	IV	IV
1971, Oconee County, SC	I-III	IV
1979, Lake Jocassee, SC	II-III	IV

78. The Charleston earthquake is one of the largest historic earthquakes (MM X) that has occurred in North America and the largest for the southeastern United States. This earthquake has been studied and described in detail by Bollinger and Stover, 1976; Bollinger, 1977; Visvanathan, 1980; Armbruster and Seeber, 1981; Talwani, 1983; and Peters and Herrmann, 1986. Specific details and information about this earthquake can be obtained from these references. Hartwell and Clemson Dams are both located more than 300 km from the Charleston source area. The Charleston earthquake is interpreted to have caused the maximum historic ground shaking at the Hartwell and Clemson sites (Visvanathan, 1980). The isoseismal in Figure 14 identifies Hartwell and Clemson Dams as borderd by areas experiencing more severe effects. The three dams are located within an island of lower intensity as compared to the surrounding area.

79. The Union County earthquake is identified as an MM VIII event in the earthquake catalogue in Appendix B and also by Reagor, Stover, and Algermissen (1980) for the state seismicity map of South Carolina. This

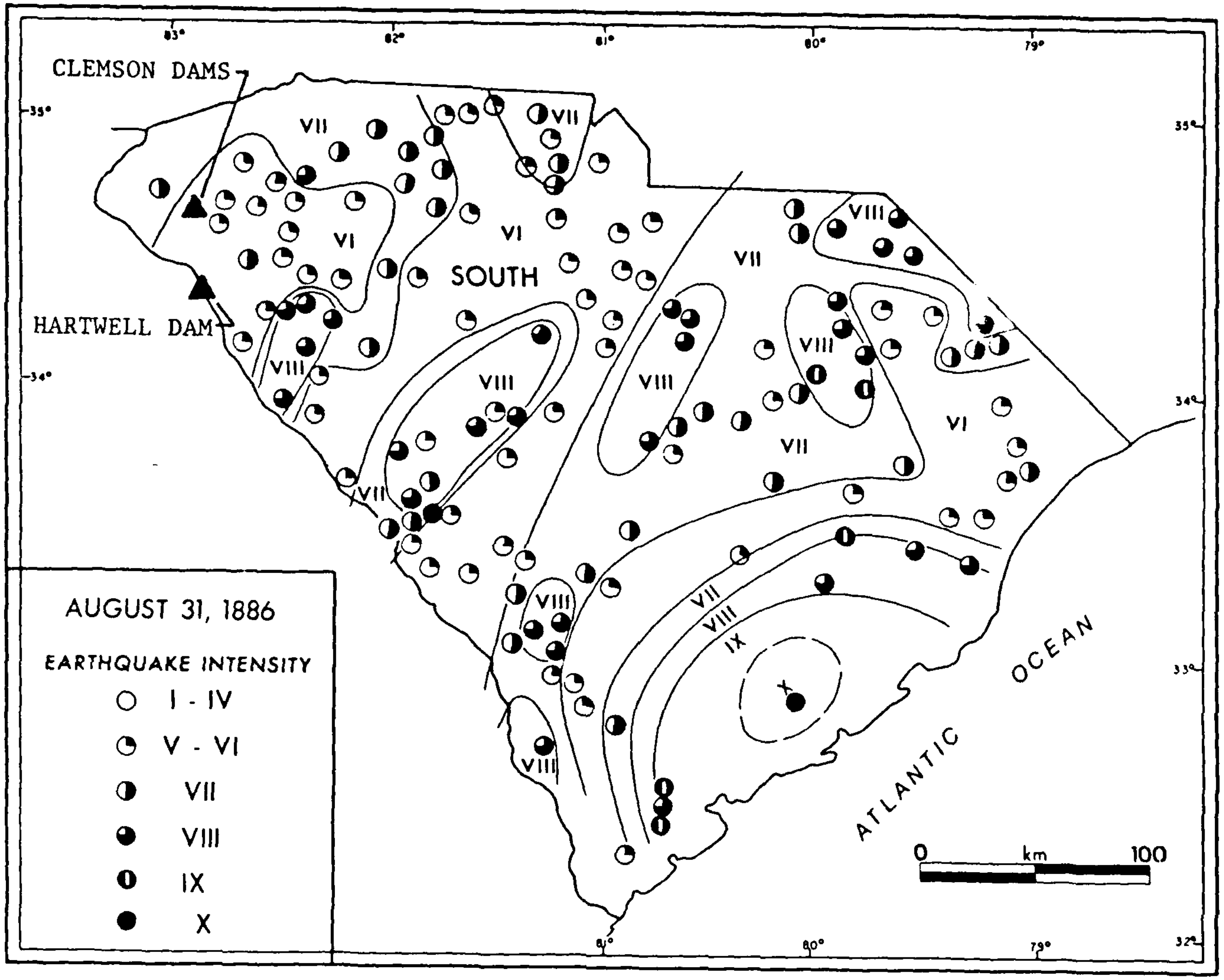


Figure 14. Isoseismal of the Charleston, South Carolina, earthquake of 31 August 1886 (from Visvanathan, 1980)

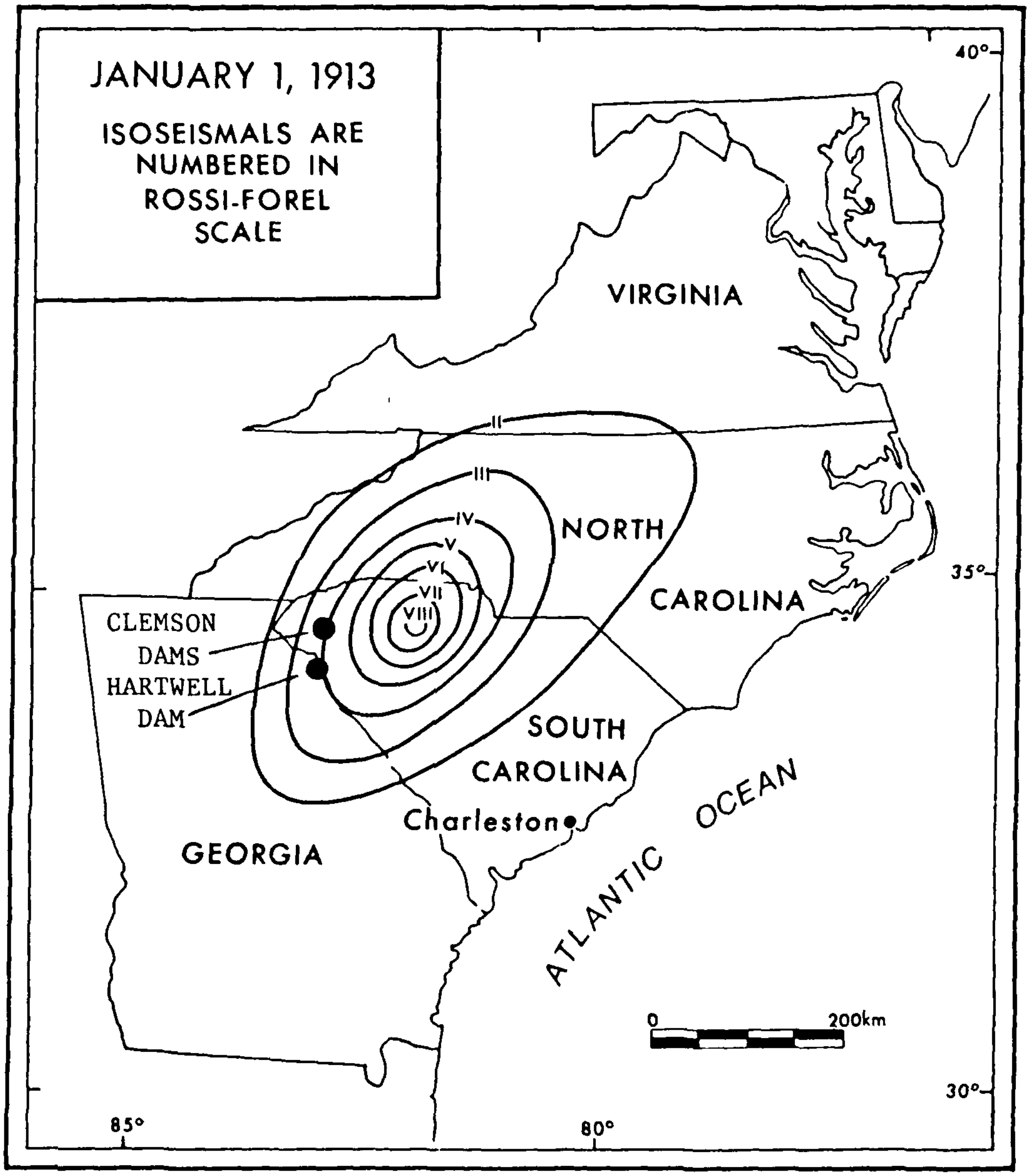


Figure 15. Isoseismal of the Union County earthquake of 1 January 1913 (from Visvanathan, 1980)

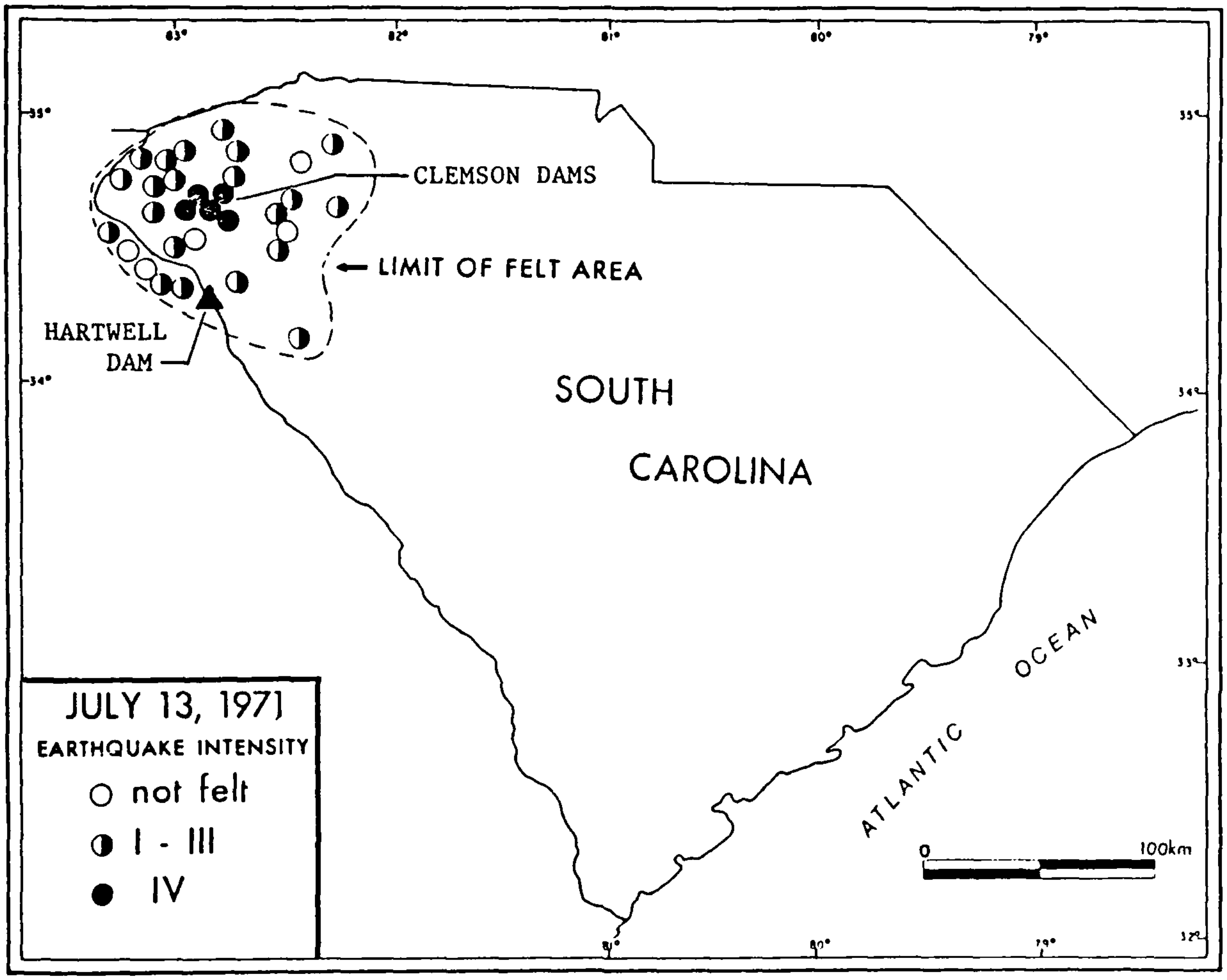


Figure 16. Isoseismal of the Oconee County earthquake of 13 July 1971 (from Visvanathan, 1980)

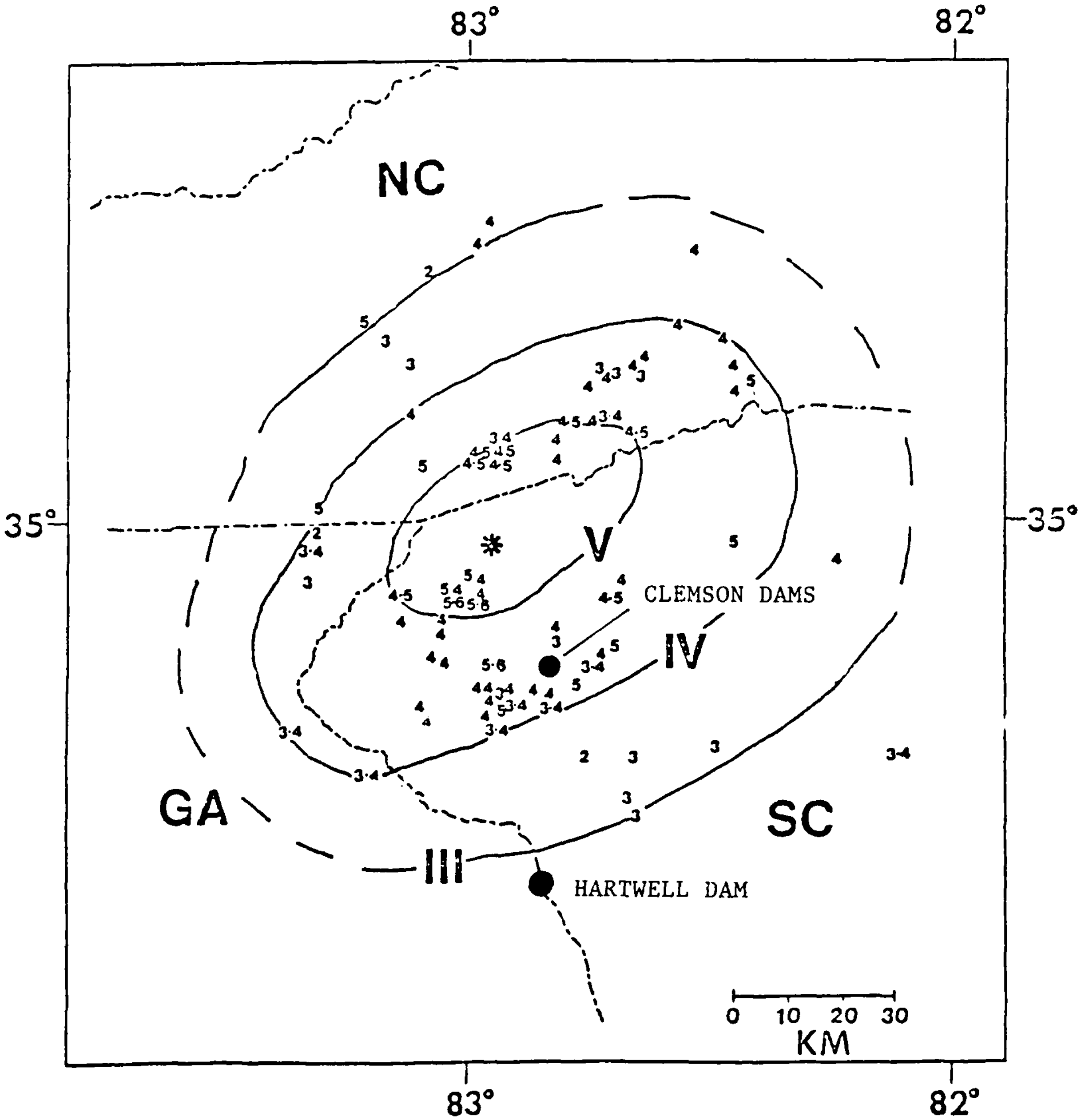


Figure 17. Isoseismal of the Lake Jocassee earthquake of 26 August 1979 (from Talwani, Rastogi, and Stevenson, 1980)

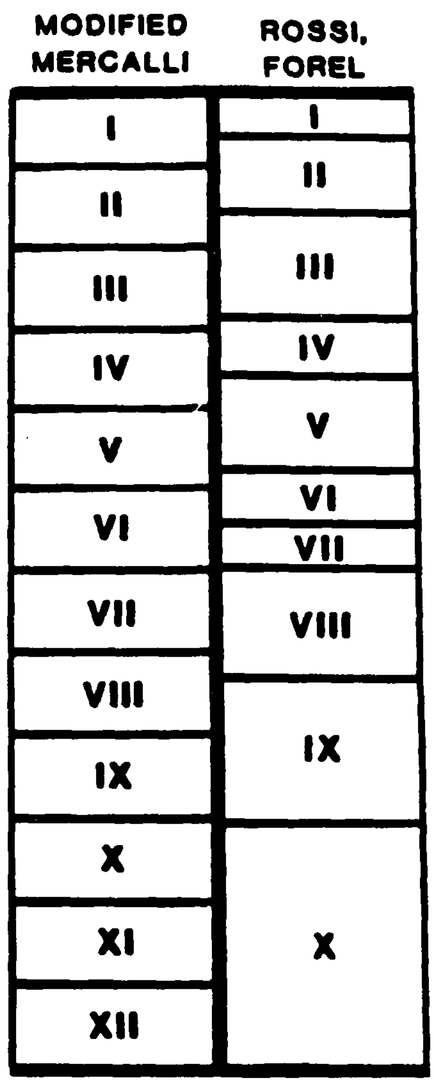


Figure 18. Correlation between the Modified Mercalli Intensity and Rossi-Foreli scales

earthquake has been reinterpreted and downgraded in this study by the present authors. The reasons for downgrading this earthquake are described below.

80. The Union County earthquake was investigated by the U.S. Army Corps of Engineers, Savannah District, during a previous earthquake study of the Clemson Dams (U.S. Army Corps of Engineers, 1983). The Savannah District downgraded the Union County earthquake to an MM VI event following a detailed review of old newspaper articles about the earthquake. Their report is presented in Appendix E. Their report summarizes the damage and compares it to characteristic damage for intensity MM VII. A primary characteristic of intensity MM VII is damage to chimneys. The report in Appendix E indicates chimney damage; however, the condition (loose or solid) of the bricks is unknown and is questioned. It can be interpreted that significant chimney damage represents a level of damage which corresponds to intensity MM VII.

81. The isoseismal from the Union County earthquake is described by Visvanathan (1980) as having been obtained from Taber (1913) and is presented in the Rossi-Forel scale (see Figure 15). The comparable level in MM intensity would be MM VII. Visvanathan (1980) also includes a summary of felt reports as quoted from Taber (1913) in addtion to the isoseismal. The summary from Visvanathan is presented below and identifies significant chimmey damage throughout the area.

> "At Union, cracks were formed on the stone walls of the jail...and to the terror of the prisoners, considerable plaster fell; cracks also appeared in the new brick courthouse, and in the court room the plastering was seriously damaged. Chimneys were thrown down in all parts of town. Vases and other ornaments were overturned; plaster fell in many residences, and everybody rushed into the streets. The vibrations are said to have been in a northwest-southeast direction, and the earthquake was accompanied by a loud roaring noise. At Monarch, a mile and a half south of [the] Union courthouse, a house was partially shaken down. At Colerain, nine miles west of Union, the shock was reported to be more severe.... A report from West Springs,...11 miles northwest of Union,...the vibrations...were of sufficient intensity to destroy some chimneys....At Cross Keys,...11 miles southwest of Union, several chimneys were thrown down....Here, [Spartanburg], goods fell from the shelves....Many persons ran into the streets....Several chimneys were damaged....At Enoree, Pacolet and Pauline, in Spartanburg County, and also at Gaffney,...a few chimnesy fell. [There were]...breaking of some glass and china and overthrowing of a chimney at Kings Mountain.... Shock was reported from points in North Carolina and Virginia. At Raleigh, North Carolina,...the shock...lasted 30 seconds or more....Several citizens of Danville, Virginia, felt a distinct trembling...."

The Union County earthquake for purposes of this study is interpreted to be an MM VII event. This earthquake was felt at Hartwell and Clemson Dams at intensity MM IV as defined by the isoseismal in Figure 15.

82. The description of the Oconee County earthquake by Visvanathan (1980) describes Clemson, South Carolina as located in an area of MM V and Hartwell, Georgia as located in an area of MM IV rather than the values indicated above or those defined in Figure 16.

83. The Lake Jocassee earthquake is an MM VI event and is described in detail by Talwani, Rastogi, and Stevenson (1980). The earthquake was centered about 22 km northwest of Clemson Dam. The earthquake epicenter is indicated by the large asterisk. The isoseismal in Figure 17 identifies the Clemson Dams as midway between the MM IV and MM V isoseismal. Hartwell Dam is located between the MM II to MM III isoseismal.

84. The isoseismal data and Table 1 identify the largest felt earthquake at the Hartwell and Clemson Dams as MM VI. Isoseismal data also indicates that the maximum number of MM VI events is less than estimated by the attenuation-distances procedure described above.

PART IV: EARTHQUAKE GROUND MOTIONS

Maximum Credible Earthquake

Source Zones

85. The largest earthquake estimated for Hartwell and Clemson Dams is an earthquake originating from the South Carolina seismic zone (see Figure 10). The maximum earthquake interpreted for this zone is MM VII. Ground motions from earthquakes originating outside of the South Carolina seismic zone would be attenuated with distance to the site of interest and would be less severe than motions from earthquakes originating within this zone. Consequently, earthquakes from outside the South Carolina seismic zone are not interpreted to be the main hazard.

Field Conditions

86. Ground motions from an earthquake source are characterized as being either near field or far field. Ground motions for the same intensity level are different for each field. Near field motions, those originating near a site, are characterized by a large range of ground motions that are caused by complicated reflection and refraction patterns, and focusing effects of the waves that are in addition to the effects of geometric damping. In contrast, for far field motions the wave patterns are more orderly, they are generally more muted or dampened, and they incorporate wave spreading and attenuation effects that are characteristic for the region.

87. The limits of the near field are variable, depending on the severity of the earthquake. The relationship between earthquake magnitude (M), epicentral intensity, and the limits of the near field are given in the following set of relations (from Krinitzsky and Chang, 1987).

M	MM Maximum Intensity, Io	Limit of Near Field, km from Source
5.0	VI	5
5.5	VII	15
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45

88. Far field conditions are recommended for the selection of motions at Hartwell and Clemson Dams. Near field conditions are specified only when the site of interest is within or near (15 km or less for MM VII) a seismic hotspot.

89. It is uncertain what the maximum earthquake potential is for shallow hydroseismic events such as those identified by Professor Long (see Appendix C). If a maximum credible earthquake does occur near the reservoir by the hydroseismic mechanism, it could produce near field conditions. However, the spectral content for the high frequency components are considered to be not as severe as near field tectonic events originating at much greater depths. For shallow events the total energy involved would probably not be as great as for near field tectonic earthquakes. The shallow earthquakes would generate very sharp spikes (high amplitude), but with low total energy (area under the curve for the high amplitude spikes). Consequently, far field motions are considered appropriate even for these conditions if an earthquake were to occur at the reservoir. It should be noted again that microseismic monitoring has not identified reservoir induced seismicity at the Hartwell Reservoir, and there is no evidence by which we may expect such events at or near the damsites. Thus, near field motions of any sort are not warranted.

Recommended Peak Motions

90. The parameters for earthquake motions specified in this report are horizontal peak values for acceleration, velocity, and duration. Duration is bracketed duration equal to or above 0.05 g (g = gravity; 1 g = 980 cm/sec^2). Values specified are for free-field motions on rock at the surface.

91. The ground motion parameters of interest are determined from the Krinitzsky-Chang curves for MM intensity and ground motions. The far field curves for acceleration, velocity, and duration are presented in Figures 19, 20, and 21 (from Krinitzsky and Chang, 1987). Recommended motions are at the mean plus one standard deviation or the 84 percentile.

92. The values for peak horizontal ground motions at MM intensity VII are as follows:

3

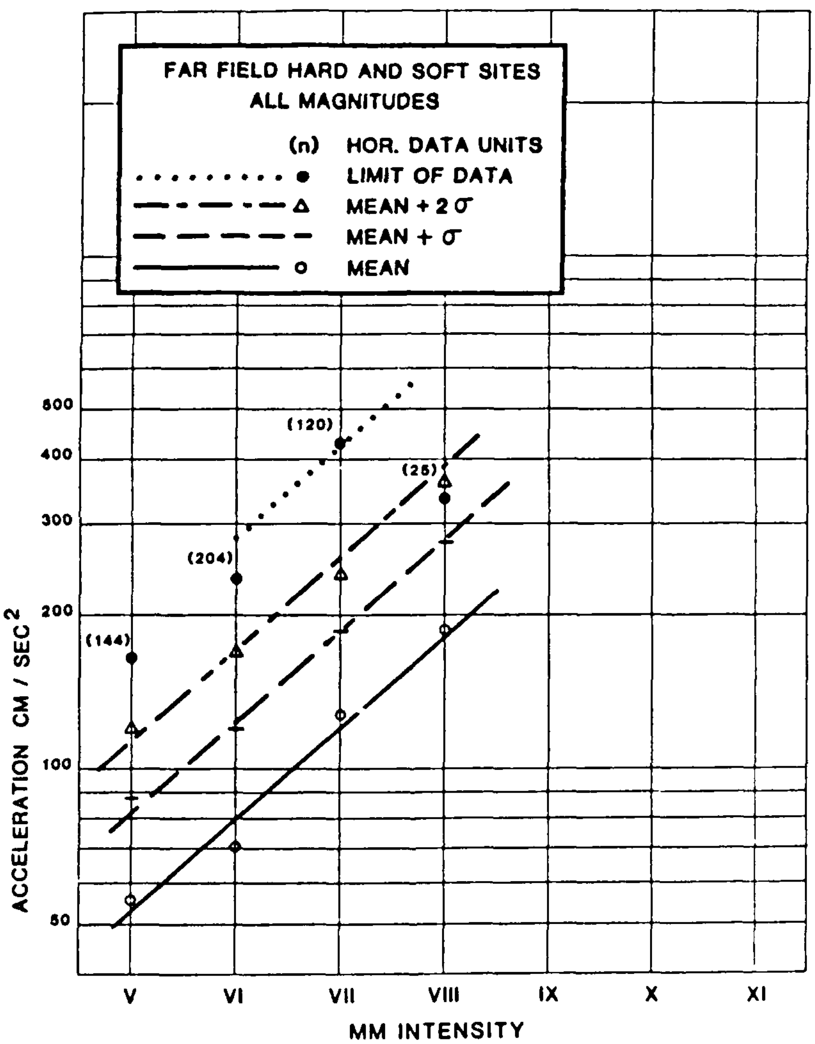


Figure 19. Chart for acceleration (from Krinitzsky and Chang, 1987)

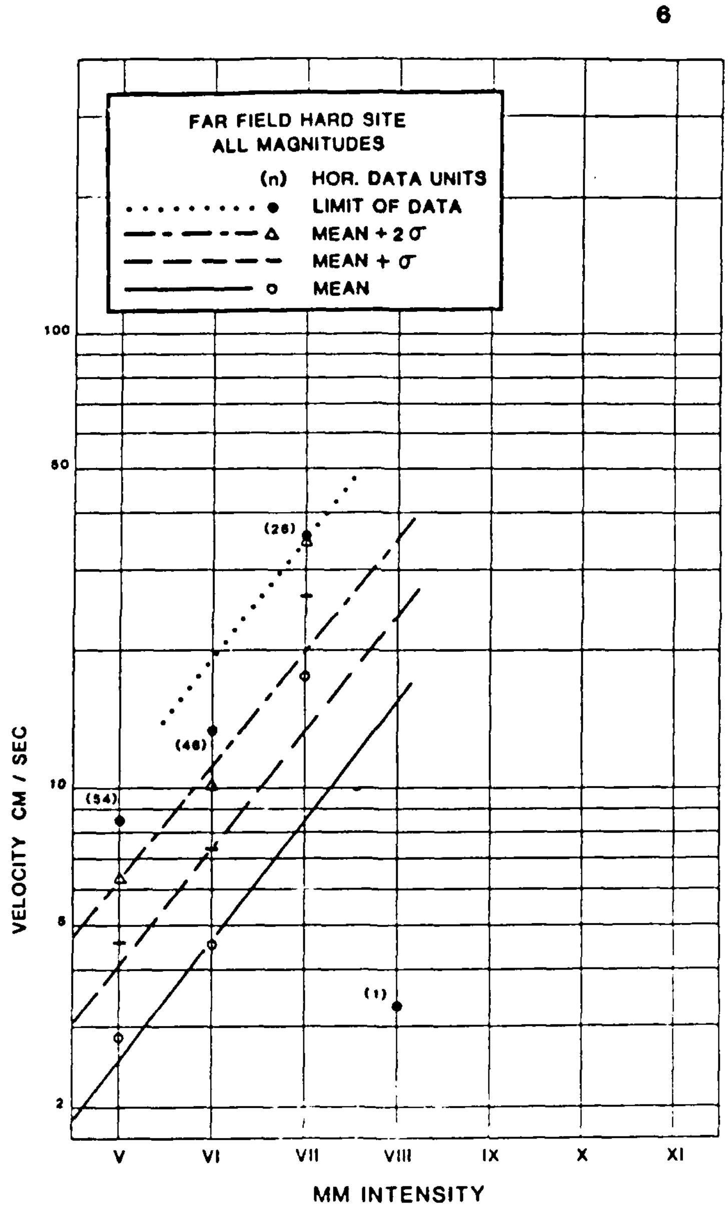


Figure 20. Chart for velocity (from Krinitzsky and Chang, 1987)

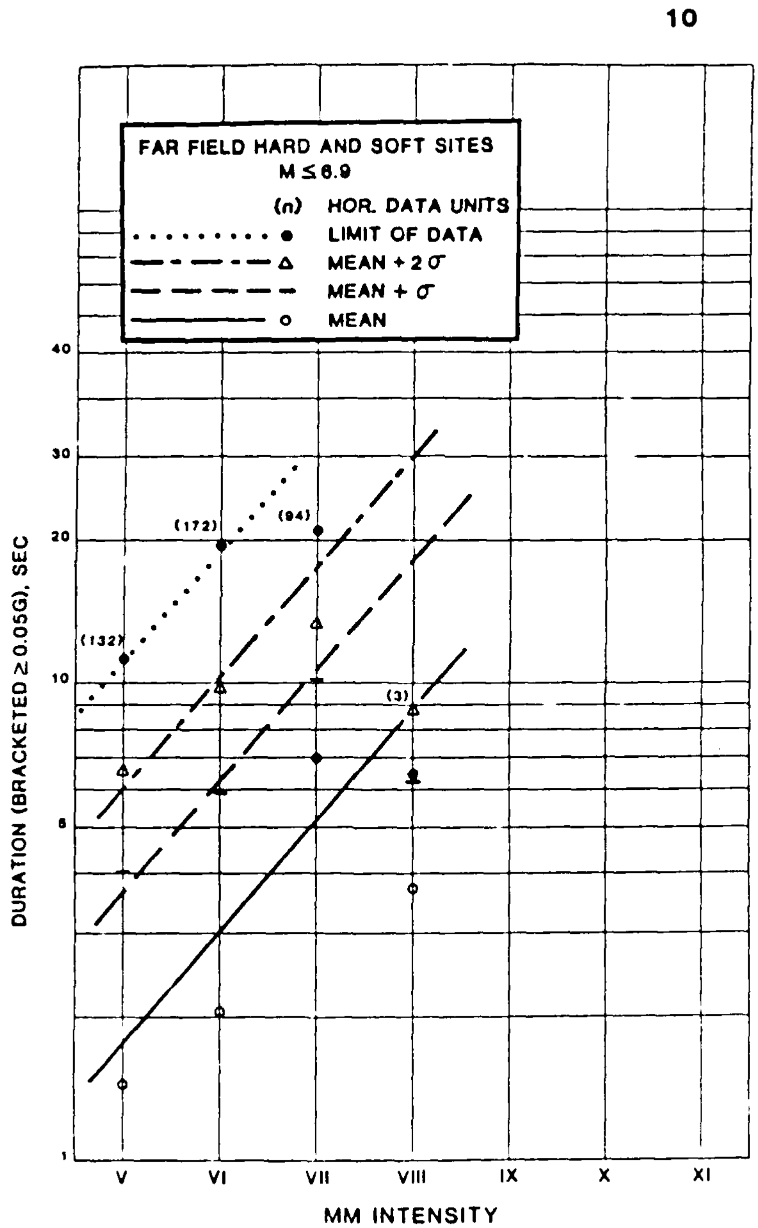


Figure 21. Chart for duration (from Krinitzsky and Chang, 1987)

Earthquake Source	Acceleration (cm/sec^2)	Velocity (cm/sec)	Duration Sec. ≥ 0.05 g
South Carolina Seismic Zone	190	14	11

93. Where vertical motions are desired they may be taken at 2/3 of the horizontal.

Recommended Accelerograms

94. Four accelerograms are recommended for the Hartwell and Clemson damsites. The selected accelerograms are summarized in Table 2 and are illustrated in Appendix F where the accelerograms are shown along with the velocity response spectra, and quadripartite response spectra for each specified time history (from the California Institute of Technology, 1971-1975 catalogue).

95. Two of the accelerograms are for soft sites and the two are for hard sites. The scaling factor for the four accelerograms ranges from 0.96 to 1.14 and is considered negligible. The scaling factor is the ratio between the recommended acceleration and the specified acceleration. The distance from the source area to the site ranges from 29 to 61 km and is representative of study area conditions.

96. The records presented in Table 2 are not the only records that may be used. However, they are presented as accelerograms that are appropriate for an engineering analysis.

Operating Basis Earthquakes and Motions for Nearby Nuclear Power Plants

97. Table 3 and Figure 22 identify the nearby nuclear power plants, their locations, the values for safe shutdown earthquakes (SSE), and the values for operating basis earthquakes (OBE). The SSE is equivalent to the maximum credible earthquake. The OBE is the earthquake for which the structure is designed to resist and remain operational though damage may occur to the structure. The OBE is taken either as the earthquake producing the maximum motions at the site once in 100 years or, arbitrarily at half the peak

Table 2

Selected Earthquake Records for

Hartwell and Clemson Dams - Far Field

Earthquake	Record	Date	Focal Distance (km)	Component Degress	Peak Accel (cm/sec^2)	Peak Velocity (cm/sec)	Duration (sec)	Magnitude	Intensity	Site	Scaling
Puget Sound, Washington Olympia, Highway Test Lab	B032	4/29/65	61.1	S86W	194.3	12.7	9.20	6.5	VII	Soft	1.0
San Fernando, Los Angeles 14724 Ventura Boulevard	Q233	2/9/71	29.3	N78W	197.0	17.6	15.12	6.6	VII	Soft	0.96
San Fernando, Los Angeles Griffith Park Observatory	O198	2/9/71	34.0	S00W	176.9	20.2	6.60	6.6	VII	Hard	1.08
San Fernando, Los Angeles Griffith Park Observatory	O198	2/9/71	34.0	S90W	167.4	14.6	8.34	6.6	VII	Hard	1.14

Table 3.

Nuclear Power Plants near Hartwell and Clemson Dams

Plant Name, Location	Acceleration (g)* SSE	OBE	Foundation
Vogtle, GA	.20	.12	Soil
Oconee, SC	.15	.08	Rock
Virgil C. Summer, SC	.15	.10	Soil
Cherokee, SC	.15	.08	Rock (weathered)
Catawba, SC	.15	.08	Soil
Robinson, SC	.20	.10	Soil
McGuire, NC	.12	.08	Rock
Brunswick, NC	.16	.08	Soil

* Acceleration values are at mean, SSE = safe shutdown earthquake, OBE = operating basis earthquake

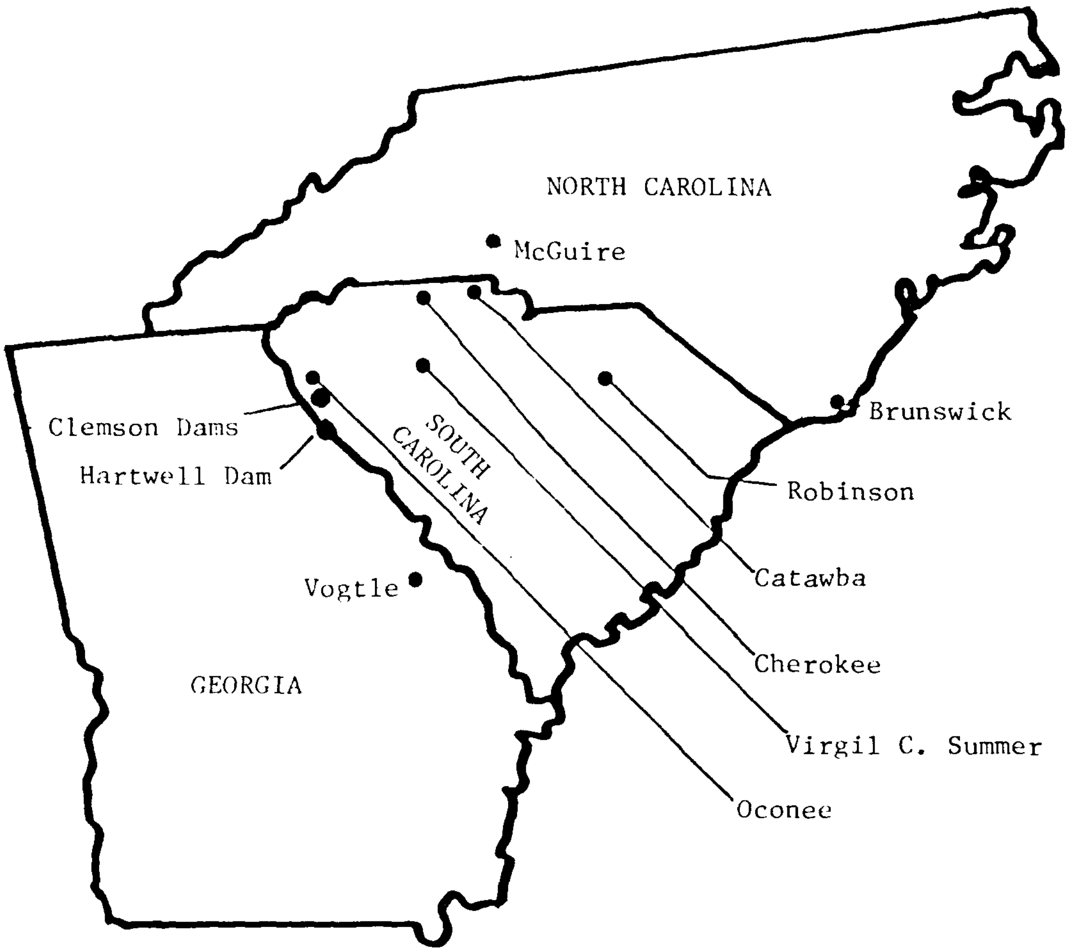


Figure 22. Locations of nuclear power plants near Hartwell and Clemson Dams (from Nuclear News, 1982)

motions for the SSE. The OBE is an engineering decision. It is based on cost-risk considerations where a design less than the SSE poses no hazard to life according to the judgment of the engineer.

98. The values for peak acceleration for the SSE in Table 3 are not comparable to similar values for the maximum credible earthquake at Hartwell and Clemson Dams. The accelerations for the SSE in Table 3 represent mean values while the recommended values for the damsites are at the mean plus one standard deviation (S.D.). However, when comparisons are made at equal levels for motions, i.e., mean or mean + S.D., the values at the Hartwell and Clemson Dams are similar to the values for the surrounding nuclear power plants. The mean acceleration values for the SSEs range from 0.12 to 0.16, with an exception at 0.20 g. The comparable mean acceleration by the Krinitzsky-Chang method (see Figure 19) is 0.14 g. The values arrived at in this study for the damsites are generally in agreement with values that have been used for nuclear power plants in this region.

PART V: CONCLUSIONS

99. A seismic zoning was developed for the southeastern United States based on the geology and seismic history. Floating earthquakes were assigned to each seismic zone since active faults were not identified for the southeastern United States. Hartwell and Clemson Dams are situated within the South Carolina seismic trend or zone. The Hartwell and Clemson Dams are subject to a maximum credible earthquake originating from a far field source within this zone that is equal to MM VII (M = 5.5).

100. Recommended peak horizontal motions based on intensity curves by Krinitzsky and Chang (1987) for a far field, MM VII earthquake are as follows:

Earthquake Source	Acceleration (cm/sec^2)	Velocity (cm/sec)	Duration Sec. ≥ 0.05 g
South Carolina Seismic Zone	190	14	11

Accelerograms and response spectra are included (see Appendix F) as representative of appropriate ground motions. Where vertical motions are considered, they may be taken at 2/3 of the horizontal.

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APPENDIX A

Geology of Hartwell and Clemson Dams

Hartwell Dam

Hartwell Dam is a 5,440 meter long earth and concrete dam on the Savannah River. The concrete portion (approximately 610 meters in length) was built on firm rock in 40 monolithic sections. There are five hydroelectric generating units in the structure. The eastern embankment of the dam is on the South Carolina side of the river, measures 1,924 meters in length, and is a homogenous rolled earth fill embankment with a 4.6 meter wide imperviou. ore to rock. The western embankment is similar in construction to the eastern embankment on the Georgia side of the river and measures 2,940 meters in length.

The geology of the area surrounding Hartwell Dam has been mapped in detail by Griffin (1978, 1979, 1981, and in review), by Nelson and Clarke (1978), and updated by Nelson, Horton, and Clarke (Nelson, personnel communication, unpublished mateial). Hartwell Dam is built on high grade metamorphic rocks as shown by Figure A1. Two main types of metamorphic rocks are identified in the foundation (U.S. Army Corps of Engineers, 1952 and 1960b; and Pope, 1987). These are a gray, biotite gneiss (massive to banded, medium to coarse grained, granitic texture) and a dark gray, garnet-biotite gneiss (lenses of medium to coarse grained garnets, quartz, and feldspars in a groundmass of biotite and hornblende with interstitual quartz and feldspar). In addition, both felsic (pegmatite) and mafic (basalt) dikes are present in the foundation. The basalt dike is described as striking S 30-60 E and is interpreted as being Triassic in age (U.S. Army Corps of Engineers, 1952). Griffin (in review) has mapped another basaltic dike south of the dam that strikes in a northeast direction.

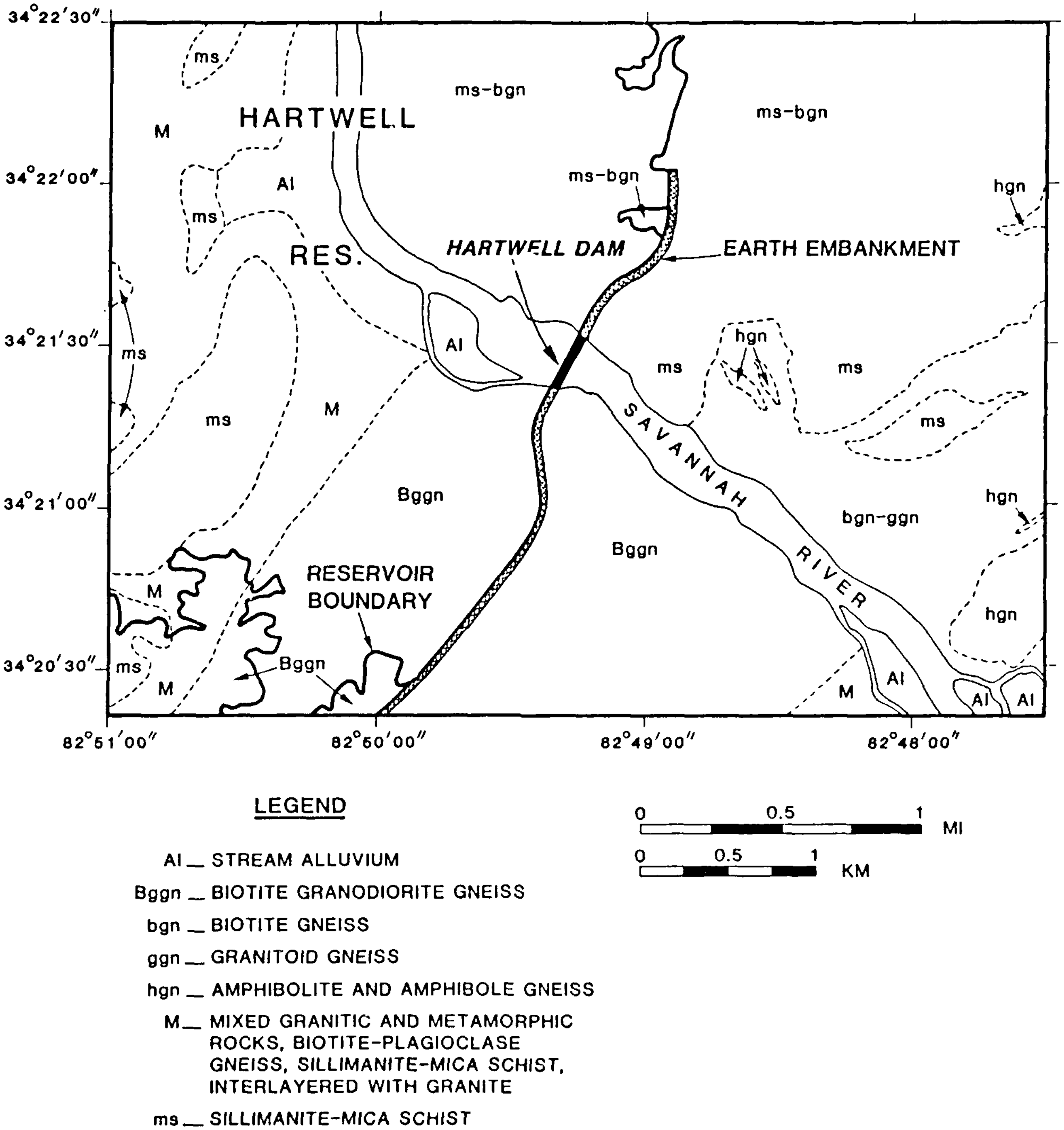

Figure A1. Geology of Hartwell Dam (from Griffin, 1981 and in review; and Grant, 1958)

The strike and dip of rock units are locally variable (i.e., near the river) but as a whole are in general agreement with the regional structure. The strike and dip are determined primarily from foliation and banding in the rocks. Rocks at the dam generally dip towards the northwest but can vary locally from horizontal to vertical.

No major faults were determined to exist at the damsite. Minor faulting is identified beneath the dam in the foundation rocks (term "minor movement" is used to describe faulting in the U.S. Army Corps of Engineers Report, 1960b, p. 5-8). Faulting was indicated by slickenslides in extremely jointed areas. A shear zone was identified in the concrete portion of the dam in the area of Monoliths 7 and 8 (Georgia side of the river) and striking N 60 W. The shear zone is described as near vertical or steeply dipping. The age of these faults is estimated to be Mesozoic.

The foundation report on Hartwell Dam identifies jointing as the primary structural problem. The joints serve as avenues for ground water flow (U.S. Army Corps of Engineers, 1960b). The attitude and condition of the joints was not however considered to be detrimental to the integrity of the foundation. Several areas of well developed and concentrated joints are identified in Monoliths 7, 8, 14, 17, 23, 29, and 30. The individual joints range from hairline cracks to 1/2-in. width. The joints are considered high angle, commonly dipping at 70 degrees or more. Another type of jointing caused by stress relief is described by Pope (1987). He identifies foliation and sheet breaks in which the joints are less steep than the high angle joints.

Other tectonic discontinuities are present in the Hartwell Dam area. Griffin (1981) describes normal faults in the general vicinity of the dam that have displacements of less than one meter in the thick saprolite deposits that cover the area. These small scale normal faults show slickenslides and coatings of manganese minerals. In addition, an 8 km long northeast trending fault or shear zone is mapped by Griffin (1981) approximately 9 km northeast of the dam. He has identified this fault as the Little Mountain microbreccia zone. This is a zone of repeated shearing and recrystallization. These faults are described by Griffin as probably formed during the Post-Paleozoic uplift of the Southern Appalachian Mountains.

Clemson Dams

The Clemson Dams are two rolled fill earth embankment dams on the Seneca River, a tributary to the Savannah River. These dams were constructed to prevent flooding on lands forming part of Clemson University. The two dams separate approximately a 2 km reach of the Seneca River from the main channel. The upper diversion dam extends southwest-northeast for 640 meters. The lower diversion dam extends north-south for 915 meters.

Both dams were rehabilitated during the 1980's to repair seepage problems. The Clemson Dams have experienced a long history of emergency repairs particularly to control seepage boils (U.S. Army Corps of Engineers, 1982 and 1987). The rehabilitation work to repair the seepage problems involved excavating to rock and constructing an impermeable, interlocking concrete-panel core along the center line of the dam to seal against seepage.

The geology of the Clemson Dams area has been mapped by Brown and Cazeau (1964), by Nelson and Clarke (1978), and updated by Nelson, Horton, and Clarke (Nelson, personnal communication, unpublished materials). The Clemson Dams are built primarily on Seneca River alluvium as shown by Figure A2. The alluvium beneath the dam is variable in thickness ranging from 6 to 18 meters. Soils are predominantly coarse grained. Soil types are primarily an SM or SP as

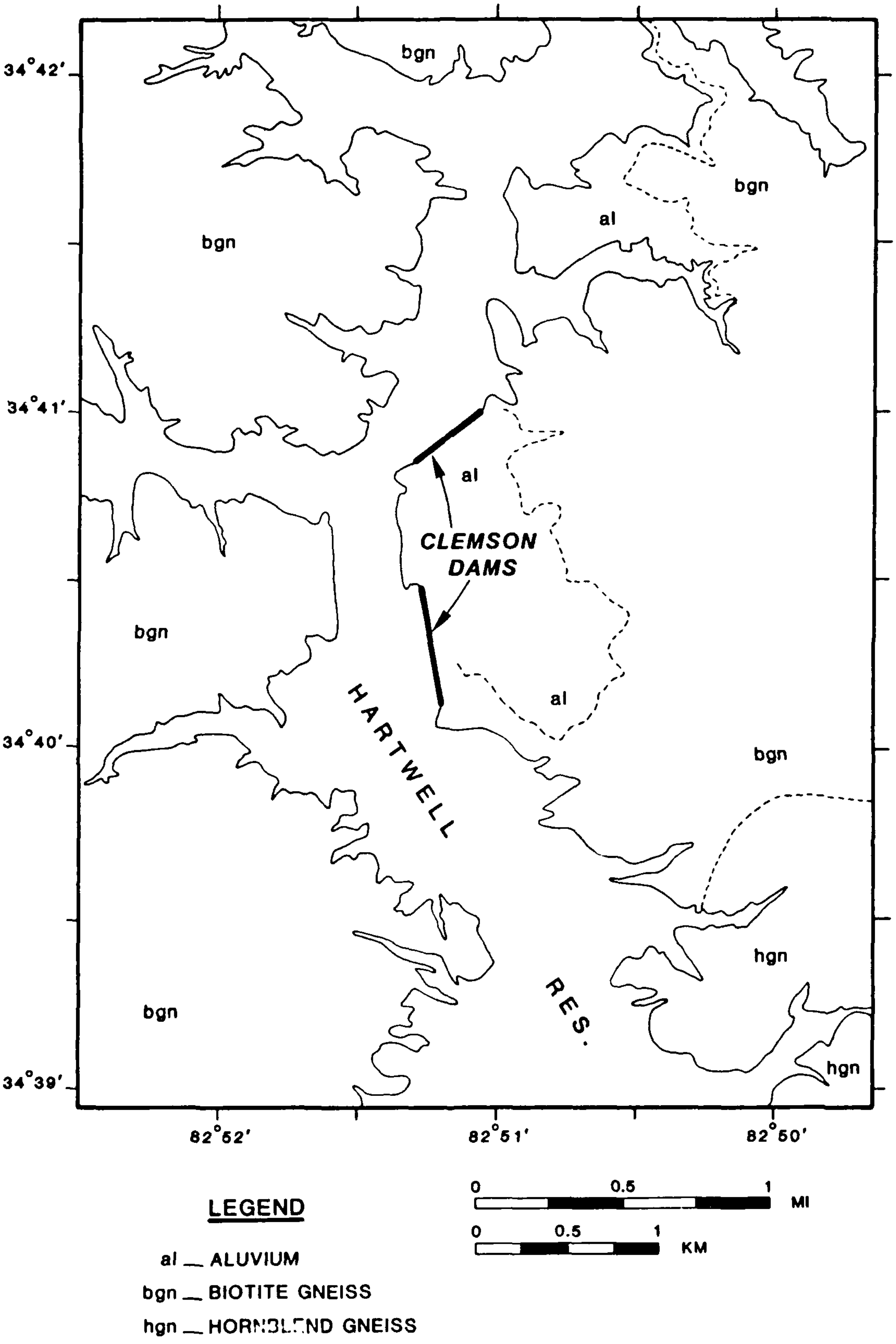

Figure A2. Geology of the Clemson Dams (from Brown and Cazeau, 1964) identified by the cross sections in Figure A3 (from U.S. Army Corps of Engineers, 1960a). The rock underlying the alluvium is a hard crystalline granitic gneiss.

The abutments of the dams are founded on residual soils. Residual soils have developed from weathering processes of the underlying rocks and have created a saprolite or saprolitic soil. The residual soils are composed of a fine-grained, red, sandy clay (CL). The typical residual soil profile at the Clemson Dams is described as being 1.5 to 3.0 meters of fine sandy clay, underlain by 6 to 9 meters of micaceous silty sand containing fragments, boulders, and lenses of hard rock, grading downward through slightly oxidized rock to unaltered granitic gneiss (U.S. Army Corps of Engineers, 1960a).

Information on the geologic structure of the Clemson Dams area was obtained from published maps since specific information about the foundation rock was not available in the construction documents. Brown and Cazeau (1964) identify the rock units as dipping to the southeast. They map a synclinal axis approximately 5 km southeast of Clemson, South Carolina. The Clemson Dams are located on the north limb of the syncline. No faults are identified near the damsite except for those previously discussed (see Figure 6).

The alluvial soils beneath the Clemson Dams have the potential to produce liquefaction failures from earthquake shaking. The Savannah District has evaluated the Clemson Dams for earthquake induced liquefaction failures. The results of their analysis are contained in two reports (U.S. Army Corps of Engineers, 1982 and 1983).

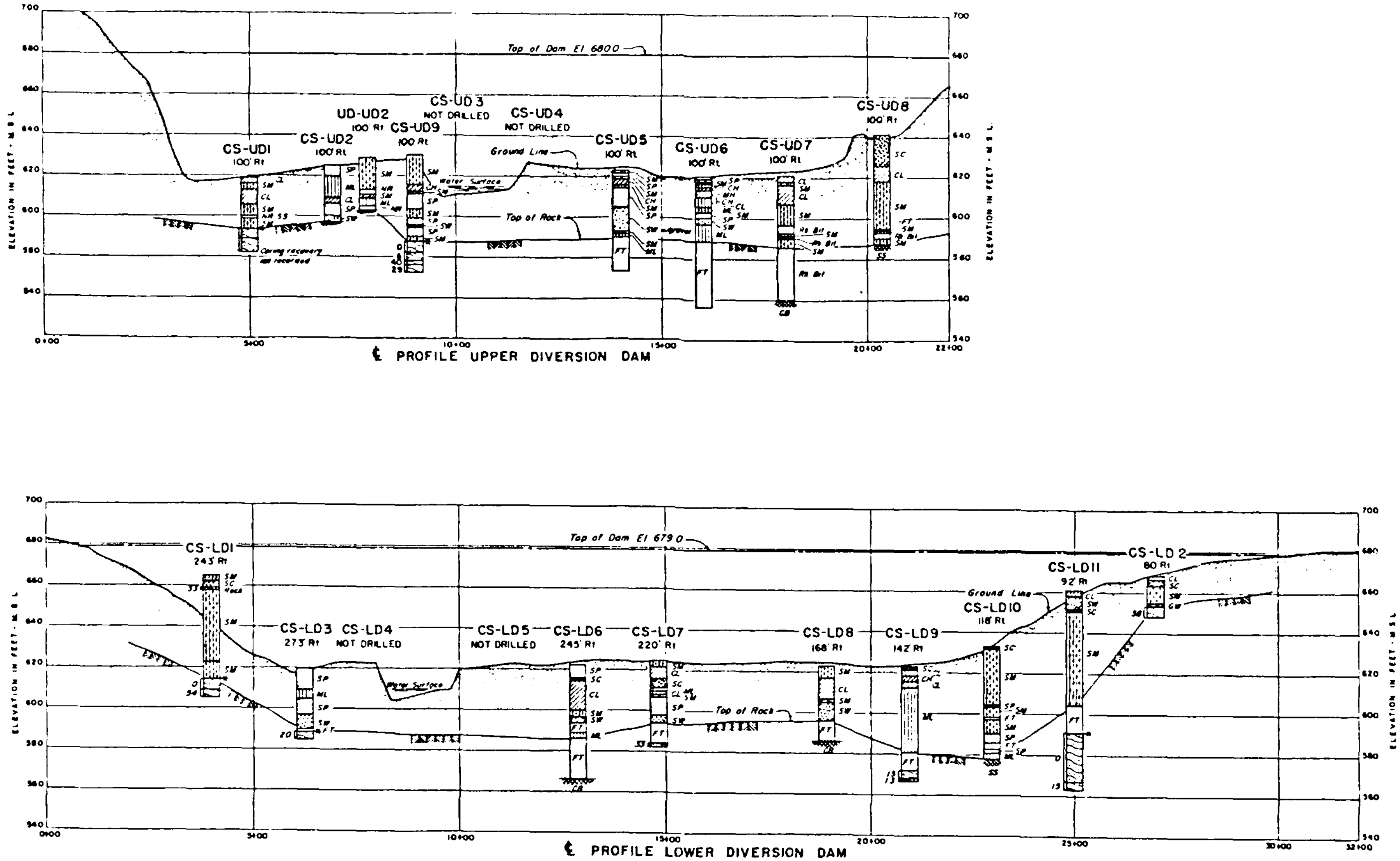

Figure A3. Cross section through Clemson Upper and Lower Dams showing foundation soil types prior to construction (from U.S. Army Corps of Engineers, 1960)

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APPENDIX B

Historic Earthquake Catalogue for the Hartwell and Clemson Dams Area

(North Latitude: 33.5 to 36.0, West Longitude: 81.0 to 84.5)

From Rinehart, 1987

GEORGIA

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	MAGNITUDE m_b	MAGNITUDE M_L	MAGNITUDE M_S	MM INT	C/E*	REF**
1875	11	2	2	55	33.8	82.5					VI	F	EQH
1875	11	2	2	55	33.8	82.5					VI		STO**
1875	11	2	2	55	33.8	82.5					VI		USN**
1884	3	31	10		33.8	82.5					II		USN
1914	3	5	20	5	33.5	83.5					VI		USN
1914	3	5	20	5	33.5	83.5					VI		STO
1914	3	5	20	5	33.5	83.5					VI	F	EQH
1914	3	5	21		33.5	83.5						F	STO
1963	10	8	6	1	33.9	82.5				3.2			STO
1964	3	7	18	2	33.7	82.4	5.0			3.3			STO
1965	4	7	7	41	33.9	82.5							STO
1969	5	5	17	14	33.9	82.5						F	STO
1969	5	9			34.0	82.6				3.3			STO
1969	5	18			34.0	82.6				3.5		F	STO
1969	11	8	1	52	33.9	82.5							STO
1971	4	16	7	31	33.9	82.5							STO
1973	10	8	13	38	33.9	82.5							STO
1974	8	2	8	52	33.9	82.5	1.0	4.3			V		USN
1974	8	2	8	52	33.9	82.5	1.0	4.3		4.9	V	D	PDE**
1974	8	2	8	52	33.9	82.5	4.0	4.3		4.1	V		STO**
1974	10	8	23	22	33.9	82.4		3.1			III		STO
1974	11	5	3		33.7	82.2				3.7	II		STO
1974	11	5	3		33.7	82.2				3.7	III	F	CSC**
1974	12	3	8	25	34.0	82.5				3.6	III	F	CSC
1974	12	3	8	25	34.0	82.5				3.6	IV		STO**
1975	10	18	4	31	34.9	83.0					IV		STO
1978	6	5	21	37	33.5	82.6	3.0			2.5			STO
1979	8	13	5	19	33.9	82.5	23.0			4.1			STO

NORTH CAROLINA

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	MAGNITUDE m_b	MAGNITUDE M_L	MAGNITUDE M_S	MM INT	C/E*	REF**
1776	11	5			35.3	83.0					IV		USN
1776	11	5			35.2	83.0					IV		STO**
1829					35.2	83.8						F	STO**
1829					35.2	83.8							USN
1844	6				35.3	83.0							USN
1844	6				35.3	83.3						F	STO**
1848					35.7	82.1						F	STO
1851	8	11	1	55	35.6	82.6					V		STO
1874	2	10			35.7	82.1					IV		USN
1874	2	10			35.7	82.1					V		STO**
1874	2	22			35.7	82.1					IV		USN
1874	2	22			35.7	82.1					IV		STO**

* Cultural effects, see end of catalog for description of symbol.

** Reference for listing, see end of catalog for description of source. Possible duplicate listing is identified when dual asterisk follows reference symbol.

								MAGNITUDE			MM		
YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	m_b	M_L	M_S	INT	C/E*	REF**
1874	3	17			35.7	82.1					IV		USN
1874	3	17			35.7	82.1					IV		STO**
1874	3	26			35.7	82.1					IV		STO
1874	3	26			35.7	82.1					IV		USN**
1874	4	14			35.7	82.1					IV		STO
1874	4	14			35.7	82.1					IV		USN**
1874	4	17			35.7	82.1					IV		STO
1874	4	17			35.7	82.1					IV		USN**
1876	1	23			35.7	82.1						F	STO
1877	4	26	22		35.2	83.4					III		STO
1877	4	26	22		35.2	83.4							USN**
1877	10	9	1		35.0	82.7							STO
1880	1	28			35.7	82.1					III		STO
1880	1	28			35.7	82.0							USN**
1880	1	29			35.7	82.1					III		STO
1880	1	29			35.7	82.0							USN**
1880	2	10			35.7	82.0							USN
1880	2	10			35.7	82.1					III		STO **
1884					35.7	82.5							USN
1884	1	18			35.7	82.1							USN
1884	7				35.7	82.5					III		STO
1904	3	5		30	35.7	83.5					V	F	EQH
1904	3	5		30	35.7	83.5					V		USN**
1904	3	5		30	35.7	83.5				4.0	V		STO**
1911	4	20			35.2	82.7					V		USN
1911	4	20			35.1	82.7					V		STO**
1911	4	21	3		35.2	82.7					V		USN
1915	10	29	5	23	35.8	82.7					IV		STO
1915	10	29	5	25	35.8	82.7					V		USN
1915	10	29	5	25	35.8	82.7					V		STO**
1915	10	29	6		35.8	82.7					V	F	EQH
1916	2	21	22	39	35.5	82.5					VI		USN
1916	2	21	22	39	35.5	82.5					VI	D	EQH**
1916	2	21	22	39	35.5	82.5					VII		STO**
1916	8	26	19	36	36.0	81.0					V		USN
1916	8	26	19	36	36.0	81.0					V		STO**
1916	8	26	19	36	36.0	81.0					V	F	EQH**
1918	1	16	15	45	35.9	83.9		4.2			V		OWN**
1923	10	18	19	30	35.3	82.5						F	STO
1924	10	20	8	30	35.0	82.6					V	F	EQH
1924	10	20	8	30	35.0	82.6					V		USN**
1924	10	20	8	30	35.0	82.6					V		STO**
1924	10	20	20	30	35.0	82.6					V		USN
1926	7	8	9	50	35.9	82.1					VI	D	EQH
1926	7	8	9	50	35.9	82.1					VII		STO**

								MAGNITUDE			MM		
YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	m_b	M_L	M_S	INT	C/E*	REF**
1926	7	8	9	50	35.9	82.1							USN
1928	11	20	3	45	35.8	82.3							USN
1928	11	20	3	45	35.8	82.3					IV		STO**
1935	1	1	8	15	35.1	83.6					V		USN
1935	1	1	8	15	35.1	83.6					V	F	USE**
1935	1	1	8	15	35.1	83.6					V		STO**
1938	3	31	10	10	35.6	83.6					IV		STO**
1940	12	25	1	30	35.9	82.9					III		STO
1940	12	25	1	50	35.6	82.6							USN
1940	12	25	6	49	35.6	82.6							USN
1940	12	25	6	50	35.9	82.9					IV		STO**
1940	12	26			35.9	82.9					III		STO
1941	5	10	11	12	35.6	82.6					IV		STO
1941	5	10	11	12	35.6	82.6							USN**
1957	5	13	14	24	35.8	82.1	5.0			4.1	VI		STO
1957	5	13	14	24	35.8	82.0	18.0		4.3		VI		USN**
1957	7	2	9	33	35.6	82.6	7.0		4.6		VI		USN
1957	7	2	9	33	35.6	82.7	7.0				VI		STO**
1957	11	24	20	6	35.0	83.5					VI	F	USE
1957	11	24	20	6	35.0	83.5					VI		USN**
1957	11	24	20	6	35.0	83.5				4.0	VI		STO**
1958	5	16	22	30	35.6	82.6					IV		USN
1958	5	16	22	30	35.6	82.6					IV		STO**
1960	1	3	7	30	35.9	82.1					IV		STO
1960	1	4			35.9	82.1					II		STO
1960	2	9	14		35.3	82.5						F	STO
1960	4	15	10	10	35.8	83.9				3.8	V		STO
1964	1	20	13	37	35.9	82.3					IV		STO
1964	1	20	13	37	35.9	82.3					IV		USN**
1969	12	13	10	19	35.0	82.9	6.0			3.4	IV		STO
1969	12	13	10	19	35.1	83.0	33.0						USN**
1969	12	13	10	19	35.1	83.0	33.0				V	F	USE**
1971	10	9	16	43	35.8	83.4	8.0	3.4		3.7	V		STO
1971	10	9	16	43	35.9	83.5	18.0	3.4			IV		USN**
1971	10	9	16	43	35.9	83.5	18.0	3.4			V	D	PDE**
1973	10	30	22	58	35.7	83.9		3.4			V		OWN**
1973	11	30	7	48	35.9	84.0	12.0			4.6	VI		STO
1973	11	30	7	48	35.8	84.0	3.0	5.6		4.6	VI	D	PDE**
1973	11	30	8	51	35.8	84.0					II		STO
1973	11	30	9	27	35.8	84.0						F	STO
1973	12	13	15		35.8	84.0					III		STO
1973	12	14	20	58	35.8	84.0				3.1	III		STO
1973	12	21	8		35.8	84.0					III		STO
1973	12	21	18	30	35.8	84.0					III		STO
1974	5	16			35.4	82.7					III		STO
1975	12	8	18	2	35.0	82.9					II		STO

								MAGNITUDE			MM		
YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	m_b	M_L	M_S	INT	C/E*	REF**
1978	5	16	16	6	35.0	81.8	1.0			2.6			STO
1978	7	9	7	3	35.5	82.8	10.0			2.8			STO
1979	9	6	20	38	35.3	83.2	10.0			3.2			STO
1979	9	12	6	24	35.6	83.9	5.0		3.2		V	F	PDE
1979	9	12	6	24	35.6	83.9	27.0			3.2	V		STO**
1980	6	10	23	47	35.5	82.8	1.0			3.0			STO
1980	6	10	23	47	35.4	82.9	5.0		3.0				PDE**
1981	4	9	7	10	35.5	82.1	1.0			3.0	V		STO
1981	4	9	7	10	35.5	82.1	5.0			3.0	V	F	PDE**
1981	4	9	12	2	35.5	82.1	7.0			2.5			STO
1981	4	10	6	4	35.5	82.1	1.0			2.0			STO
1981	5	5	21	21	35.3	82.4	10.0			3.5	VI		STO
1981	5	5	21	21	35.3	82.4	13.0			3.5	VI	D	PDE**
1983	3	25	2	47	35.3	82.5	9.0			3.2	V	F	PDE
1985	3	19		2	35.3	82.5	10.0			2.3	III	F	PDE

SOUTH CAROLINA

1853	5	20			34.0	81.2					VI		STO
1860	10	22			34.2	82.4					III		STO
1879	10	27	1		34.4	81.1					III		STO
1897	5	9			33.9	81.6					III		STO
1899	1	20			34.2	81.7					III		STO
1899	11	4			34.3	82.8					III		STO
1899	12	19			34.3	81.4					III		STO
1901	10	1	16	40	34.2	81.7						F	STO
1902	6	10			34.2	81.7					III		STO
1904	3	14	3	30	34.5	82.0						F	STO
1904	4	30			34.0	81.6						F	STO
1906	4	18			34.1	81.3						F	STO
1912	12	7			34.7	81.7					III		USN
1912	12	7	19	10	34.7	81.7					IV		STO
1913	1	1	18	28	34.7	81.7					VIII		USN
1913	1	1	18	28	34.7	81.7					VII		STO**
1913	1	1	18	28	34.7	81.7					VII	D	EQH
1914	3	6	20	30	34.7	81.2					III		STO
1916	3	2	5	2	34.5	82.7					IV		USN
1916	3	2	5	2	34.5	82.7					IV		STO**
1923	5	4	10	55	34.2	82.5					II		USN
1923	5	4	10	55	34.3	82.4					II		STO**
1924	1	1	1	6	34.8	82.5					IV		STO
1929	10	28	2	15	34.3	82.4							USN
1929	10	28	2	15	34.3	82.4					IV		STO**
1929	10	28	2	15	34.3	82.4						F	USE**
1930	12	10		2	34.3	82.4							USN

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	MAGNITUDE m_b	M_L	M_S	MM INT	C/E*	REF**
1930	12	10		2	34.3	82.4					IV		STO**
1930	12	10		2	34.3	82.4						F	USE**
1930	12	10	8		34.3	82.4					II		STO
1931	5	6	12	18	34.3	82.4					IV		STO
1942	11	1	1	20	34.4	81.1							USN
1942	11	1	2	20	34.4	81.1					II		STO
1945	7	26	9	32	34.3	81.4					IV		USN
1945	7	26	10	32	34.5	81.5			5.6		V	F	G-R
1945	7	26	10	32	33.8	81.4	5.0			4.4	VI		STO**
1956	1	5	5		34.3	82.4							USN
1956	1	5	5	30	34.3	82.4							USN
1956	1	5	8		34.3	82.4					IV		STO
1956	1	5	8	30	34.3	82.4					IV		STO
1956	5	19	19		34.3	82.4							USN
1956	5	19	19		34.3	82.4					IV		STO**
1956	5	27	23	25	34.3	82.4					IV		STO
1956	5	27	23	25	34.3	82.4							USN**
1958	10	20	6	16	34.5	82.7					V		STO
1958	10	20	6	16	34.5	82.7							USN**
1963	4	11	17	45	34.9	82.4					IV		STO
1963	4	11	17	45	34.9	82.4					IV		USN**
1964	4	20	19	4	33.8	81.1	3.0			3.5	V		STO
1964	4	20	19	4	34.0	81.0					V		USN**
1965	9	9	4	37	34.7	81.2							USN
1965	9	9	4	37	34.7	81.2						F	STO**
1965	9	9	14	42	34.7	81.2							USN
1965	9	9	14	42	34.7	81.2				3.9		F	STO**
1965	9	10	7	32	34.7	81.2							USN
1965	9	12	18	25	34.7	81.2							USN
1965	9	12	18	25	34.7	81.2				2.9		F	STO**
1968	9	22	21	41	34.1	81.5	1.0	3.7		3.5	IV		STO
1968	9	22	21	41	34.0	81.5	22.0	3.7			IV		USN**
1968	9	22	21	41	34.0	81.5	22.0	3.7			IV	F	USE**
1971	6	10	4	19	34.7	82.9				2.8			STO
1971	7	13	8	15	34.8	83.0						F	STO
1971	7	13	9	39	34.7	82.9				2.8			STO
1971	7	13	10	54	34.7	82.9				2.9			STO
1971	7	13	11	7	34.7	82.9				2.7			STO
1971	7	13	11	42	34.8	83.0				3.8	VI		STO
1971	7	13	11	49	34.7	82.9				2.9			STO
1971	7	13	15	6	34.7	82.9				3.0			STO
1973	3	28	11	19	34.3	81.4							STO
1973	3	29	8	28	34.3	81.4							STO
1973	3	29	12	19	34.3	81.4							STO
1973	3	29	16	19	34.3	81.4							STO
1974	10	28	11	33	33.8	81.9				3.0	IV		STO

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	MAGNITUDE m_b	M_L	M_S	MM INT	C/E*	REF**
1974	10	28	11	33	33.8	81.9				3.0	IV	F	CSC*
1975	11	25	15	17	34.9	83.0	5.0			3.2	IV	F	PDE
1975	11	25	15	17	34.9	82.9	10.0			3.2	IV		STO**
1977	9	7	14	41	35.0	82.9				2.5			STO
1978	1	25	3	29	34.3	81.3	2.0			2.8			STO
1978	1	25	8	29	34.3	81.2	5.0			2.6			STO
1978	1	25	8	29	34.3	81.2	1.0			2.6			PDE**
1978	2	4	9	14	34.3	81.3	1.0			2.6			STO
1978	2	8	20	35	34.1	82.1	11.0			2.5			STO
1978	2	9	19	19	34.6	81.8	5.0			2.6			STO
1978	2	10	20	[illegible]	34.3	81.3	1.0			2.5			STO
1978	2	11		19	34.3	81.4	3.0			2.5			STO
1978	2	11	5	19	34.3	81.3	1.0			2.7			STO
1978	2	11	12		34.3	81.3	2.0			2.6			STO
1978	2	14	12	45	34.3	81.3	2.0			2.5			STO
1978	2	14	13	9	34.4	81.3	2.0			2.6			STO
1978	2	14	17	6	34.8	81.8	6.0			2.5			STO
1978	2	15	21	14	34.3	81.3				2.5			STO
1978	2	16	2	14	34.3	81.4	2.0			2.6			STO
1978	2	22	7	13	34.3	81.4	1.0			2.6			STO
1978	2	22	12	13	34.3	81.4	1.0			2.8			STO
1978	2	22	13	4	34.4	81.4				2.5			STO
1978	2	24	7	34	34.3	81.3	1.0			2.7			STO
1978	2	25	4	2	34.3	81.4	1.0			2.5			STO
1978	2	26	6	52	34.3	81.3	1.0			2.6			STO
1978	2	26	11	52	34.4	81.4	1.0			2.8			STO
1978	2	26	18	17	34.3	81.3				2.9			STO
1978	3	27	20	56	34.8	82.6	1.0			2.5			STO
1978	4	22	6	36	34.4	81.3			2.6				PDE
1978	4	22	6	36	34.2	81.3				2.6			STO**
1978	5	2	1	46	34.2	82.7	16.0			2.9			STO
1978	5	2	1	46	34.2	82.7	10.0			2.8			STO**
1978	6	11	5	28	34.1	81.6	4.0			2.5			STO
1978	6	12	6	33	34.8	81.9	2.0			2.5			STO
1978	7	9		26	34.3	82.8	1.0			2.5			STO
1978	8	24	10	23	34.3	81.3	2.0			2.6			STO
1978	8	27	10	23	34.3	81.3	2.0			2.7			STO
1978	8	27	10	58	34.3	81.3	7.0			2.5			STO
1978	10	27	16	27	34.3	81.3	2.0			2.9			STO
1978	11	24	11	54	34.3	81.3	1.0			2.6			STO
1979	1	19	8	55	34.7	83.0	1.0		2.8		IV	F	PDE
1979	1	19	8	55	34.6	82.8	1.0			2.9	IV		STO
1979	2	1	1	25	34.3	81.3	1.0			2.6			STO
1979	2	16	14	37	34.3	81.3				2.7			STO
1979	5	4	12	13	34.3	82.0	1.0			2.7			STO
1979	5	28	11	45	35.0	82.9	1.0			2.5			STO

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	MAGNITUDE m_b	M_L	M_S	MM INT	C/E*	REF**
1979	7	17	20	13	34.7	82.6				2.5			STO
1979	8	7	19	32	34.3	81.4	3.0			3.0			STO
1979	8	26	1	31	34.0	83.0	2.0		3.7		V	F	PDE
1979	8	26	1	31	34.9	82.9	2.0			3.7	VI		STO**
1979	9	14		45	34.3	81.3	2.0			2.7			STO
1979	10	7	8	54	34.3	81.3	1.0			2.8			STO
1979	10	8	7	54	34.3	81.3	2.0			2.5			STO
1979	10	8	8	54	34.3	81.3	2.0			2.6			STO
1979	10	8	23	20	34.3	81.4	5.0			2.9		F	PDE
1979	10	8	23	20	34.3	81.3	1.0			2.9	III		STO**
1979	10	14	8	24	34.3	81.3	2.0			2.9			STO
1979	10	16	7	6	34.3	81.3	1.0			2.8			STO
1979	10	21	15	56	34.3	81.3	2.0			2.6			STO
1980	4	24	6	16	34.3	81.3	3.0			3.0			STO
1980	7	29	1	10	34.4	81.4	1.0			3.2			STO
1980	9	10	19	49	34.1	82.9	13.0			2.5			STO
1980	12	16	17	40	34.8	82.6	4.0			2.5			STO
1980	12	27	8	40	34.3	81.3	7.0			2.5			STO
1981	2	21	4	48	33.6	81.2	1.0			2.0	II		STO
1982	3	2	16	48	34.3	81.4	5.0			2.5	III	F	PDE
1982	4	13	9	25	34.3	81.4	5.0			2.7	III	F	PDE
1986	2	13	11	35	34.8	82.9	5.0			3.5	V	F	PDE

TENNESSEE

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	m_b	M_L	M_S	MM INT	C/E*	REF**
1777	11	16	7		36.0	84.0					IV		STO
1844	11	28	13		36.0	84.0					VI	D	EQH
1844	11	28	13		36.0	83.9		4.7			VI		OWN**
1844	11	28	13		36.0	84.0					VI		STO**
1875	11	12	7		36.0	84.0					III		STO
1877	5	25			36.0	84.0					III		STO
1877	11	16	7	20	36.0	84.0				4.0	IV		STO
1877	11	16	7	38	35.5	84.0					V	F	EQH**
1877	11	16	7	38	35.5	84.0					V		USN
1878	11	23	15		35.1	84.0							USN
1878	11	23	15		35.1	84.0					III		STO**
1882	10	15	17	30	35.1	84.0					III		STO
1884	4	30	11	46	35.1	84.1					I		STO
1884	4	30	11	46	35.1	84.1							USN**
1884	8	25		45	36.0	83.9					IV		USN
1884	8	25		45	36.0	84.0					IV		STO**
1913	4	17	16	30	35.3	84.2				3.9	V		STO
1913	4	17	16	30	35.3	84.2					V		USN**
1913	4	17	16	30	35.3	84.2					V	F	EQH**
1913	5	2	6		35.5	84.3					III		USN
1913	5	2	6		[illegible].5	84.4					III		STO**
1913	7	3	16	45	36.0	83.9					IV		USN

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	MAGNITUDE m_b	M_L	M_S	MM INT	C/E*	REF**
1913	8	3	16	45	36.0	84.0					IV		STO
1914	1	24	3	24	35.6	84.5					IV		STO
1914	1	24	3	24	35.6	84.5					V	F	EQH**
1914	1	24	3	24	35.6	84.5		4.2			V		OWN**
1914	1	24	3	24	35.6	84.5					V		USN**
1914	1	24	3	41	35.6	84.5					IV		USN
1914	1	24	3	41	35.6	84.5					III		STO**
1917	1	26	12	15	36.0	83.8					III		USN
1917	3	5	2	7	36.0	84.0					III		STO
1917	3	5	2	7	36.0	83.9					III		USN**
1918	1	16	15	[illegible]	36.0	83.9					V		USN
1918	1	16	15	45	36.0	84.0					V		STO**
1927	7	20	8	58	36.0	84.0							STO
1928	11	3	4	3	36.0	82.6					VI		USN
1928	11	3	4	3	36.0	82.6					VI	D	PDE**
1930	8	30	9	28	35.9	84.4						F	USE
1930	8	30	9	28	35.9	84.4		3.0					OWN**
1930	8	30	9	28	35.9	84.4					V		USN**
1930	8	30	9	28	35.9	84.4					V		STO**
1930	10	16			36.0	83.9		4.2			V		OWN
1930	10	16	21	50	36.0	84.0					IV		USN
1930	10	16	21	50	36.0	84.0					V		STO**
1930	10	16	21	50	36.0	84.0						F	USE**
1930	10	17	2	15	36.0	84.0					III		STO
1936	1	1	8		35.1	84.0					III		STO
1936	1	1	8		35.1	84.0					III		USN**
1938	3	31	10	10	36.0	83.9					IV		USN
1941	3	4			36.0	83.9		3.2			III		OWN
1941	3	4	6	15	36.0	83.9					III		USN
1941	3	4	6	15	36.0	83.9					III		STO**
1947	6	6	12	55	36.0	84.0					III		STO
1947	6	6	13	55	36.0	83.9					III		USN
1950	6	18			35.8	84.0		3.8			IV		OWN
1950	6	19	4	19	35.8	84.0				4.2	IV		STO
1950	6	19	5	19	35.8	84.0					IV		USN
1951	6	4			36.0	8.0					III		STO
1953	10	11	4		36.0	83.9					IV		USN
1953	11	10	14	45	36.0	84.0					IV		STO
1953	11	10	15	45	36.0	83.9		3.8			IV		OWN
1953	12	5	13	45	36.0	84.0					IV		STO
1954	1	14			36.0	84.0					IV		STO
1954	1	23	1		35.3	84.4					V		STO
1955	1	12	6	25	35.8	84.0		3.8			IV		OWN
1955	1	12	6	25	35.8	84.0					IV		STO**
1955	1	12	17	25	36.0	83.9					IV		USN

YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	MAGNITUDE m_b	M_L	M_S	MM INT	C/E*	REF**
1955	1	25	19	24	36.0	83.9					IV		USN
1955	1	25	19	34	36.0	84.0					IV		STO
1955	1	25	20	34	36.0	83.9		3.8			IV		OWN
1956	9	7	13	36	35.5	84.0					VI	D	USE
1956	9	7	13	36	35.5	84.0					VI		USN**
1956	9	7	13	49	35.5	84.0					VI		USN
1956	9	7	13	49	35.5	84.0				4.1	V		STO**
1957	6	23	6	34	36.0	84.1	5.0				V		STO
1957	11	7	17	15	36.0	84.0					IV		STO
1959	6	13	1		35.4	84.3		3.8			IV		OWN
1959	6	13	1		35.4	84.3				3.6	IV		STO**
1960	2	22	13	45	36.0	84.0					IV		STO
1960	2	22	20	30	36.0	84.0					IV		STO
1960	4	15	10	10	35.8	84.0		4.2			V		OWN**
1960	4	15	10	10	35.8	84.0					V		USN**
1964	7	28			36.0	83.9		3.0			II		OWN
1964	7	28			36.0	84.0					III		STO**
1964	10	13	16	30	36.0	83.9							USN
1964	10	13	16	30	36.0	84.0					III		STO**
1964	10	13	16	30	36.0	83.9		3.2			III		OWN**
1966	8	24			35.8	84.0		3.8			IV		OWN
1966	8	24	6		35.8	84.0					IV		STO
1969	7	14	11	15	36.0	83.9		3.0			II		OWN
1969	7	14	11	15	36.0	84.0					III		STO**
1969	7	24	18	10	36.0	83.9		3.4			III		OWN
1969	7	24	18	10	36.0	84.0					III		STO**
1971	5	29	21	21	36.0	82.0				2.9			STO
1971	7	13	2	3	36.0	84.0				3.4	V		STO
1971	10	22	21	55	36.0	83.0				3.3			STO
1973	10	30	22	58	35.8	84.0	33.0						USN
1973	10	30	22	58	35.8	84.0	33.0			3.4	V	F	PDE**
1973	10	30	22	58	35.8	84.1	1.0			3.5	V		STO**
1973	10	30	23	9	35.8	84.1						F	STO
1973	11	30	7	48	35.8	84.0		4.6			VI		OWN**
1973	11	30	7	48	35.8	84.0	3.0	5.6			VII		USN**
1975	5	2	16	22	36.0	84.5	12.0			2.6	III		STO
1975	5	2	16	22	35.9	84.4	15.0			2.6	III	F	PDE**
1977	7	27	22	3	35.4	84.4	13.0			3.5	V		STO
1977	7	27	22	3	35.4	84.4	7.0		3.5		V	F	PDE**
1979	8	13	5	18	35.2	84.4	5.0		3.7		V	F	PDE
1979	8	13	5	18	35.2	84.4	22.0			3.7	V		STO**
1980	4	21	20	44	35.8	84.1	5.0			2.6	III		STO
1980	4	21	20	44	35.8	84.1	5.0			2.6		F	PDE**
1980	4	21	23	20	35.8	84.1	5.0			2.4			PDE

								MAGNITUDE			MM		
YEAR	MO	DAY	HR	MIN	LAT	LONG	DEPTH	m_b	M_L	M_S	INT	C/E*	REF**
1980	4	21	23	20	35.8	84.1	5.0			2.6			STO**
1980	6	25	18	2	35.8	84.0	5.0		3.3		IV	F	PDE
1982	9	24	21	57	35.7	84.2	10.0		3.2	3.0	V	F	PDE
1982	9	24	22	19	35.7	84.2	10.0		3.5	3.4	V	F	PDE
1983	7	8	19	29	35.5	84.2	11.0		3.2	3.3	III	F	PDE
1984	3	17	23	26	35.8	84.0	3.0			3.0	IV	F	PDE
1984	8	30	16	26	35.6	84.3	14.0		3.2	3.2			PDE
1984	8	30	16	41	35.6	84.4	15.0			2.4			PDE
1987	3	27	7	29	35.6	84.2	19.0	4.3	4.2	4.2	VI	D	PDE

CULTURAL EFFECTS

F = Felt, H = Earthquake Heard, C = Repoted Casualties, D = Reported Damage

REFERENCE SYMBOL*

USN	U.S. Network Catalogue (Hays and Others, 1975)
STO	Stover and Others (1984)
EQH	Earthquake History of the U.S.
OWN	O. W. Nuttli (1979)
PDE	Preliminary determination of epicenters (U.S. Geological Survey)
G-R	Guttenberg and Richter (1954)
USE	United States Earthquakes (U.S. Department of Commerce)
CSC	Seismological station, Columbia, South Carolina

* see below for complete reference listing

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APPENDIX C:

MAXIMUM EARTHQUAKE AT HARTWELL RESERVOIR:

COMPARISON OF

PROBABILISTIC AND MECHANISTIC ESTIMATES

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MAXIMUM EARTHQUAKE AT HARTWELL RESERVOIR: COMPARISON OF PROBABILISTIC AND MECHANISTIC ESTIMATES

Preface

The Piedmont Province, the host geologic province for Hartwell reservoir, may experience a maximum earthquake on the order of magnitude 5.5. The existence of a maximum earthquake can be argued on the basis of a developing mechanism for earthquakes in the Piedmont. Confidence in the existence of a maximum magnitude now depends on the acceptance of the uniqueness of the Piedmont earthquake mechanism and our sparse knowledge of the state of stress in the crust. Although a probabilistic approach can also be taken, the determination of activity level and maximum earthquake would be even less certain because the seismic activity level in the Piedmont may be contaminated by reservoir induced earthquakes and other cultural activities.

The essence of the request for this analysis is to develop and qualify the arguments and data for a maximum earthquake in the Piedmont province near Hartwell reservoir. The analysis will not include an explanation for major earthquakes, except as necessary to consider the effects of a major event in southeastern Tennessee. I believe that the causal mechanism for a major intraplate earthquake is very different from the Piedmont earthquake mechanism. Furthermore, I know of no geologic evidence suggesting a major earthquake could occur in the Piedmont, thus making the consideration of major earthquakes irrelevant to seismic hazard in the Piedmont.

This manuscript will summarize and interpret the results of nearly 20 years of research projects, directed studies and student theses at Georgia Tech and other institutions. The topics of these works relate to the seismicity and structure of the Piedmont province. I welcome the opportunity to try to pull these thoughts together into one package. The work is extensive, attributing to the dedication and hard work of many students and colleagues. I express appreciation to each, and apologize for any omissions.

Leland Timothy Long

MAXIMUM EARTHQUAKE AT HARTWELL RESERVOIR: COMPARISON OF PROBABILISTIC AND MECHANISTIC ESTIMATES

INTRODUCTION

Area of Study

Hartwell reservoir, on the Savannah River, is situated in the Piedmont province of Georgia and South Carolina (Figure 1). The Southern Piedmont province extends from eastern Alabama to Virginia. Its northwest boundary is defined by the Brevard shear zone in Georgia, South Carolina and North Carolina. Its southeast boundary is marked by the onlap of Coastal Plane sediments. In Georgia and South Carolina, Piedmont type rocks have been traced under the Coastal Plane sediments to the edges of Triassic/Jurassic rift basins. The area of concern in this study is the Southern Piedmont; however, a definition in terms of crustal structure and rock type would be more appropriate. In general, the Piedmont type seismicity applies to areas of stable, thick crust with crystalline rocks at the surface. Typically, the weathering layer, although pervasive and frustrating to geologists, seldom extends to great depths. The surface topography is determined by a complex combination of rock type and joint or fracture patterns. This analysis will be limited to the Southern Piedmont, but it might apply equally well to other areas of similar geological framework, such as much of New England.

Geologic Setting

Igneous and metamorphic rocks dominate surface exposures in the Piedmont. Most pre-80's studies of the surface geology have emphasized the division of the Piedmont into Belts. Because the rock assemblages exhibit considerable heterogeneity, the belts were erroneously large, lumping together too many terranes to be useful tools in structural interpretation. The belts were more closely related to late stage structures and not internally consistent features. As such, the boundaries would be artificial. Recently, Higgins (1987) has abandon the "belt" concept in favor of an accretionary wedge-terrane paradigm. The Piedmont may best be divided into components of an accretionary wedge complex consisting largely of accreted terranes now arranged in a series of imbricate thrust slices. Following thrusting, much of the Piedmont accretionary complex was highly metamorphosed, migmatized and intruded by granites. This complex history has generated a complex surface distribution of rock types, including metadacites, granites, granite gneisses, and schists. It will be argued below that the rock type and ease in failure as measured by schistosity or fractures influences the susceptibility to seismicity. In particular, earthquakes tend to occur in granite gneisses with low fracture density and weak schistosity.

Relation to Seismic Zones

Seismic zones are areas in which one defines the probability of occurrence of earthquakes. Most classical seismic zones are areas of greater historical seismicity than their surrounding areas; however, some recent analyses such as the EPRI and LLL projects have extended the justification for defining seismic zones to include crustal structure, hypotheses for major events, and expert opinion. This extension mixes observational data with unsubstantiated causal mechanisms and imagination, thus creating patterns of risk that may appear incompatible with existing data. The inconsistency of predicted versus historical risk is acceptable only because the poor statistical behavior of earthquakes and the short period of available quality observation does not allow definition of the statistical parameters. In either the classical or extended definitions, seismic zones remain the basis for probabilistic estimates of seismic risk using techniques proposed by Cornell (1968).

The classical seismic zones which cover portions of the Southern Piedmont are evident in the historical seismicity as presented by Hadley and Devine, (1974) (Figure 2). Two of these zones, the Central Virginia Zone and the Georgia-South Carolina Transverse Seismic Zone were defined by Bollinger (1973) (Figure 3). The Georgia-South Carolina Transverse Seismic Zone was created largely to connect the Charleston, South Carolina, seismicity and the seismicity in the Southern Appalachian Seismic Zone (Bollinger, 1973), and to explain the greater number of events in the Piedmont of South Carolina than in western Georgia or North Carolina. This zone is referred to as transverse because its longer dimension is transverse to the northeast trend of the geologic structures of the Southern Appalchians. The Central Georgia Seismic Zone (Allison, 1980) is very similar to the Central Virginia Seismic Zone in its defuse pattern of epicenters. Bollinger (1973) included this seismicity in the Georgia-South Carolina Transverse Seismic Zone.

When examined in detail, not one of these seismic zones has a uniform distribution of seismicity, and all are strongly influenced by reservoir induced seismicity. The seismicity is so sparse and transient that more detailed zones are not practical. The seismicity of the southeastern United States (Figure 4) shows the general scatter of events. The Piedmont seismicity through 1988 (Figure 5) does reveal an interesting pattern. Two northeast trending zones of greater activity are apparent. One begins at Columbus, Georgia, and extends northeast through the Lake Sinclair, Clarks Hill Reservoir (J. Strom Thurmond), and Monticello Reservoir, South Carolina. The second extends northeast from Jocassee Reservoi through North Carolina. The southwest end may extend into Georgia, based on the occurrence of a few small events near Gainesville which were felt very locally and recorded on a portable seismograph in June, 1982. These two trends might describe the seismicity of the Piedmont better than existing zones; however, in either case the seismicity may correlate with geologic or lithologic units rather than with zones. The appropriate lithologic units may just be more prevalent in the suggested zones. In this analysis, the objective is to define the maximum earthquake that could be experienced at Hartwell reservoir. An estimate of seismic activity based on uniform distribution of seismicity and a restriction of seismicity to these two trends will be generated for comparison with the historical seismicity. However, the emphasis of this report will be on examining the statistical evidence for a maximum earthquake and the estimation of a maximum earthquake under the assumption that a unique mechanism exists for Piedmont earthquakes.

Exclusion of Major Events

A major earthquake, one of magnitude 6.0 or greater, can occur only by the rupture of the strongest portion of the crust, a stress channel which exists in the depth range of 10 to 20 km. Stress is released in the shallow crust by failure on existing fault planes. Below 20 km, stress is limited by viscosity. The mechanism for such a failure is a transient phenomenon which differs significantly from the mechanism for the shallow Piedmont earthquakes. Such a mechanisms has not been recognized in the Piedmont and would not occur without an observable change in the characteristics of the seismicity; namely the appearance of deep focus (15 km) earthquakes. The maximum earthquake at Hartwell would be influenced only by such large events occurring outside the Piedmont. Southeastern Tennessee, Giles County, Virginia, and Charleston, South Carolina are the only currently known possible sites for such an event. The effect of a major event at these sites would at most generate intensity VIII level damage at Hartwell. I consider their occurrence as transient events which will probably be predicted and have not considered them as part of the estimate of the maximum earthquake at Hartwell. These large events will not be considered viable at the Hartwell Reservoir.

LIST OF EVENTS

Definition of the Area

The Southern Piedmont physiographic province serves as the definition of the area of seismicity in this analysis. The Southern Piedmont province extends from eastern Alabama to Virginia. Its northwest boundary is defined by the Brevard shear zone in Georgia, South Carolina, and North Carolina. Its southeast boundary is marked by the onlap of Coastal Plane sediments. In Georgia and South Carolina, Piedmont type rocks extend under the Coastal Plane sediments to where the crust is disrupted by Triassic/Jurassic rift basins. Also, similar crystalline rocks are found at the surface northwest of the Brevard shear zone in the Blue Ridge province. For seismicity analysis, a definition in terms of crustal structure and rock type would be more appropriate since the Piedmont type seismicity applies to areas of stable, thick crust with crystalline rocks at the surface. An extension of the area of interest to some such areas would be ambiguous because the surface geology is hidden. For this reason and the fact that few events occur outside the Piedmont physiographic province, the choice of boundary for the seismic zone is equal to the boundary of the physiographic province.

Complete Catalog of Significant Events

The seismicity for the Piedmont has been collected in a single list of magnitude 2.0 and larger or significant events (Appendix I) The seismic data are derived from the LLL and EPRI seismicity lists with modifications and additions suggested by recent publications and studies. The recently relocated earthquakes of the Charleston aera (Seeber and Armbruster, 1987) were not included in the list because the detection and location methods are questionable. The list has been updated with data from quarterly earthquake lists from Georgia Tech and the SEUSSN Bulletin.

Appendix I lists the origin time (preceded by a minus sign if unknown), location, intensity, magnitude, and estimated magnitude. The locations are plotted in Figure 5. The intensities are the maximum modified Mercalli intensity reported in the literature or other lists and are listed as 0.0 if not available. For some events in the 1800's, an intensity was not given, and these were arbitrarily assigned intensity III. The magnitudes are equivalent to m_b, but rarely are they true m_b. Most instrumental magnitudes are m_{bLg} (or m_N) proposed by Nuttli to relate the Lg phase amplitude to m_b. The net data from the late 1970's and 1980's are largely based on a duration magnitude M_D (Teague and Sibol, 1984) which is scaled to m_{bLg} for large events. This scale is often extended from its calibrated range of above magnitude 2.0 to as small as magnitude 0.0; however, the character of seismograms vary significantly at short durations and this extension is questionable. Johnson (1984), in a study of events near Macon, Georgia, obtained relations to correct for a significant deviation in linearity in the magnitude scales. The estimated magnitude is either the measured magnitude or a magnitude based on the relation $m_b = 1.2 + 0.6I$, which was used in the LLL study and is very similar to the generally accepted relation $M = 1.0 + (2/3)I$. The LLL relation was used in statistical relations for the entire data set except in cases involving only intensity.

Minor Lists from Reservoirs etc.

The monitoring of reservoir induced earthquakes has yielded many well located and even more detected events. In the typical Piedmont reservoir area, the crystalline rocks which are close to the surface are efficient transmitters of seismic energy and background noise levels are low. These conditions are favorable for the detection of events as small as m = -3.0 for stations within 2.0 km of the hypocenter. For example, one day's record during the aftershock monitoring of the August 2, 1974, Clarks Hill earthquake showed over 500 small events. Unfortunately, such close monitoring of the seismicity is field work intensive and the data coverage is typically uneven. Reservoirs where seismic monitoring has been concentrated include Jocassee, Clarks Hill (J. Strom Thurmond), Sinclair, Keowee, and Monticello. The transient and long term behavior of the reservoir induced Seismicity is evident in the Clarks Hill and Sinclair Reservoir seismicity.

Clarks Hill Reservoir (McCormick, S. C.)

The Clarks Hill (J. Strom Thurmond) Reservoir area was intermittently monitored prior to the August 2, 1974, earthquake and nearly continuously monitored following the earthquake to the present. The detection threshold for uniform coverage is about 1.5, but during many time periods a threshhold of less than 0.0 was possible. Two trends can be observed that relate the seismicity to aftershock sequences and seasonally triggered swarms.

A. Aftershock sequence

Bridges (1975) listed the major aftershocks of the August 2, 1974 earthquake and showed that the activity decayed to significantly less than one magnitude 1.8 event per day within 10 days. A normal decay rate of time to the first power for Omari's law was observed (see Figure 6) suggesting that the sequence should have been completed in essentially 10 days. However, late in August and in September two swarms occurred that contained more magnitude 2.0 events than appeared in the aftershock sequence (see Figure 7). This extended or delayed "aftershock" sequence has proven typical of the Clarks Hill (J. Strom Thrumond) Reservoir seismicity, as well as the seismicity in other reservoirs.

B. Seasonal variations

Seismicity in the Clarks Hill (J. Strom Thurmond) Reservoir area for the years 1978 through 1980 (see figure 8) show two swarms initiating in the spring and extending through the summer. Both swarms followed by about one month a rise in the water level. A general observation of the rate of this seismicity is that there may be a tendency to increase the activity level in the spring and summer; however, these were the only two years with an apparent triggering by a change in water level.

Central Georgia Seismicity

Lake Sinclair was impounded in the 1950's, and a Magnitude 4.0 event occurred in 1964. Since that time, the vicinity of the reservoir has shown a steady rate of seismicity, typically occurring in swarms of a few weeks to months in duration (See Figure 9 for earthquake occurrences versus time). A reasonable measure of the activity has required local monitoring, since the larger events in many of the swarms are about magnitude 2.0 and the threshold for detection by station ATL (WWSSN) was also about 2.0 for the Lake Sinclair area. The list of events for the Lake Sinclair area is given in Appendix II.

The spatial distribution of seismicity in the Lake Sinclair area was re-evaluated by Radford (1988). Revised epicenters based on a uniform evaluation of arrival picks and a revision in the travel time curve are shown in Figure 10. No alignments suggestive of faults were observed. Instead, the epicenters define four clusters of activity adjacent to the reservoir.

STATISTICAL ANALYSIS

Analysis of time dependence

Either the consistency in the documentation or the rate of occurrence of Piedmont earthquakes has been non-stationary. The completeness of the record in the 1800's is understandably less than after the installation of the WWSSN stations BLA and ATL in the early 1960's. Never-the-less, differences in the rate of occurrence exist that are not easily explained by detection threshold alone. Some possible explanations for these variations and their effect on the statistical treatment of the seismicity will be discussed below.

Aftershock Removal

The usual procedure in statistical studies of seismicity is to remove suspected aftershocks. The rate of decay in the numbers of events per day in an aftershock sequence clearly violates the stationarity and random distribution assumptions invoked in most statistical treatments of seismicity. In the Piedmont, aftershock sequences are of normal length and with few exceptions aftershocks do not appear in the list of events. Hence, the removal of normal aftershocks would not significantly change any derived statistical parameters. On the other hand, most active areas in the Piedmont are identified by swarms of significant events, each event with its own aftershock sequence. If the swarm is short, usually only one significant event is listed; however, if the swarm extends over a period of months, many of the events may be listed.

The swarms could be treated either as single events or as multiple events, depending on the physical basis assumed for the statistical model. Under the assumption that the seismicity is used to identify areas of potential seismicity and not the level of activity, the swarms should be treated as single events. Such a treatment would be appropriate for models used to compute the risk when the historical seismicity is considered insufficient to define the rate of seismicity or when other factors, such as reservoir impoundment, might change the rate of seismicity. If the seismicity is used to define the rate of energy release, then the individual events in the swarm should be used. The latter treatment would be appropriate for models in areas where the seismicity has been shown to be stationary and the level of activity is expected to be constant.

The treatment of swarms as single events is the more appropriate assumption for the Piedmont. This treatment is consistent with the mechanism for Piedmont events described herein and the non-stationarity apparent in detection and occurrence. The distribution of active areas near Hartwell Reservoir will be used to evaluate the maximum event. The rate of activity based on all events will be used to compute the risk at Hartwell Reservoir for comparison with the maximum earthquake

Seasonal Variations

At all magnitude levels, the earthquakes in the Piedmont occur more often in the winter months (see figure 11). The magnitude 4 (intensity V) and larger follows the same pattern as the magnitude 3 (intensity III) and larger events. The seven peak months registered 10 to 15 events and the four low-seismicity months registered only about 5 events. An explanation for this may be found in the average monthly rainfall recorded in Charlotte, North Carolina, chosen as a typical central location in the Piedmont. The averages are for 1951 through 1980 and are assumed to be typical of the last 200 years. The March peak in rainfall is followed by a peak in seismicity in May. On the other hand, the spring and summer high levels are 6 months out to phase with the fall and winter high-level seismicity. Hence, the relation to water level increases noted in the Clarks Hill (J. Strom Thurmond) Reservoir seismicity may carry over to a general relation between rain fall and Piedmont seismicity, but the relation may not be direct.

In addition to mean monthly rainfall, the annual rate of seismicity versus sun spot activity was plotted (Figure 12). The sun spot activity may be an indicator of general weather patterns and might provide data on longer term variations in rainfall. Although an association of strong sun spot activity with increased activity is suggested in the annual energy release, the correlation is weak and may be difficult to isolate from variations in completeness and uncertainties in the maximum intensity. If possible, average annual rainfall should be extended back for direct comparison. Costain et al. (1988) discuss a possible correlation between stream flow and strain energy release in central Virginia for the period 1925 to 1987.

Premonitory Variations

The large numbers of small events that have occurred in the Clarks Hill Reservoir area and near Jocassee Reservoir have made these areas appealing as laboratories for the study of earthquake prediction. Talwani et al.(1978) and Fogle et al., (1976) have monitored the seismicity at Lake Jocassee for variations in seismicity parameters such as the changes in the ratio of P-wave to S-wave velocity first observed as precursors of large events at Blue Mountain Lake, New York. Significant variations with time were observed in the b and a values. The data suggested that some of the magnitude 2+ events might have been predicted, but overall a satisfactory criteria for prediction was not developed. The perturbations in activity level and b values were only observed in the smallest events and such variations would not affect the statistics for larger events considered in this study.

Relations to Cultural Activity

The correlation of Piedmont seismicity with rain noted above is only one factor in the connection between rainfall, ground water and induced seismicity. In addition to having the water available through rain fall, the water must gain access to seismic depths through ground water recharge. This process may have been influenced by industrial development and forest cover in the Piedmont.

The relation between seismicity and large reservoirs filled in the last 30 years has been well documented. The possible relation between smaller reservoirs that predate these major reservoirs and seismicity has not been considered in detail. In general, many of these smaller mill ponds were probably built during the population expansion and industrialization that evolved in the Piedmont following the Civil War. A notable decrease in Piedmont activity exists in the depression years of the 1930's (see figure 12). The amount of ground surface covered by forest versus the area cleared for agriculture could be a factor also in the facility and rate in which surface waters gain access to ground water systems.

The industrialization and agricultural development in the Piedmont in the late 1800's and the building of large reservoirs after the 1940's, if responsible for the increased seismicity during those times, would suggest that the Piedmont seismicity may in part be transient. The transient character of reservoir induced seismicity is well known, with activity typically increasing to a peak usually within a few years of filling. This peak is then followed by sporadic swarms of activity that decrease in frequency and intensity with time. The possibility then exists that Piedmont seismicity will continue to decline, except near new reservoirs, and will stabilize at a significantly lower level than apparent today. This assumption would hold provided that the reservoirs are triggering existing stresses and provided that the reservoirs or other mechanisms are not in some way creating stress in the rocks.

Discussion of confidence in statistics

The recursion relation,

$$\mathrm{Log}(Nc) = a - bM$$

where a is the Logarithm of the number of magnitude M = 0 events per unit time and b is the rate of decrease in activity with increased magnitude is a prime objective of statistical evaluations of lists of earthquakes. It is the usual basis for computation of expected number of events of a particular size at a site. Complex statistical and probabilistic techniques have been developed for evaluation of a and b from large data sets. Traditionally, the completeness of the data set is evaluated for a given magnitude range by Stepp's (1972) method and the uncertainties in the determination of a and b are computed using maximum likelihood estimators (Aki, 1965). For the Piedmont events with measures of maximum intensity in appendix I, the recursion relation is shown in figure 13. The number of events (about 50 of intensity V and larger) is marginally sufficient for the use of maximum likelihood estimators. Furthermore, as will be seen below, the distribution of intensities with magnitude varies with time.

The value of b for the total Piedmont data set for intensity V or greater is 0.5 +/-0.15. The b value is for intensity and should be divided by 0.6 to convert to magnitude. The resulting value of 0.8 for magnitude is consistent with other observed b values for tectonic earthquakes. The value for a is dependent on the length of time assumed for complete coverage. The earliest reported event was 1776 and the cumulative magnitude per year versus year suggests a reasonably steady rate of activity from 1875 to present. The historical data cover 110 to 210 years. For this analysis a time of 150 years is assumed with the understanding that the uncertainty is +/- 30 years. The corresponding a value is 2.0 +/- 0.2, or 100 intensity 0 events per year in the Piedmont. The area defined for the Piedmont seismicity consists of 17 one degree quadrangles or 170000 km^2 assuming an average of 10000 km^2 for each degree quadrangle. The a value for quarter degree quadrangles, the units assumed in risk computation below, is then 0.2 +/- 0.2 for each year in each quarter degree. The resulting recursion relation for the Piedmont seismicity is,

$$\mathrm{Log}(Nc) = 0.2 \pm 0.2 - (0.5 \pm 0.5)\, I$$

where Nc is the cumulative number of events per year per 2500 km^2 of intensity greater than or equal to I (MM).

A plot of the recursion relation for three separate time periods (figure 14) illustrates the uneven distribution of observed intensities as a function of time. The pre-1928 data contain all the intensity VII earthquakes in the Southern Piedmont. Otherwise, the b value is within the uncertainty for the total data set, and the a value is also the same after corrections for the reduced time period. Hence, the pre 1928 data and the total data set are consistent. After 1948 the recursion relation is more normal except for a b value (b = 0.7) which is higher than the average value. The period between 1928 and 1948 represents 20 years when the overall level of seismicity was low and only intensity IV events were reported. This type of distribution is not consistent with a normal statistical distribution. Either these 20 years are anomalous or seismic documentation during this time period was inconsistent. For these reasons, the uncertainties of the values of a and b are probably greater than suggested by the maximum likelihood method.

Criteria for Maximum Earthquake

The recursion relation implies no bounds at higher magnitudes, indicating only a reduced probability for the occurrence of the larger events. The recursion relation implies that two intensity VIII events should have been reported; however, none were reported. The probability that this would happen is 0.15 and is within the uncertainty of the data, particularly considering that one or more of the intensity VII events could have been in sparsely populated areas where intensity VIII reports would not be available.

A maximum intensity (i.e. maximum magnitude) event would be suggested by a significant under reporting of events, or equivalently, an increase in b value. Long (1974) noted a change in b value with magnitude but the observed change in value with increased magnitude was toward a lower b value. Although this relation indicates abnormally large numbers of small events, the low b values at higher magnitudes suggests a normal tectonic distribution without a maximum magnitude. As noted above, the lack of intensity VIII events would indicate an increase in b value, but the observed data are still within the statistical uncertainty of the data. Hence, the data are suggestive, but inconclusive, for a maximum intensity at intensity VIII.

An alternate technique is to consider, arbitrarily, that the maximum intensity would correspond to an event that would occur in a given (long) time period. A justification for this approach could be found in a consideration of the length of time that stresses could be retained in the shallow crust, given the processes of chemical weathering that would be accelerated by high stress levels. If a 10000 year period is chosen, then the maximum intensity (or magnitude) event can be found by calculating the effect of uniform seismicity in the surrounding area. Figure 15 shows the expected rate of occurrence for the Hartwell area for two models of seismicity. The first is uniform seismicity for the entire Piedmont. The second is a concentration of activity into two sub-parallel bands, one extending through the Hartwell area and the other along the fall line. These two distributions of seismicity give return periods for the Hartwell area of 10,000 years and 8,000 years respectively for intensity VI.

The return periods were computed in terms of particle velocity in order to utilize the attenuation relation from Long (1974). The relations from Nuttli (1973) were used to convert intensity at the source to particle velocity prior to attenuation to the site. Standard methods for numerical integration of seismicity were used to obtain the expected rate of occurrence.

CHARACTERISTICS OF PIEDMONT EARTHQUAKES

General Review

Introduction

Earthquakes in the Piedmont Province have unique properties that distinguish them from events in other seismic areas of the continental interior. These properties are their shallow depth of focus (0 to 2 km), their swarm type occurrance (high b values for low magnitude events), their high-frequency spectral decay (frequency cubed dominates), their association with reservoirs, and the similarity between joint directions and focal mechanism solutions. These properties have been studied and compared to properties of earthquakes in other areas by Long (1974), Marion and Long (1980), Bollinger and Wheeler (1982), and Archarya (1980).

Reservoir Induced

The question of reservoir induced seismicity versus natural seismicity as an origin for Piedmont events must be considered because many recent events are clearly associated with reservoir impoundment. These include earthquakes at Lake Jocassee, Lake Oconee, Monticello Reservoir, and Richard B. Russell Reservoir. Other seismic areas are close to reservoirs, but the timing and spatial associations are not as clear cut. These include Lake Keowee, Lake Sinclair, and Clarks Hill (J. Strom Thurmond) Reservoir. Those few examples of seismic activity that appear removed from reservoirs can usually be associated of other types of ground water perturbation. The Columbus,Georgia, events of 1984 (Jones et al., 1986) were located near quarries that had recently been flooded. The Macon, Georgia, events were in the immediate vicinity of an area of kaolin mining that had recently ceased water removal operations and had thus allowed the ground water table to recharge.

Depth of Focus

Because the Piedmont earthquakes are shallow and in high-velocity near-surface rocks, the accurate determination of depth requires stations at less than 1.0 km spacing and timing precision of .02 seconds if a depth precision of 0.1 km in the 0.3 to 2.0 km depth range is desired. In the Clarks Hill (J. Strom Thurmond) Reservoir area, Dunbar (1977) relocated eighty one microearthquakes recorded on smoked paper and magnetic tape recorders. The velocity model for the study area was determined from local travel time data obtained by Dunbar (1977) and by Leary et al. (1974). The Dunbar model, which includes a gradient, was used in the relocation. The effect of the gradient over constant velocity model is to shallow the hypocenters an average of 10 percent. The depths (figure 16) ranged from 0.1 to 1.8 km with a mean depth of 0.6 km +/- 0.3 km. Only 5 of the eighty events were deeper than 1.5 km.

A significant implication of the use of a gradient model is that the change in travel time with respect to depth changes sign when the distance is approximately twice the depth of focus. A constant velocity layered model will not show this effect. Hence, a depth solution that does not include two or more stations within a distance of twice the depth will be unreliable (possibly non-unique), even though the solution is stable. It can be verified for the majority of Piedmont earthquakes that have depths computed at greater than 3.0 km do not satisfy this criteria for locating depths of focus.

Depths of focus have been computed for Jocassee Lake earthquakes by Talwani (1977) and Fogle et al., (1976). The analysis of Fogle et al. (1976) used the technique proposed by Dunbar (1977) while the analysis of Talwani (1977) used the traditional constant velocity layered model of program HYPO74. The range in focal depths in both independent studies vary from the surface to 3.0 km. A few events located as deep as 4 km, but these were usually low-quality hypocenters. The average station separation was 3 to 7 km, thus severely limiting depth computation for events shallower than 1.3 km in the center of the reservoir and shallower than 3 km for most of the active area. The events located above the Brevard shear zone in the Henderson Gneiss. In a field study of microearthquakes in a swarm at Lake Keowee, South Carolina, Talwani et al., (1979) found a similar distribution of hypocenters in the surface to 2 km depth.

The depths of focus for Monticello earthquakes are difficult to assess, again because the station spacing was at best 2 km. The subsequent uncertainty in depth computation has yielded a depth range of near-surface to 4 km. The design of the original net with its 7 km spacing was of marginal use in depth computation and some early reports suggested deeper, but poorly constrained, hypocenters. In a short field monitoring study using five portable recorders spaced at less than 0.5 km apart, Smith (1980) obtained depths of focus that were typically 0.5 km deep.

In summary, the depths of focus reported for reservoir induced events has depended strongly on station spacing; however, where stations are close together, the depth are typically 0.5 to 2.0 km.

Swarm Activity

An earthquake swarm is characterized by events of similar magnitude occurring over a short period of time. The Piedmont earthquakes often occur in swarms. A b value which is high would be typical of swarm type occurrences and high b values have been documented by Long (1974) for the Seneca (or Keowee) earthquake sequence (figure 17). Talwani et al., (1979) also obtained a high b value for the Keowee swarm. Johnson (1984) documented a swarm of earthquakes in Twiggs County, Georgia, which occurred from December, 1982, through May, 1983. The b value for all events was 0.73 +/-0.03, but the recursion relation was not linear and the b value increases to greater than 1.0 for the larger events. In McDowell County, North Carolina, over 75 events were felt between February 10, 1874, and April 17,1874.

Focal Mechanisms

Focal mechanisms for the Clarks Hill (J. Strom Thurmond) Reservoir area and Lake Jocassee have were reviewed by Guinn (1980). Focal mechanisms for other areas and other studies in these areas show similar results. The focal mechanisms tend to cluster in groups that are consistent with surface joint systems. The dominant clusters also tend to vary with time.

Spectral Properties

The theory of seismic spectra and the observed spectra for the Lake Sinclair area, Clarks Hill (J. Strom Thurmond) Reservoir area and the Monticello Reservoir area were evaluated by Johnston, (1980), with the objective of identifying a spectral discriminant for reservoir induced seismicity. This study included an analysis of available instrumentation and found that the data appropriate for spectral analysis is limited by dynamic range of the instruments and attenuation. Johnston (1980) computed a Q of 900 +/- 100 for P waves and 450 +/- 75 for S waves in the Piedmont crystalline rocks. The source theory suggests that a discontinuous rupture front speed will generate high-frequency energy which dominates the spectrum for frequencies higher than the corner frequency. These spectra (which decay as the square of the frequency) decay more slowly than spectra dominated by a gradual change of rupture velocity. Hence, the velocity and smoothness of faulting control the high-frequency spectral content. Earthquakes on lubricated or smooth-slipping shallow faults, which are hypothesized to be typical of reservoir induced earthquakes, would generate less high-frequency seismic energy. The displacement spectra of these types of earthquakes would consequently decay as the cube of frequency at frequencies above the corner frequency. Spectra from Clarks Hill, Jocassee, and Monticello Reservoir areas generally exhibit a cubic decay with frequency above the corner frequency. The high-frequency slope from Lake Sinclair earthquakes were mixed and often with a high-noise component. Marion and Long (1980) showed a distinct difference in spectral properties between Piedmont earthquakes and earthquakes in southeastern Tennessee, with those in southeastern Tennessee having a significantly lower slope (1.5 to 2.0).

The potential influence of depth of focus on the spectral slope was studied by Wilson (1983). He evaluated the hypothesis that the increased normal stress with increased depth would increase the frictional resistance on the fault surface and increase the high-frequency spectral content. Relations among depth, spectral slope, and corner frequency were examined for 70 digitally recorded events at Monticello Reservoir, South Carolina, and 35 events at Mammoth Lakes, California. At the Monticello Reservoir, the digital data were obtained on stations separated by 2.0 or more km, thus severely limiting the ability to determine depths shallower than 2.0 km. The "pseudo" depths computed from three-component data fell in the range of 0.5 to 2.0 km with an uncertainty of +/- 1.0 km. With this narrow range for depth, no variation in spectral slope with depth could be observed. The high-frequency slope, however, does vary with depth for the Mammoth Lakes events. At Mammoth Lakes, the average slope of -3.0 at 4.0 km depth changes to 2.5 at 11 km depth. A significant correlation was observed between an increase in corner frequency and more rapid decay of spectra above the corner frequency. This correlation may indicate that the number of barriers on a fault plane is proportional to the size of the fault plane. Hence, small areas of rupture which produce high corner frequencies, are more likely to encounter only a few barriers.

Studies of Piedmont Earthquakes, Aftershocks and Swarms

The Lake Keowee Seismicity

Lake Keowee is located at the head waters of Hartwell reservoir in South

Carolina. Because Hartwell reservoir and Lake Keowee are adjacent and share much of the same geology, the seismic activity at Lake Keowee is an important factor in estimating the potential for seismic activity near Hartwell Reservoir. The seismicity at this location was first noticed with the intensity VI (MMI) Seneca earthquake of 13 July, 1971 (Bollinger, 1972; Long, 1974). An intensity V (MMI) earthquake on 13 December, 1969, may also be located near the Seneca epicenter.

The unusual swarm characteristics of the Seneca events on 13 July, 1971, and records of microearthquakes recorded during aftershock monitoring were studied by Long (1974) in a comparison of b values in the Southeast United States. The b values observed near McCormick and Seneca should be associated with small source dimension or low stress drop. The high b values further imply frictional sliding, perhaps along existing fractures, and shallow focus. Also, the high b values are consistent with observations of Gupta et al. (1972 a and b) that, near reservoirs, the b values are often high in contrast to regional values. The variation in b values suggests that southeastern United States earthquakes may originate from varying conditions of ambient stress.

The Seneca area has continued to exhibit sporadic bursts of activity in swarms including significant swarms in January and February of 1978 and near the 19 January, 1979, event of magnitude MD 3.4 (Talwani et al., 1979).

The most recent activity consisted of swarms in February, June and July 1986 (Acree, et al., 1988). The largest event in these swarms was a magnitude 3.2 event on 13 February 1986. Acree et al., (1988) suggest that the 1986 activity was located 1. to 2.0 km south of the 1978 activity reported by Talwani et al., (1979). Depths of focus, where sufficiently close stations were available, were typically in the range of 0 to 2 km. Deeper hypocenters were typically more poorly constrained. Focal mechanisms obtained for some of the larger events typically show oblique motion on nearly vertical fault planes. The strike of the fault planes are consistent with mapped joint strikes and a northeast trending compressive crustal stress.

The Jocassee Seismicity

The spectra of earthquakes in the Jocassee Reservoir vicinity were studied by Marion and Long (1980), in a comparison with spectra from events in McCormick, S.C., and Maryville, Tennessee. The spectra of the Piedmont events are best modeled by an equidimensional fault which nucleates rupture at a point and has a rupture velocity approaching the P-wave velocity. The high-frequency content and stress drop of a typical Piedmont microearthquake can be explained by brittle fracture of an irregularity or rigid portion of the fault plane. The transonic slip can be explained by pre-existing surfaces with low frictional resistance such as shallow joints. In these areas, the the earthquakes occur at depths typically less than 2.0 km. Variations in the high-frequency trends can be explained by variations in the orientation of the fault plane. The most prominent distinction between the Piedmont events and the southeastern Tennessee earthquakes interpreted from spectra is the difference in rupture velocity and the implied nonexistence of frictional resistance exceeding 5.357 times the driving shear stress on the fault plane. The frictional resistance is determined by confining pressure as well as the existence of compressional or tensional deviatoric stresses. Therefore, movements on shallow-joint planes with minimal resistance are compatible with the low-stress shallow earthquake mechanisms such as the strike slip and normal mechanisms found in the Jocassee Reservoir area (Fogle et al., 1976; Talwani, 1977) or the normal faulting mechanism found in the Clark Hill (J. Strom Thurmond) Reservoir area (Guinn, 1977; Long et al., 1978).

The Richard B. Russell Seismicity

The Richard B. Russell Lake, directly below Hartwell Reservoir on the Savannah River, was filled in December 1983. Only about three magnitude less than 1.0 events were detected each year since filling until December, 1987. On December 12, 1987, a M_D 2.3 event occurred close to station LDV (Loundsville, South Carolina) on the Savannah River in the Richard B. Russell Lake. A normal aftershock sequence of 30 detected events occurred during the eight days following the main event. A M_D 2.5 earthquake occurred on December 24, 1987, at 22:46 UT, a M_D 2.0 on January 26, 1988, at 01:46, and a M_D 2.0 on January 27, 1988, at 22:06 UT. The last three $M_D \geq 2$ events did not exhibit measurable aftershock sequences. Although four years have passed since filling of this reservoir, the activity is typical of reservoir induced sequences. A large portion of the Richard B. Russell Lake is underlain by mafic geologic rocks; however, in the area of the recent activity the geologic units are a granite gneiss. An association of reservoir induced seismicity with granite gneiss has been noted in Clarks Hill (J. Strom Thurmond), Jocassee, and Monticello reservoirs.

The Clarks Hill Reservoir Seismicity

The spectra of the Clarks Hill (J. Strom Thurmond) Reservoir microearthquakes (also known as McCormick, S. C., seismicity) were studied by Marion and Long, (1980), and compared with events from the Jocassee Reservoir area. The spectral properties of the Clark Hill microearthquakes were identical to those of the Jocassee microearthquakes described with the Jocassee seismicity. The hypocentral depths, which are in the 0 to 1.2 km range, were discussed under depths of focus above.

The Monticello Reservoir Seismicity

The induced seismicity of the Monticello Reservoir has been extensively studied. An in situ study of the physical mechanisms controlling induced seismicity (Zoback and Hickman, 1982) suggested that the earthquakes were caused by an increase in pore pressure large enough to trigger reverse-type fault motion on pre-existing fault planes. The activity occurs in a zone of relatively large shear stresses at a depth of less than 300 meters. Zoback and Hickman speculate that the increase in pore pressure reduces the normal stress on the fault, and Fletcher (1982) states that fault friction then causes the sudden failure. The pore pressure also allows larger displacements and a lower final stress than where the effective stress is high. Zoback and Hickman's (1982) model of the seismicity at Monticello suggests that futuree p240Xearthquakes occur infrequently and will be a result of eventual pore fluid diffusion into isolated zones of low permeability. In addition, they state that these earthquakes are expected to be limited in magnitudeby thee small dimensions of the seismogenic zones. Stress drops for the Monticello Reservoir earthquakes ranged from 0.2 to 4.0 bars (Fletcher, 1982) for events in to 0 to 1.0 Magnitude range.. Four events of Magnitude 2.8 to 3.0 showed stress ' ops of 13 to 92 bars. are consistent with shear stresses measured by Zoback and Hickman (1982) at depths of 0.2 to 1.0 km in a drill site north of the reservoir.

The Central Georgia Seismicity

The seismicity of central Georgia is contained within a circle of radius 75 km, centered on Milledgville, Georgia, and includes Lake Sinclair and Lake Oconee. The seismicity is moderate and includes historic events as large as 4.9 $m_{b,3}$. The larger historical earthquakes are documented by Allison (1980). Central Georgia continues to experience sporadic activity. The impoundment of Lake Sinclair in the 1950's and the continued seismicity in central Georgia, along with occurrences of reservoir induced seismicity at the Jocassee and Monticello reservoirs in South Carolina, raised the possibility that the Lake Sinclair seismicity is reservoir induced and increased concern that the new reservoir, Lake Oconee, would induce significant activity. Because of this concern, the seismicity was closely monitored during the impoundment of Lake Oconee by Wallace Dam in 1977.

The impoundment of Lake Oconee by Wallace Dam was followed by only a few small events and significant reservoir induced seismicity was not triggered. A post-filling swarm with M_c between -0.3 and 0.8 that occurred in May, 1980, showed little variation in magnitude and did not precede a M_c 1.5 or larger event as in the usual case of earthquake swarms near Lake Sinclair. The events in the Lake Oconee swarm occurred in a very tight cluster.

The majority of the seismicity in central Georgia occurs in the Lake Sinclair area The spatial distribution of the epicenters with respect to Lake Sinclair and the characteristics of the swarms suggests possible reservoir induced seismicity. A study of the high-frequency decay of displacement spectra, however, suggested a natural cause for the Lake Sinclair events (Johnston, 1980).

The epicenters of Lake Sinclair events occur in clusters (Allison, 1980; Radford, 1988). Radford (1988) revised the velocity model for the Lake Sinclair region and reread and relocated 189 better recorded events. The significant change in the velocity model was the discovery of shallow high-velocity mafic crust that affected travel times at distances beyond 20 km. The relocation significantly reduced the scatter of the locations and identified four distinct clusters. The location program was revised to isolate origin time computation from location computation and to assure greater consistency in the data. The depths of focus are constrained to 0.5 km based on records from smoked-paper seismographs deployed before the implementation of the Wallace Dam Net. All data available that are capable of determining depths suggest depths in the 0.0 to 1.0 km range. The distribution of relocated events are given in figure 10. An association of the seismicity with surface geology is inhibited by the lack of outcrops and the limited control on available geologic maps. No detailed geologic maps are available; however, the area has been described by Higgins et al. (1986) as a series of thrusts from the south that were subsequently metamorphosed and intruded. Weathered outcrops suggest that granite gneiss is a common rock type underlying the area.

The Union County Earthquake

The January 1, 1913, Union County, South Carolina, earthquake may have been the largest in the Southern Piedmont. Long (1976) in an evaluation of attenuation of intensity with distance estimated a magnitude of 5.45 (m_b) based on the observed intensities. The maximum intensity in a small area was a VIII RF or VII-VIII MM.

Central Virginia Seismicity

The Central Virginia Seismic Zone (Bollinger, 1973; Bollinger, 1975) has all the properties of other Piedmont earthquakes except reported depth. However, computations of depth in central Virginia suffer from the same uncertainty as most depth computations in the Piedmont, namely insufficient station density. Bollinger et al., (1985) discussed the anomalously shallow depth of focus for these Piedmont earthquakes and related their shallow depth to anomalies in crustal strength. If a depth computation criteria of two stations within a distance of twice the focal depth were applied, then few of the existing depths would be indistinguishable from surface focus events. The possibility that many of these events are shallow is illustrated by a study of the December 1986 - January 1987 Richmond, Virginia, felt earthquake sequence (Davison and Model, 1987). These events, which occurred in a swarm, were interpreted as being shallow, less than 2.2 km.

MECHANISM FOR PIEDMONT AND RESERVOIR INDUCED EARTHQUAKES

Summary of Published Explanations

Mechanisms for the Piedmont seismicity, exclusive of induced seismicity, are limited. Although most mechanisms have been applied to the Piedmont at one time or another, very few can satisfy the description of a Piedmont earthquake given above. Evidence for Cretaceous and Cenozoic faulting (York and Oliver, 1976; Wentworth and Mergner-Keefer, 1981; Prowell and O'Connor, 1978; Prowell, 1983; Reinhardt et al., 1984) is often sited as an explanation for seismicity. The fact that many of these faults are observed along the fall line and a possible increase in activity in a broad zone following the fall line suggests that a flexure of the crust may, in part, be responsible for the stresses released in these events. The observed seismicity does not fit this model. The focal mechanisms, where available, are not consistent with the orientation of the Cretaceous and Cenozoic faults and the hypocenters are neither on these faults nor at the depth of the fault where it penetrates into the crust.

The distribution of earthquakes in the Piedmont along two parallel trends suggests a possible correlation with rock type or crustal structure. The correlation with the Piedmont fault system proposed by Hatcher and Zietz (1980) fails for the same reasons as does the hypothesis for the more recent Cretaceous and Cenozoic faulting. The rock type, as characterized by the division of the Piedmont into belts of similar properties, is also parallel to the major crustal structures. Because reservoir induced seismic activity correlates with jointing and rock type, the existence of the two parallel trends is perhaps best explained by the occurrences of appropriate granite gneiss geologic units at the surface.

Induced seismicity is usually related to the changes in water pressure at depth induced by loading the reservoir or by changes in the water level. Water levels in the Clarks Hill (J. Strom Thurmond) Reservoir were related to seismicity by Talwani (1976). Talwani noted an increase in seismicity two days after a 4 foot fluctuation in the water level and proposed a delay caused by the time required to propagate the pressure pulse to the depth of the seismicity. However, a direct correlation of seismicity with changes in water level is not always observed. Water level in Lake Sinclair changes only slightly and the seismicity occurrs in swarms. The pattern in the Clarks Hill (J. Strom Thurmond) Reservoir ares, which is not well developed, consists of swarms of earthquakes occurring about one month after a return to normal pool elevation in the spring. The swarm activity decreases to background over a three to 6 month period. The seasonal variation of the rate of occurrence of the larger historical earthquakes and the seasonal variation in rainfall supports a reservoir induced earthquake mechanism for all Piedmont events.

Recently, Costain et al., (1987) have discussed the role of water in generating intraplate seismicity and refer to the mechanism as hydroseismicity. Hydroseismicity is identical to induced seismicity in principle, except that they also attempt to use the mechanism to explain intraplate seismicity occurring at significant depths (10 to 20 Km). In effect, Piedmont seismicity may be hydroseismicity restricted to shallow depths. Costain et al. (1987) may have been misled by reported depths of central Virginia earthquakes in the 5 to 10 km depth range; whereas, these events could actually be within 1.0 km of the surface. The capability of hydroseismicity to explain large intraplate earthquakes is limited by a mechanism to concentrate and release stress in large areas of the crust, particularly at depth.

Relation to Joint Intensity

A geologic field study of the area of induced seismic activity at Monticello Reservoir, South Carolina, Secor, et al. (1982) identified the source rock for the seismicity as the Winnsboro plutonic complex, a heterogeneous quartz monzonite. According to Secor et al. (1982)

> "The Winnsboro complex contains numerous diversely oriented small fractures and lithological inhomogeneities having a maximum length of the order of 1-2 km. These local inhomogeneities, together with an irregular stress field, are interpreted to control the diffuse seismic activity that is occurring around Monticello Reservoir."

The possible relation of joints and small fractures to seismicity has been studied further at Georgia Tech in a field survey (Sorlien, 1987) of the Clarks Hill (J. Strom Thurmond) Reservoir area. The results of that study suggest that the seismicity correlates with the edges of zones of granite gneiss with low measures of the tri-mean joint intensity (figure 18). The trimean joint intensity was devised as a means of standardizing estimates of rock quality. The low values corresponds to zones of strong rock, rock able to accumulate significant stress and release that stress along existing joints or small fractures as microearthquakes. The surrounding areas which consist of more highly fractured rock, rock with significant schistosity, or weathered mafic rock, are unable to store the stresses required for significant induced seismicity. The Keowee seismic zone was studied by Malcolm Schaefer, (Personal Communication) with similar results. This technique may prove to be the best method to predict susceptibility to induced seismicity, or equivalently, Piedmont seismicity.

MECHANISM PROPOSAL FOR A MAXIMUM EARTHQUAKE

The 1982 New Brunswick earthquakes have all the properties of a Piedmont earthquake, except an association with a reservoir. Hence, these earthquakes will be used as a model for a maximum Piedmont earthquake. The magnitude range of 5.6 to 5.8 for the larger event is considered appropriate for the maximum Piedmont earthquake. The largest event would suggest a maximum magnitude of 5.8.

The maximum depth for the New Brunswick earthquakes was about 7 km. The maximum Piedmont earthquake is constrained to shallow depths by hydrostatic pressure, which increases the strength of joints or minor fractures with increased depth. For tensional stress conditions, the average regional plate stress is below the stress needed for failure at depths below about 10 km; however, this relation, form Meissner and Streahlau (1982), is highly dependent on properties of the joint surface. The depth of rupture for the New Brunswick earthquakes may be considered a reasonable limit to the depth of Piedmont earthquakes. Its stress drop of 35 to 70 Bar is high compared to other earthquakes and consistent with its occurrence in a zone of high crustal strength. The combination of stress drop and maximum fault size are consistent with a maximum magnitude 5.8 event as computed from the relations of Randal (1973).

The New Brunswick earthquakes were located in a large undeformed granite. The granite is more rigid than the surrounding rocks, consistent with the location of events in rocks of high measured rock quality in the Clarks Hill (J. Strom Thurmond) Reservoir area. The only association of geology with seismicity is the correspondence between the joint directions and inferred faulting. This correspondence was also observed in reservoir induced seismic activity in the Southern Piedmont. The concentration of activity in the granite is consistent with the lack of evidence for activity on nearby faults and shear zones. These shear zones and other surface geology features are unrelated to the seismicity. The implication of this fact is that the many faults and shear zones in the Southern Piedmont should not pose a seismic risk.

The lack of surface rupture and the apparent dissipation of displacement at the surface by joints is characteristic of a release of volume stress. The volume stress release mechanism is consistent with the observation of clusters of earthquakes in Lake Sinclair area and other reservoir induced seismicity areas. The source of stress for these events is not known. A proposed mechanism for the New Brusnwick earthquakes was glacial rebound and the resulting bending of the crust. Because this mechanism is not operative in the Southern Piedmont, the maximum Piedmont earthquake might actually be less than those observed in the New Brunswick events. A second mechanism would be the triggered release of stored tectonic plate stress which has been proposed for the reservoir induced activity in the Southern Piedmont.

CONCLUSIONS

The earthquakes in the Southern Piedmont have all the characteristics of reservoir induced earthquakes. Their occurrence correlates with the hypothesis that they are triggered by surface water, they are shallow focus, and are unrelated to geologic features except joints. Because the industrialization of the last century and the building of large dams in the last 30 years has disturbed the ambient ground water conditions, the rate of recent activity may not represent a rate appropriate for long term natural seismic activity. With this caveat, an intensity recursion relation of

$$\mathrm{Log}(Nc) = a - bI = 0.2 - 0.5I$$

where Nc is the number of events of intensity I per year in each quarter degree square, and I is Modified Mercalli intensity. At Hartwell Dam, the return period for intensity VII events would be about 30,000 years, if the seismicity were uniformly distributed.

The maximum earthquake, based on the model for the Piedmont earthquake and the Miramichi earthquakes as type examples of a maximum earthquake, would be 5.8. The magnitude 5.45 (intensity VII-VIII) Union County earthquake may have been close to a maximum earthquake for the Southern Piedmont.

MAXIMUM EARTHQUAKE AT HARTWELL RESERVOIR: COMPARISON OF PROBABILISTIC AND MECHANISTIC ESTIMATES

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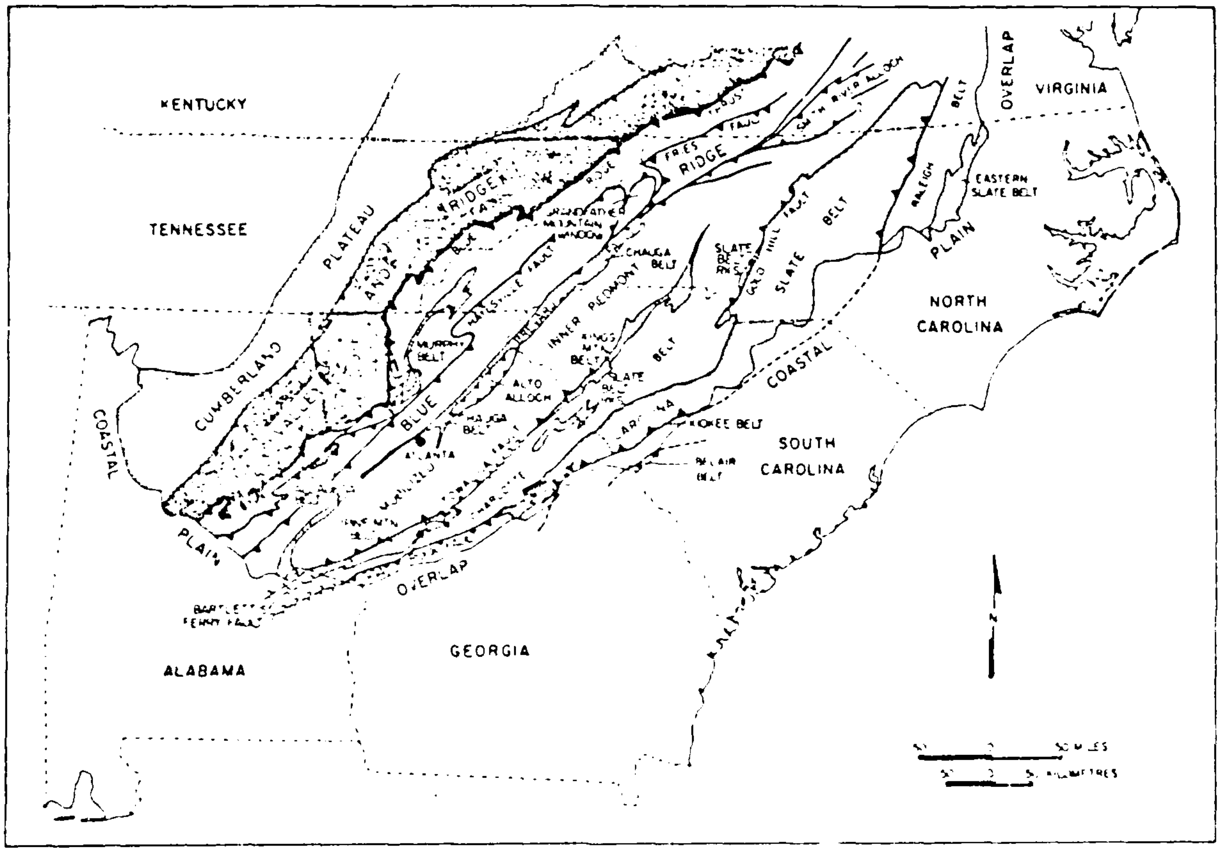

Figure 1. Map of the Piedmont and associated Provinces and Belts in the southeastern United States (after Hatcher and Zietz, 1980)

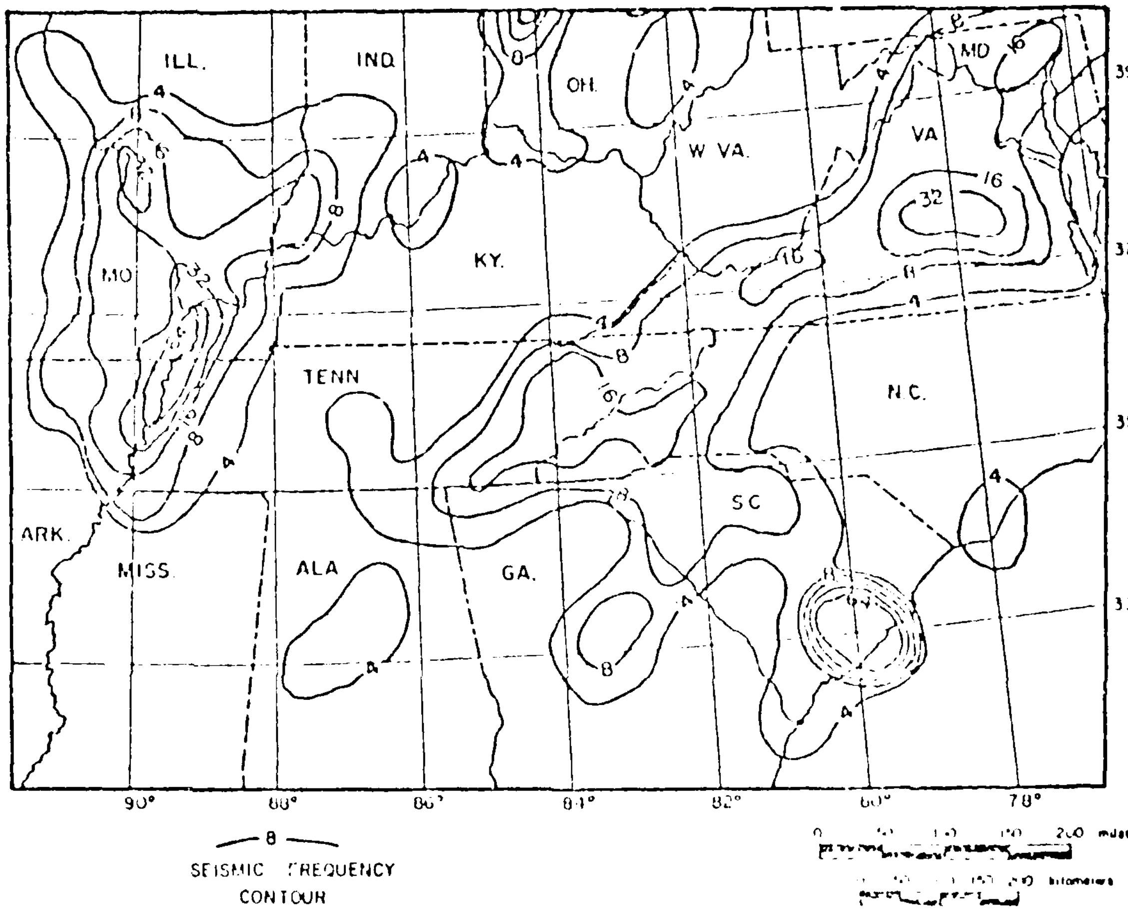

Figure 2. Seismic Intensity Occurrence Contour Map of the Eastern United States. Each contour encloses areas experiencing equal numbers of earthquakes (I > III) for the period 1800 - 1972 (*from* Hadley and Devine, 1974).

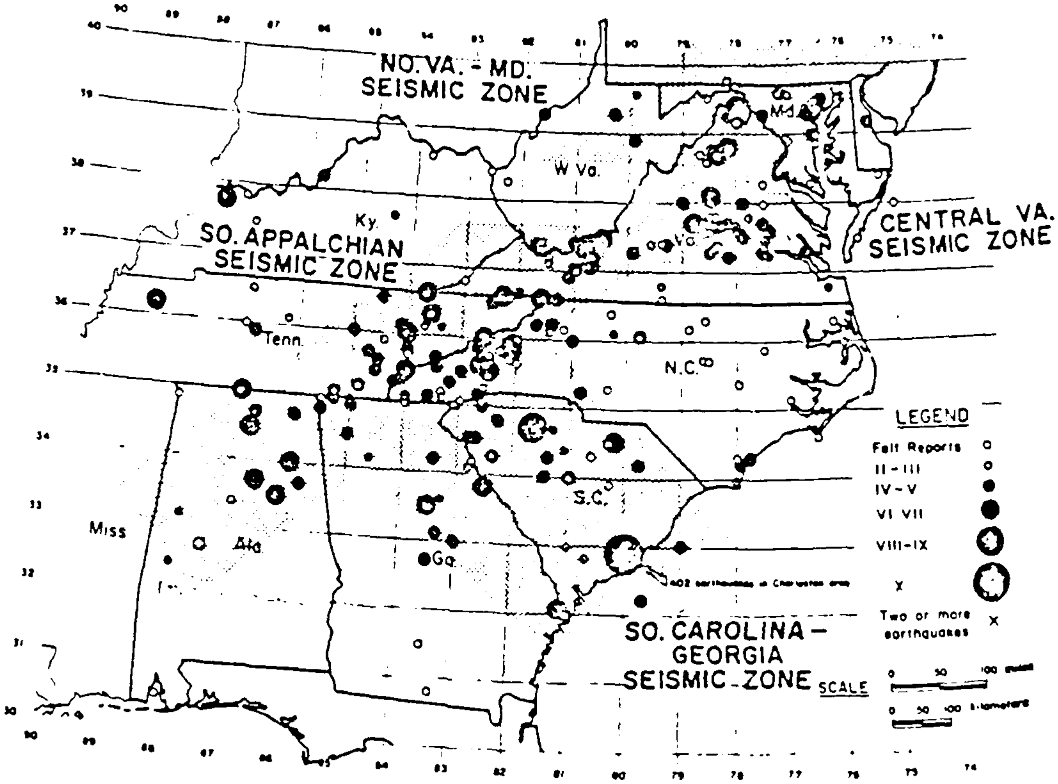

Figure 3. Historical seismicity (1754 - 1970) and definition of seismic zones in the southeastern United States (from Bollinger, 1973).

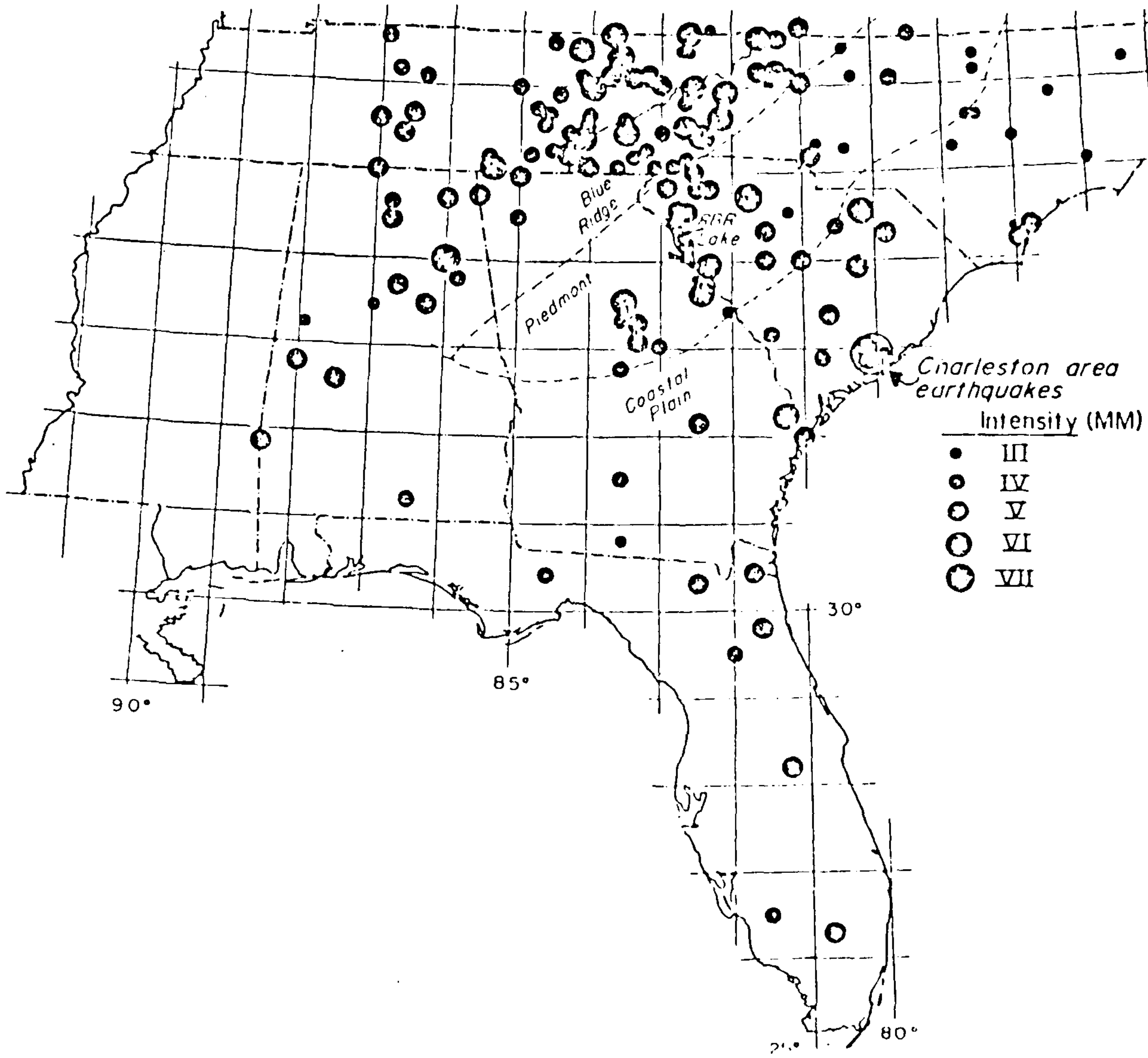

Figure 4. Distribution of earthquakes in the southeastern United States relative to the Piedmont Province. The Hartwell Reservoir is at the head of RBR Lake. Epicenters from Bollinger (1975) with updates and corrections through 1980.

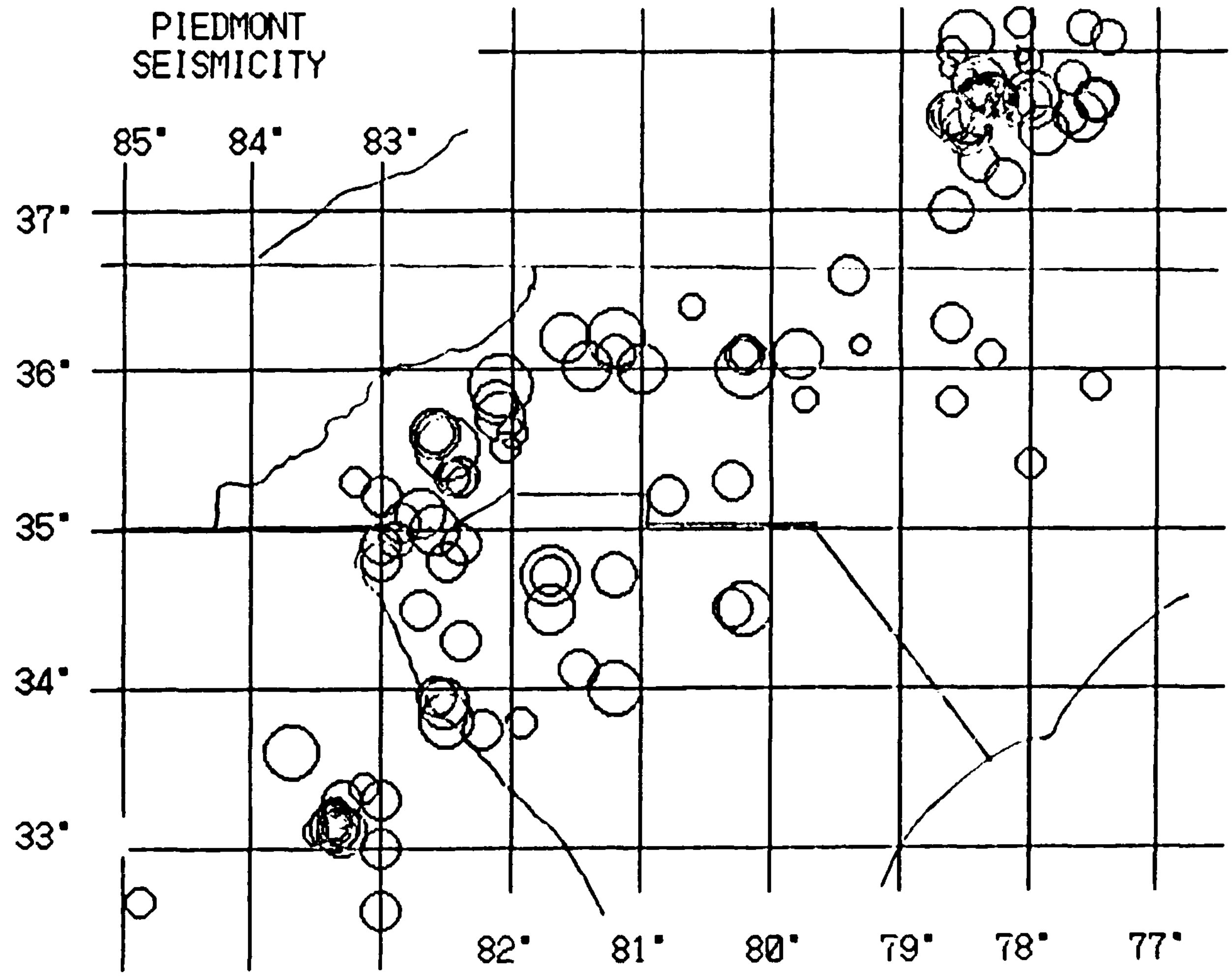

Figure 5. Seismicity of the Piedmont. Data are from Appendix I and events outside the Piedmont are not plotted.

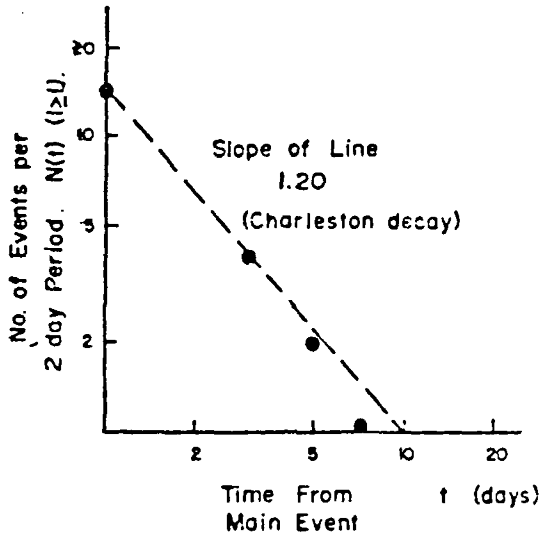

Figure 6. Aftershock decay plot of August 2, 1974, earthquake in the Clarks Hill Reservoir Area. Data from Bridges (1975).

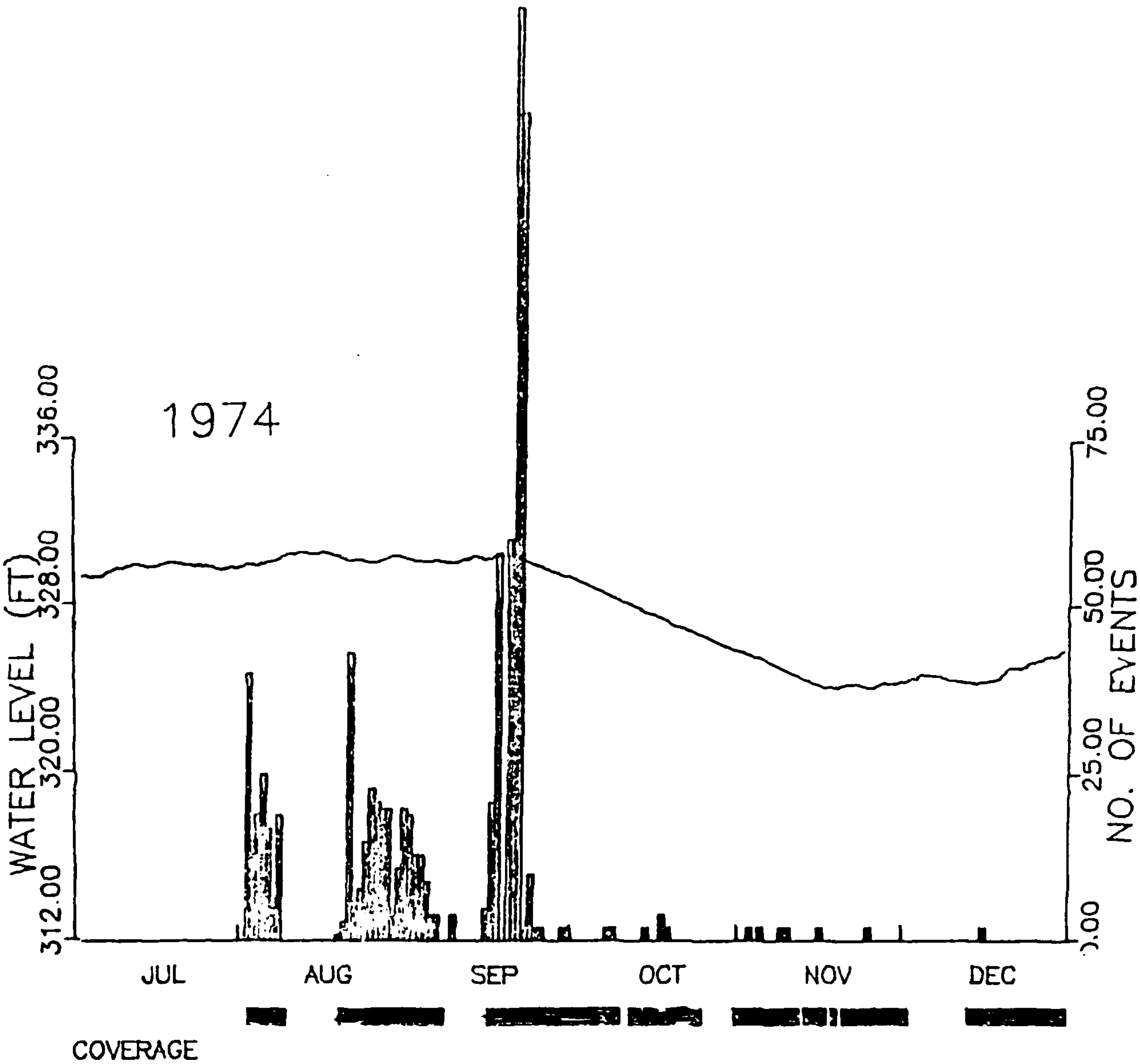

Figure 7. Variations in water level and number of earthquakes for June - December, 1974, for the Clarks Hill Reservoir Area.

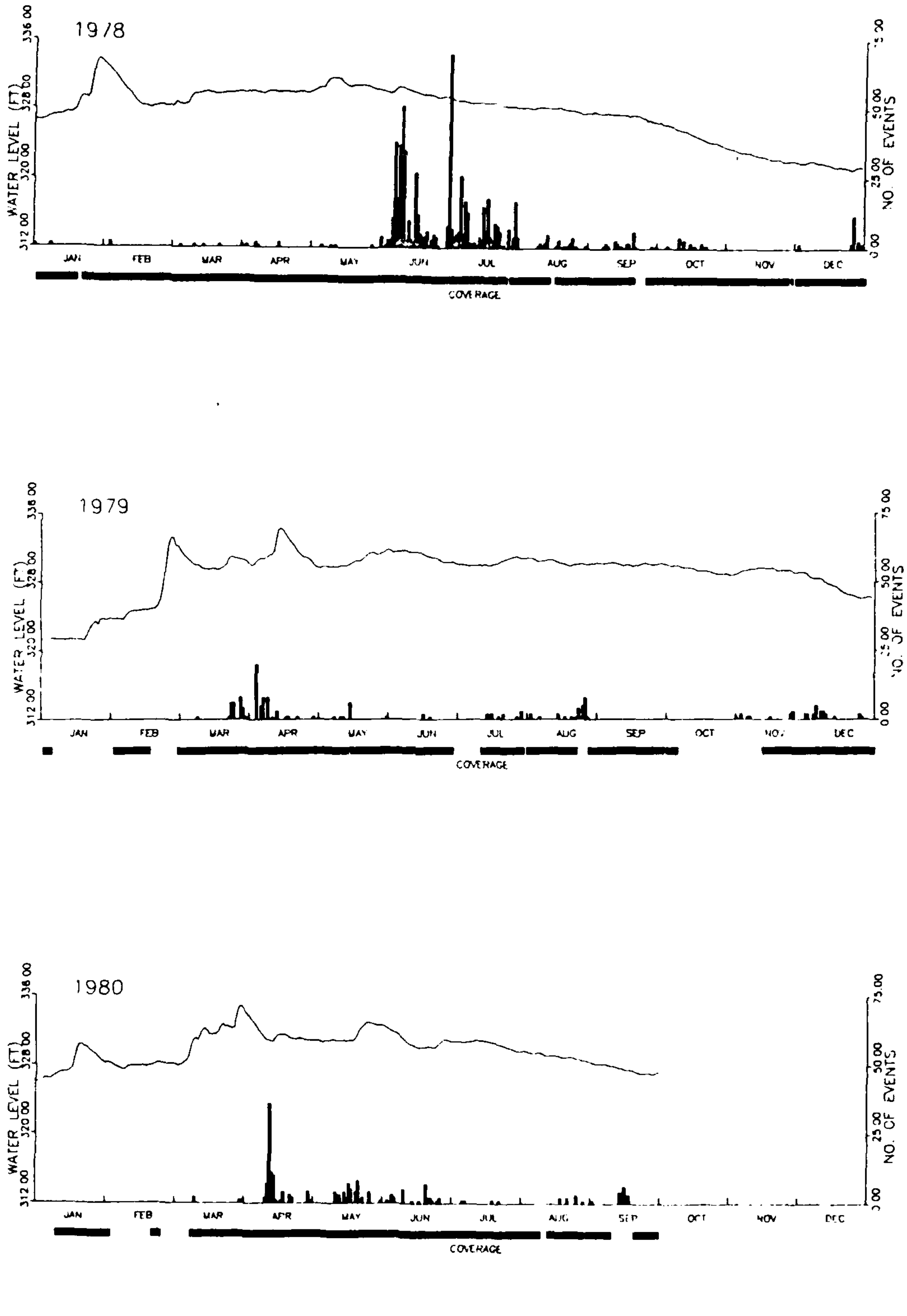

Figure 8. Variations in water level and number of earthquakes for years 1978, 1979, and 1980, for the Clarks Hill Reservoir Area.

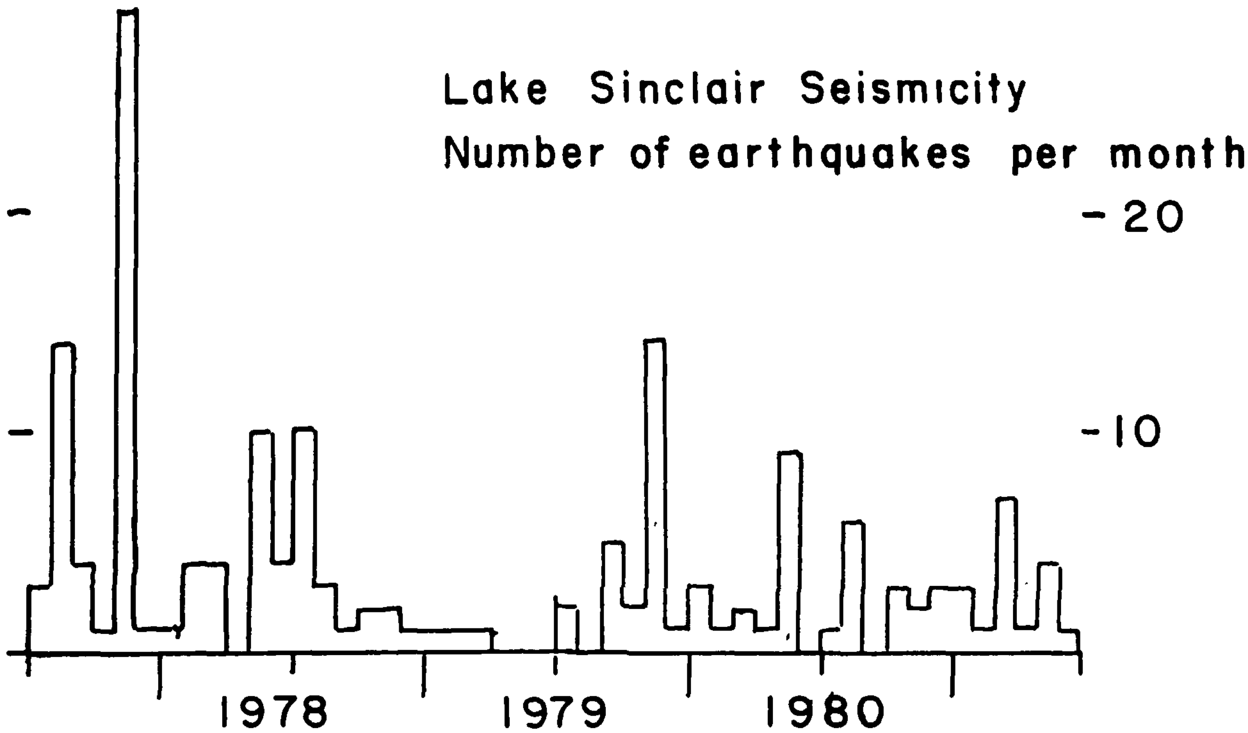

Figure 9. Seismic activity versus time for the Lake Sinclair seismicity. Data are from Appendix II (from Radford, 1988).

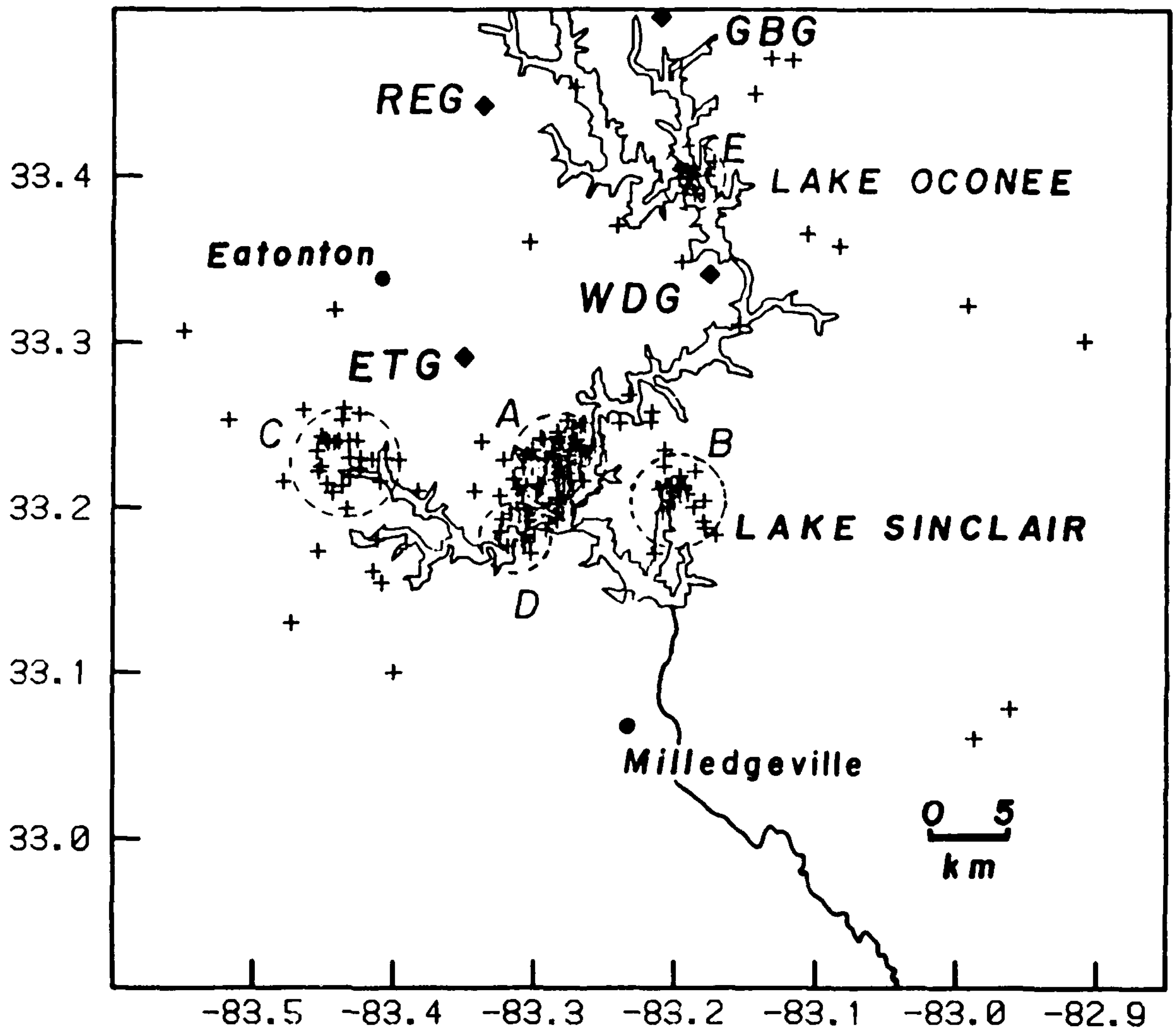

Figure 10. Earthquake epicenters in the Lake Sinclair vicinity for the years 1976 - 1980 (after Radford, 1988). Data are listed in Appendix II.

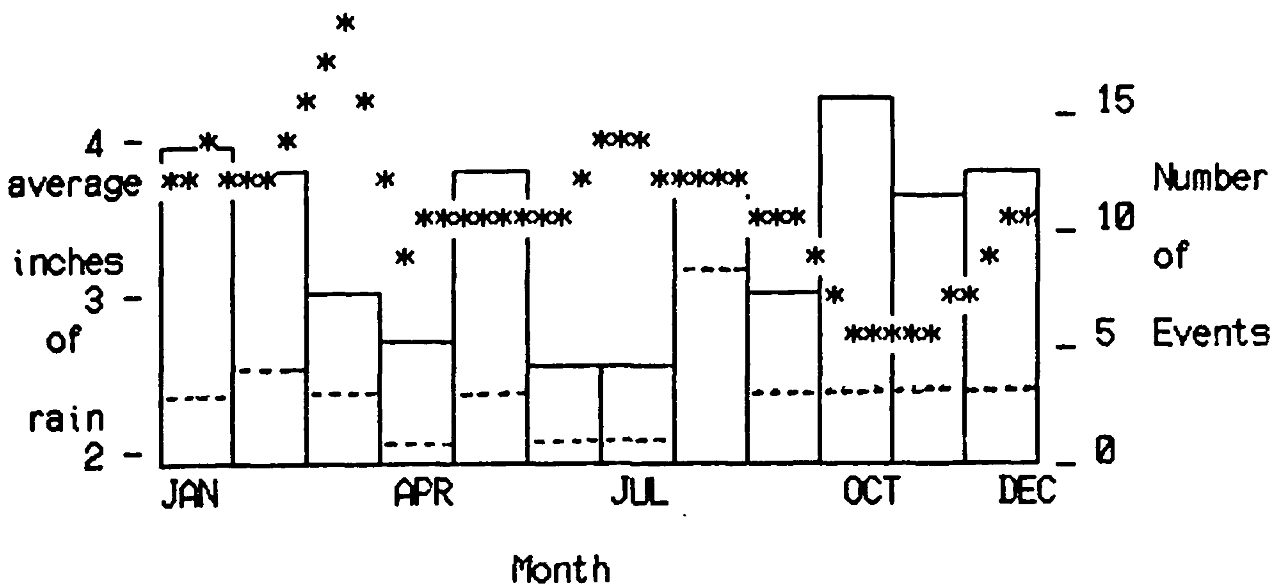

Figure 11. Number of earthquakes per month in the Piedmont. Solid line for magnitude > 3.0 and dashed line for magnitude > 4. The stars are average inches of rain each month from 1955 to present.

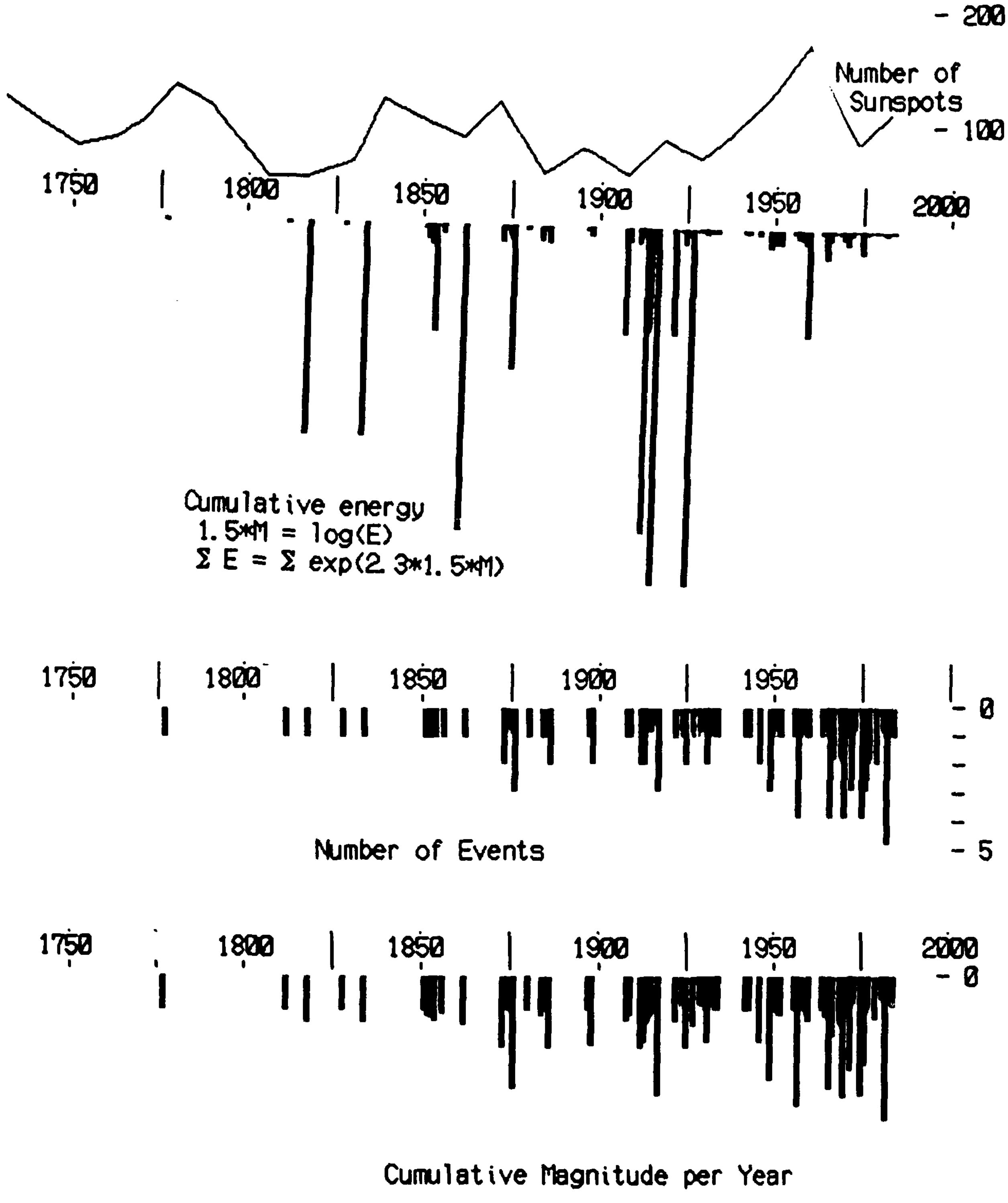

Figure 12. Annual occurrence of earthquakes verses year. Earthquakes rates are compared by energy, total magnitude and number of events per year. Peaks in sun spot cycles are shown for comparison.

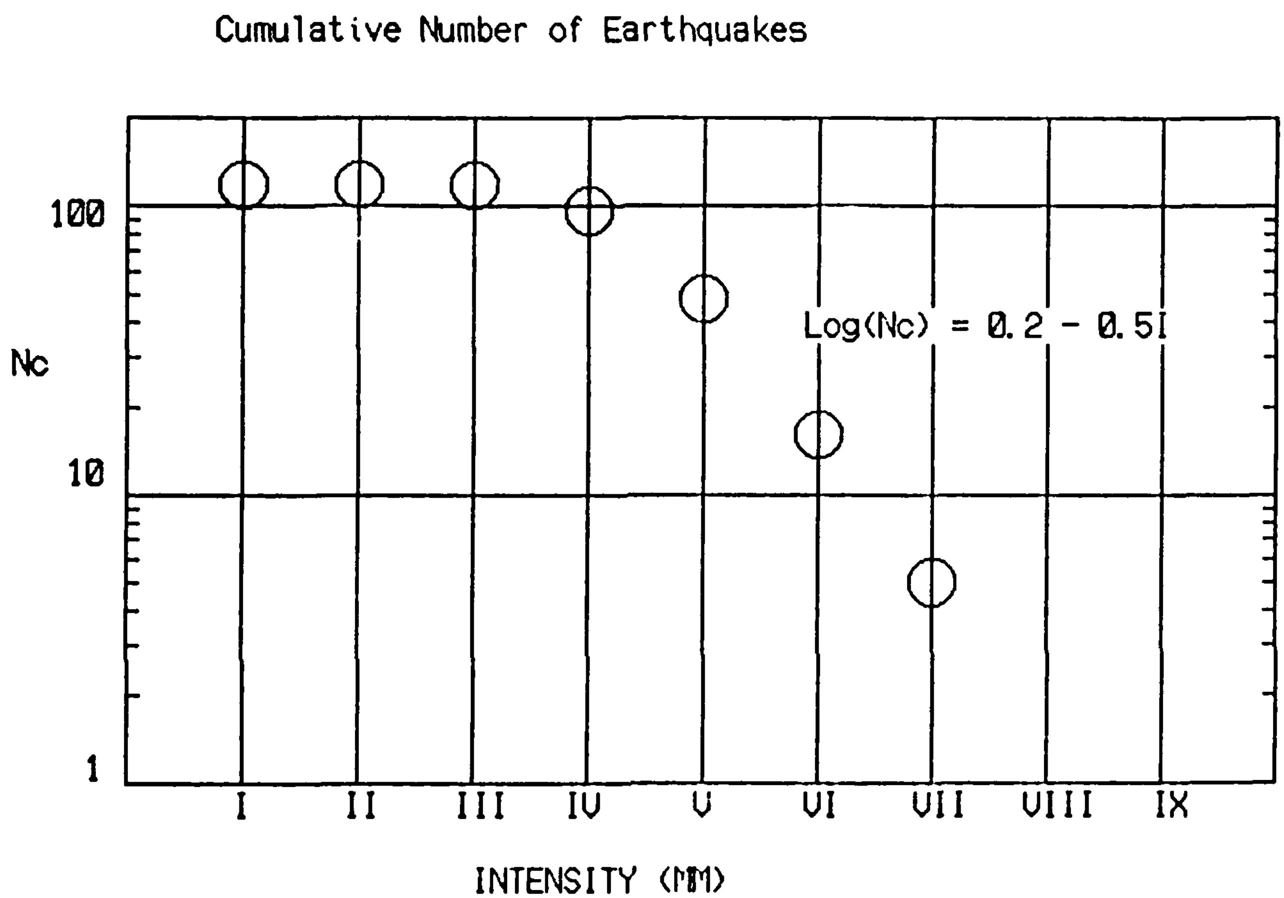

Figure 13. Recursion relation for southern Piedmont. Nc is number of events of intensity I and greater per year per 2500 km^2.

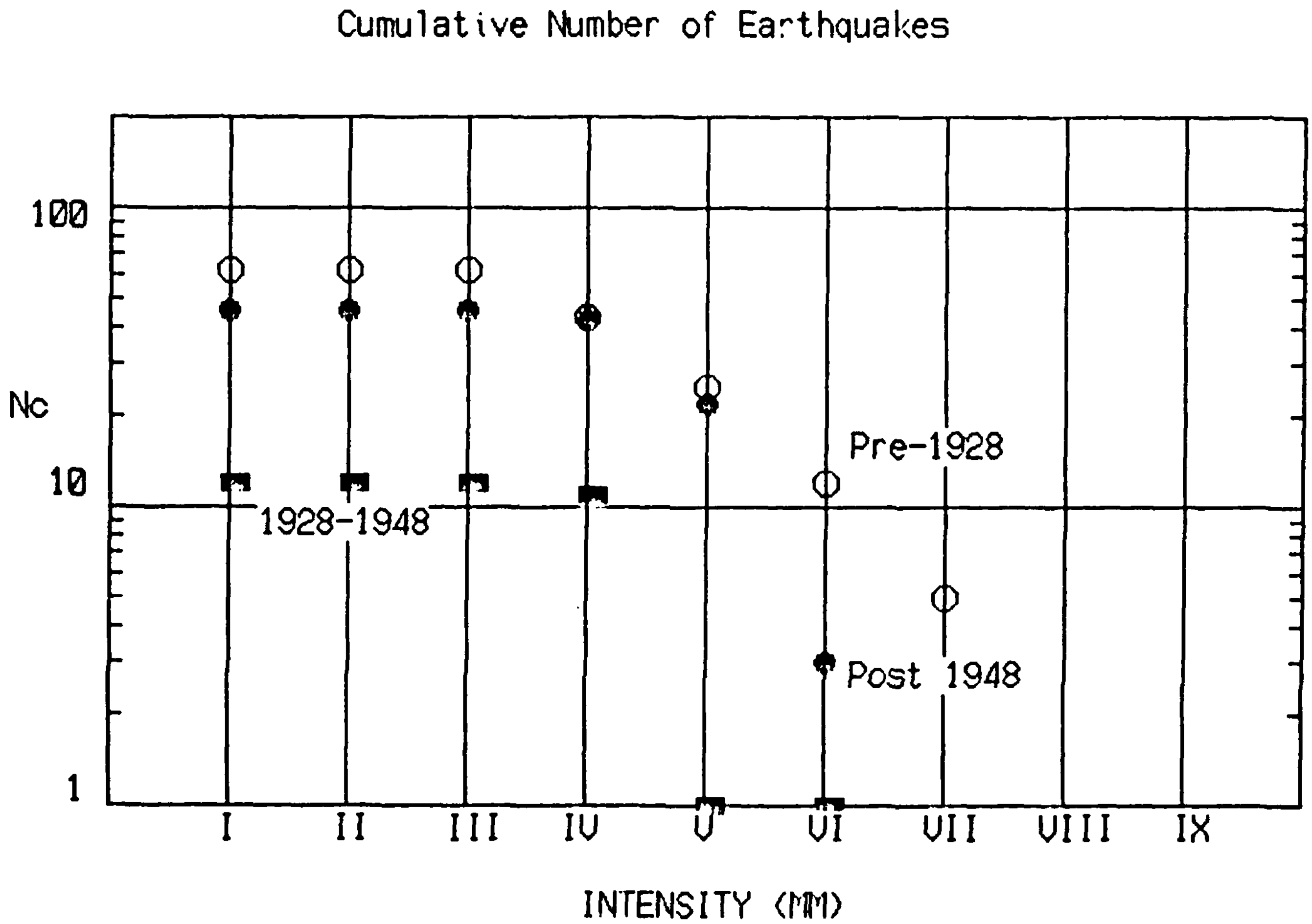

Figure 14. Recursion relations for data preceding 1928, data from 1928 to 1948, and data after 1948. These relations show the possible unevenness in reporting intensities.

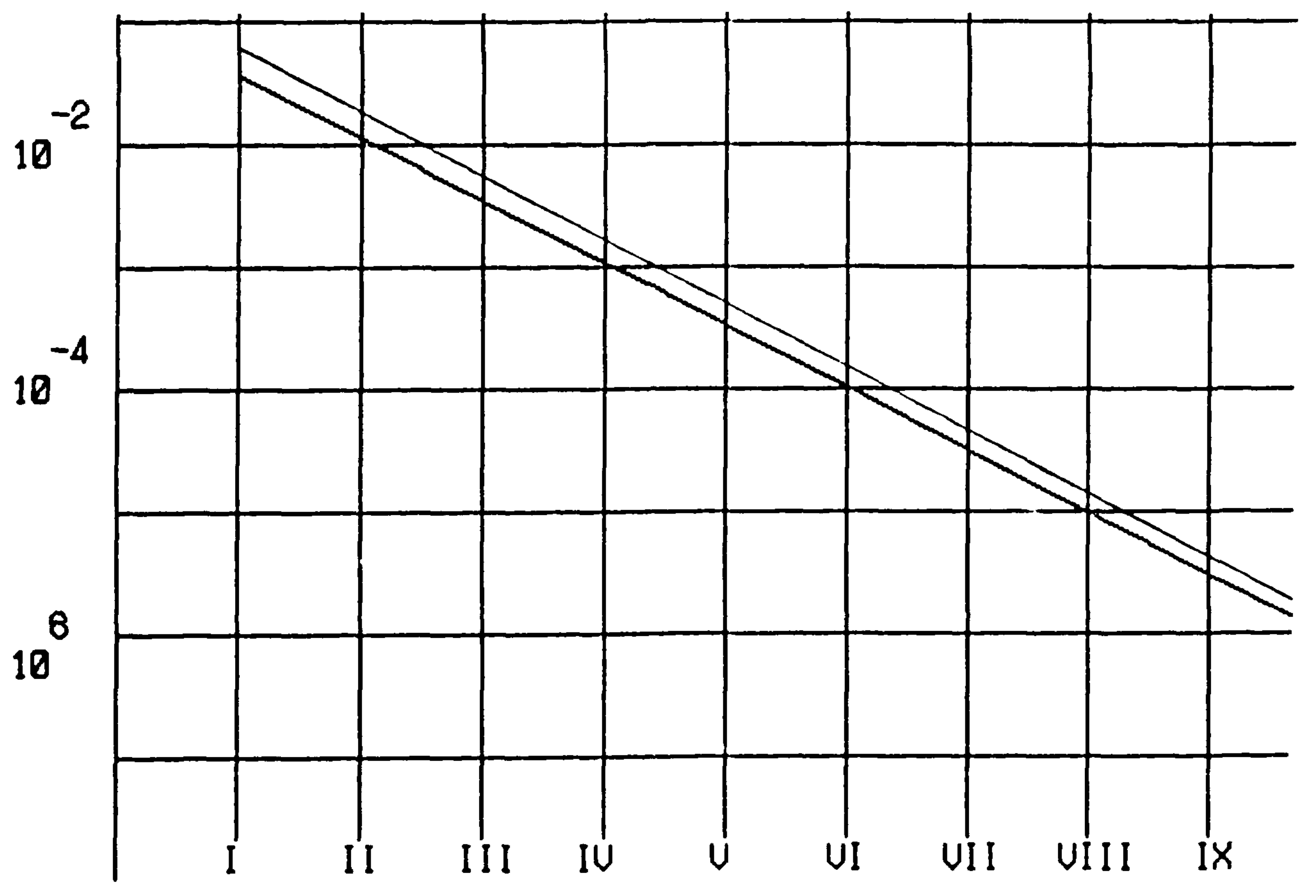

Figure 15. Recurrance rate versus intensity of expected earthquakes at Hartwell Reservoir.

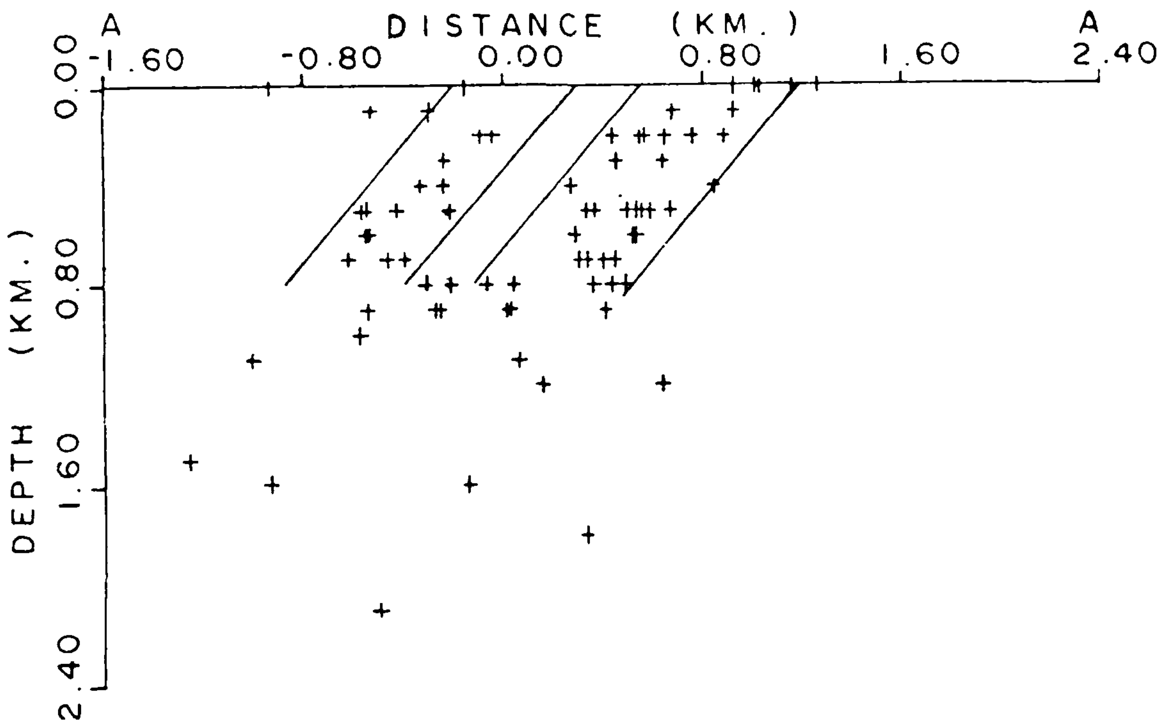

Figure 16. Depths of focus of Clarks Hill Reservoir earthquakes (from Dunbar, 1977)

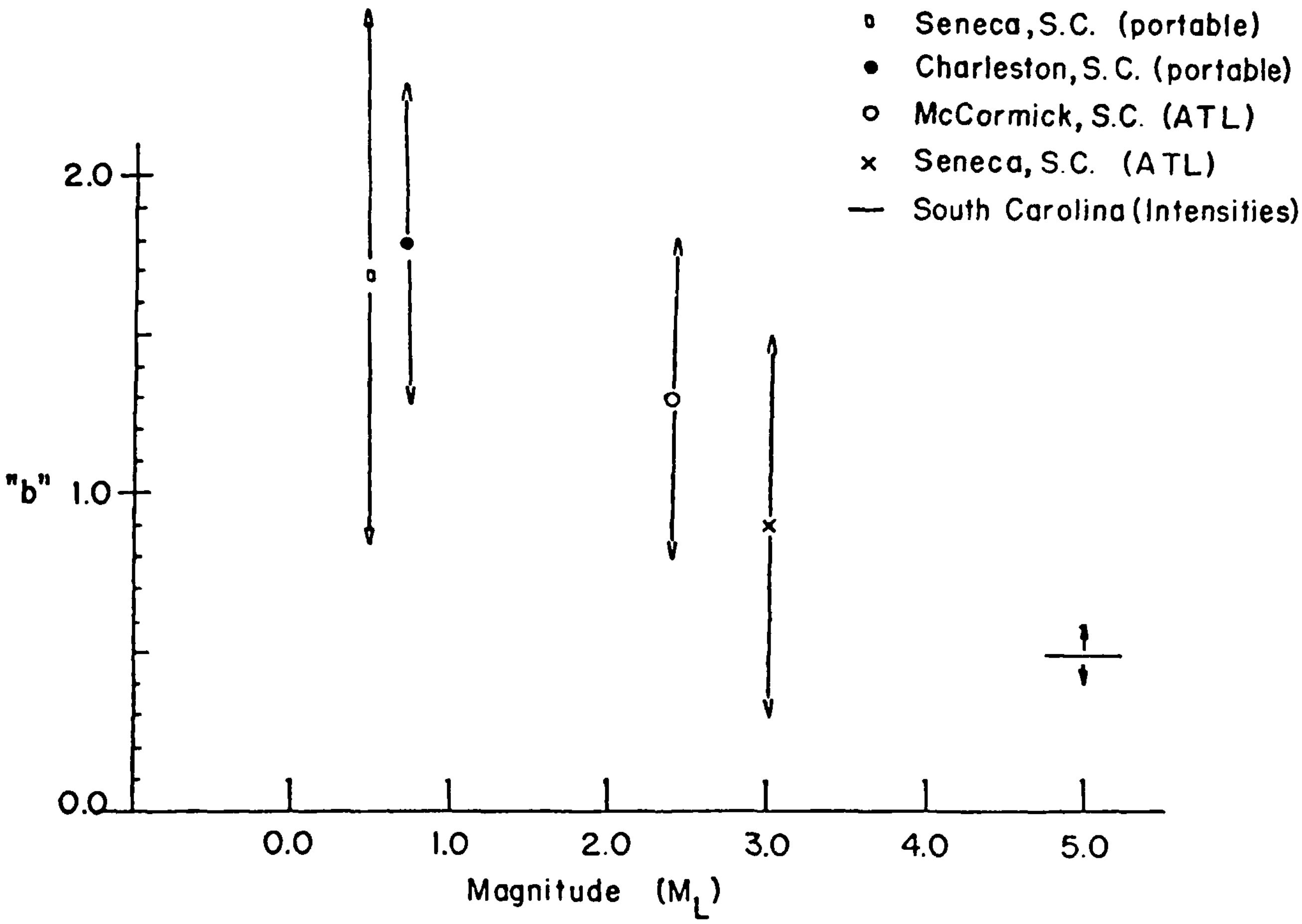

Figure 17. Relation between b value and magnitude observed in the southeastern United States (after Long, 1974).

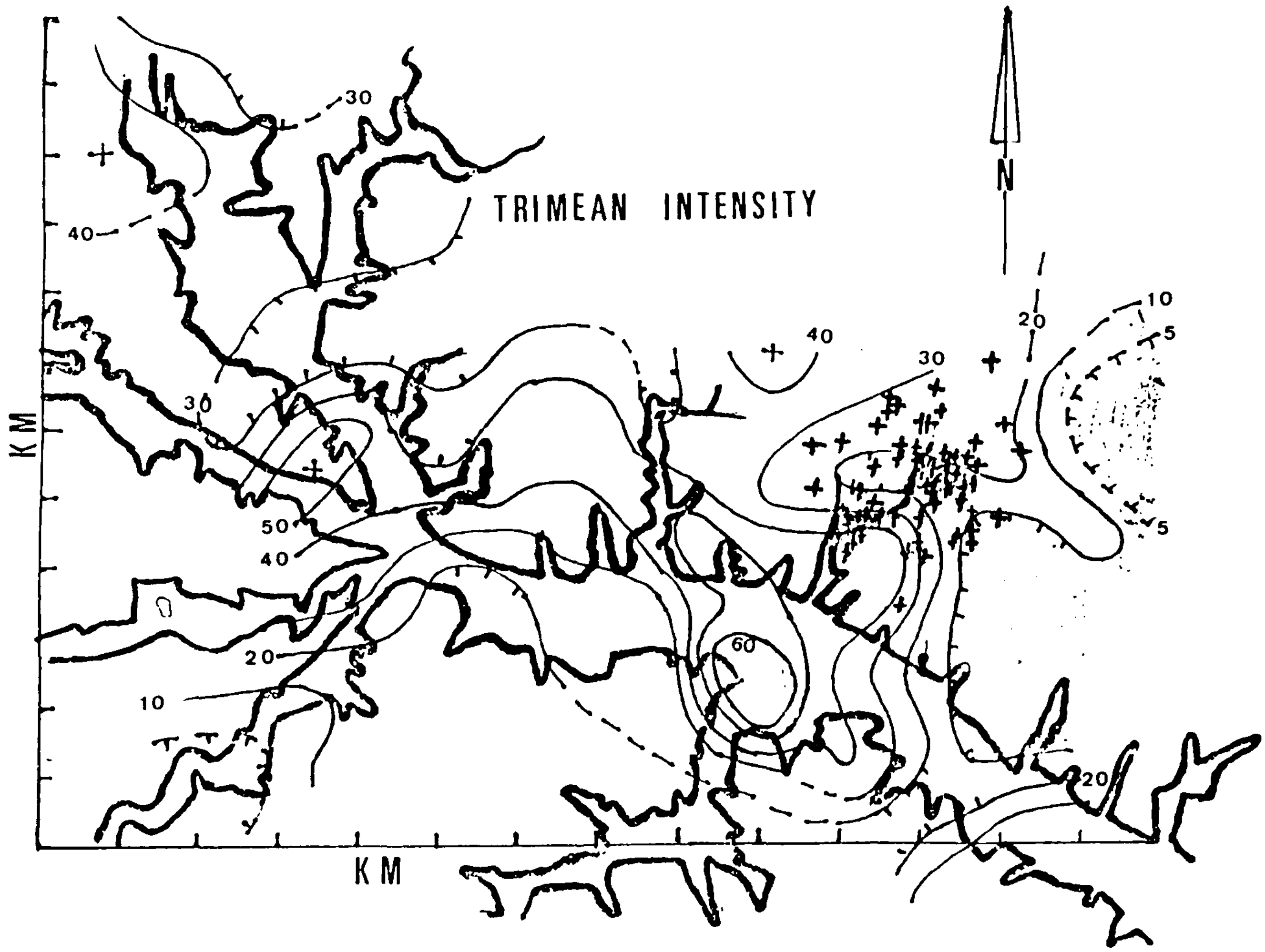

Figure 18. Trimean joint intensity measures for the Clarks Hill Reservoir Area and their relation to reservoir induced earthquakes (from Sorlien, 1987).

Appendix I, List of Piedmont Earthquakes

YEAR	MO	DA	TIME UT			LAT	LONG	INT	MAG	E. MAG
1774	2	21	0	-0	-.0	3610	8020	3.0	0.0	3.0
1776	11	5	0	-0	-.0	3520	8300	4.0	0.0	3.6
1787	11	9	0	-0	-.0	3610	8020	3.0	0.0	3.0
1792	8	11	0	-0	-.0	3610	8020	3.0	0.0	3.0
1808	12	13	9	30	-.0	3580	7860	3.0	0.0	3.0
1811	11	27	8	-0	-.0	3610	8020	4.0	0.0	3.6
1817	1	8	4	-0	-.0	3600	8020	5.0	0.0	5.0
1823	8	23	-0	-0	-.0	3610	8020	3.0	0.0	3.0
1826	11	11	-0	-0	-.0	3610	8020	3.0	0.0	3.0
1827	5	11	-0	-0	-.0	3610	8120	4.0	0.0	3.6
1833	8	27	11	0	-.0	3770	7800	6.0	0.0	5.0
1844	6	-0	-0	-0	-.0	3530	8320	3.0	0.0	3.0
1848	-0	-0	-0	-0	-.0	3560	8200	3.0	0.0	3.0
1850	3	30	15	-0	-.0	3540	7800	3.0	0.0	3.0
1850	10	17	0	0	-.0	3730	7840	4.0	0.0	3.6
1851	8	11	1	55	-.0	3560	8260	5.0	0.0	4.2
1852	11	2	23	35	-.0	3760	7860	6.0	0.0	4.3
1853	5	20	0	0	-.0	3400	8120	6.0	0.0	4.8
1855	2	2	8	0	-.0	3700	7860	5.0	0.0	4.0
1861	8	31	10	22	-.0	3620	8120	6.0	0.0	5.1
1872	6	5	3	0	-.0	3770	7800	4.0	0.0	3.6
1872	6	17	20	0	-.0	3310	8330	5.0	0.0	4.2
1873	10	3	12	45	-.0	3720	7820	4.0	0.0	3.6
1874	2	10	0	0	-.0	3570	8210	5.0	0.0	4.2
1875	7	28	23	5	-.0	3310	8330	3.0	0.0	3.0
1875	11	2	2	55	-.0	3380	8250	6.0	0.0	4.8
1875	12	23	4	45	-.0	3760	7850	7.0	0.0	4.5
1876	1	23	-0	-0	-.0	3560	8200	3.0	0.0	3.0
1877	4	26	22	-0	-.0	3610	7830	3.0	0.0	3.0
1877	10	9	1	-0	-.0	3530	8240	3.0	0.0	3.0
1879	12	13	7	0	-.0	3520	8080	4.0	0.0	3.6
1880	1	28	-0	-0	-.0	3560	8200	3.0	0.0	3.0
1880	2	10	-0	-0	-.0	3560	8200	3.0	0.0	3.0
1883	9	21	11	45	-.0	3610	7980	5.0	0.0	4.2
1884	1	-0	-0	-0	-.0	3560	8200	3.0	0.0	3.0
1884	3	31	10	0	-.0	3330	8300	4.0	0.0	3.6
1885	8	6	13	-0	-.0	3620	8160	5.0	0.0	4.2
1885	10	17	22	20	-.0	3300	8300	4.0	0.0	3.6
1895	10	7	4	30	-.0	3590	7750	3.0	0.0	3.0
1896	2	11	1	45	-.0	3630	7860	4.0	0.0	3.6
1897	11	27	20	56	-.0	3770	7750	4.0	0.0	3.6
1897	12	18	23	45	-.0	3770	7750	5.0	0.0	4.0
1898	2	11	4	30	-.0	3580	7860	3.0	0.0	3.0
1907	2	11	00	30	-.0	3780	7850	3.0	0.0	3.0
1907	2	11	13	22	-.0	3770	7830	6.0	0.0	4.8
1908	8	23	9	30	-.0	3750	7790	5.0	0.0	4.2
1911	2	10	10	22	-.0	3660	7940	4.0	0.0	3.6
1911	4	20	22	-0	-.0	3510	8270	5.0	0.0	4.2
1912	8	8	1	-0	-.0	3770	7840	4.0	0.0	3.6

Appendix I, Continued

YEAR	MO	DA	TIME UT			LAT	LONG	INT	MAG	E. MAG
1912	10	23	1	15	-.0	3260	8300	5.0	3.6	3.6
1912	12	7	19	10	-.0	3470	8170	4.0	0.0	3.6
1913	1	1	18	28	-.0	3470	8170	7.5	0.0	5.1
1914	3	5	20	5	-.0	3360	8370	7.0	0.0	4.8
1916	2	21	22	39	-.0	3550	8250	7.0	0.0	5.4
1916	3	2	5	2	-.0	3450	8270	4.0	0.0	3.6
1916	8	26	19	36	-.0	3600	8100	5.0	0.0	4.2
1921	8	7	6	30	-.0	3780	7840	6.0	0.0	4.8
1923	12	31	20	6	-.0	3480	8250	4.0	0.0	3.6
1924	1	1	1	6	-.0	3480	8250	4.0	0.0	3.6
1924	10	20	8	30	-.0	3500	8260	5.0	0.0	4.2
1926	7	8	9	50	-.0	3590	8210	7.0	0.0	5.4
1928	12	23	2	30	-.0	3530	8030	4.0	0.0	3.6
1929	10	28	2	15	-.0	3430	8240	4.0	0.0	3.6
1929	12	26	2	56	-.0	3810	7850	6.0	0.0	4.8
1930	12	10	0	2	-.0	3430	8240	4.0	0.0	3.6
1930	12	26	3	0	-.0	3450	8030	4.0	0.0	3.6
1931	5	6	12	18	-.0	3430	8240	4.0	0.0	3.6
1932	1	5	4	5	-.0	3760	7840	4.0	0.0	3.6
1933	6	9	11	30	-.0	3330	8330	4.0	0.0	3.6
1941	5	10	11	12	-.0	3560	8260	4.0	0.0	3.6
1942	10	7	2	15	-.0	3760	7840	4.0	0.0	3.6
1945	10	12	19	-0	-.0	3750	7850	4.0	0.0	3.6
1945	10	30	1	29	-.0	3750	7850	4.0	0.0	3.6
1946	5	24	19	40	-.0	3800	7860	3.0	0.0	3.0
1948	1	4	23	-0	-.0	3760	7860	4.0	0.0	3.6
1948	1	5	2	45	-.0	3770	7830	4.0	0.0	3.6
1948	1	5	3	20	-.0	3750	7850	5.0	0.0	4.2
1949	5	8	11	1	-.0	3760	7760	5.0	0.0	4.2
1950	11	26	7	45	-.0	3770	7830	5.0	0.0	4.2
1951	3	9	7	-0	-.0	3760	7760	5.0	0.0	4.2
1955	1	17	12	37	-.0	3730	7840	4.0	0.0	3.6
1956	1	5	8	-0	-.0	3430	8240	4.0	0.0	3.6
1956	1	5	8	30	-.0	3430	8240	4.0	0.0	3.6
1956	5	19	19	-0	-.0	3430	8240	4.0	0.0	3.6
1956	5	27	23	25	-.0	3430	8240	4.0	0.0	3.6
1957	5	13	14	24	51.1	3580	8214	6.0	4.1	4.1
1958	10	20	6	16	-.0	3450	8170	5.0	0.0	4.2
1959	10	27	2	7	28.0	3450	8020	6.0	0.0	4.8
1963	4	11	17	45	-.0	3490	8240	4.0	0.0	3.6
1964	3	13	1	20	16.7	3314	8336	5.0	3.9	4.4
1965	7	22	23	55	32.0	3324	8336	0.0	0.0	2.5
1965	9	9	14	42	20.0	3470	8120	0.0	3.9	4.1
1965	11	8	12	58	1.0	3314	8336	0.0	0.0	2.5
1965	11	8	13	4	11.0	3314	8336	0.0	0.0	3.3
1966	5	31	6	18	59.5	3766	7813	5.0	3.5	3.7
1966	6	27	17	29	-.0	3310	8350	0.0	0.0	2.8
1968	3	18	23	58	-.0	3320	8330	0.0	0.0	2.0
1968	9	22	21	41	18.2	3411	8148	4.0	3.5	3.7

YEAR	MO	DA	TIME UT			LAT	LONG	INT	MAG	E. MAG
1969	5	18	0	-0	-.0	3395	8258	0.0	3.5	3.8
1969	11	4	18	58	23.0	3320	8330	0.0	0.0	2.4
1969	12	11	23	44	37.4	3784	7767	5.0	3.4	3.4
1969	12	13	10	19	29.7	3504	8285	5.0	3.7	3.7
1970	9	10	1	41	5.2	3602	8142	5.0	3.1	4.2
1971	7	13	11	42	26.0	3480	8300	5.0	3.8	3.8
1971	9	12	0	6	27.6	3815	7759	5.0	3.6	3.4
1971	9	12	0	9	22.6	3810	7740	4.0	3.2	3.2
1972	9	5	16	-0	-.0	3760	7770	4.0	3.3	3.4
1974	8	2	8	52	11.1	3391	8253	6.0	4.1	4.3
1974	10	8	9	17	-.0	3320	8330	0.0	0.0	2.2
1974	10	28	11	33	-.0	3379	8192	4.0	3.0	3.0
1974	11	5	3	-0	-.0	3373	8222	3.0	3.7	3.7
1974	11	7	21	31	4.5	3775	7820	4.0	2.4	2.4
1975	4	1	21	9	39.7	3338	8313	0.0	3.9	3.0
1975	10	18	4	31	-.0	3490	8300	4.0	0.0	3.6
1975	11	25	15	17	34.8	3493	8290	4.0	3.2	3.2
1976	8	8	3	28	00.2	3323	8333	0.0	0.0	2.5
1976	8	9	1	56	-.0	3320	8330	0.0	0.0	1.5
1977	2	27	20	5	34.6	3790	7863	5.0	2.4	2.4
1978	2	25	3	53	27.2	3615	7932	4.0	2.2	2.2
1978	10	7	0	24	57.7	3322	8342	0.0	0.0	2.3
1978	10	29	12	22	42.9	3803	7811	0.0	1.1	1.1
1980	4	22	3	14	4.6	3640	8061	4.0	2.8	2.8
1980	5	18	22	33	55.5	3797	7807	0.0	0.0	0.0
1981	1	19	21	54	19.3	3773	7844	0.0	0.6	0.6
1981	1	21	16	29	58.1	3777	7842	0.0	0.3	0.3
1981	2	11	13	44	16.4	3772	7844	4.0	3.4	3.4
1981	2	11	13	50	31.4	3775	7841	4.0	3.2	3.2
1981	2	11	13	51	38.6	3772	7845	3.0	2.9	2.9
1981	2	12	10	41	59.0	3773	7842	0.0	-.6	-.6
1981	3	4	20	44	43.8	3581	7974	4.0	2.8	2.8
1981	4	9	7	10	31.2	3551	8205	5.0	3.0	3.0
1981	4	16	13	49	20.5	3761	7821	0.0	0.1	0.1
1981	5	5	21	21	56.7	3533	8242	5.0	3.5	3.5
1981	7	30	11	59	48.5	3819	7809	3.0	3.1	3.1
1982	1	13	13	16	25.0	3775	7807	0.0	1.5	1.5
1982	4	11	20	01	14.6	3773	7842	0.0	0.9	0.9
1982	10	31	3	7	36.7	3267	8487	5.0	2.9	2.9
1983	3	25	2	47	11.1	3533	8246	5.0	3.2	3.2
1983	7	3	16	29	24.9	3764	7837	0.0	1.2	1.2
1983	8	10	12	29	34.1	3777	7842	0.0	1.8	1.8
1984	4	12	23	46	30.6	3794	7802	0.0	-.8	-.8

APPENDIX II

TABLE A-1: LIST OF RELOCATIONS USING ALLISON'S (1980) VELOCITY MODEL.

DATE	ORIGIN TIME (GMT)			LATITUDE	LONGITUDE	MAGNITUDE
(YR MO DAY)	(HR	MIN	SEC)	(NORTH)	(WEST)	(MD)
770621	9	42	1.12	33.163	83.214	.8
770716	14	56	28.93	33.208	83.301	.0
770723	14	42	54.53	33.192	83.317	-1.3
770723	14	56	38.58	33.189	83.321	-1.3
770724	1	47	38.20	33.188	83.309	.7
770724	11	25	11.06	33.171	83.310	-1.0
770724	15	31	24.43	33.184	83.309	-1.7
770729	0	53	3.19	33.188	83.315	-1.7
770729	1	1	13.95	33.186	83.328	-2.8
770730	12	22	52.50	33.175	83.303	.4
770801	13	15	29.48	33.228	83.282	.8
770801	22	52	44.86	33.234	83.295	-1.5
770804	14	8	25.12	33.234	83.284	-.4
770805	5	9	15.87	33.219	83.298	-1.6
770805	7	19	4.80	33.227	83.315	.9
770805	7	33	35.78	33.240	83.277	-2.1
770813	9	54	25.71	33.211	83.285	-1.7
770813	9	56	57.97	33.194	83.289	-1.5
770818	21	23	2.96	33.185	83.416	-1.7
770819	13	6	4.76	33.320	82.979	-1.1
770819	23	31	57.52	33.211	83.448	-1.1
770820	12	1	11.27	33.215	83.447	-1.2
770820	19	10	32.17	33.196	83.432	-2.1
770821	12	25	14.22	33.164	83.380	-1.7
770825	3	47	26.07	33.199	83.425	-1.9
770831	16	56	40.82	33.218	83.284	-.4
770902	22	49	19.66	33.245	83.237	.0
770903	4	46	.82	33.210	83.287	-1.4
770919	13	9	42.86	33.201	83.346	-.6
770920	3	5	8.17	33.192	83.276	-.6
771030	16	36	10.51	33.238	83.288	.7
771104	14	47	38.48	33.344	83.160	1.7
771107	1	34	19.22	33.200	83.314	-.4
771120	5	8	22.77	33.213	83.281	.8

771120	20	8	10.96	33.226	83.287	1.4
771120	20	20	46.14	33.235	83.289	-.1
771121	8	11	38.42	33.226	83.273	-1.5
771121	8	55	43.91	33.242	83.269	.3
771121	12	1	48.39	33.207	83.283	.5
771122	5	30	2.43	33.231	83.277	-1.9
771122	8	44	1.38	33.218	83.277	-1.5
771123	10	1	41.06	33.192	83.303	1.6
771123	19	43	58.08	33.223	83.271	.8
771123	19	45	46.51	33.226	83.295	.3
771123	22	30	40.39	33.225	83.207	1.6
771124	1	10	38.71	33.221	83.271	-.6
771124	15	7	52.95	33.221	83.270	.3
771124	17	59	11.18	33.221	83.283	-1.1
771124	20	10	26.45	33.226	83.273	-1.5
771125	5	19	11.39	33.220	83.276	-1.5
771125	8	53	50.87	33.231	83.277	-.7
771125	9	3	22.12	33.230	83.280	1.7
771125	9	4	45.40	33.219	83.271	-.3
771125	11	24	44.29	33.226	83.281	-1.7
771126	8	38	45.14	33.232	83.275	1.0
771126	21	50	43.01	33.244	83.280	-1.0
771127	1	43	36.87	33.215	83.275	.5
771127	1	44	48.46	33.240	83.270	-1.9
771127	1	54	36.30	33.222	83.282	-.3
771127	1	56	28.57	33.216	83.295	-1.7
771203	0	8	37.71	33.187	83.293	1.7
780113	13	10	33.69	33.110	83.447	.0
780207	5	33	54.05	33.206	83.287	-.3
780207	12	30	14.42	33.185	83.174	-1.5
780208	19	45	32.92	33.171	83.171	-.5
780216	8	6	9.07	33.199	83.285	-.6
780302	8	8	54.32	33.307	83.149	.6
780310	7	25	49.61	33.458	83.277	1.1
780320	12	26	32.11	33.018	83.076	.5
780321	19	21	26.27	33.453	83.138	-1.1
780501	21	29	30.22	33.224	83.287	1.1
780502	1	9	26.47	33.219	83.304	-.6
780502	1	24	18.16	33.220	83.304	-.5
780502	1	29	23.06	33.223	83.302	-.6
780502	1	45	57.84	33.223	83.306	1.9
780502	2	54	59.60	33.204	83.306	-.6
780502	2	4	2.02	33.221	83.324	-1.1
780502	2	53	19.87	33.220	83.280	-.9
780502	2	54	59.88	33.216	83.302	-.4
780502	3	17	11.07	33.216	83.308	-1.5
780622	12	36	43.03	33.237	83.299	-1.0
780625	5	25	7.11	33.202	83.194	-1.1

780628	22	41	9.30	33.209	83.197	-.6
780630	14	4	14.32	33.212	83.185	.3
780704	10	49	30.42	33.195	83.199	.4
780704	16	44	44.89	33.203	83.191	-2.1
780704	18	24	31.46	33.204	83.210	-1.4
780709	7	3	27.64	33.203	83.200	1.9
780710	3	9	25.35	33.192	83.204	.4
780710	5	40	57.36	33.193	83.179	-1.3
780710	7	52	25.88	33.201	83.189	-.5
780710	9	24	15.74	33.202	83.196	-1.8
780711	8	43	41.63	33.204	83.195	-.1
780711	9	9	14.42	33.203	83.202	-1.8
780711	9	11	33.17	33.191	83.207	-2.3
780711	10	2	21.92	33.208	83.190	-2.6
780715	21	47	41.56	33.196	83.201	-1.2
780822	10	29	40.72	33.201	83.345	-1.7
780826	16	2	40.57	33.202	83.311	-.9
780830	17	20	30.43	33.477	83.111	-.4
780907	0	53	34.62	33.358	83.099	-.9
781002	0	24	57.53	33.207	83.417	2.0
781003	22	42	3.37	33.206	83.283	.5
781113	4	49	1.21	33.184	83.287	-.1
781117	10	1	51.81	33.208	83.287	-2.1
781124	9	39	15.43	33.202	83.307	-1.6
781124	9	51	31.12	33.214	83.296	-2.0
781222	23	20	49.05	33.222	83.295	-1.5
790110	18	9	18.17	33.243	83.217	-2.4
790111	3	38	50.30	33.251	83.214	-1.6
790211	16	29	9.39	33.217	83.205	-.7
790328	11	7	59.38	33.200	83.303	.1
790617	0	15	42.96	33.229	83.440	-2.6
790625	13	18	10.25	33.411	83.166	-2.4
790702	17	59	16.50	33.356	83.299	-.4
790706	14	33	15.48	33.180	83.331	-1.9
790902	8	37	13.92	33.208	83.287	-.2
790902	12	12	2.56	33.222	83.303	.0
790902	22	16	53.58	33.219	83.389	-1.2
790906	16	21	56.78	33.219	83.424	-.7
790917	16	38	2.53	33.206	83.420	-1.3
791015	5	17	54.67	33.401	83.193	.2
791022	14	47	29.67	33.404	83.186	.0
791106	9	49	40.92	33.217	83.368	-1.9
791106	10	20	56.58	33.231	83.421	-1.9
791106	10	21	10.80	33.219	83.415	-2.3
791106	11	8	36.90	33.230	83.435	-1.6
791106	16	45	21.79	33.224	83.450	-.3
791106	23	20	14.55	33.231	83.447	-.1
791107	1	39	20.82	33.229	83.444	-.7
791107	2	21	23.92	33.230	83.453	1.7
791107	3	2	59.91	33.217	83.404	-1.3

791107	4	17	52.11	33.206	83.392	-1.5
791107	5	27	44.09	33.213	83.415	-1.7
791108	5	8	48.57	33.399	83.185	.8
791108	23	55	55.47	33.210	83.331	.5
791109	13	47	46.60	33.228	83.260	-.4
791124	22	28	1.00	33.205	83.300	.0
791212	20	13	32.60	33.400	83.172	.0
800109	6	51	38.23	33.168	83.325	-1.9
800113	8	3	34.22	33.299	82.894	.1
800120	8	25	12.10	33.247	83.465	.1
800205	14	53	3.02	33.207	83.272	.7
800318	7	23	3.31	33.401	83.186	.1
800333	18	16	1.60	33.195	83.292	-1.6
800424	20	13	21.52	33.393	83.180	-.7
800501	8	8	49.20	33.394	83.184	.4
800502	9	56	43.48	33.397	83.187	.3
800502	10	23	59.28	33.406	83.189	.5
805002	10	30	47.65	33.398	83.186	.5
800502	16	14	40.52	33.400	83.184	.7
800502	17	35	2.59	33.398	83.185	.5
800503	10	30	32.59	33.398	83.185	.6
800503	10	54	49.79	33.401	83.185	.2
800505	18	17	5.40	33.400	83.182	-.1
800722	7	42	24.21	33.205	83.205	.4
800804	7	47	55.68	33.220	83.291	2.0
800804	9	9	7.14	33.231	83.341	2.1
800806	3	32	3.80	33.357	83.073	-1.5
800806	3	34	21.37	33.357	83.073	-2.1
800808	12	26	9.55	33.244	83.435	-.1
800808	12	30	38.95	33.244	83.435	.3
800816	18	45	36.26	33.476	83.127	-.6
801011	19	57	44.94	33.062	82.954	1.6
801012	8	38	19.72	33.100	83.400	-2.1
801014	16	49	35.50	33.203	83.206	-1.3
801022	10	8	14.51	33.316	83.448	-1.0
801105	4	40	50.93	33.252	83.434	-1.7
801115	1	29	55.93	33.232	83.289	1.9
801210	10	20	1.92	33.211	83.448	.4
801210	11	12	50.63	33.202	83.440	.1
801216	9	6	7.89	33.371	83.236	.5
810120	5	14	22.21	33.228	83.428	-.4
810130	22	23	9.88	33.297	83.557	1.4
810131	20	35	39.18	33.245	83.522	-.7
810224	12	34	14.57	33.178	83.175	.1
810303	13	10	7.43	33.204	83.477	1.1
810303	15	3	58.64	33.173	83.313	.7
810305	6	20	26.54	33.184	83.310	1.6
810308	4	33	44.97	33.178	83.295	.5
810313	10	43	37.05	33.241	83.267	-.2
810314	11	30	45.62	33.189	83.187	.4

810315	11	55	9.96	33.224	83.269	-.3
810404	9	19	39.16	33.261	83.229	2.4
810525	11	46	40.84	33.166	83.308	.7
810526	20	4	36.28	33.147	83.416	1.7
810526	20	26	12.34	33.153	83.422	1.0
810527	4	25	5.17	33.157	83.435	.4
810615	4	7	34.47	33.248	83.423	-.4

APPENDIX D:

REPORT: CONTRACT NO. DACW 3988M0429

SEISMIC POTENTIAL NEAR LAKE HARTWELL, SOUTH CAROLINA

by

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1. INTRODUCTION

The Hartwell project is located on the Savannah River, 305 miles above the mouth and 89 miles above Augusta, Georgia. The project, on the South Carolina-Georgia border, is located 67 miles upstream from Clark Hill (J. Strom Thurmond) dam and 7 miles downstream from the confluence of the Seneca and Tugaloo Rivers and about 7 miles east of Hartwell, Georgia (Figure 1). This nearly 200 ft high dam, constructed in the late 1950's and early 1960's, lies in the Piedmont geological province.

In the preliminary geological studies that were carried out in the early 1950's prior to the construction of the dam, potential seismic hazards were not a factor and the regional tectonics picture was not well understood. However, in recent years it has been recognized that seismic hazard is an important element that needs to be considered in the siting of critical facilities.

Approximately 25 miles downstream, the Richard B. Russell dam was constructed in the late 1970's and early 1980's. One of the important elements that was considered prior to its construction was the potential of seismically induced ground shaking at the project site. This was because of the realization that the 1886 Charleston, 1811-1812 New Madrid, 1913 Union County, and several smaller earthquakes had been felt at the site. Also, the phenomenon of reservoir induced seismicity (RIS) had been recognized. In recent years RIS has been suggested to occur at Clarks Hill (J. Strom Thurmond) and Richard B. Russell reservoirs downstream and at Lakes Jocassee and Keowee upstream. RIS has also been observed at Monticello Reservoir in central South Carolina and Lake Sinclair in Georgia. The Hartwell project, as well as all of the sites of RIS, are in the Piedmont geological province.

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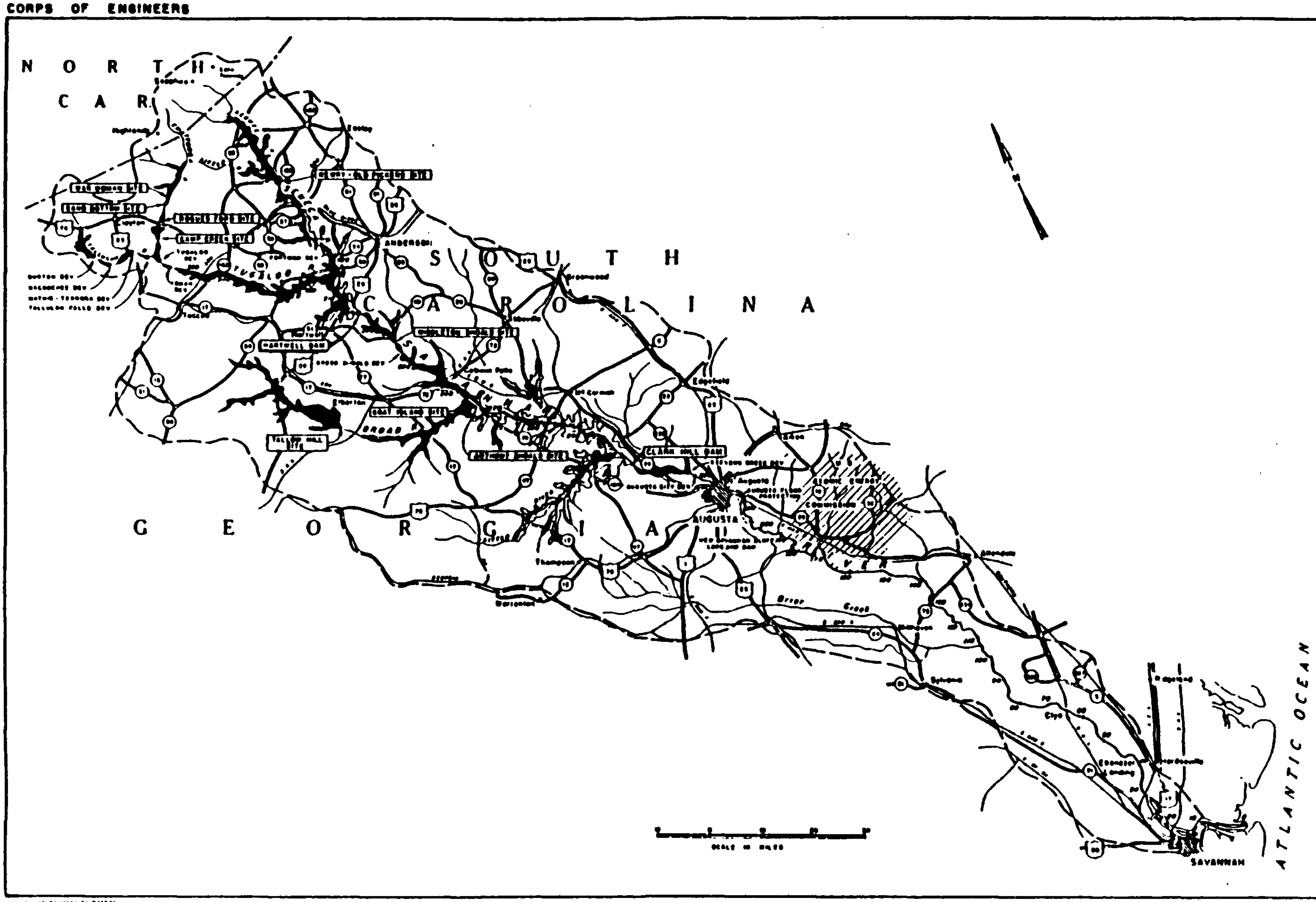


Figure 1. Location of Lake Hartwell and other dams on the Savannah River.

This review, aimed at assessing the seismic potential at the Hartwell project site, consists of the following sections. The current thinking on the tectonics of the region is reviewed in the next section. Section 3 consists of a review of the historical and current seismicity, with a special emphasis on RIS. At several locations worldwide, it has been suggested that the nature of RIS is influenced by the size of the reservoir and the rates of filling and drawdown. The relevent data for Hartwell are reviewed in Section 4. Unfortunately a meaningful analysis of any microearthquake activity possibly related to the filling of Hartwell lake and annual fluctuations therein, could not be made due to the paucity of adequate seismic instrumentationin the area. In any event, available seismicity data were reviewed in a search for evidence of seismicity in the vicinity of the project site. These efforts are described in Section 5. The nature of seismicity in the region appears to be related to the geological belts and potential seismic zones therein. A variety of current data suggest that there is a general pattern of stationarity in the pattern of seismicity. That is, a comparison of historical and current seismic network data suggests that the same (major) sources of seismicity have been active since historical times and occurs in response to a regional stress field. Therefore in assessing the seismic potential (Section 6), these seismic sources, were kept fixed, especially at Charleston. In the Piedmont, extra conservatism in the assessment of seismic hazard was built-in by allowing the Union county earthquake of 1913 to "move" to the immediate vicinity of the Hartwell dam. Considering all potential locations of seismicity, we conclude that the largest ground shaking at the project site can be due to an earthquake of magnitude 5.0 to 5.5 (MMI VII - VIII), the size of the Union county event, occurring in the vicinity of the site (Section 7).

2. REGIONAL TECTONICS

The Appalachian Orogen was constructed along the ancient Precambrian continental margin of eastern North America by a series of compressional events that began in the Ordovician and episodically spanned much of the Paleozoic era (Hatcher, 1987). The southern and central Appalachians may best be described using subdivisions based upon the stratigraphic and lithotectonic characteristics of the rocks. These tectonostratigraphic subdivisions include the Valley and Ridge, the Blue Ridge,and the Piedmont Provinces and are separated from one another by major fault zones (Figure 2).

The Blue Ridge province, bounded to the west by the Blue Ridge Thrust and to the east by the Brevard fault zone, consists primarily of metasediments and metavolcanic rocks with numerous intrusive bodies. The Blue Ridge is subdivided into the western and eastern parts by the Hayesville thrust fault (Hatcher, 1978).

2.1 The Geologic belts of the Piedmont Province

The Piedmont Province, in which the project site is located, extends from Virginia to Alabama and consists of northeast trending belts defined on the basis of tectonic history, metamorphic grade,and structural relationships. The province consists of variably deformed and metamorphosed igneous and sedimentary rocks ranging in age from Middle Proterozoic to Late Permian. The Piedmont Province in South Carolina and Georgia can be further subdivided into 7 distinctive tectonostratigraphic belts: the Chauga belt, Inner Piedmont, Kings Mountain belt, Charlotte belt, Carolina Slate belt, Kiokee belt and the Belair belt. These are described in turn.

2.1.1 The Chauga belt (Hatcher, 1972), located between the Blue Ridge and Inner Piedmont provinces, consists of stratified, low to medium grade,

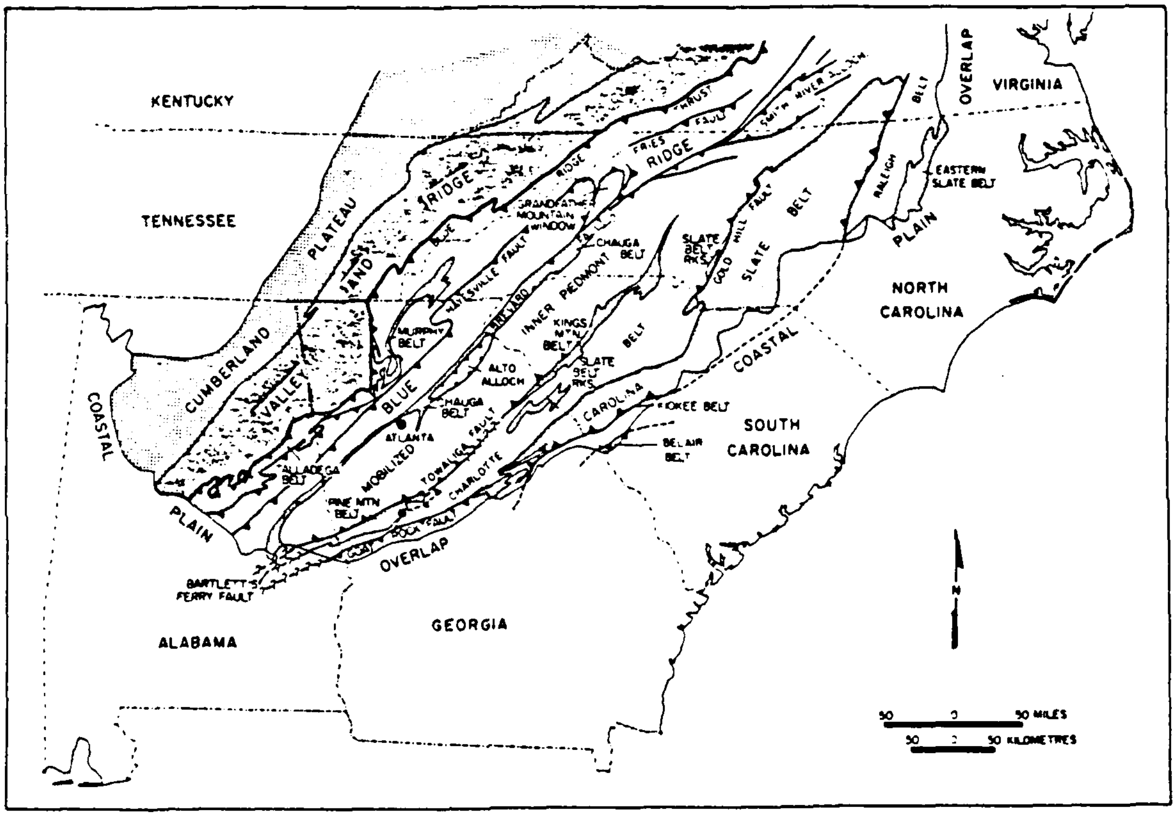


Figure 2. Map of tectonic subdivisions of southern Appalachians (From Hatcher, 1978).

nonmigmatitic metasediments and metamafic rocks of Precambrian to Early Cambrian age. This succession of rocks is overlain by the Henderson Gneiss (Hatcher, 1970) and Alto allochthon (Edleman and others, 1987; Hatcher, 1987). The Alto allochthon consists of migmatitic amphibolite facies rocks which were probably transported northwest from the Inner Piedmont (Hatcher, 1987).

2.1.2. The Inner Piedmont belt contains rocks of the highest metamorphic grade found in the southern Appalachian Piedmont. These include volcanic and sedimentary rocks metamorphosed to the Almandine-Amphibolite facies. These rocks consist of amphibolite, granitic gneiss, paragneiss, metasandstone, and schist. Structures generally verge towards the northwest (Hatcher, 1987). Folds are overturned to the northwest and are recumbent to reclined forming large thrust nappes in the northwestern Inner Piedmont (e.g. Six mile thrust nappe in South Carolina) (Griffin, 1974; Hatcher, 1987) and overlying the Chauga belt.

2.1.3. The Kings Mountain belt, separates the Inner Piedmont from the Charlotte belt. The Kings Mountain belt is separated from the Inner Piedmont by the Kings Mountain shear zone (Horton, 1981). The greenschist facies metamorphic grade of the Kings Mountain belt is generally lower than the adjacent Inner Piedmont and Charlotte belts. However, parts of the Kings Mountain belt are in the Sillimanite zone of the Upper Amphibolite facies (Horton and Butler, 1977; Horton and others, 1981). Major structures within the Kings Mountain belt are gently plunging folds and faults. The rocks within the Kings Mountain belt consist of a volcanic-intrusive complex of felsic metavolcanic and metasedimentary rocks. The Union County earthquake of 1913 (Taber, 1913) was located within this geological belt.

The Kings Mountain belt is associated with a pronounced anomaly in the potential field data. In the aeromagnetic map of Zietz and others (1982), the low frequency and low amplitude magnetic field anomalies of the Inner Piedmont change to high frequency and high amplitude anomalies at the Kings Mountain belt. In the gravity data, the location of the Kings Mountain belt is spatially associated with the change in the gravity gradient as it decreases to the northwest and is relatively flat to the east.

2.1.4. The Charlotte belt is a belt of numerous intrusions and moderate to high grade metamorphism. Much of the belt has been metamorphosed to amphibolite grade. The oldest rocks are amphibolite, biotite gneiss, hornblende gneiss, and schist which are thought to be derived from volcanic, volcaniclastic, or sedimentary protoliths.

The rocks of the Charlotte belt were intruded by several premetamorphic and postmetamorphic plutons of diverse compositions and ages ranging from 550 to 265 Ma (Fullagar, 1971; Dallmeyer and others, 1986).

2.1.5. The Carolina Slate belt, which extends from Virginia to Georgia, is characterized by felsic to mafic metavolcanic rocks and thick sequences of metasedimentary rocks derived from volcanic source terranes of Cambrian age (Secor and others, 1983). These rocks have been subjected to low to medium grade regional metamorphism during the period from 500 to 300 Ma and subsequently intruded by granitic and gabbroic plutons about 300 Ma (Carpenter, 1982). Based on detailed structural analysis, the Charlotte belt has been interpreted as a tectonic infrastructure of the Carolina Slate belt (Secor and others, 1986).

The gravity and aeromagnetic anomalies associated with both the Charlotte and Carolina Slate belts consists of broad highs and lows.

2.1.6. The Kiokee belt is located between the Carolina Slate belt and the Atlantic Coastal Plain in central Georgia and South Carolina. The interior of the Kiokee belt is a migmatitic complex of biotite amphibole paragneiss, leucocratic paragneiss, sillimanite schist, amphibolite, ultramafic schist, serpentinite, feldspathic metaquartzites, and contains granitic intrusions of Late Paleozoic age (Secor, 1987).

2.1.7. The Belair belt, located near Augusta, Georgia, is a small belt of greenschist grade metasediment and metavolcanic rocks and is separated from the Kiokee belt by the Augusta Fault zone (Hatcher and others, 1977; Maher, 1978, 1987; Prowell and O'Conner, 1978). As determined from geophysical and well data, the Belair belt extends beneath the Atlantic Coastal Plain (Daniels, 1974). The age of the main metamorphism and deformational event is uncertain but appears to be analogous to that in the Carolina Slate belt which is 530 to 580 Ma to 385 to 415 Ma (Dallmeyer and others, 1986; Secor and others, 1986).

2.2. Fault Zones in the Piedmont Province

There are essentially four major fault zones within the Piedmont Province of southeast North America (The Brevard zone, Kings Mountain shear zone, Modoc zone and the Augusta fault zone). All of these fault zones exhibit a complex history of polyphase deformation and metamorphism during the Paleozoic orogenic events. Mesozoic diabase dikes cut across the fault zones and are not offset by the faults. This implies that there has been no movement since the emplacement of the dikes. The Brevard zone and the Kings Mountain shear zone are the two major fault zones located near Lake Hartwell.

2.2.1. The Brevard zone, located north of Lake Hartwell, extends northeast from North Carolina and into Georgia and Alabama. The Brevard zone separates the Blue Ridge Province in the northwest from the Chauga belt and Inner Piedmont in the southeast. The zone is principally located within the northwest flank of the Chauga belt.

Movement on the Brevard zone has been interpreted as having a polyphase history of movement and deformation (Hatcher, 1978; Edleman and others, 1987). Edleman and others (1987) interpret the Brevard zone as an Alleghanian dextral shear zone reactivated by a later Alleghanian thrust fault and thrust splays, the orientation of the zone being controlled by reworked pre-Alleghanian nappes.

Seismic reflection studies (Clark and others, 1978; Cook and others, 1979) indicate that the Brevard zone and Inner Piedmont are allochthonous and that the zone is a southeast dipping thrust fault that merges with a subhorizontal sole thrust at depths of 15 km.

2.2.2. The Kings Mountain shear zone, located approximately 30 miles south of Lake Hartwell, extends from North Carolina into Georgia, where it is called the Lowndesville belt (Griffin, 1970, 1981; Hatcher, 1972). The shear zone truncates rock units on both sides and appears to be a metamorphic as well as lithologic and structural discontinuity (Horton, 1981; Horton and others, 1987). The shear zone is characterized by phyllonitic and mylonitic rocks and is steeply dipping to the southeast (Horton, 1981). The latest movement on the shear zone has been interpreted as dextral and occurring in the late Alleghanian orogeny (Horton and others, 1987).

In Georgia, the Kings Mountain shear zone is correlatable with the Middleton-Lowndesville cataclastic zone (Griffin, 1970; Hatcher, 1972; Rozen, 1981) where it is characterized by a narrow zone of intense cataclasis and is typified by quartz-sericite phyllonite and mylonitic rocks (Griffin, 1981).

2.2.3 The Modoc zone, located in South Carolina and Georgia, essentially separates the Carolina Slate belt to the northwest from the Kiokee belt. Recent interpretations of detailed structural investigations of the zone suggest that it is characterized as a brittle and ductile zone with a deformation and metamorphic polyphase history produced primarily during the middle-late Paleozoic Alleghanian orogeny (Secor and others, 1986; Secor, 1987). The northwest, steeply dipping zone is interpreted as originally dipping gently to the northwest with major components of normal slip and dextral strike slip.

The Irmo shear zone, near Columbia, South Carolina, is a zone of heterogeneous ductile deformation which is localized near and overprints the Modoc zone (Secor and others, 1986; Dennis and others, 1987).

2.2.4. The Augusta fault, located near Augusta, Georgia, dips approximately 45° to the southeast and has been interpreted as a dextral strike slip fault (Bobyarchick, 1981) and as a thrust fault (Maher, 1979). Maher (1978, 1987) suggests that the fault is a normal fault with dextral oblique slip movement and was active around during the Alleghanian orogeny. The tectonic and metamorphic history of the Augusta fault are very similar to that of the Modoc zone and may therefore have a common origin (Maher, 1987).

Near Augusta, Georgia, the southeast edge of the Kiokee belt and the Augusta fault are offset by the north-northeast trending Belair fault. Bramlett and others (1982) suggest that the Belair fault represents an Alleghanian age tear fault which linked two thrust segments of the Augusta fault zone. The last stages of movement on the Belair fault were interpreted as Cenozoic high angle reverse faults where it offsets the late Cretaceous and early Eocene unconformities within the Atlantic Coastal Plain sediments by approximately 30 and 12 meters, repectively (Prowell and O'Conner, 1978).

2.2.5. The Eastern Piedmont Fault System

Hatcher and others (1977) proposed the existence of an extensive series of faults and splays, extending from Alabama to Virginia, and called it the Eastern Piedmont Fault System. In South Carolina and Georgia, this fault system includes the Modoc zone, the Irmo shear zone and the Augusta fault.

Aeromagnetic, gravity, and seismicity data indicate that this fault zone continues beneath the Coastal Plain sediments.

2.3. Regional Stress Field

The observed seismicity is the response of local structures to the stress field. Seismicity can result due to the action of anomalous local stress concentrations or due to the action of the tectonic stress field on pre-existing zones of weakness or both. Therefore, it is of great importance to determine the state of the ambient in-situ stress field.

The orientation of the maximum horizontal principal stress (S_{Hmax}) can be determined from a variety of data. These include earthquake focal mechanisms, in-situ stress measurements by hydrofracture and overcoring techniques, and from geologic evidence of recent deformation (see e.g. McGarr and Gay, 1978; Zoback and Zoback, 1980). In recent years analysis of stress-induced wellbore elongation (or breakouts) has been increasingly used to determine the direction of S_{Hmax} (see e.g. Bell and Gough, 1979). The results of overcoring measurements on surface outcrops are not considered reliable due to a variety of local stress heterogeneties such that these results do not represent the tectonic stress field.

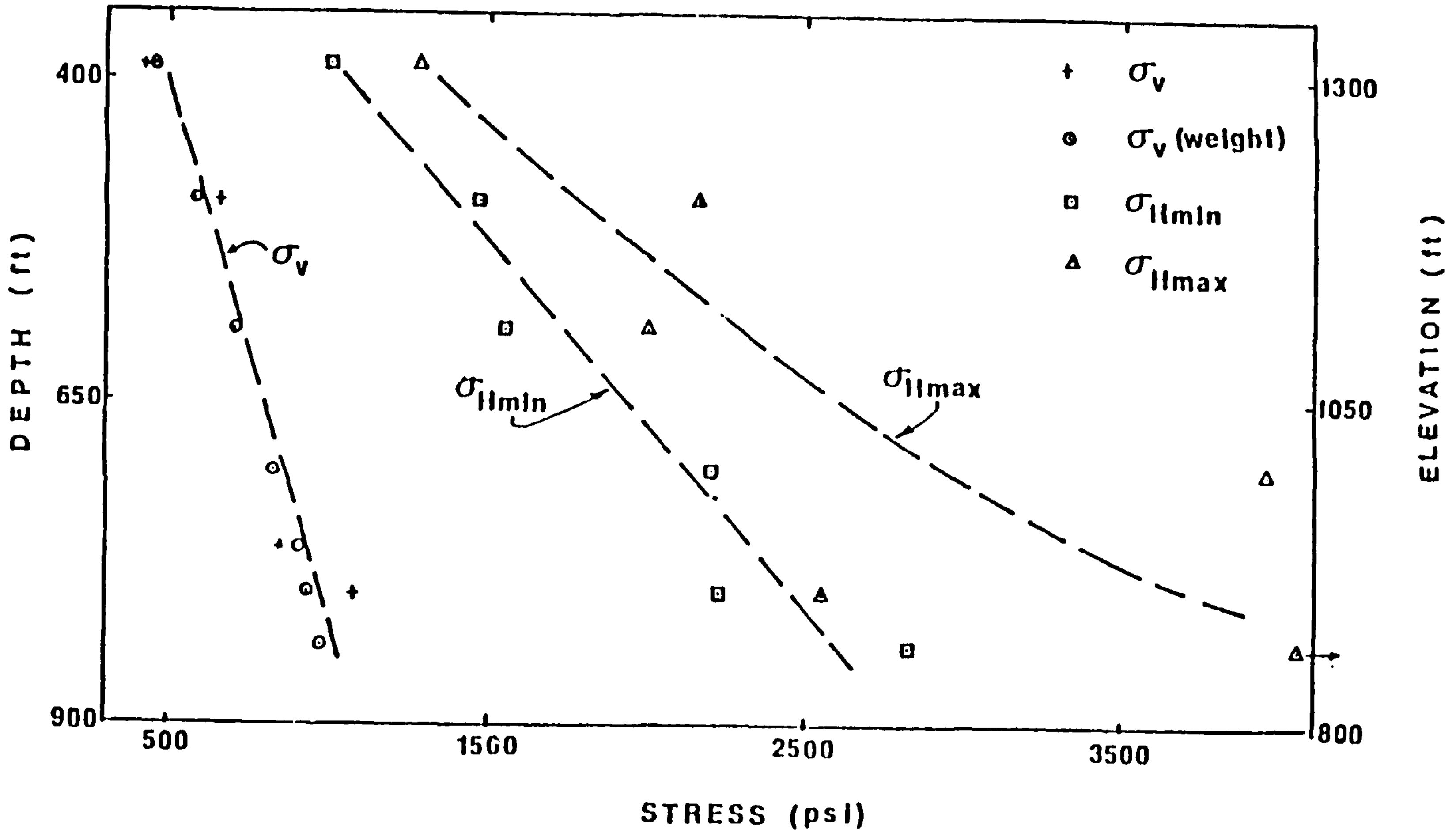
In the southeastern United States, several studies have described the direction of S_{Hmax}. Some of the initial results were conflicting due to inclusion of few, poor or questionable data (e.g. Sbar and Sykes, 1973; Zoback and others, 1978; Zoback and Zoback, 1980; Talwani, 1985). In the latest compilation by Zoback and others (1987), the questionable data have been weeded out and additional data incorporated (especially from wellbore breakouts). The results described a clearer picture. In the southeastern United States, these authors found that the geological, seismological and in-situ stress data all suggest a NE to ENE compressive stress regime (characterized by strike-slip or reverse faulting). This direction is consistent with plate tectonic ridge push forces for the North American plate (Zoback and others, 1987). One implication of this observation, that the observed stress regime in the region can be explained by plate tectonic sources, is that the probable cause of most of the observed seismicity at the active locations is due to the action of tectonic stress on zones of locally weak structures, rather than due to inherently local stress concentrations.

2.3.1. Stress Field in the Project Area

The stress field in the project area is available from two sources - in-situ stress measurements near the proposed site of the Bad Creek project 50 miles upstream of the Hartwell dam and from focal mechanisms at Lakes Jocassee and Keowee. Stress data at other locations in the Piedmont are available primarily from focal mechanisms and one set of in-situ measurements at Monticello Reservoir. Other stress data in the southeastern U.S., at Charleston, eastern Tennessee, Virginia, and Kentucky are available mainly from focal mechanisms. These are all described in the following sections.

2.3.1.1. In-situ stress measurements at the Bad Creek site

The Bad Creek site is unique in that in-situ stress observations have been made here before impoundment. These consist of hydrofracture measurements in a borehole by Haimson (1975) and overcoring in a pilot tunnel by Schaeffer and others (1979). The well head was located at an elevation of about 400 meters on a hillside whereas the pilot tunnel was drilled about 180 meters below the surface. The results of these measurements are shown in Figure 3 and given in Table 1. These data indicate very large stresses in the top 300 m. In Haimson's analyses, the vertical stress was computed assuming it to be due to the load with a density of 2.67 g/cm^3. However in the overcoring results of Schaeffer and others (1979), the vertical stress was



From Haimson (1975)

Figure 3. Plot of the comparison of in situ stress data with the calculated stress variation with depth at Bad Creek (modified from Haimson, 1975).

Table 1

Average Principal Stress Values

Hydrofracture Data (Haimson, 1975)

Elevation a.s.l.(m)	Depth Below Surface (m)	Hmin (Mpa	bars)	Direction	Hmax (MPa	bars)	Direction
398	119	6.9	69	N66•W	8.8	88	N24•E
367	151	10.2	102	N84•W	14.8	148	N06•E
338	181	10.6	106	N12•W	13.8	138	N78•E
308	215	15.2	152	N22•W	27.2	272	N68•E
283	243	≥15.5	≥155	N48•W	≥17.6	≥176	N42•E
272	255	19.5	195	N34•W	34.0	340	N56•E
Av. at 290	236	15.9 ± 2.5 MPa 159 ± 25 bars		N20•W	22.8 ± 5.5 MPa 228 ± 55 bars		N60•E
(Site of planned powerhouse)							

Overcoring Data (Schaeffer *et al.*, 1979)

338	181	18.4	184	N32•W	29.3	293	N57•E

σ_v = 10.2 MPa (102 bars)

measured to be about 10.2 MPa (102 bars) at a depth of approximately 180 m. This is almost twice what one would expect due to the load ($V_v = \rho gh$ = 4.9 MPa (49 bars)). The results of the two studies are similar if adjustment is made in the hydrofracture result for the high vertical stress (Schaeffer and others, 1979).

Such observations are rare but not unheard of. For example, Fyfe and others (1978, p. 226) note that "...in the Snowy Mountain region of Australia the vertical pressure at a depth of 300 m was found to be over 120 bars, rather than 80-90 bars one would forecast using $V_v = \rho gh$."

Thus in addition to the very high horizontal stress gradients encountered at shallow depths, there are large vertical stresses also. This suggests that the rocks at shallow depths (< 500 m?) are highly stressed.

2.3.1.2. Focal mechanisms at nearby reservoirs

Focal mechanism data were available for seismicity at Lakes Jocassee, Keowee, and Clarks Hill (J. Strom Thurmond) reservoir (Talwani and Rastogi, 1981; Rastogi and Talwani, 1984; Talwani and others, 1979; Talwani, 1976). Most of the solutions were for composite focal mechanisms. Those at Lakes Jocassee were from large events and their aftershocks. Two sets of solutions were available for Lake Keowee earthquakes: one for the January-February swarm (Talwani and others, 1979) and single event solutions for two felt events in February and June, 1986 (Acree and others, 1988). All these solutions yield P-axes in the NE direction in general agreement with the directions obtained from in-situ measurements at the Bad Creek site located about 10 miles NW of Jocassee dam.

2.3.2. Stress data in the Piedmont

The orientation of S_{Hmax} in the Piedmont was inferred from focal mechanisms in the Monticello Reservoir area (Talwani and Acree, 1987), for a series of earthquakes near Newberry, S.C. (Rawlins, 1986) and in NE Georgia. Figure 4 shows the average of 22 focal mecanisms for well recorded events in 1978 and 1979 at Monticello Reservoir. The P-axes lie in the NE quadrant. A NE orientation of S_{Hmax} was also obtained from the well break out data in two 1 km deep holes at Monticello Reservoir. Hydrofracture in-situ stress measurements in Monticello wells 1 and 2 are shown in Figure 5 and given in Table 2. The data suggest high compressional stresses that favor thrust faulting at shallow depths. The P-axes for events in Newberry county and NE Georgia all lie in the NE direction.

2.3.3. Stress field in the region

Talwani (1985) reviewed the available stress data in the region. Besides those discussed above, the data consisted of focal mechanisms for earthquakes in the Charleston, S.C., Giles County, Va., eastern Tennessee, and Kentucky regions. All of the data suggest that the orientation of S_{Hmax} in the region is oriented in the ENE-WSW to NE-SW directions.

2.3.4. Conclusions

Detailed data at reservoirs in the Piedmont and for other earthquakes in the region all suggest that the orientation of S_{Hmax} in the southeastern U.S. is oriented in a NE-SW to ENE-WSW direction. Where the magnitude of the stresses are available (e.g. Bad Creek and Monticello Reservoir), the shallow stresses are very high and the data support the regional picture, i.e. the project lies in a compressional stress regime and that any seismicity will be a result of the interaction of this regional stress field on local zones of weakness.

2.4. Conclusions

The Hartwell project site lies in the Piedmont physiographic province. A review of the geology and tectonics of the region shows that it consists of

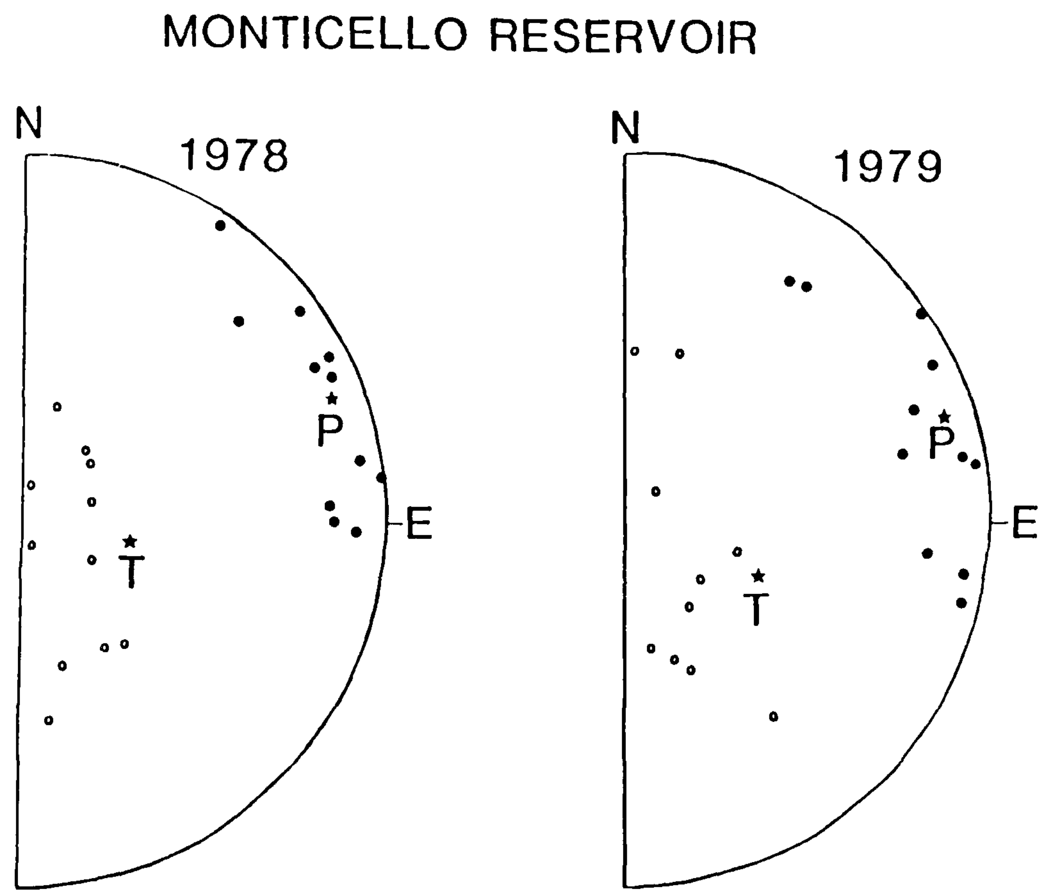


Figure 4. Plot of P & T axes obtained from composite solutions for seismicity at Monticello Reservoir. Average P and T axes are designated by stars (From Talwani & Acree, 1987).

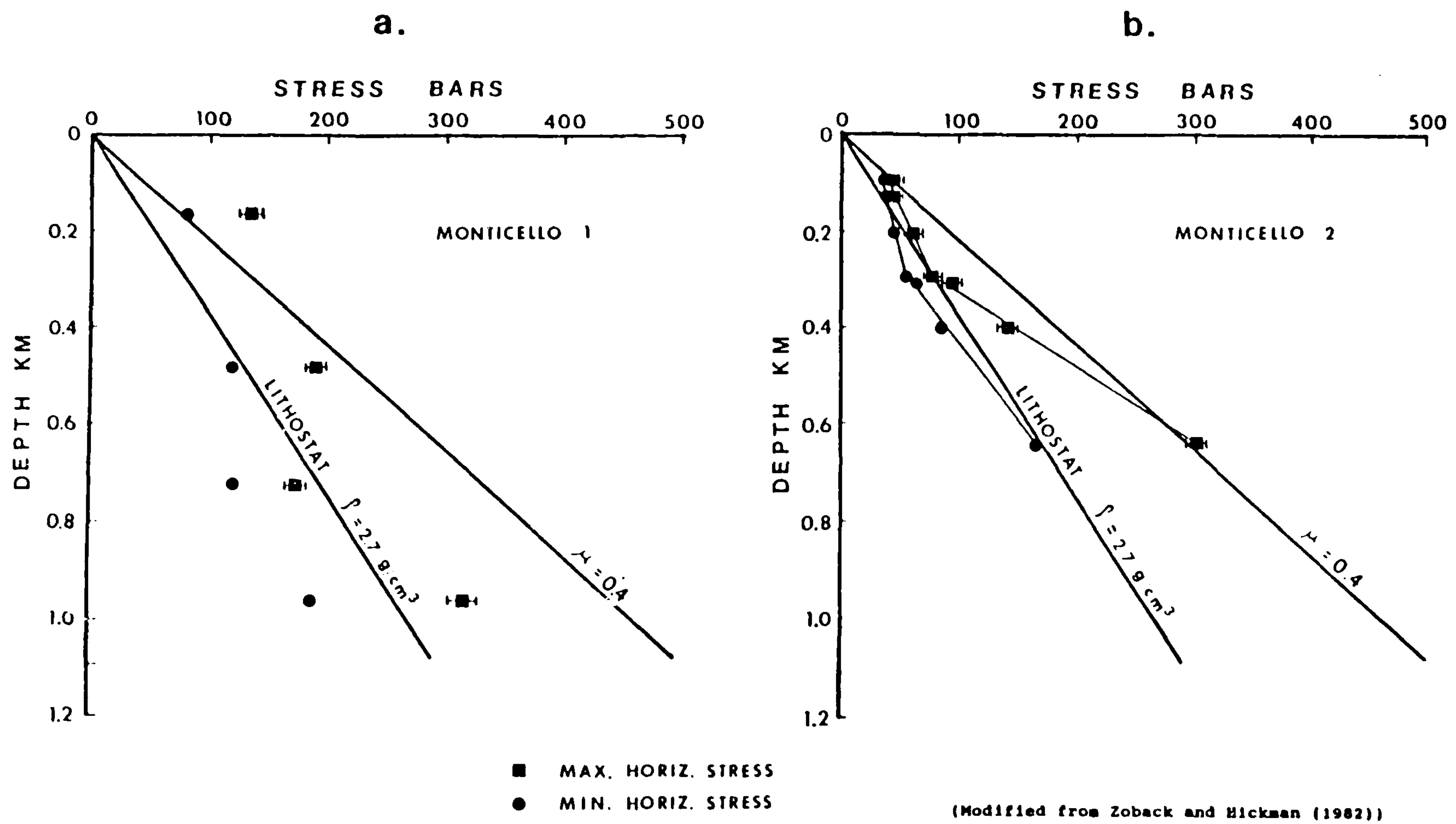


Figure 5. In-situ stress values at U.S.G.S. deep wells at Monticello Reservoir. The line labelled $\mu = 0.4$ represents the magnitude of S_{Hmax} required to initiate thrust faulting assuming a coefficient of friction of 0.4 and hydrostatic pore pressure. (From Talwani & Acree, 1987).

TABLE 2

MONTICELLO HYDROFRACTURE DATA

	Depth (M)	Pore Pressure (Bars)	Vert. Stress (Bars)	Min. Horiz. Stress (Bars)	Max. Horiz. Stress (Bars)	Comments
Mont. 1						
	165	17	44	79 ± 2	135 ± 9	
	486	49	129	119 ± 2	193 ± 9	
	728	73	193	119 ± 2	173 ± 9	
	961	97	255	186 ± 2	317 ± 13	
Mont. 2						
	97	10	26	34 ± 2	44 ± 9	
	128	13	34	36 ± 2	45 ± 9	
	205	21	54	47 ± 2	58 ± 9	
	298	30	79	56 ± 2	75 ± 9	
	312	31	83	64 ± 2	95 ± 9	
	400	40	106	87 ± 2	142 ± 9	Possible Preexisting Fracture
	646	64	171	166 ± 2	305 ± 9	

(Data from Zoback and Hickman, 1982)

alternating belts of differing lithologies and metamorphic grades. No active faults are known to exist. Any seismicity that might result, would therefore be due to the interaction of high compressional stresses observed in the Piedmont on pre-existing zones of weakness. The predominant zones of weakness in the Piedmont are networks of joints, thus limiting the size of the largest earthquake. We do not anticipate any earthquakes larger than the Union County event of 1913, i.e. 5.0 to 5.5 corresponding to MM intensity VII to VIII.

3. SEISMICITY

In this section we describe the historical and instrumental seismicity within each physiographic province in the region surrounding Lake Hartwell. Large felt earthquakes have occurred in the historical past. The most notable and the largest event (Modified Mercalli intensity (MMI) = X, magnitude (m_b) = 6.7) is the 1886 Charleston, South Carolina earthquake.

3.1 Historical and Instrumental Seismicity

The historical activity was studied by Bollinger (1973) who divided the felt activity from 1754 to 1970 into distinct seismic zones, with the southern Appalachian parallel and the central Virginia and South Carolina-Georgia seismic zones transverse to the Appalachian trend. Later Bollinger and Visvanathan (1977) extended the historical seismicity back to 1698 without a change in the pattern.

Recently Bollinger and others (1987) have reviewed the seismicity of the southeastern U.S. from 1698-1986 for a forthcoming Decade of North American Geology (DNAG) volume. In the section below, we present some of the important results relative to the tectonics of the region taken from that review.

Bollinger and others (1987) note that their catalog lists 1088 events (483 with M > 3) for the pre-network period, 1698- 1977 (Figure 6). The most recent issue of the SEUSSN bulletin (Sibol and others, 1987) lists 639 events (Figure 7) (50 with M > 3, Figure 8) for the network period, July 1977 through June 1987. Bollinger and others (1987) further note that the historical seismicity was characterized by "...the decidedly non-random spatial distribution of epicenters with patterns that are parallel as well as oblique to the northeasterly tectonic fabric of the host region...". Seismicity was observed throughout the extent of the Appalachian highlands (south of 40°

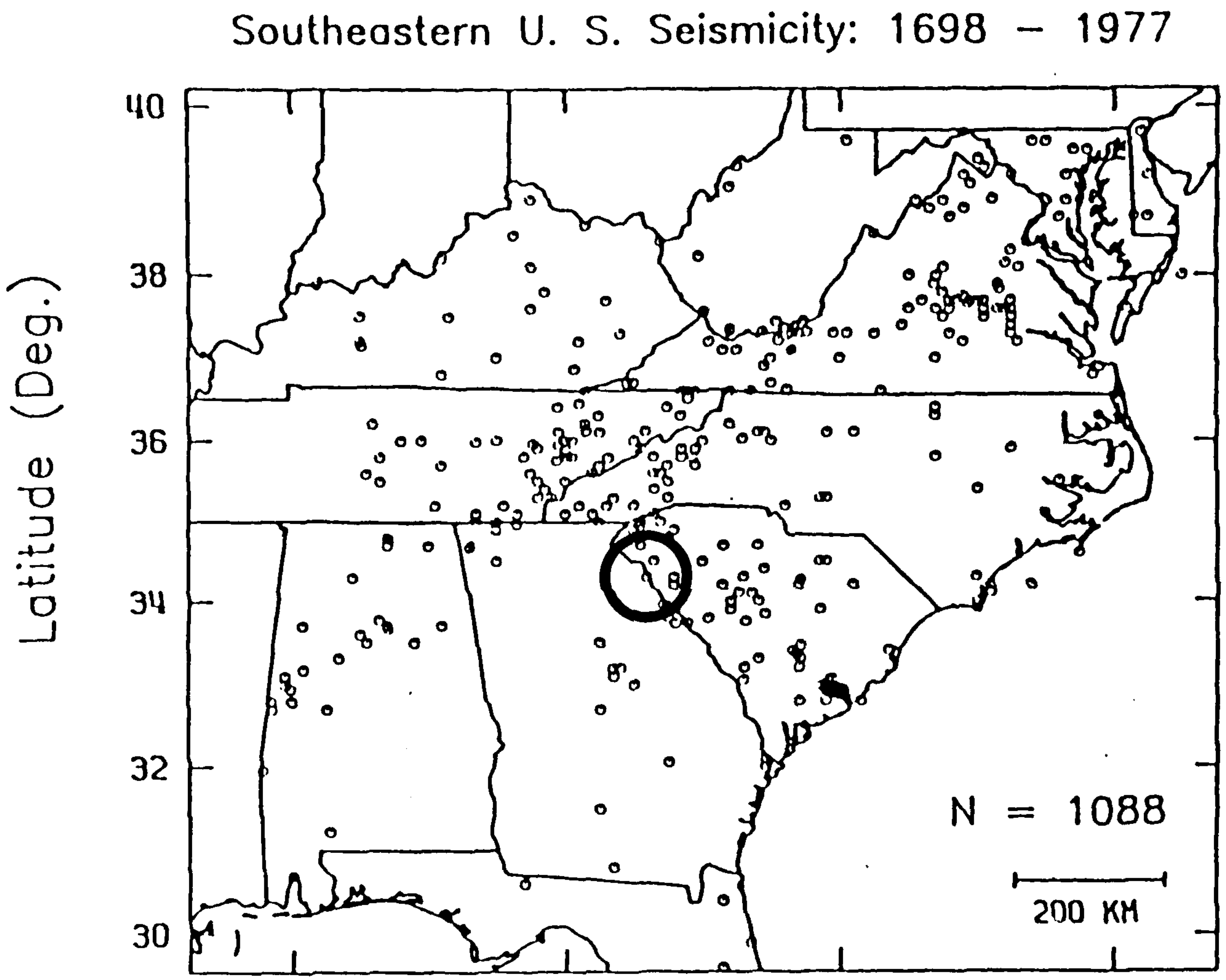


Figure 6. Historical seismicity of the southeastern U.S. (1968-1977). The open circles are the locations of the felt events. Solid circle is with 50 mile radius centered at Lake Hartwell. (From Bollinger & others, 1987).

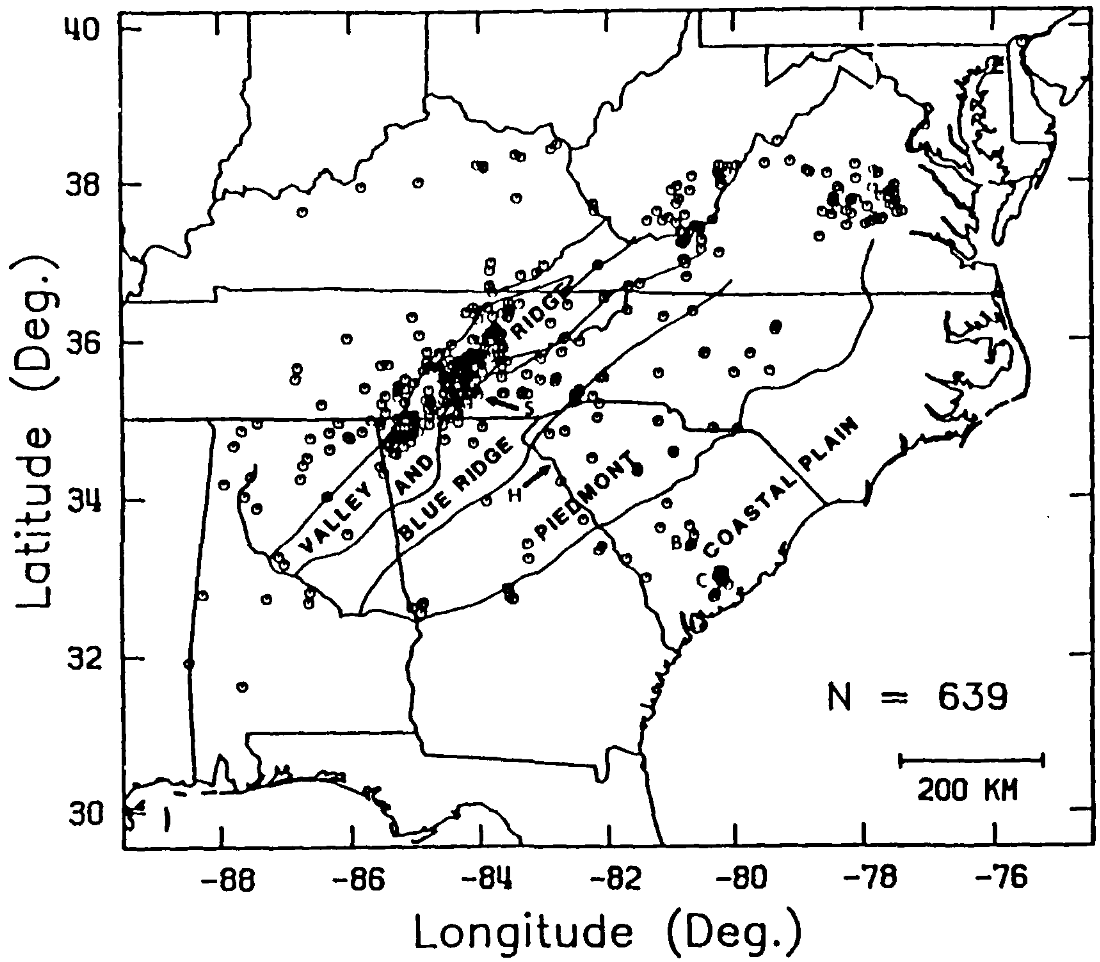


Figure 7. Network seismicity of the southeastern U.S. (1977-6/1987). The open circles are locations of events with $M_D \geq 0.0$. (Modified from Bollinger & others, 1987).

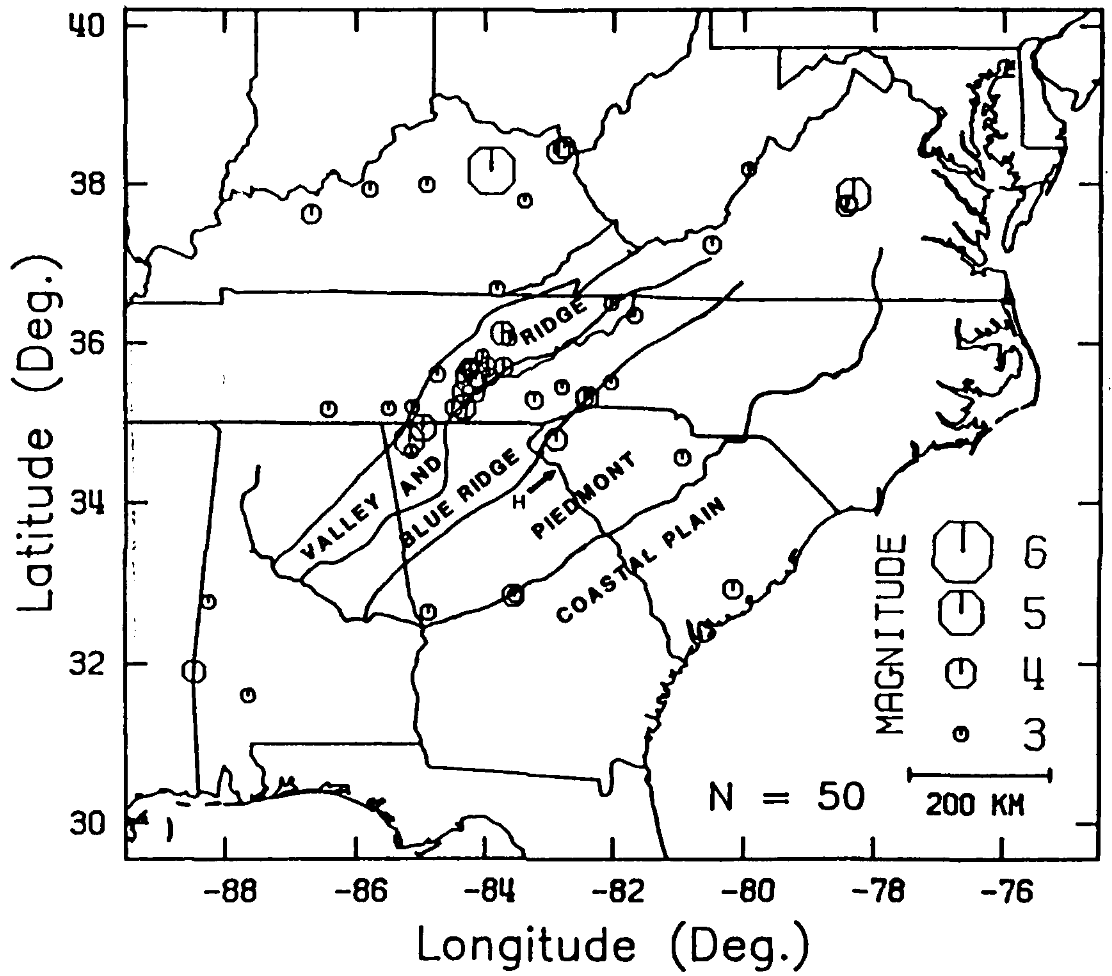


Figure 8. Network seismicity of the southeastern U.S. (1977-6/1987). The hexagons are locations of events with $M_D \geq 3.0$ and are scaled by size. (Modified from Bollinger & others, 1987).

north), while the seismicity was observed in the Piedmont province only in Virginia, South Carolina, and Georgia. Only the Coastal Plain of South Carolina was seismically active.

The instrumentally recorded seismicity lowered the detection threshold and allowed for more accurate locations. A comparison of the epicenters located by network monitoring (Figure 7) and the non-instrumental historical epicenters (Figure 6) shows that they both display the same general spatial patterns--some local clusters in the Piedmont and Coastal Plain, and an elongated trend along the Appalachian highlands. However, temporally we note some distinctions. To quote Bollinger and others (1987), "...modern seismic activity decreases are seen in the northern Virginia Appalachians and the South Carolina Piedmont while relative increases of seismicity have occurred recently in the northeastern Kentucky Plateau and on the southeastern Tennessee Appalachians...". Thus, in a time frame of a few hundred years, the seismicity is spatially stationary. For purposes of consideration of seismic hazard within the lifetime of critical facilities, the seismicity sources can be considered regionally fixed and not floating.

3.2. Seismicity in the Geological Provinces

The maximum magnitude earthquake which has occurred to date within each physiographic province can now be identified. These events for areas within 400 km of the Lake Hartwell dam site are discussed in the following sections.

3.2.1. South Carolina Coastal Plain

Within the South Carolina Coastal Plain, two significant seismic sources, the Charleston-Summerville and Bowman seismic zones, have been identified (Tarr and others, 1981). The most important of these is the Charleston-Summerville seismic zone, site of the largest recorded earthquake on the east coast of the United States (August 31, 1886 - MMI=X) (Bollinger, 1975). This earthquake was located approximately 300 km from the present site of the Lake Hartwell dam.

3.2.1.1. The Charleston-Summerville seismic zone

The Charleston-Summerville seismic zone has been the subject of multidisciplinary studies by the U.S. Geological Survey (Rankin, 1977; Gohn, 1983) and by the University of South Carolina. Talwani (1985) reviewed the various data and postulated models. Dewey (1985) reviewed the various hypotheses. Both authors described a general absence of consensus on the cause.

However, recent studies (Talwani, 1986; Lennon, 1985; Muthanna and others, 1987; Poley and Talwani, 1986; Talwani and Cox, 1985) have supported the earlier suggestions by Talwani (1982) that seismicity in the Charleston-Summerville region was concentrated on the shallow NW trending Ashley River fault (ARF) and the intersecting deeper Woodstock fault. The seismicity occurs in response to the regional stress field with S_{Hmax} oriented $\simeq$N60°E.

Paleoseismic studies by Talwani and Cox (1985) led to the identification of two large prehistoric earthquakes in the Charleston region similar to the 1886 event. These authors further suggested that earthquakes like the 1886 Charleston event occurred every 1500-1800 years. More recent paleoseismic studies by Weems and others (1986) led to the identification of one earlier earthquake $\simeq$ 7200 YBP. They also obtained an average (maximum) recurrence rate of $\simeq$ 1800 years. Recurrence rates were also estimated statistically, using historical data and yielded a return period of about 1600 years (Amick and Talwani, 1986).

Talwani (1985) reconciled all these observations in a seismotectonic model where in the seismicity in the Charleston-Summerville area occurs at the intersection of the ARF and Woodstock faults, in response to a compressional stress regime with a maximum horizontal stress oriented ENE, where large events occur every $\simeq$ 1500 years.

3.2.1.2. The Bowman seismic zone

In a recently completed seismotectonic study of the Bowman seismic zone, located about 50 km NW of the Charleston-Summerville seismic zone, Smith and others (1987) concluded that the low level of seismicity was occurring at the intersection of an unidentified NW trending feature with the ENE to EW trending border fault of a buried Triassic basin. None of the earthquakes, which began in the early 1970's, has exceeded magnitude 4.5.

3.2.1.3. Coastal Plain seismicity outside the Charleston-Summerville and Bowman seismic zones

The largest events in the Coastal Plain province outside the Charleston-Summerville and Bowman seismic zones occurred near Wilmington, N.C., in 1884 and 1958. They were assigned a MM intensity of V. The largest magnitude estimated for this zone is 5.0.

For estimating the seismically induced shaking at the project site, for events occurring in the Coastal Plain province, we therefore consider a MM intensity X in the Charleston-Summerville zone as the largest possible earthquake.

3.2.2. Piedmont Province

The largest recorded earthquake within the Piedmont physiographic province, in which the Lake Hartwell project site lies, occurred in Union County, South Carolina, on January 1, 1913 (MMI=VII-VIII) (Bollinger, 1975). This event was assigned an epicentral intensity VIII on the Rossi Forrel scale by Taber (1913). It was located approximately 100 km west of the current site of the Lake Hartwell dam.

The Union County earthquake is the largest event to have occurred in the

South Carolina Piedmont province. Its magnitude has been variously estimated as being 5.0 to 5.5. Geologically the estimated epicenter lies on the Kings Mountain shear zone.

Closer to the dam site, an earthquake (MMI=VI) occurred near Lincolnton, Ga., near the Georgia-South Carolina border on November 1, 1875, about 60 km from the present dam site. An earthquake with a maximum intensity of V was attributed to Anderson, South Carolina, in 1958, approximately 20 km from the dam site.

A swarm of shallow microearthquakes, many of which were felt, occurred in the vicinity of Newberry, S.C., located 110 km (70 miles) from the Hartwell dam. Two earthquake swarms that occurred there in 1982 and 1983 were studied by Rawlins (1985) who found that seismicity was possibly associated with the eastern flank of the buried Newberry granite pluton. The nature of the shallow seismicity - swarms, very shallow and low magnitude - is similar to reservoir induced seismicity, and it is possible that a local stress concentration in the pluton may account for the observed activity.

3.2.3. Blue Ridge and Valley and Ridge Provinces

Currently, the most seismically active region in the southeastern United States is the southern Appalachian seismic zone (or the eastern Tennessee seismic zone) within the Blue Ridge and Valley and Ridge physiographic provinces (Figure 6). The largest event within this zone occurred in Giles County, Virginia, (maximum MMI=VIII) (Bollinger, 1975) on May 31, 1897. This event was located approximately 380 km from the present site of the Lake Hartwell dam. The greatest concentration of recent seismicity (Figure 7) is located less than approximately 150 km from the dam. Historical seismicity recorded in the southern Appalachian seismic zone lies within 100 km of the present dam site.

3.3. Reservoir Induced Seismicity

Reservoir induced seismicity has been well documented in at least four sites and strongly suggested to occur at two sites in the Piedmont province surrounding Lake Hartwell (Figure 9). The largest event at any of these sites has been less than magnitude 4.5 and the microearthquake activity has been characterized by the shallow depths and the swarm-like temporal character of the observed seismicity. The best studied cases of RIS occurred at Lakes Keowee and Jocassee upstream of the project site and at Monticello Reservoir in S.C. and Lake Sinclair in Ga., east and west of the project site. A strong case has been made for RIS at Clarks Hill (J. Strom Thurmond) reservoir and a possible case has been made for the current activity being observed at the Richard B. Russell reservoir area. The latter two sites are downstream of the Hartwell project site. Thus the project site lies in the middle of six sites of RIS in the Piedmont province of South Carolina and Georgia. The seismicity at these sites is discussed below.

3.3.1. RIS at Clarks Hill (J. Strom Thurmond) Reservoir

Continuous seismicity was observed in the vicinity of the Clarks Hill (J. Strom Thurmond) reservoir following a magnitude 4.3 earthquake in August 1974 (Talwani, 1976). Swarms of earthquakes lasting for several months were observed within about 3 km from the reservoir. Excellent correlation was observed between the water level fluctuations and the ensuing activity. The observation that the seismicity occurred 43 km upstream of the Clarks Hill (J. Strom Thurmond) dam and 22 years after its impoundment led to the questioning of the suggestion that the activity was induced. In our judgement the temporal and spatial pattern of the observed activity and the corrobative delayed response of the seismicity to lake level changes argue very strongly

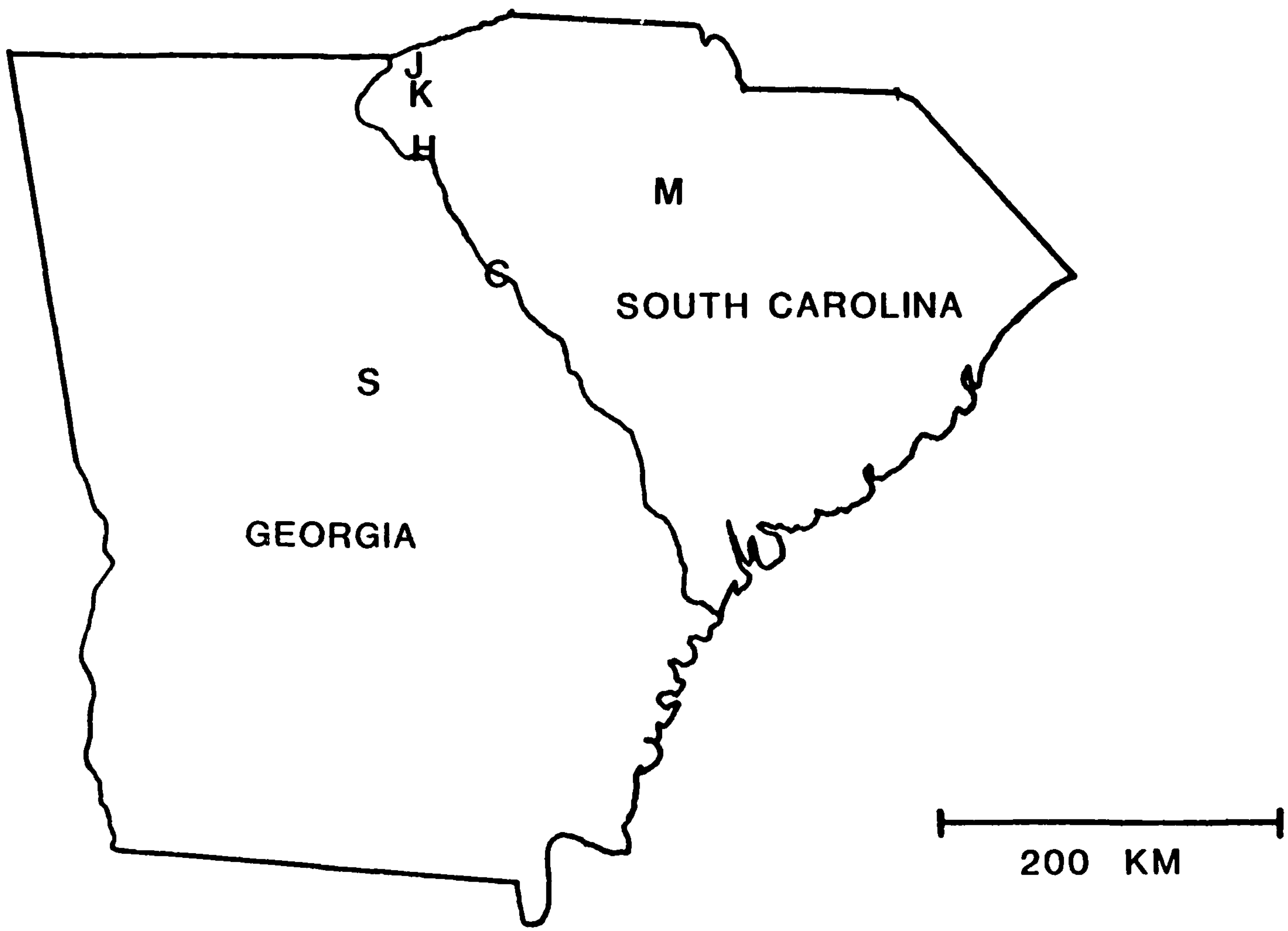


Figure 9. Locations of seismically active reservoirs in the region surrounding Lake Hartwell. The reservoirs are located with letters: J - Lake Jocassee, K - Lake Keowee, H - Lake Hartwell, M - Monticello Reservoir, C - Clark Hill Reservoir, and S - Lake Sinclair.

for the observed activity to have been induced.

3.3.2. RIS at Lake Keowee

Talwani and others (1979) studied the January-February, 1978, earthquake swarm at Lake Keowee. The low level (M < 2.2), shallow (< 3 km) and intense (up to 200 events/day) nature of seismicity in the immediate vicinity of Lake Keowee was found to occur on steeply dipping joints. The authors suggested that, "...The presence of the lake very close to the epicentral area suggests that the seismic activity may be associated with pore fluid migration along the larger set of joints...".

A search for earlier seismicity in the area and comparison with the filling curve for Lake Keowee, led to the suggestion that the Seneca earthquake of 1971 with a MM intensity IV (Sowers and Fogle, 1978) and possibly the December 1969, felt event, were associated with two stages of impoundment of Lake Keowee (Talwani and others, 1979).

Low level seismicity has continued to occur in the vicinity of Lake Keowee. Felt events in February, June and July of 1986 and their aftershocks were studied by Acree and others (1988). The events were again found to be shallow and in the vicinity of Lake Keowee. Comparison with geological, gravity and magnetic data suggested that the seismicity was associated with a local shallow body rather than throughgoing faults. No correlation was evident between the lake level changes and the February 1986 events. However rapid fluctuations in water level did precede the event in June and July 1986 providing a possible triggering mechanism.

3.3.3. RIS at Lake Jocassee

RIS has been observed (and monitored) at Lake Jocassee since October 1975 (Talwani and others, 1976, 1978, 1980). The seismicity was found to occur at shallow depths and was associated with changes in various physical parameters, and as such it was used to study techniques of predicting earthquakes (Talwani, 1981). Some of the salient facts about the RIS at Lake Jocassee are described in Talwani (1981) and are summarized here. The seismicity was found to be concentrated in the heavily fractured Henderson augen gneiss unit and was predominantly associated with strike slip faulting. Talwani (1981) noted that "...An analysis of 10-day average lake levels and changes and comparison with seismicity, suggests that...larger earthquakes follow periods of rapid sustained lake level increase...This observation together with an analysis of the stress data, focal mechanisms and detailed mapping of surface fractures lead us to conclude that the observed seismicity is triggered by pore pressure changes in a highly pre-stressed rock. These pore-pressure changes are caused by lake level fluctuations and the seismicity is related to an existing network of fractures, rather than to breaking of new rock...".

The largest event at Lake Jocassee occurred on August 25, 1979, nearly five years after impoundment. This m_{bLg} 3.7 event, which was felt in the epicentral area with a MM intensity VI, was also felt at the Hartwell project site. Talwani and others (1980) suggested that the occurrence of this event was possibly associated with a rapid, sustained period of lake level changes.

3.3.4. RIS at Monticello Reservoir

Detailed studies of RIS at Monticello Reservoir commenced soon after its impoundment in December 1977. After intense seismicity following the impoundment, shallow (< 2-3 km) and low activity (M d 2.8) has gradually decreased. Even in 1988, an occasional M 2+ event is recorded, but the general pattern of activity is one of slow decrease (Figure 10). The seismicity is associated with shallow fractures in the vicinity of several

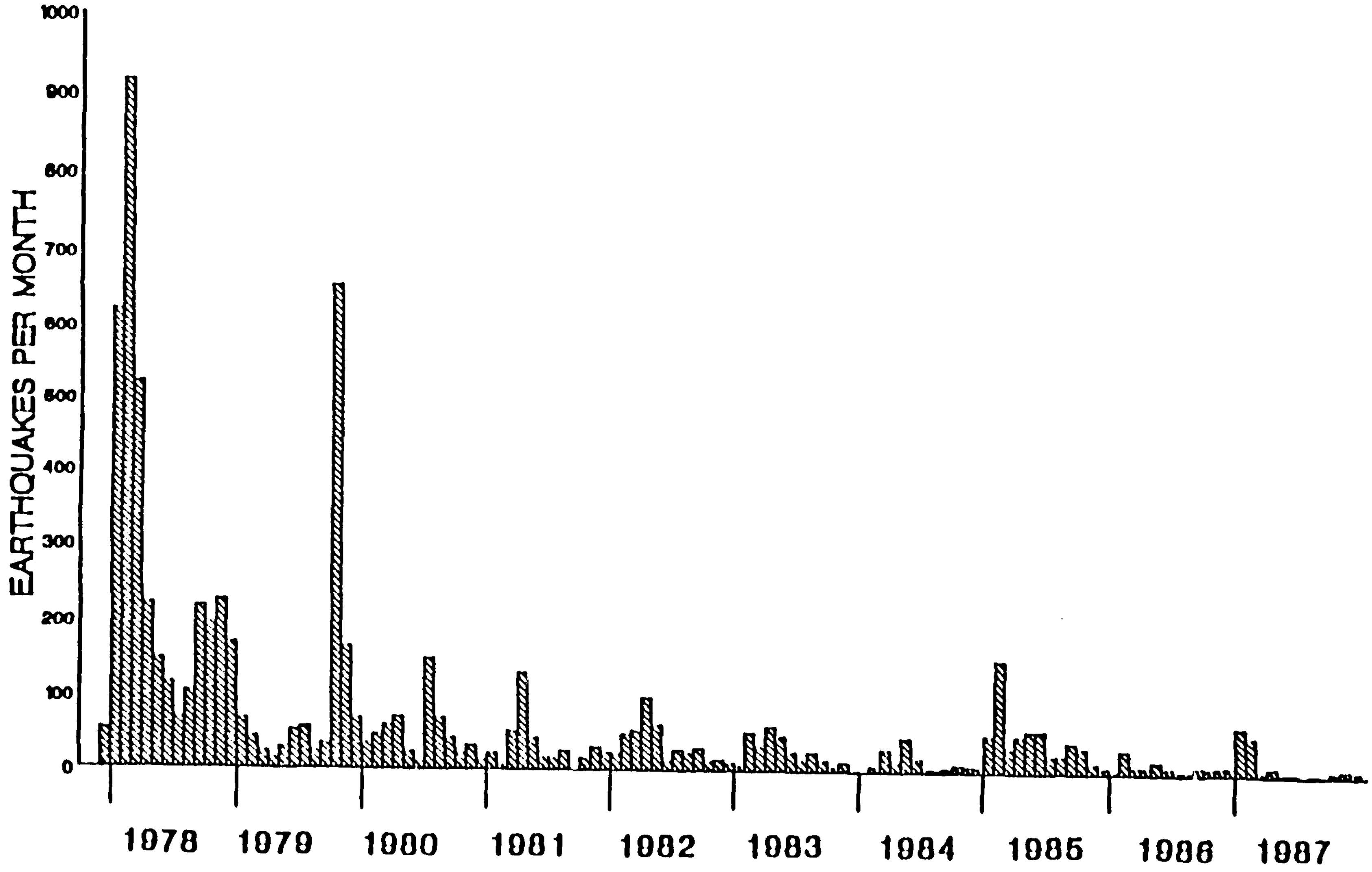


Figure 10. Earthquakes per month since impoundment of Monticello Reservoir in December 1977 - December 1987.

plutons that have intruded into the country rock. (See Talwani and Acree (1987) for a detailed study of the RIS at Monticello Reservoir).

3.3.5. RIS at Lake Sinclair, Ga. and Richard B. Russell project sites

Reservoir induced seismicity at Lake Sinclair, Ga. has been studied by Prof. L.T. Long and his students at the Georgia Institute of Technology. The seismicity was found to be shallow and occurred in swarms. No information is available as to possible association with lake level fluctuations.

After its initial impoundment of the Richard B. Russell dam in 1982, no seismicity was observed (L.T. Long, personal communication). However recently we have located some events there, the magnitude 3.1 event in May 1987 being the largest. No systematic studies of possible RIS at the Richard B. Russell site have been carried out to date.

3.3.6. Conclusions

Reservoir induced seismicity has been observed at six reservoirs surrounding the Hartwell project site. All of these sites lie in the Piedmont physiographic province. The available stress data suggest the presence of large stresses. The area is in a compressional stress regime and the observed seismicity is by thrust and strike slip faulting on what appears to be a network of joints. At many locations and for many events, the seismicity is associated with sustained, rapid periods of lake level impoundment or withdrawal. The seismicity appears to occur in regions with a characteristic hydraulic diffusivity of $\simeq 10^4$ cm^2/sec or with a corresponding effective fracture permeability of 1-10 mDarcys (Talwani and Acree, 1985).

With several man years of very detailed data, no induced event was found to occur with a magnitude greater than 4.5 suggesting that the small length of available fractures in the vicinity of the reservoir controls the maximum size of the induced earthquakes in the Piedmont.

3.4. Conclusions

The major conclusions of this review of recent and historical seismicity are:

1. The largest recorded earthquake in the eastern United States (maximum MMI=X) occurred in 1886 near Charleston, South Carolina, approximately 300 km from the present dam at Lake Hartwell. It is believed that tectonic structures associated with this event have been identified and that possibly three other events of this magnitude have occurred in the Charleston area prior to historical recording.

2. The largest earthquake within the Piedmont physiographic province, in which Lake Hartwell lies, occurred at Union County and was assigned a maximum intensity (MMI) of VII-VIII.

3. The most seismically active region in the southeastern U.S. is currently the southern Appalachian seismic zone within the Blue Ridge and Valley and Ridge physiographic provinces. The closest extent of this seismic zone lies within 100 km of the Lake Hartwell dam. The largest earthquake recorded within this zone resulted in a maximum intensity (MMI) of VIII.

4. The maximum magnitude earthquake identified as triggered by any reservoir in the Piedmont province is less than 4.5.

4. FILLING HISTORY AND HISTORY OF LAKE LEVEL FLUCTUATIONS

Following a review of RIS at locations worldwide, it was concluded that although microearthquake activity was observed at small and shallow reservoirs, destructive events (M > 5.0) were limited to very large and deep reservoirs. Although empirical data support this conclusion, our experiences in the studies of RIS has been that an important parameter is the RATE of lake level changes. Another observation has been, that in most cases, RIS is associated with the initial impoundment and is associated with a pertubation of the region's seismicity. But the seismicity pattern returns to the background pattern after a lapse of a few years, which may vary from about 5 to 20 years. A possible and important exception to this has been the observed seismicity at Clarks Hill (J. Strom Thurmond) Reservoir, nearly 22 years after impoundment.

In this section, we compare the size and lake level fluctuations at Lake Hartwell with Lake Jocassee and Monticello Reservoir, two locations of RIS, where these parameters have been monitored for over 10 years (See also Table 3).

4.1. Lake size

Lake Hartwell was filled during the years 1961-1962. Details of the initial filling history are not available. At a water elevation of 665 feet above sea level (a.s.l.) (top of the flood control gates), the lake covers approximately 61,850 acres with a capacity of approximately 2.86 X 10^6 acre-feet. The depth from the top of the crest gates to the bottom of the stream bed is approximately 190 ft (Corps of Engineers, 1952).

Lake Hartwell (61,850 acres) covers a significantly larger surface area than Lake Jocassee (7500 acres) or the Monticello Reservoir (6800 acres), two reservoirs with well documented histories of RIS. The reservoir capacity at Lake Hartwell (2.86×10^6 acre-ft) is more than twice that of the deeper Lake Jocassee (1.16×10^6 acre-ft) and significantly greater than that of Monticello Reservoir (0.4×10^6 acre-ft) (Figure 9). These are compared in Table 3.

4.2. Lake level fluctuations

Lake Hartwell experiences seasonal water level fluctuations. The highest levels are generally recorded during the spring with levels decreasing during the summer and fall. We reviewed the data provided by the Corps of Engineers (Savannah, Georgia office) covering the period 1962-1987 (Appendix 1). The maximum seasonal variation was less that 20 ft. Most yearly variations were approximately 10 ft or less. In comparison, Lake Jocassee, a pumped storage facility, experiences normal water level variations of up to 10 ft, with a maximum drawdown of 15 ft during repairs to the dam. Lake levels at Monticello Reservoir, also a pumped storage facility, vary within a 5 ft range. Thus, seasonal variations at Lake Hartwell are in the same range, though slightly higher than variations at Lake Jocassee and Monticello Reservoir.

4.3. The Duration of RIS

Seismicity triggered by reservoir impoundment is currently believed to result from adjustments of the in-situ stress field to increases in stresses (due to the water load) and pore pressures (predominantly due to diffusion from the reservoir) at hypocentral depths (Talwani and Acree, 1985). In time, the stress field adjusts to the new conditions imposed by the reservoir and induced seismicity declines.

TABLE 3

Relative size of Reservoirs in the Piedmont

Lake	Surface Area X 10^3 acres	Capacity X 10^6 acre-ft	Maximum depth ft
Hartwell	61.9	2.86	190
Jocassee	7.5	1.16	360
Monticello	6.8	0.4	160
Clark Hill	---	2.0	200*
Keowee	18.3	0.96	140

*Near the epicentral region the maximum depth was less than 50 ft.

Lake Hartwell was impounded over 25 years ago. The reservoir area was never instrumented with seismographs. Thus, no data exist concerning possible triggering of microearthquake activity associated with the initial reservoir impoundment. Based on experience at Lake Jocassee and Monticello Reservoir, it is expected that any seismic activity associated with the initial impoundment of Hartwell would have declined toward the preimpoundment background level by this time.

Water level variations also perturb the stress field and can trigger seismicity (Talwani and Acree, 1985). As discussed in Section 3, the region around the lake exhibits a low level of seismicity. The area is not sufficiently instrumented to detect any microearthquake activity that may have been triggered by lake level fluctuations.

4.4. Conclusions

1. Lake Hartwell covers a larger surface area and reservoir capacity than other seismically active lakes (Jocassee and Monticello) in the region. The maximum depth at Hartwell is within the range of depths of these other impoundments.

2. Water level fluctuations at Hartwell are comparable to those experienced at impoundments which have triggered seismicity. Such fluctuations perturb the in-situ stress field and can trigger seismicity in the immediate vicinity of the lake.

3. Due to the lack of instrumentation the existence or extent of any microearthquake activity at Hartwell is unknown.

4. Induced seismicity triggered by the initial filling of Hartwell is expected to have declined toward the background (natural) level of activity by now. Thus barring sudden large lake level changes (which exceed changes in the past) we would not expect any significant new RIS at Lake Hartwell.

5. EVIDENCE OF SEISMICITY AT LAKE HARTWELL

A three part study was conducted to determine the extent of recorded seismic activity at the present site of Lake Hartwell. Historical seismicity, as cataloged by the Department of Energy (DOE, 1984), was reviewed for evidence of pre-instrumental activity. The first seismic network in the region was installed in 1973 and by 1977, several networks were in operation. The results of network monitoring are cataloged (July 1977 - June 1987) biannually in the Southeastern U.S. Seismic Network (SEUSSN) bulletins. These bulletins were reviewed for evidence of recent seismicity at the lake. Additionally, a search of the seismographic record library at the University of South Carolina was undertaken to determine if additional earthquakes originating at Lake Hartwell had occurred but were not located and reported.

5.1. Historical Seismicity

Prior to the installation of seismographic networks earthquakes, were attributed to the area in which the intensity of motion was greatest. Thus, earthquakes were often attributed to population centers. The actual locations of these events may have been many kilometers away. With the installation of networks, the earthquake detection threshold became much lower and more accurate locations were obtained. Therefore, catalogs of pre-instrumental seismicity contain a larger percentage of larger earthquakes than catalogs of instrumental seismicity. The locations of these pre-instrumental felt events may be accurate only to tens of kilometers in some cases.

The catalog of seismicity in the southeastern United States (1698-1981) produced by DOE (1984) incorporated previous works and, therefore, was utilized in this review. Seismicity attributed to the present site of Lake

Hartwell is sparse. Figure 11 from the cataloged data of Bollinger (1975) and Figure 12 (Bollinger, 1972) are representative of the activity recorded in the southeastern United States and South Carolina, respectively. The nearest event to the Lake Hartwell dam site (MMI = V or greater) was attributed to Anderson, South Carolina. This event occurred in 1958 and was reported to have a maximum intensity of V (DOE, 1984).

5.2. Instrumentally Recorded Seismicity

A review of the SEUSSN bulletins (July 1977 - June 1987) revealed three events (Table 4) judged to be possible earthquakes associated with Lake Hartwell (Figure 13). The largest of these was of magnitude 2.7. Two of these events were attributed to Lake Richard Russell, but the reported locations are north (upstream) of the Lake Hartwell dam. Stone quarries operate in the area. Though any of these events may be dynamite blasts at one of these quarries, the early morning origin times of two of the events (3:06 a.m. EDT and 1:09 a.m. EST) render these events unlikely prospects for quarry blasts. The event located farthest from the lake originated at 3:16 p.m. EST and may, indeed, be a dynamite blast.

Seismic station JSC, located near Jenkinsville, South Carolina, has been in continuous operation since 1974 and is one of the most sensitive stations of the South Carolina Seismic Network. Based on these features and the availability of the seismographic records, data from JSC were utilized in an attempt to identify other earthquakes originating from the Lake Hartwell area since 1974.

The distance from station JSC to Lake Hartwell ranges from approximately 140 to 190 km. Seismic waves from events originating at these distances would arrive at JSC with time differences between the P and S wave arrivals of

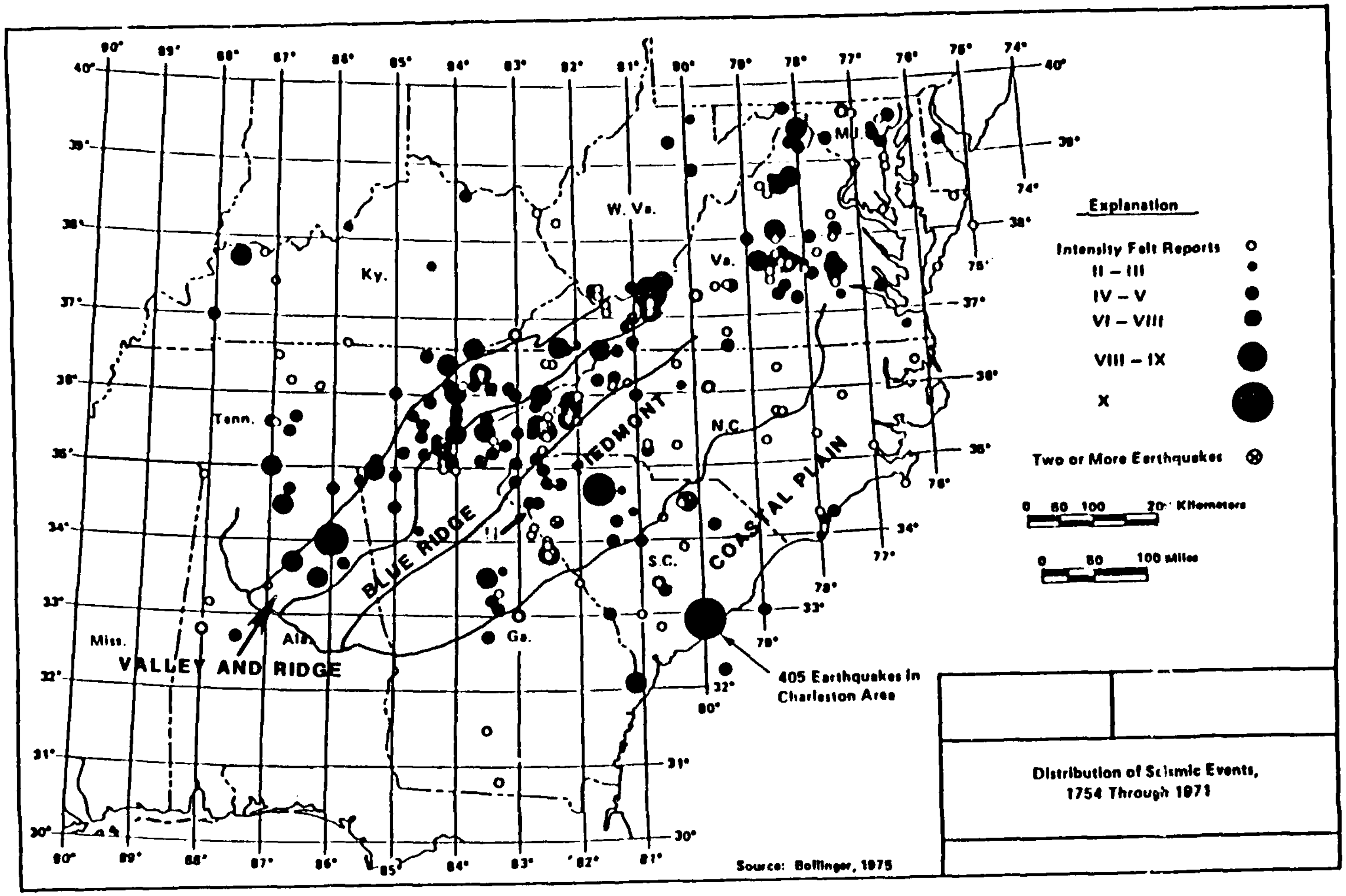


Figure 11. Historical seismicity in ou heast U.S. (From Bollinger, 1975). The earthquakes are scaled to si e and the physiographic provinces are also shown.

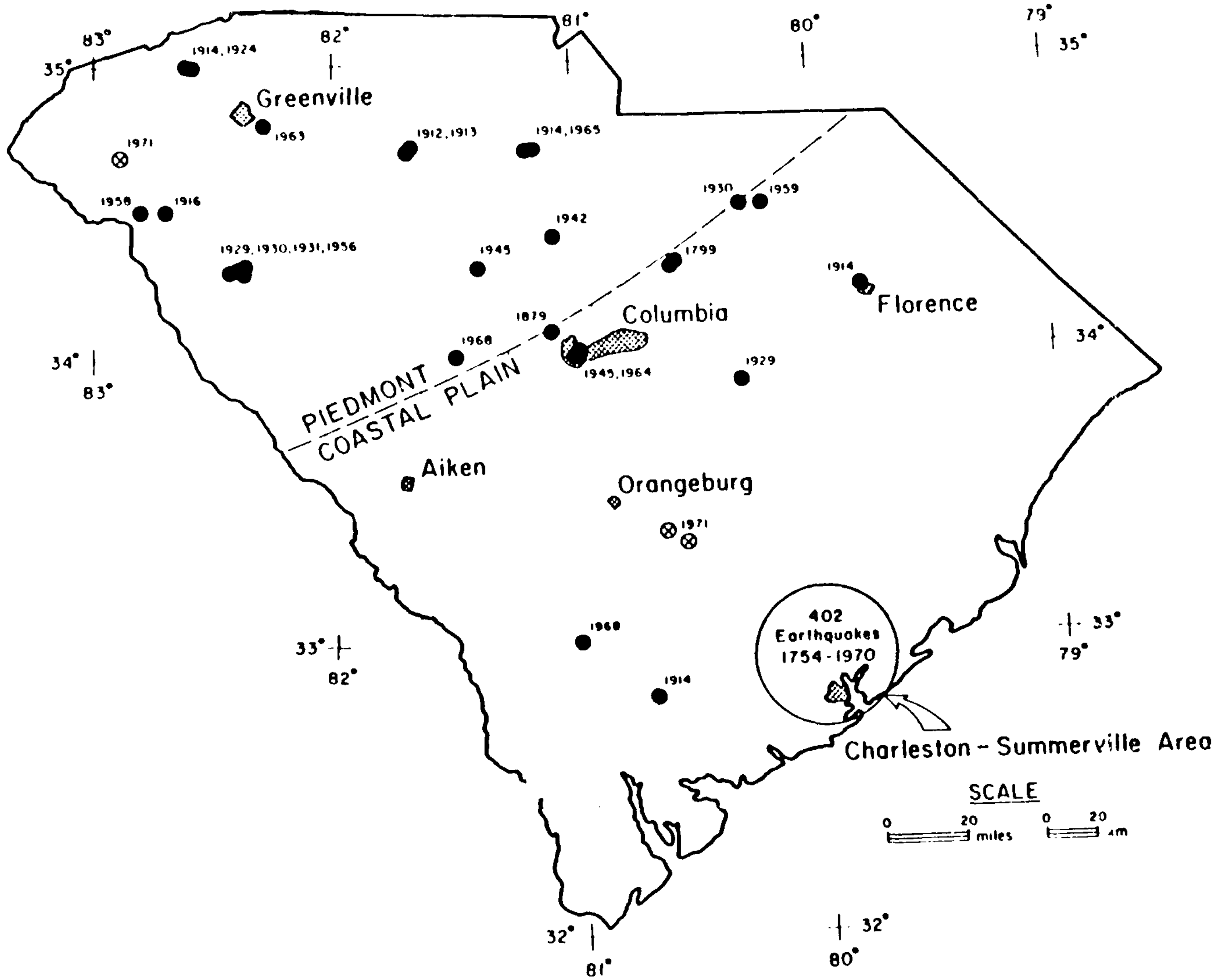


Figure 12. Historical seismicity of Soutı Carolina. (From Bollinger, 1972).

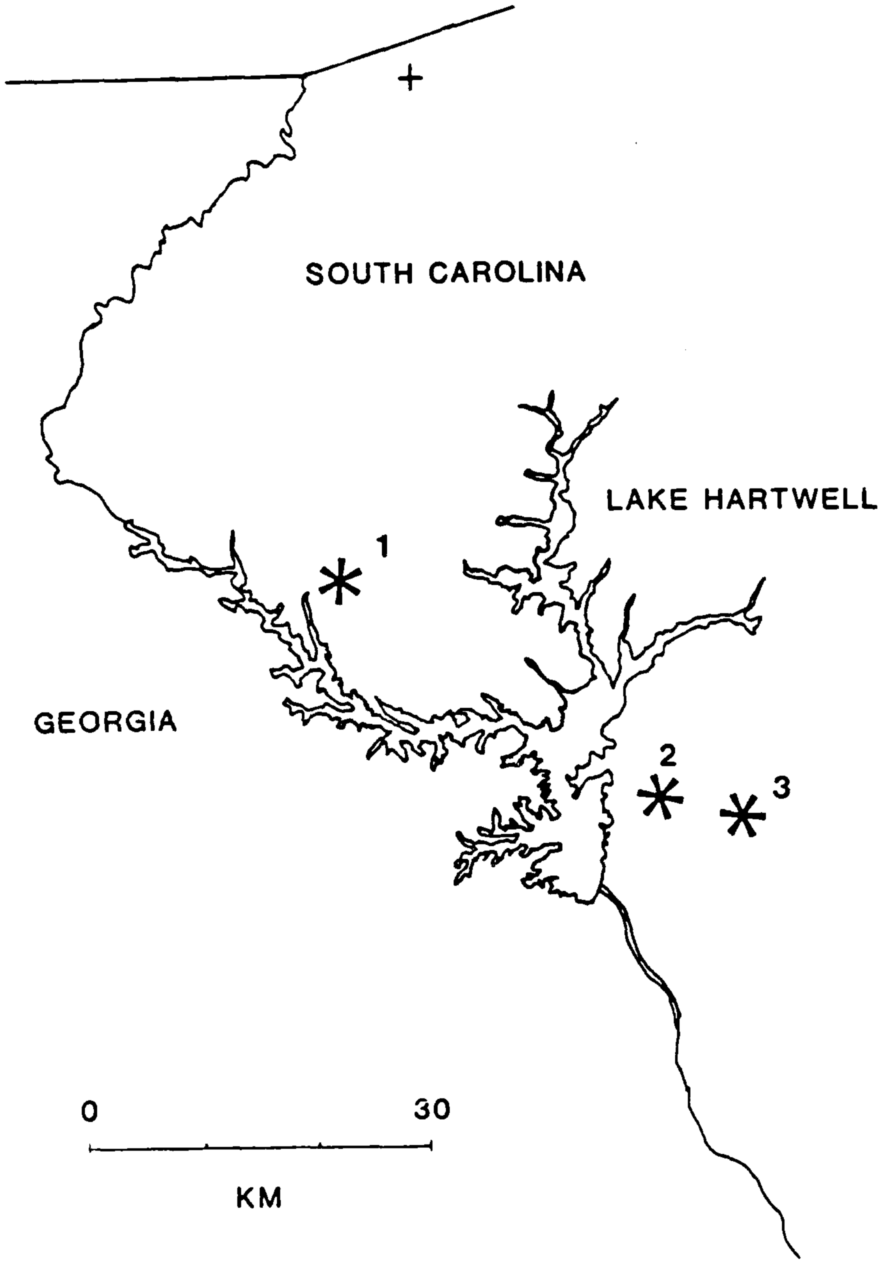


Figure 13. Locations of possible earthquakes at Lake Hartwell from SEUSSN bulletins. The events are keyed to Table 4.

TABLE 4

Earthquakes Located at Lake Hartwell as Cataloged by the SEUSSN

	DATE	ORIGIN TIME	LATITUDE DEG.	LONGITUDE DEG.	NETWORK OPERATOR	MAG	REPORTED COMMENTS
1.	07/07/83	07:06 UTC (03:06 A.M. EDT)	34.599N	83.067W	GIT	2.7	POSSIBLE BLAST
2.	12/13/85	05:09 UTC (00:09 A.M. EST)	34.425N	82.757W	TEIC	1.8	APPEARS RESERVOIR RELATED
3.	04/01/86	20:16 UTC (03:16 P.M. EST)	34.415N	82.680W	GIT	0.7	

GIT - Georgia Institute of Technology
TEIC - Tennessee Earthquake Information Center

NOTE: Events on 12/13/85 and 04/01/86 were attributed to Lake Richard Russell.

Sources

1. Bollinger and others (1984).
2. Sibol and others (1986a).
3. Sibol and others (1986b).

approximately 14 to 19 seconds. To partially offset potential errors in reading P and S wave arrival times, events with time differences of 12 to 22 seconds between the wave arrivals were identified. A duration magnitude threshold of 2.5, as determined by the duration of seismic signals recorded at JSC using the formula:

$$\text{Magnitude} = -1.83 + \text{Log}_{10} D$$

where D is the duration in seconds, was also employed.

During the period January 1, 1974 through December 31, 1987, approximately 50 events with potential origins at Lake Hartwell were identified from the log of events recorded by station JSC. Using additional data (e.g., seismograms from the stations of the Lake Jocassee and Monticello Reservoir seismic networks, records of quarry blasts), it was determined to be unlikely that any of these events were located at Lake Hartwell.

Potential errors involved in the above methodology preclude drawing firm conclusions as to the existence of recent (since 1974) earthquakes at Lake Hartwell. It appears improbable that significant numbers of earthquakes with magnitudes greater than 2.5 have occurred in the immediate vicinity of the lake since 1974.

5.3 Conclusions

Few earthquakes have been attributed to the present site of Lake Hartwell, either historically or since seismographic networks were established in the mid 1970's. Thus, since impoundment, Hartwell has been relatively aseismic at an earthquake threshold of $M > 2.5$.

6. SEISMIC POTENTIAL AT PROJECT SITE

The seismicity in the vicinity of the project site has been very sparse in historical times. Therefore, we cannot estimate accurately the nature of the seismicity by statistical techniques (from b-values). No active faults are known, and therefore the technique of using fault dimensions or slip rates cannot be used. So we have to rely almost exclusively on historical and current instrumental data to estimate the seismic hazard. In this section we first discuss the earthquake potential in the project area and then estimate the maximum intensity of seismically induced ground shaking that can be expected at the project site.

6.1. Distant earthquakes felt in the area

Not only were the large events at Charleston in 1886, New Madrid in 1811-1812, and Giles County, Virginia in 1897 felt in the project area, several lesser well known events were also felt. These include the Lincolnton, Ga., MM intensity VI event on November 1, 1875, the Union County earthquake of 1913, with an epicentral MM intensity of VII-VIII, the Greenville, S.C., event of October 1924, the Columbia, S.C., event of July 1945, with an epicentral MM intensity of VI, the Seneca, S.C., event of July 1971 and some events with MM intensities of VII-VIII in Charleston. Some of the available isosismals for these events are shown in Figures 14a to 14g. The various earthquakes described above occurred in different tectonic provinces and their causes are not well understood.

6.2. Prospect of an earthquake in the Project area

Here we present our assessment of the prospects of an earthquake in the project area in light of the information presented in earlier sections and our

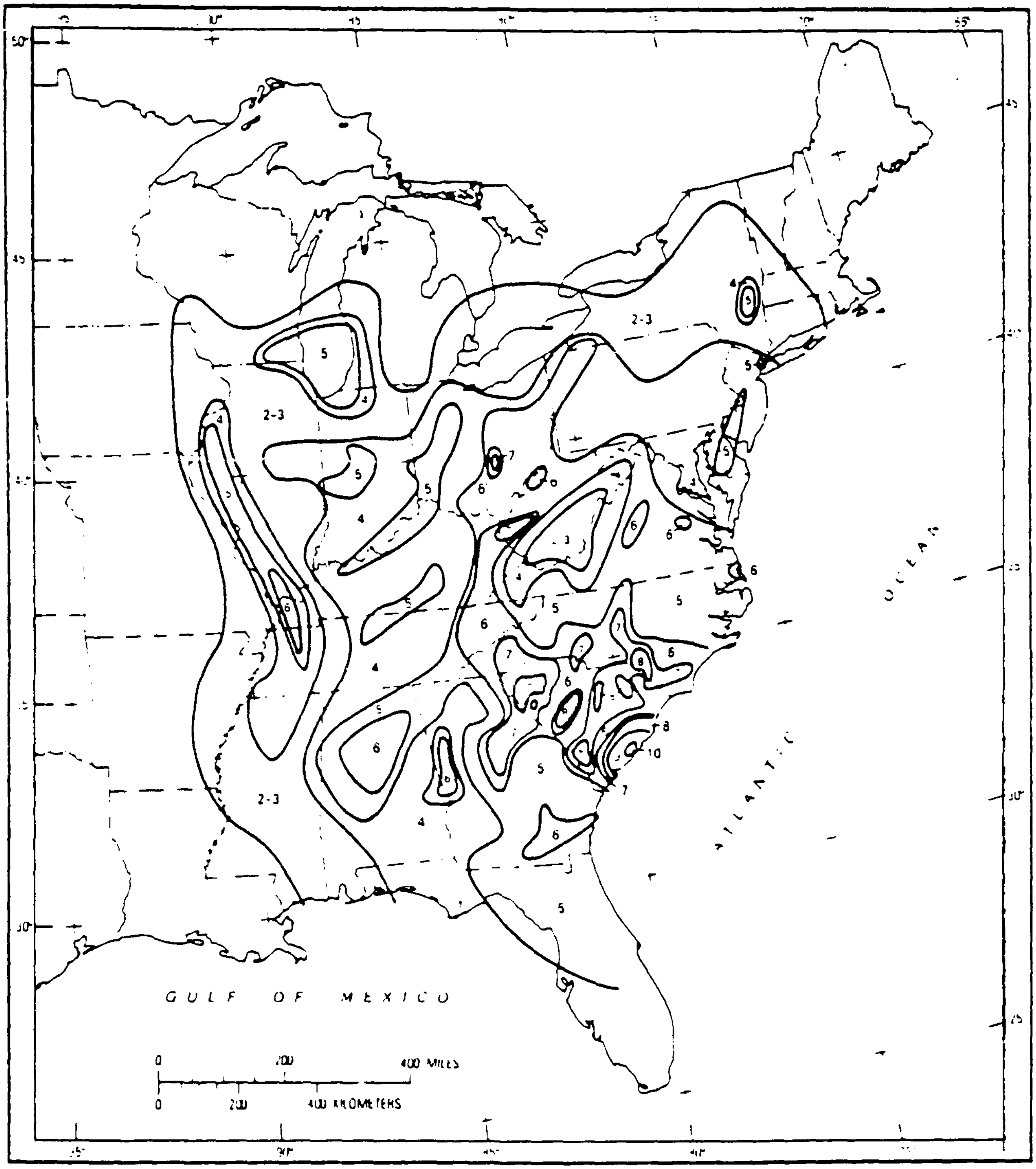


Figure 14 a. Isoseismal map of the eastern U.S. for the 1886 Charleston earthquake. Contoured MM intensity levels are shown by Arab numerals. (From Bollinger, 1977).

Figure 14b. Isoseismal map for the 1913 Union County earthquake. Intensity values are in the Rossi Forrel scale. (From Taber, 1913).

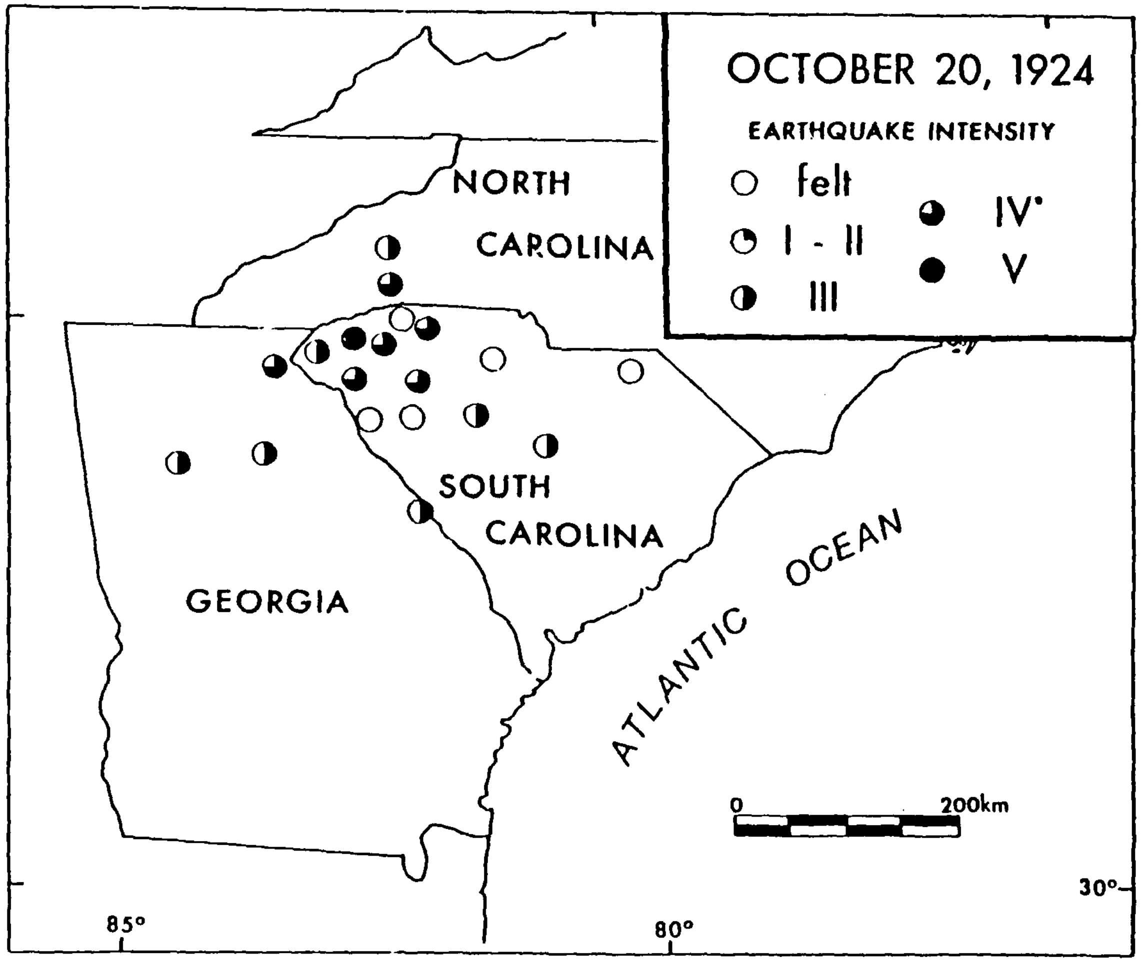


Figure 14c. MM intensity values at some locations for the intensity V Pickens County earthquake in October, 1924. (From Visvanathan, 1980).

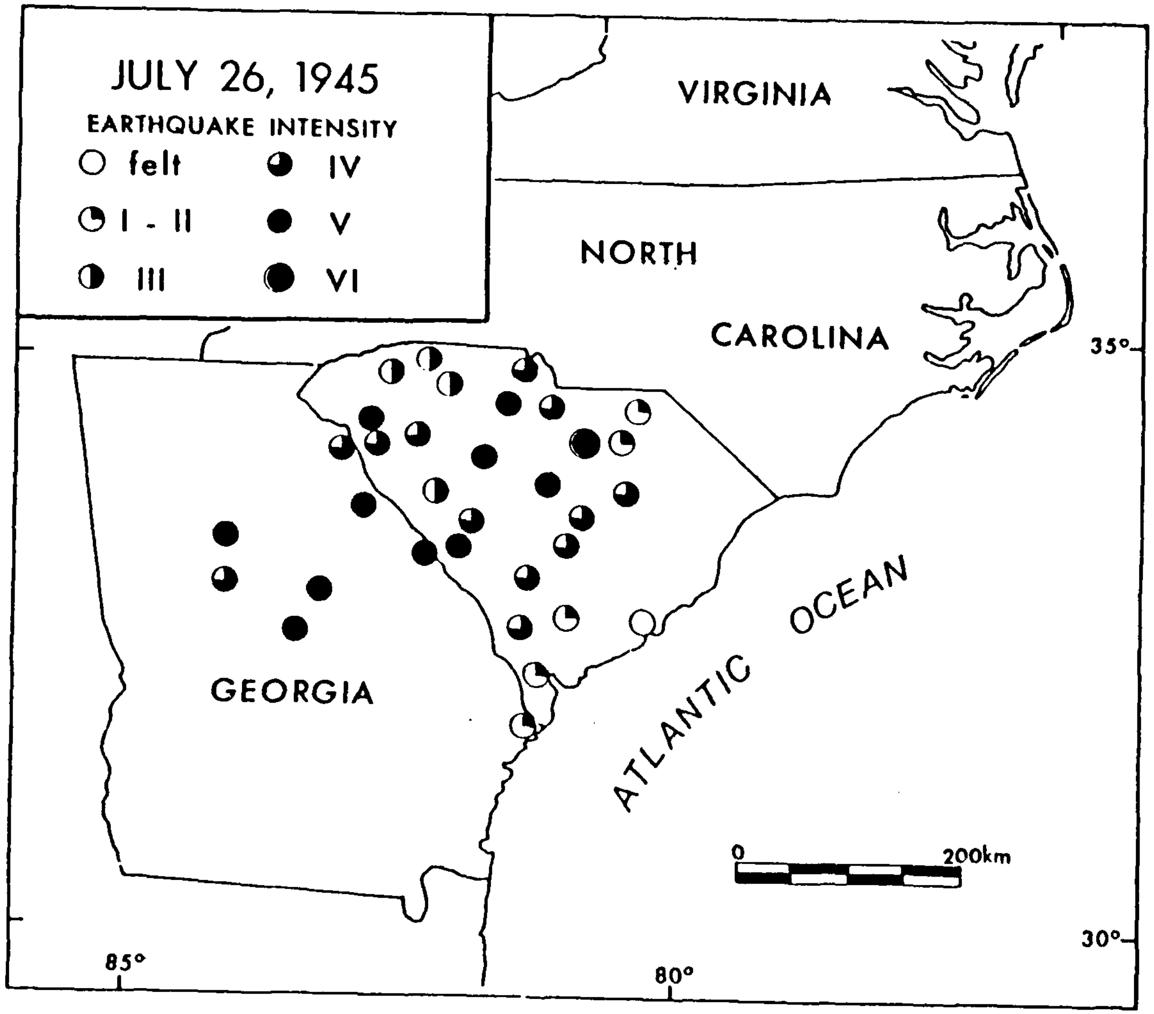


Figure 14d. MM intensity values at some locations for the intensity VI Columbia, S.C. earthquake of July, 1945. (From Visvanathan, 1980).

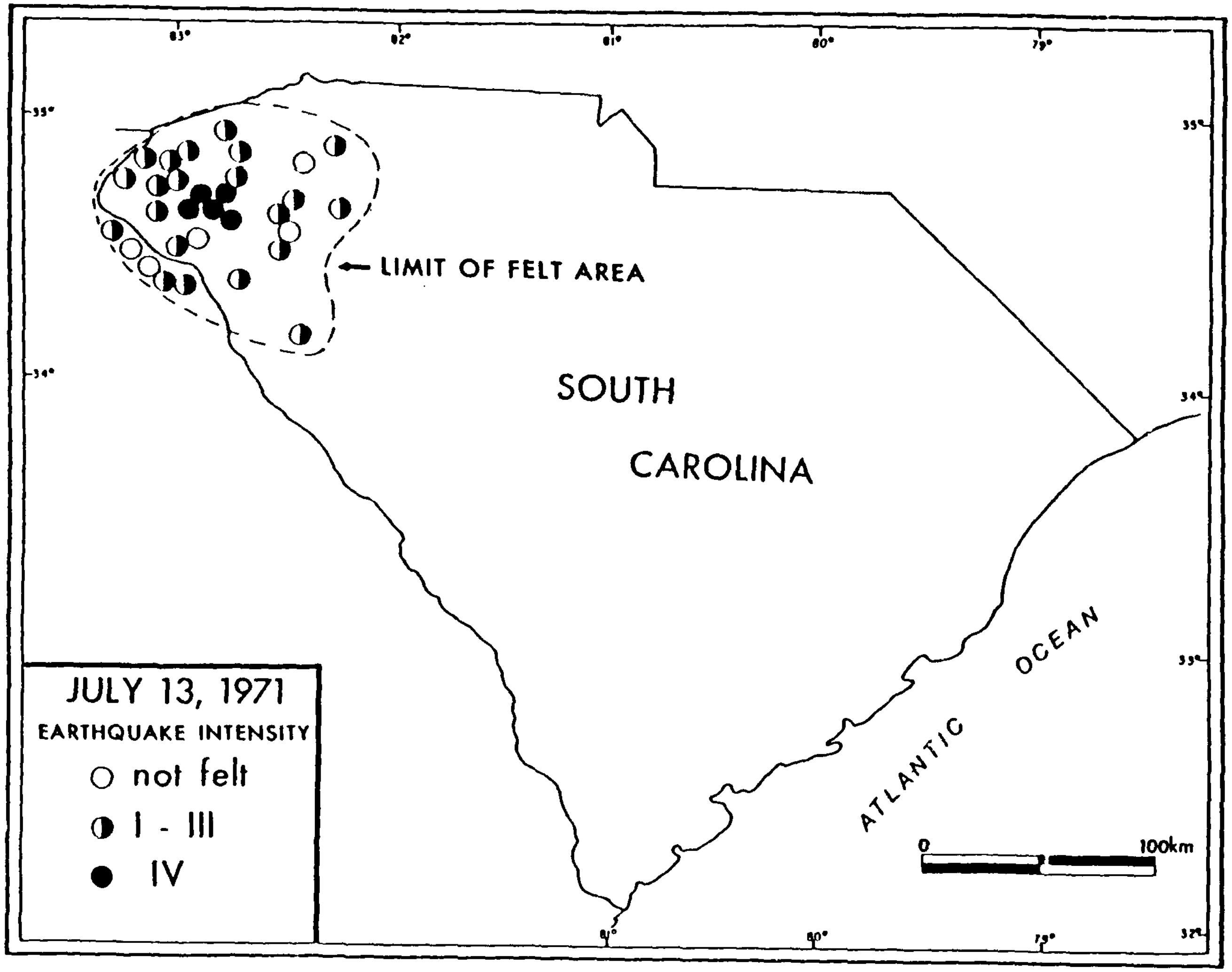


Figure 14e. MM intensity values at some locations for the intensity IV Seneca, S.C. earthquake of July, 1971. (From Visvanathan, 1980).

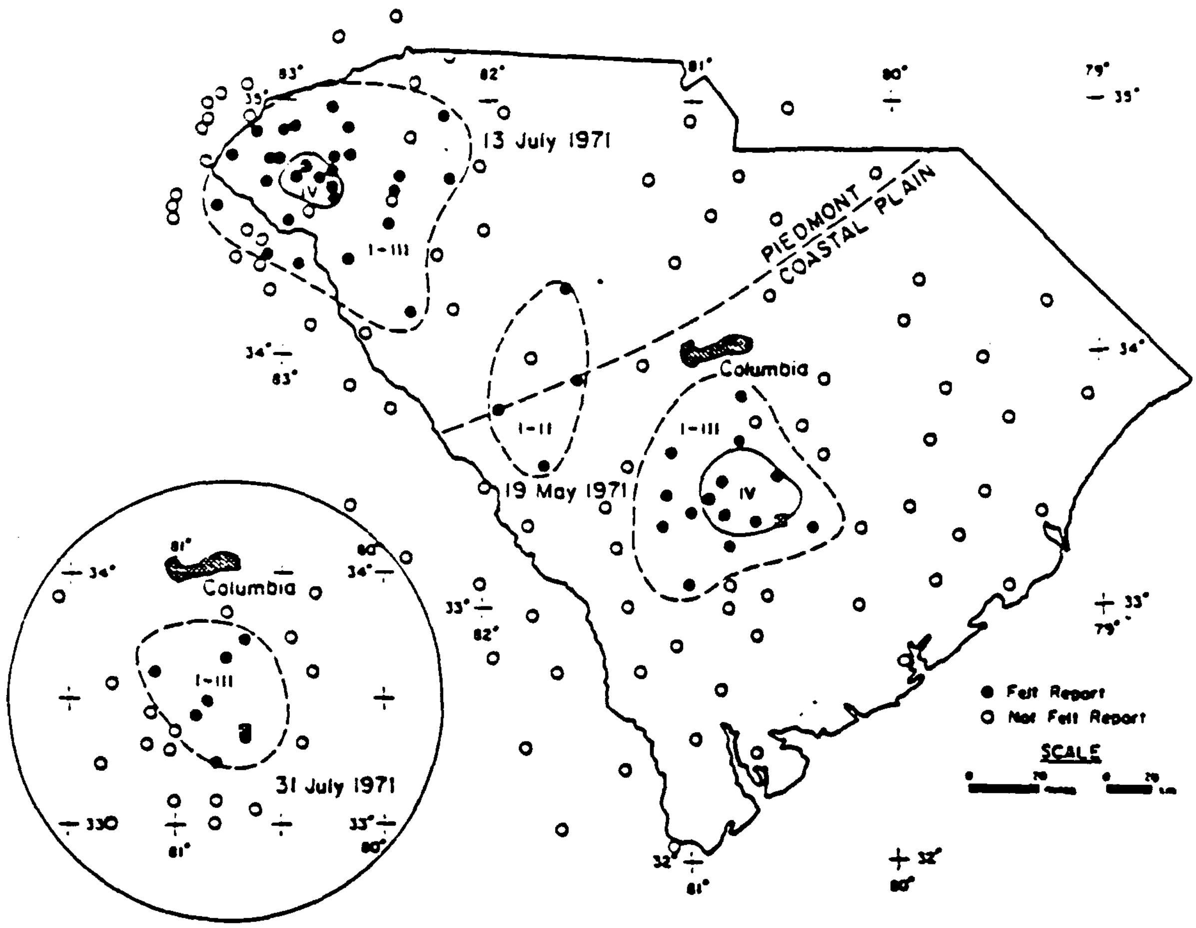


Figure 14f. Intensity values for three felt events in South Carolina in 1971 (From Bollinger, 1972). Compare the intensities for the July 1971 earthquake with Figure 14e.

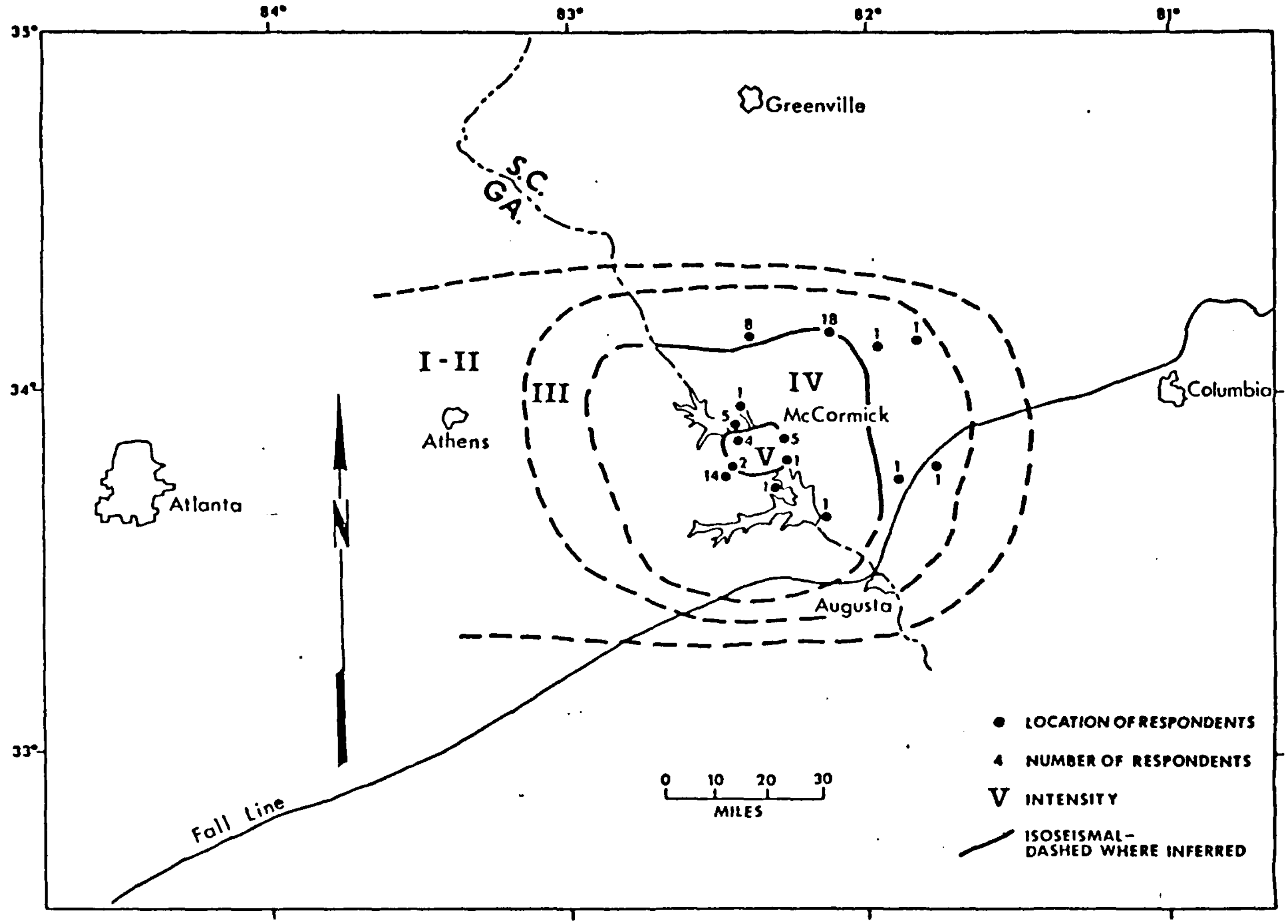


Figure 14g. Isoseismal map for the August 1974, Clark Hill earthquake of intensity V. (From Scheffler, 1976).

experience.

The project site lies in the Piedmont physiographic province, which has large tectonic stresses, is in a compressional stress regime, has rocks that are fractured and jointed, and where earthquakes have occurred in the past. Thus the microearthquake activity, the like of which is observed in other areas of the Piedmont, is likely to be observed. As no faults or major zones of weakness have been identified and no events located in the project area the prospects of seismicity must be treated as being equal to anywhere in the Piedmont region.

RIS, if it were to happen, would probably have occurred in the past. Now that over 25 years have elapsed since the impoundment of the dam, we would not expect any major RIS unless there were to be very sudden and very large changes in the lake levels that far exceed normal fluctuations.

The Kings Mountain shear zone, located to the south of the project area, has not displayed any propensity for seismicity. However, the 1913 Union County earthquake is suspected to have been associated with it. Therefore future activity on the Kings Mountain shear zone cannot be ruled out.

6.3. Maximum Earthquake

From an observation of the historical seismicity and the suggestion that the pattern of seismicity is spatially stationary, the largest event will be considered for each tectonic province and the anticipated intensity of shaking suggested for the project site.

The largest event in the Piedmont province occurred near Union County, S.C. in 1913. In our most conservative scenario, the largest event we would expect at the project site would be a repeat of this event with a MM intensity of VII-VIII.

In the next scenario a Piedmont event would be located on the Kings Mountain shear zone. Thus if the Union County earthquake was to reoccur on the Kings Mountain shear zone, which at its closest location is 10 mile to the south of the project site, a MM intensity of VI-VII would be felt at the project site.

The largest event at Charleston in 1886 was associated with intensity X. A repeat of that event would have a MM intensity of about VI at the project site.

The largest event in the southern Appalachian seismic zone has been associated with a MM intensity VIII. This zone, which is over 100 miles from the project site, would be felt at the project site with an intensity of < VI.

The largest earthquake in the Piedmont thought to have been induced had a magnitude < 4.5. Considering that we do not expect any resurgence of RIS at Hartwell, any possible RIS would be small.

6.4. Conclusions

Although distant events have been felt at Hartwell in the past, the prospect of a future large earthquake at the project site is comparable to any other location in the Piedmont, i.e. low. The most conservative estimate of the size of the maximum earthquake at the project site is an event equal in size to the Union County event, which is about a magnitude 5.0 to 5.5 with an epicentral intensity of VII-VIII.

7. SUMMARY AND CONCLUSIONS

In this report, we presented a review of available data on the tectonics and seismicity data that could be used to assess the seismic potential at the Hartwell project site. The following conclusions were reached:

1. The project site lies in the Piedmont physiographic province, which consists of alternating belts of differing lithologies and metamorphic grades. In the absence of any active faults and a high compressional stress regime, any seismicity would be due to the interaction of an ambient stress field on pre-existing zones of weakness. The predominant zones of weakness in the Piedmont are networks of joints, thus limiting the size of the largest earthquake.

2. The largest recorded earthquake in the eastern United States (maximum MMI=X) occurred in 1886 near Charleston, South Carolina, approximately 300 km from the present dam at Lake Hartwell. It is believed that tectonic structures associated with this event have been identified and that possibly three other events of this magnitude have occurred in the Charleston area prior to historical recording.

3. The largest earthquake within the Piedmont physiographic province, in which Lake Hartwell lies, occurred at Union County and was assigned a maximum intensity (MMI) of VII-VIII.

4. The most seismically active region in the southeastern U.S. is currently the southern Appalachian seismic zone within the Blue Ridge and Valley and Ridge physiographic provinces. The closest extent of this seismic zone lies within 100 km of the Lake Hartwell dam. The largest earthquake recorded within this zone resulted in a maximum intensity (MMI) of VIII.

5. The maximum magnitude earthquake identified as triggered by any reservoir in the Piedmont province is less than 4.5.

6. Lake Hartwell covers a larger surface area and reservoir capacity than other seismically active lakes (Jocassee and Monticello) in the region. The maximum depth at Hartwell is within the range of depths of these other impoundments.

7. Water level fluctuations at Hartwell are comparable to those experienced at impoundments which have triggered seismicity. Such fluctuations perturb the in-situ stress field and can trigger seismicity in the immediate vicinity of the lake.

8. Due to the lack of instrumentation, the existence or extent of any microearthquake activity at Hartwell is unknown.

9. Induced seismicity triggered by the initial filling of Hartwell is expected to have declined toward the background (natural) level of activity by now. Thus barring sudden large lake level changes (which exceed changes in the past), we would not expect any significant new RIS at Lake Hartwell.

10. A search for the occurrence of seismicity at the project site revealed that, few earthquakes have been attributed to the present site of Lake Hartwell, either historically or since seismographic networks were established in the mid 1970's. Thus, since impoundment, Hartwell has been relatively aseismic at an earthquake threshold of $M > 2.5$.

11. Although distant events have been felt at Hartwell in the past, the prospect of a future large earthquake at the project site is comparable to any other location in the Piedmont, i.e. low. The most conservative estimate of the size of the maximum earthquake at the project site is an event equal in size to the Union County event, which is about a magnitude 5.0 to 5.5 with an epicentral intensity of VII-VIII.

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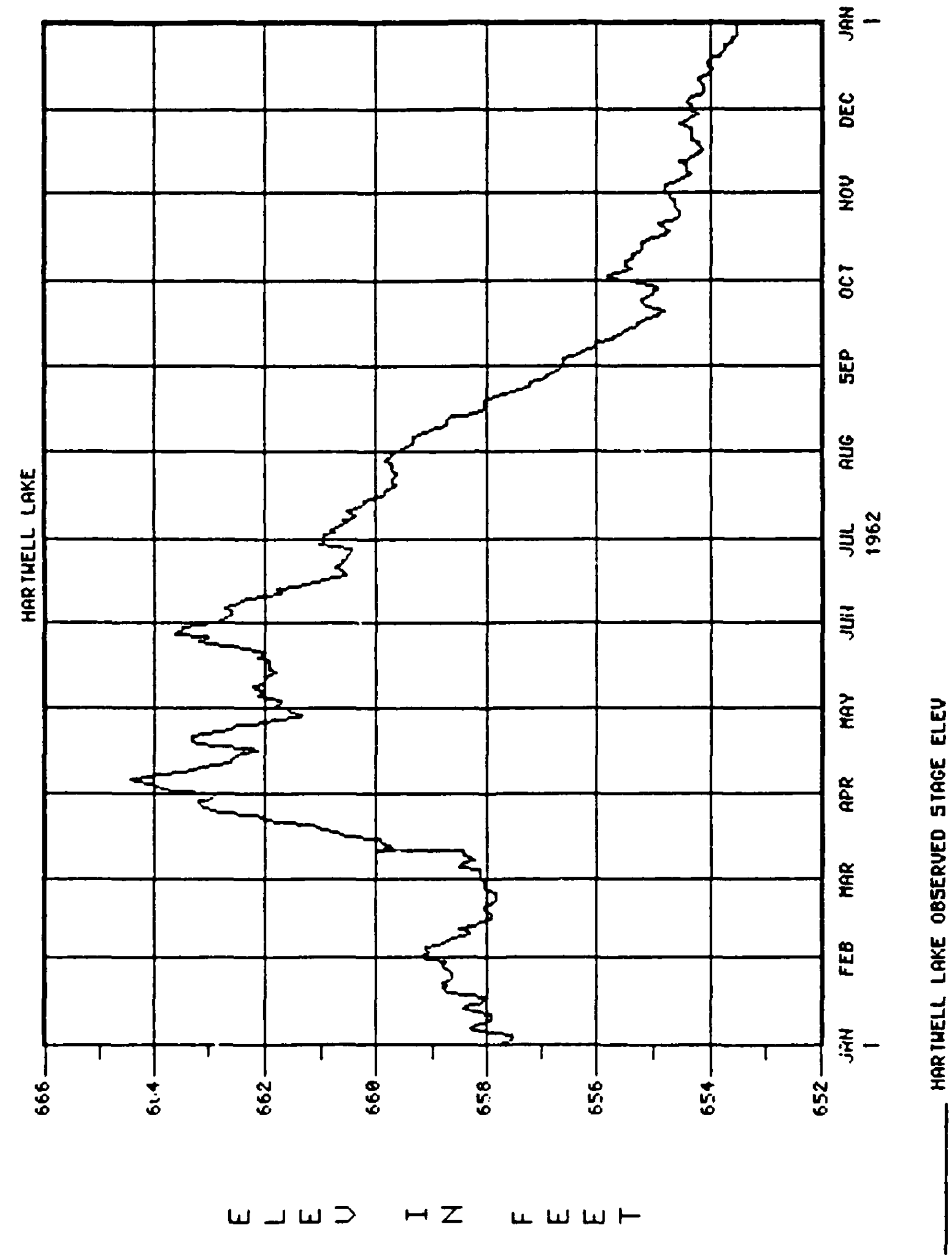
APPENDIX 1

Lake Elevation at Lake Hartwell From 1962 Through 1987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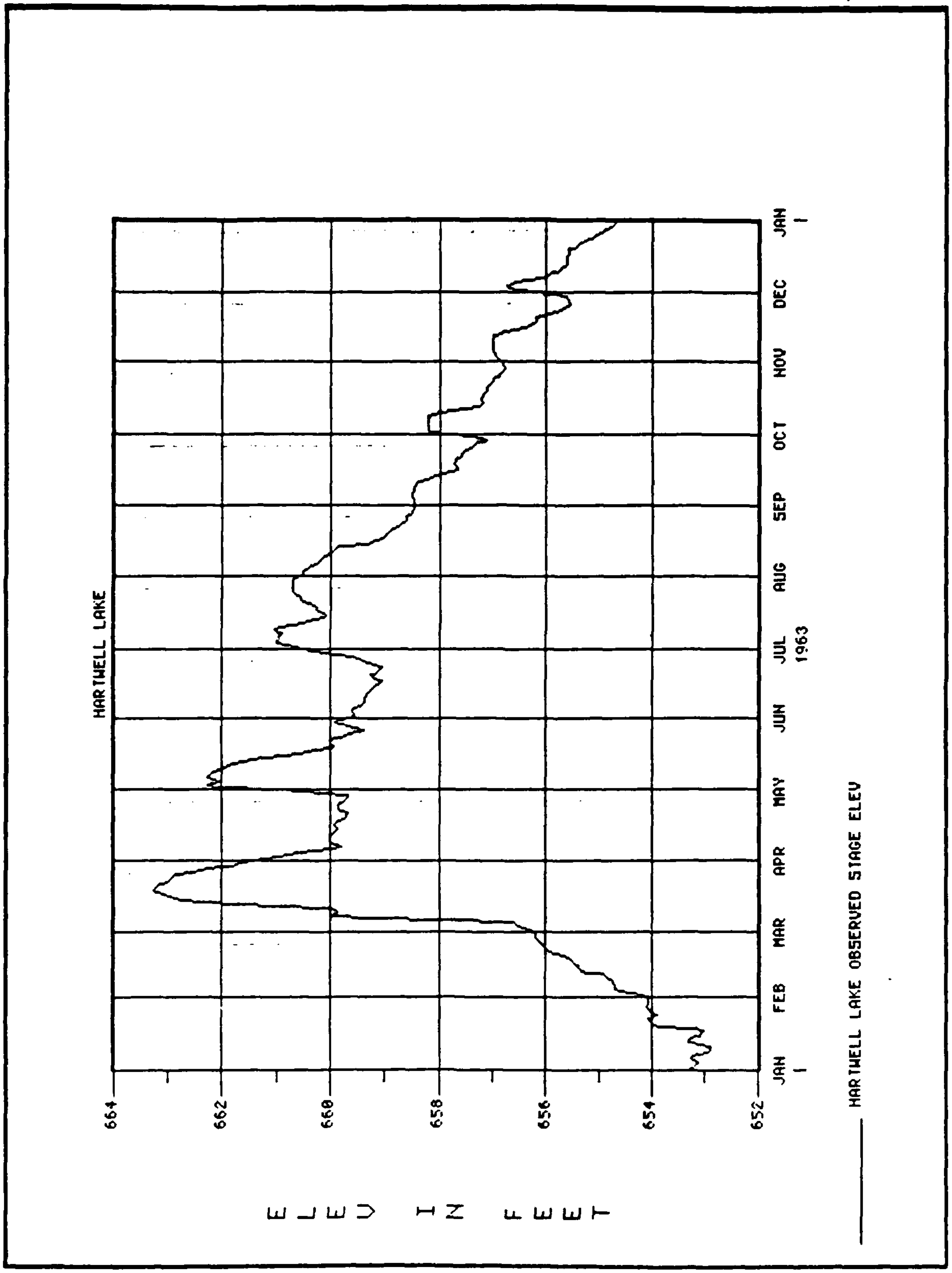
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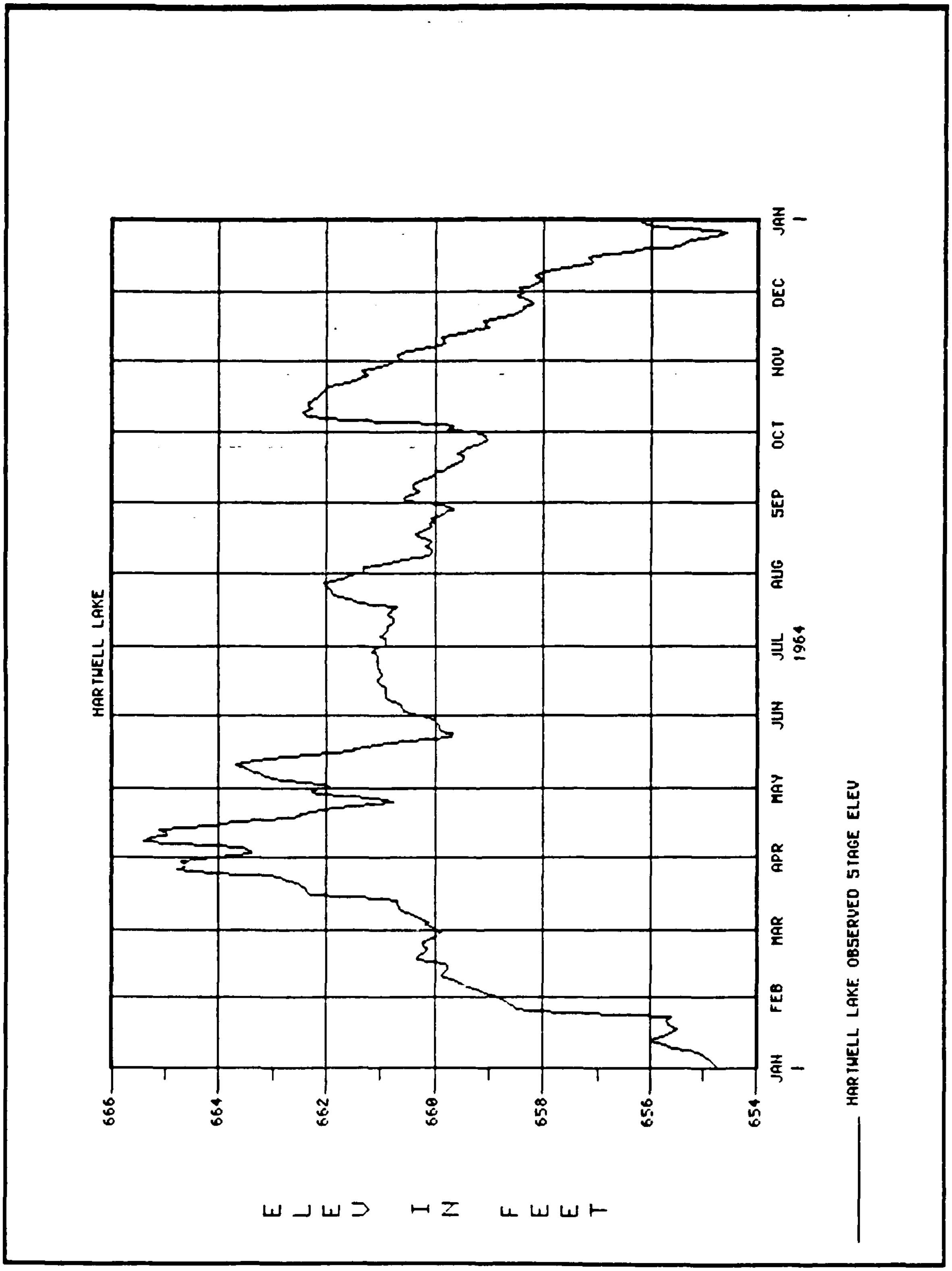
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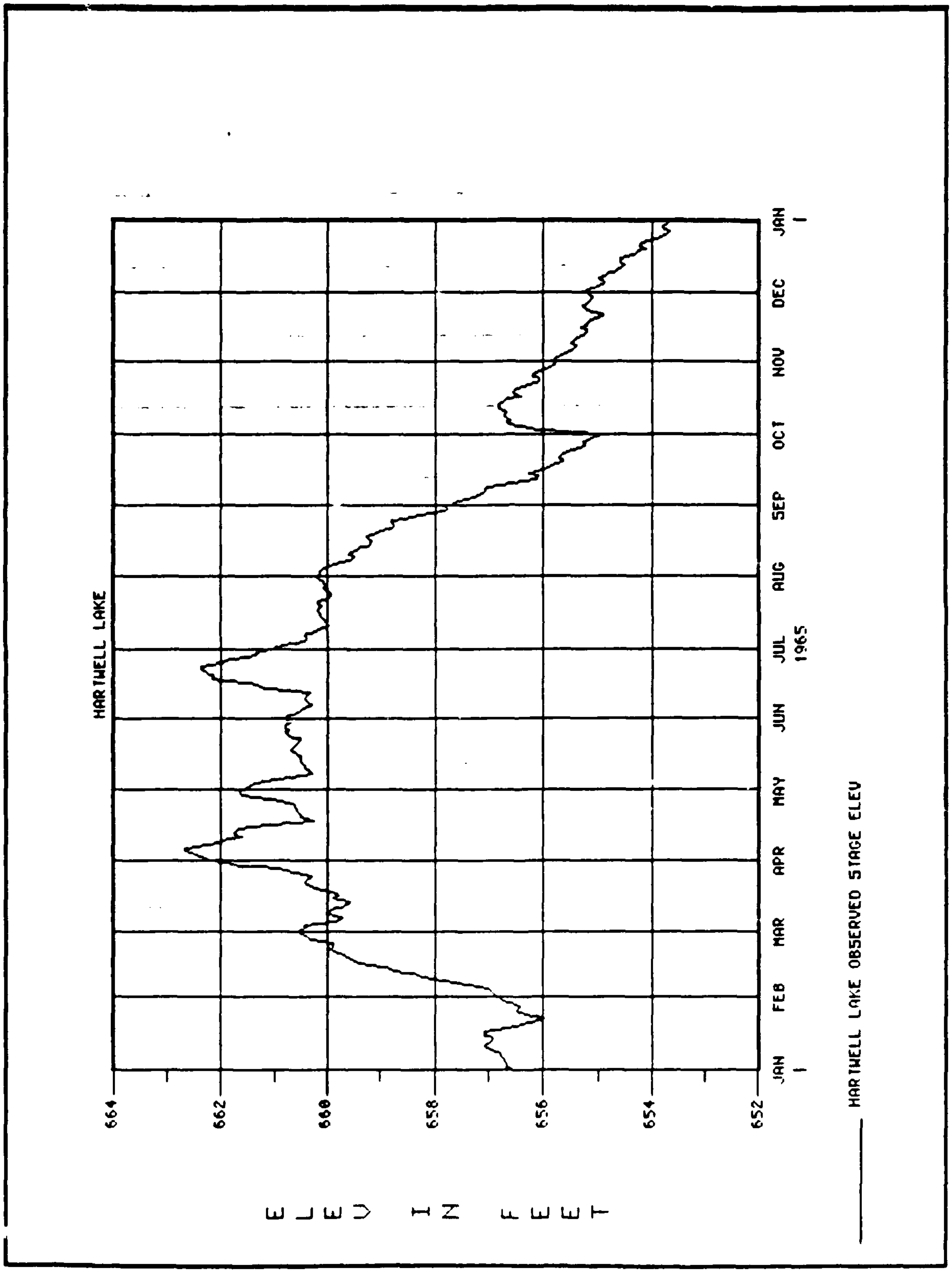
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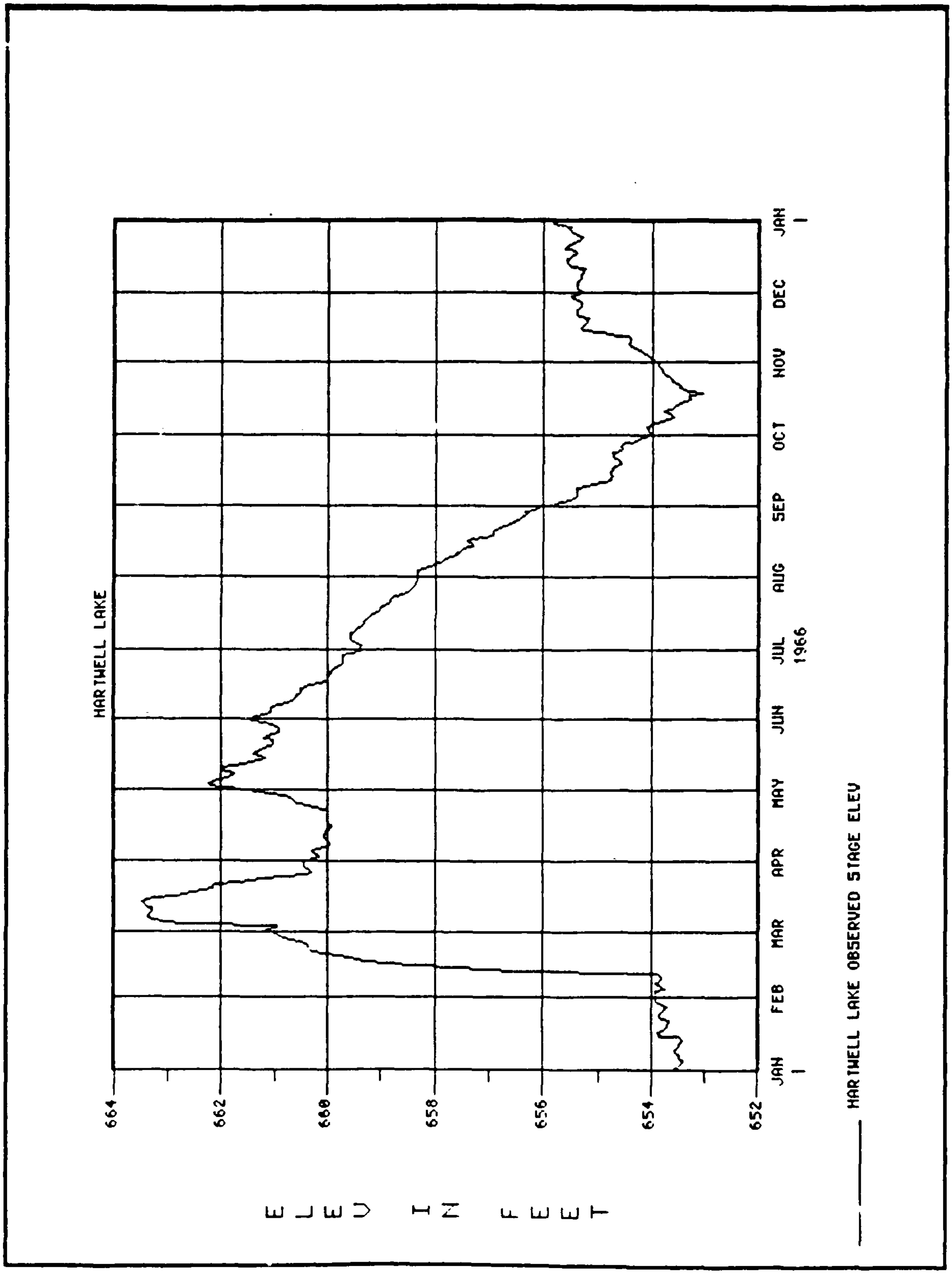
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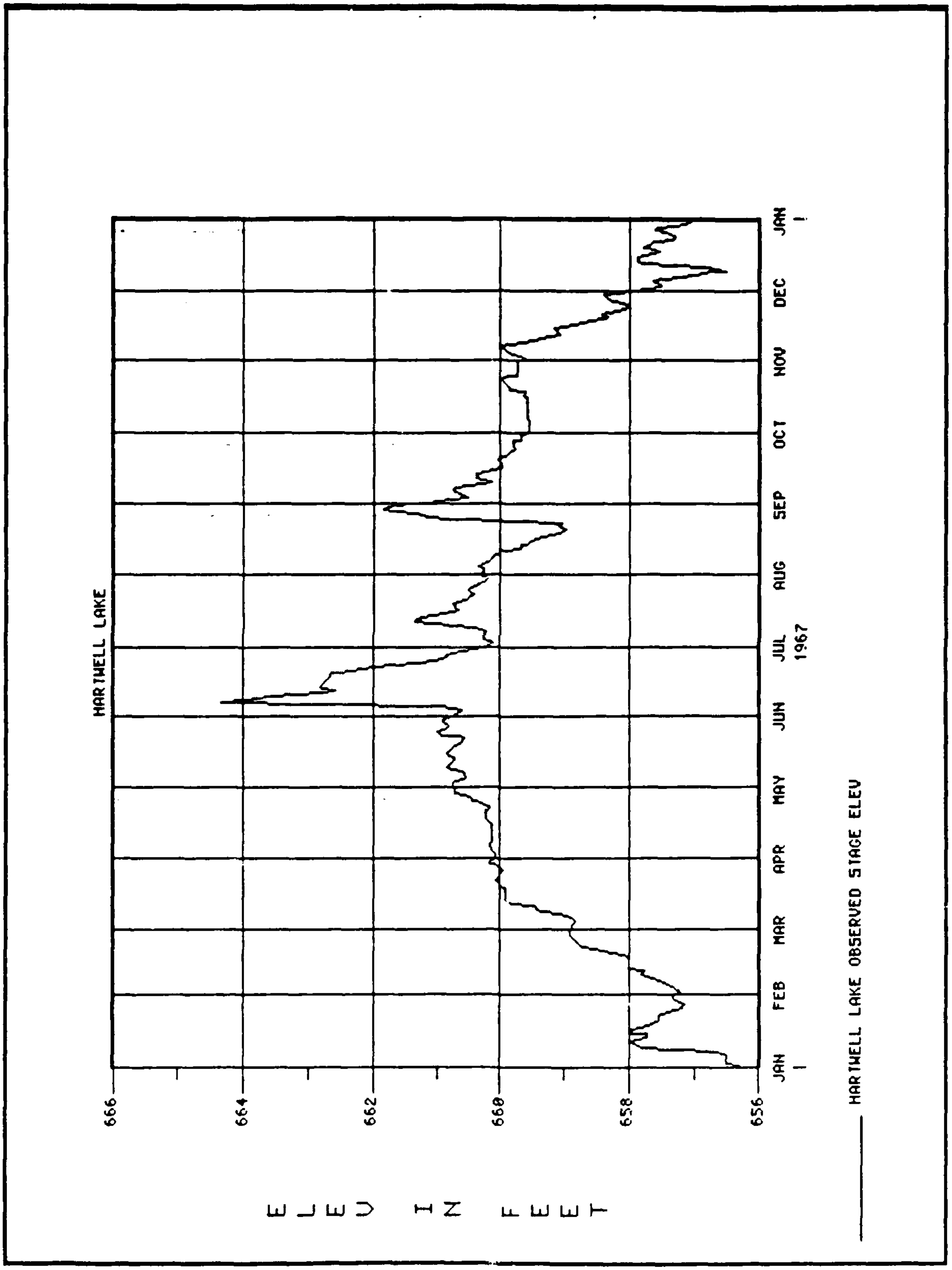
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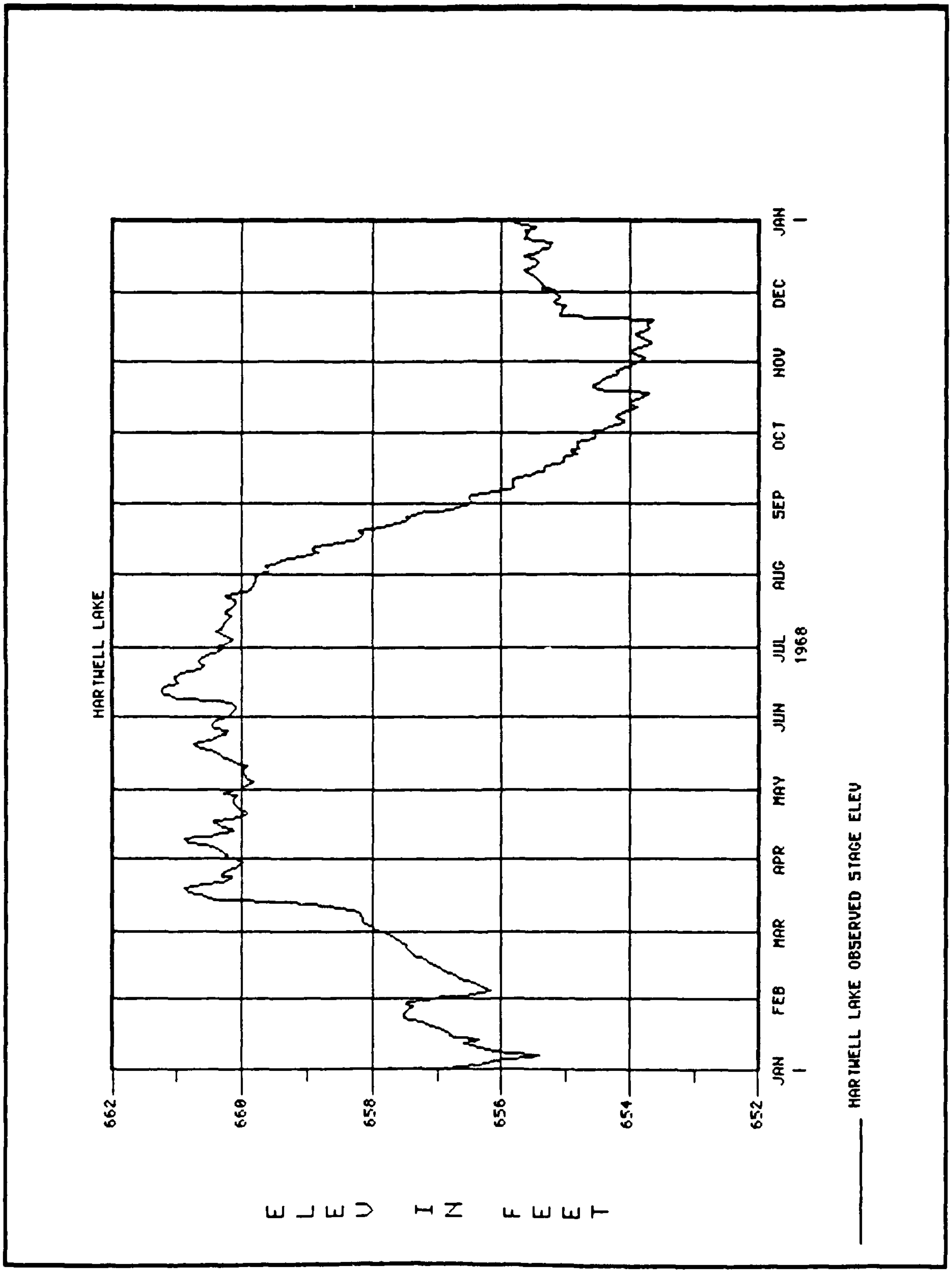
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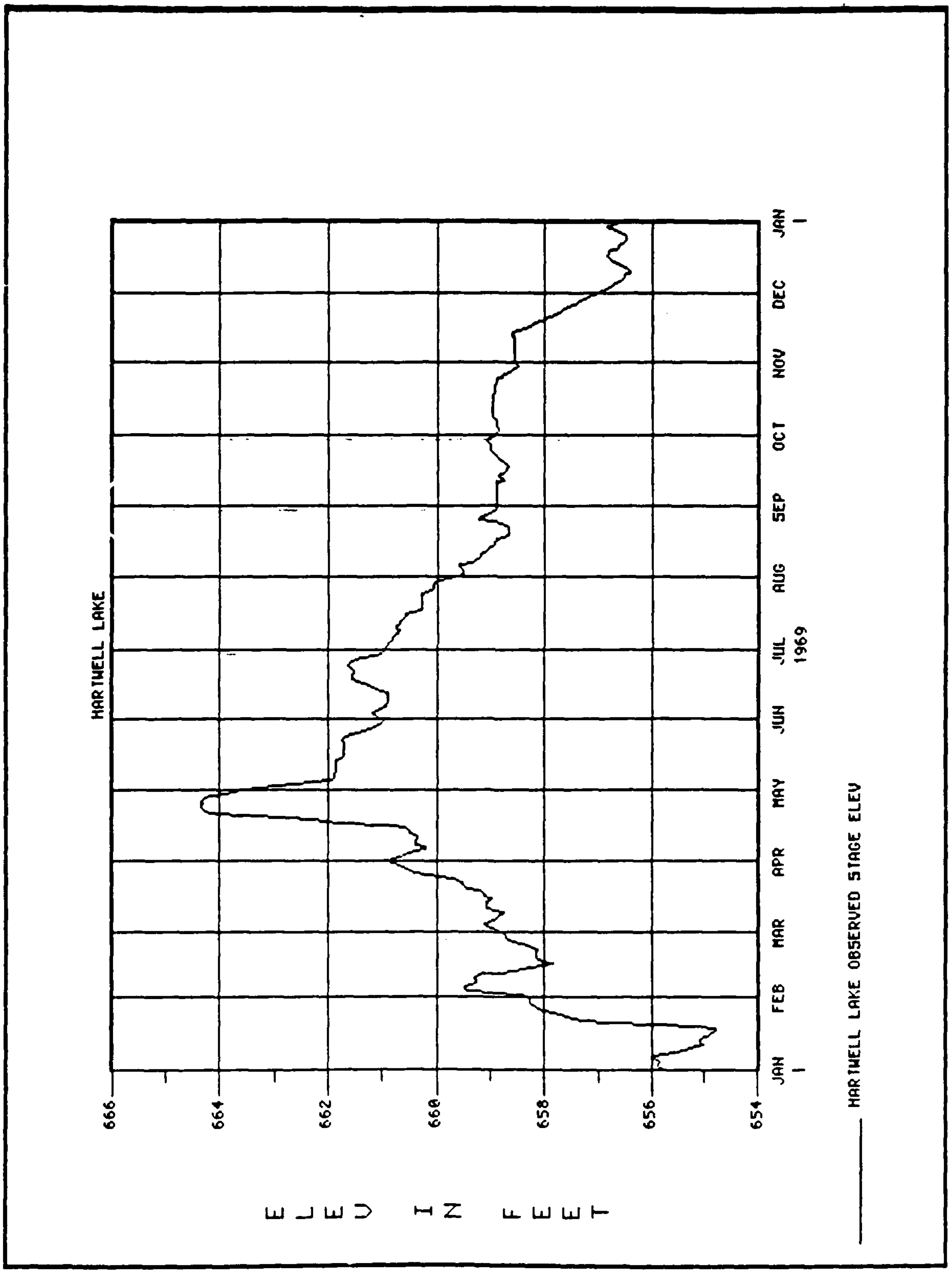
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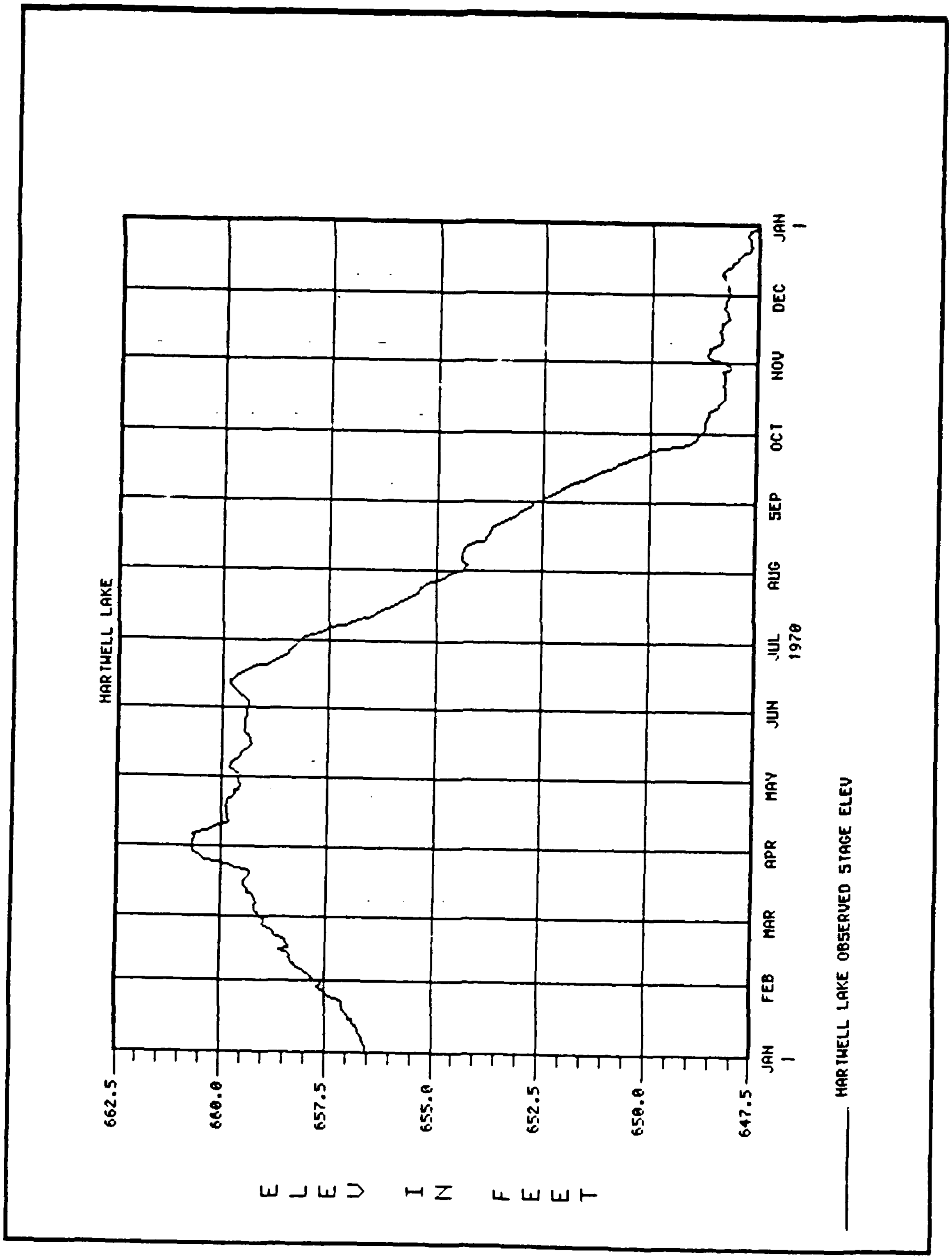
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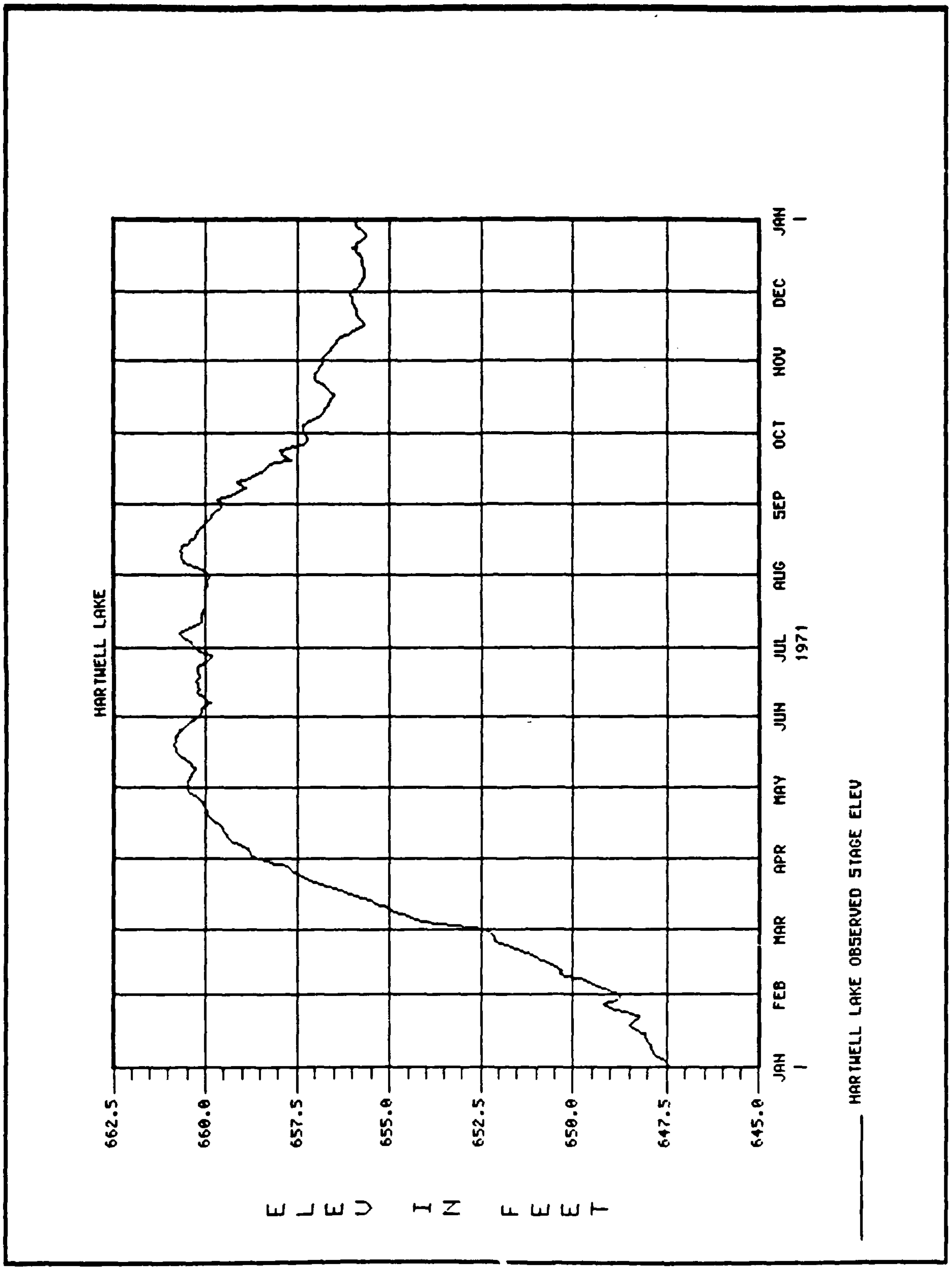
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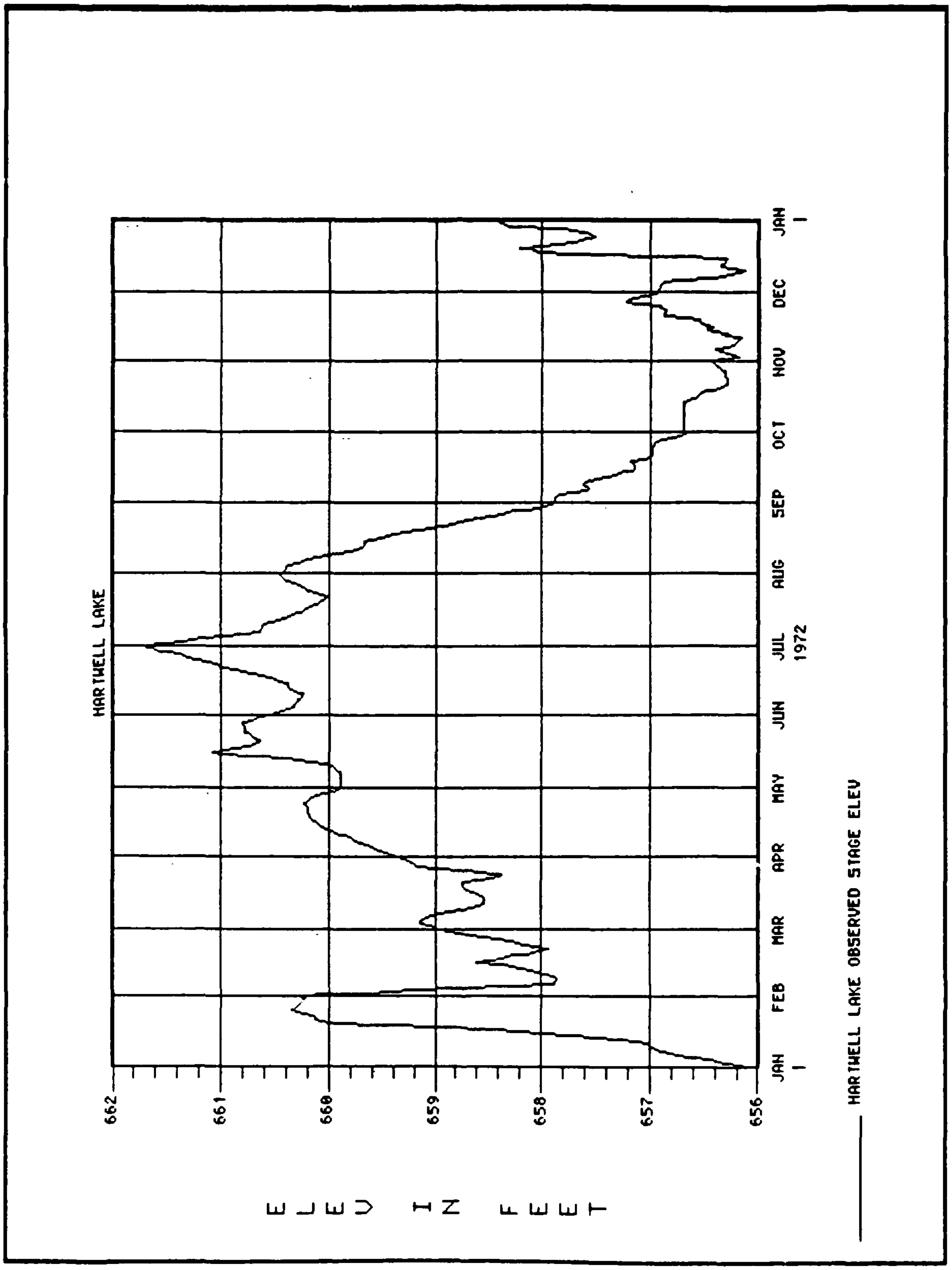
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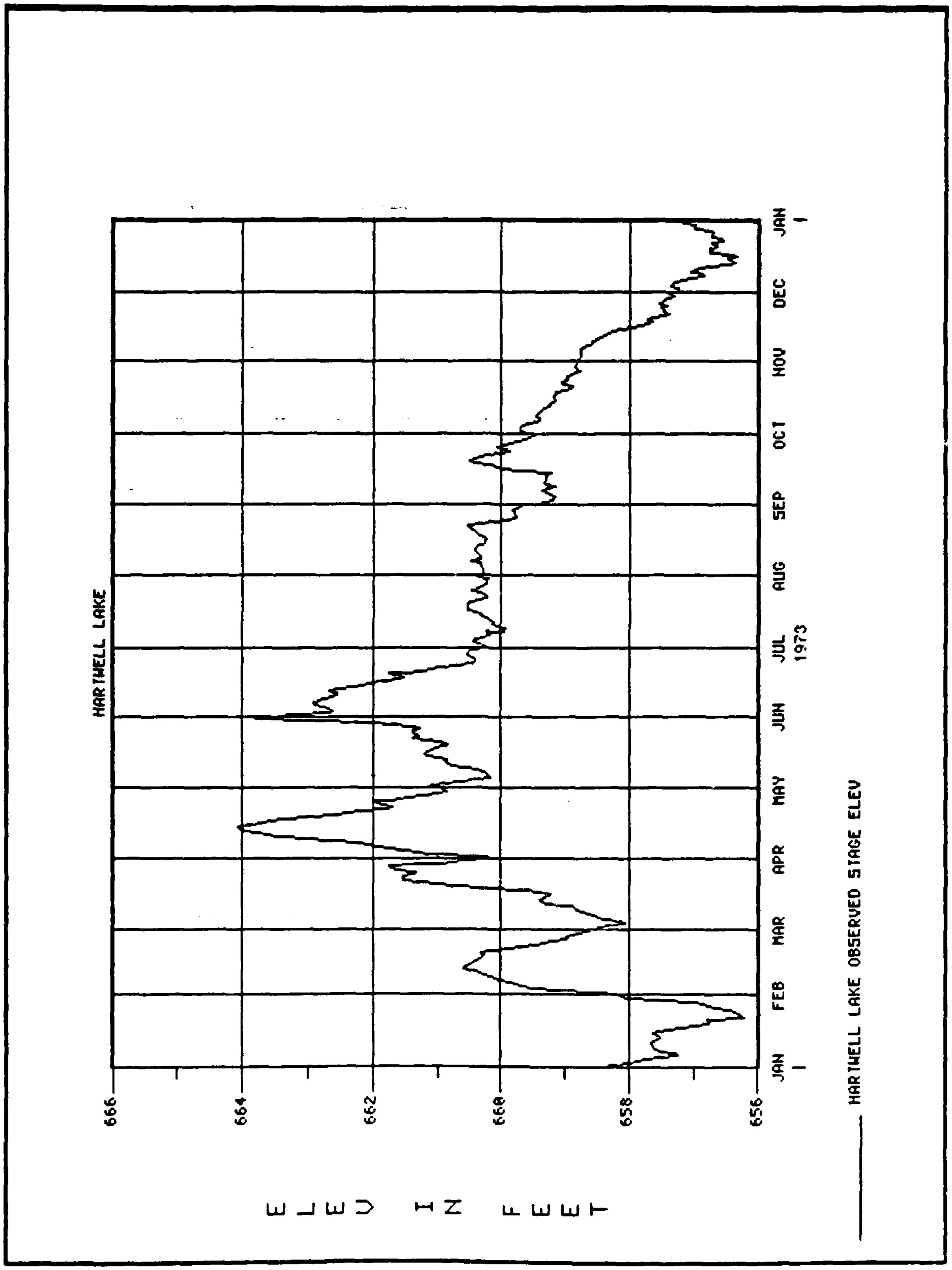
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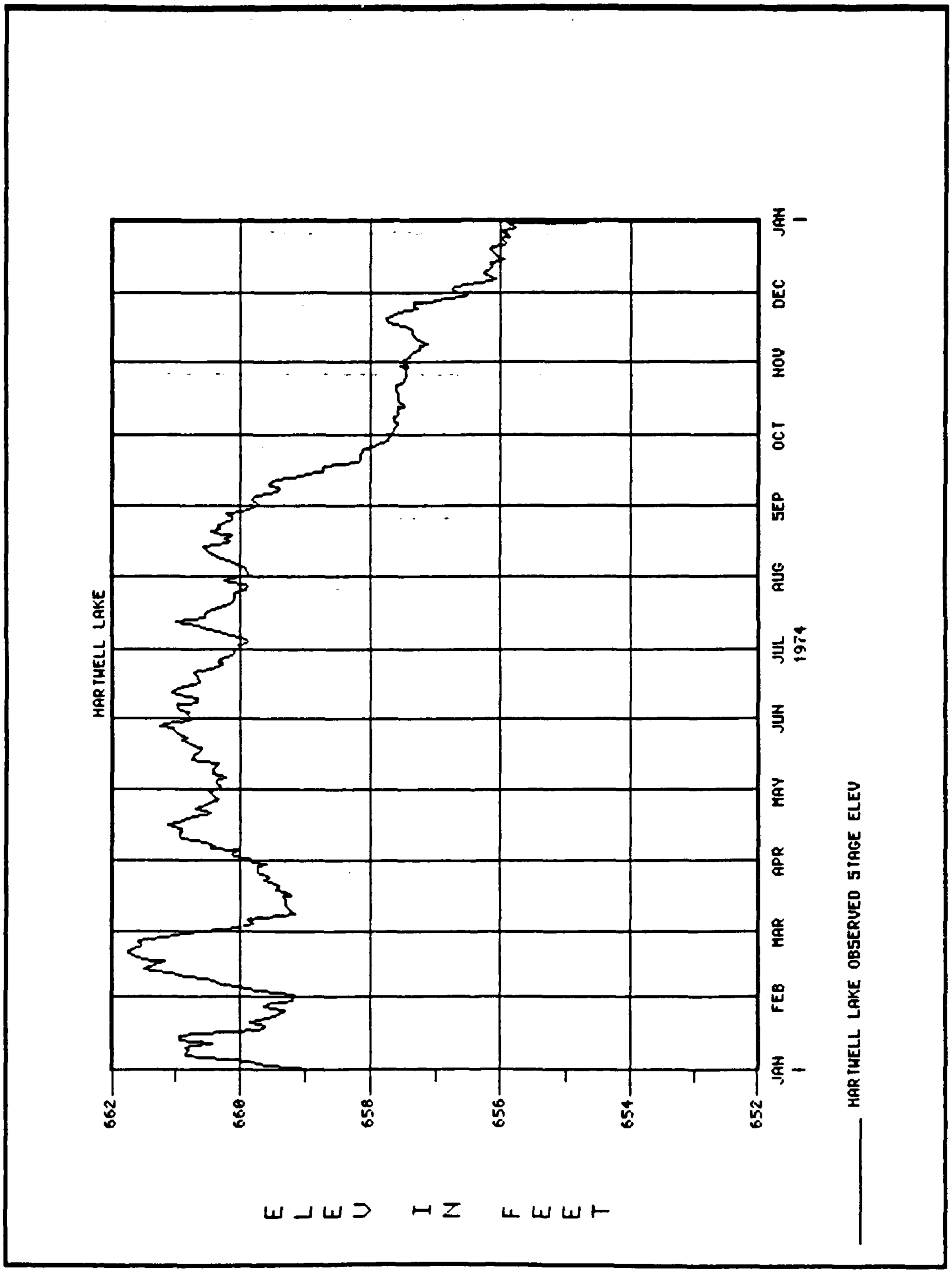
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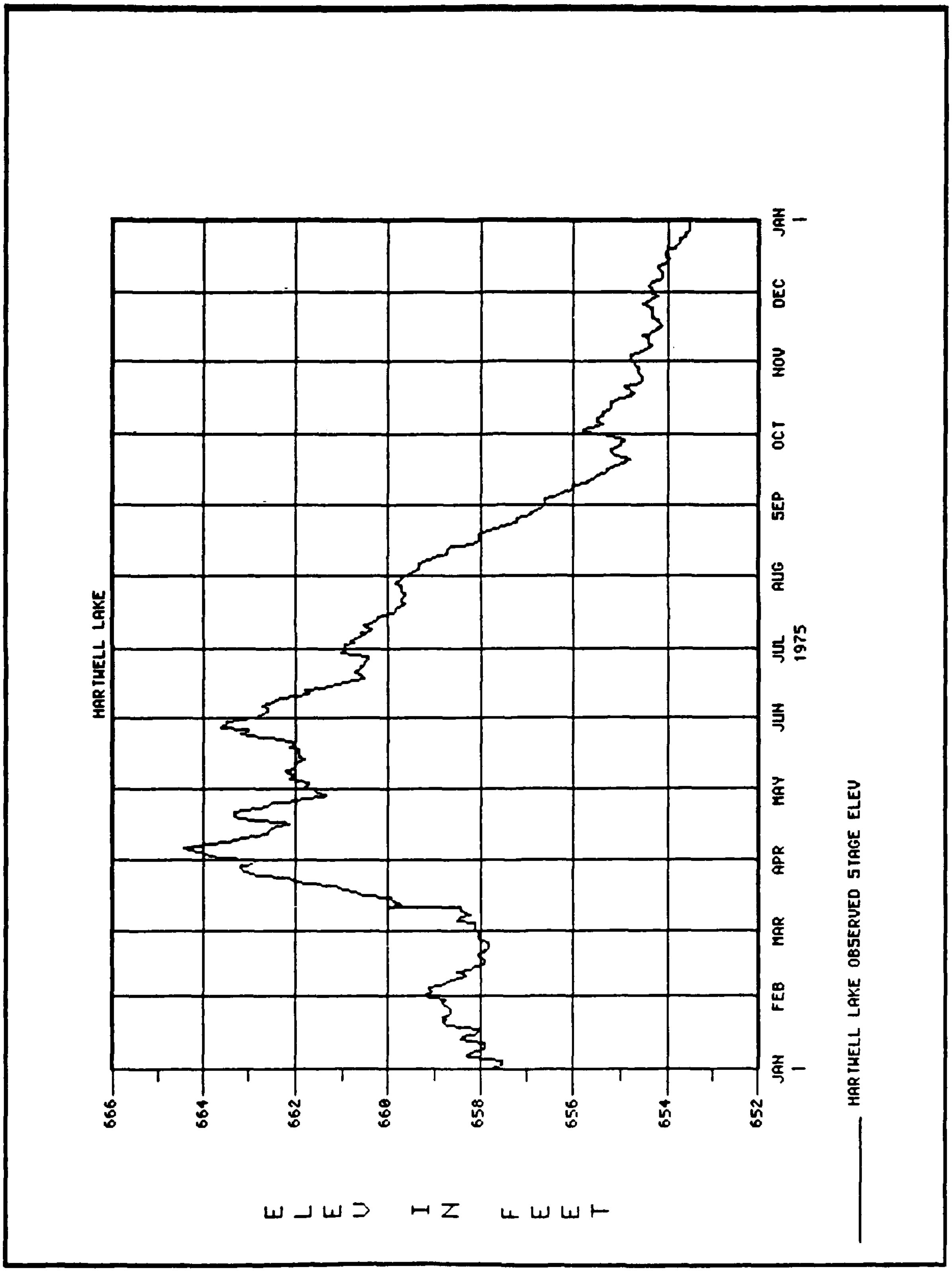
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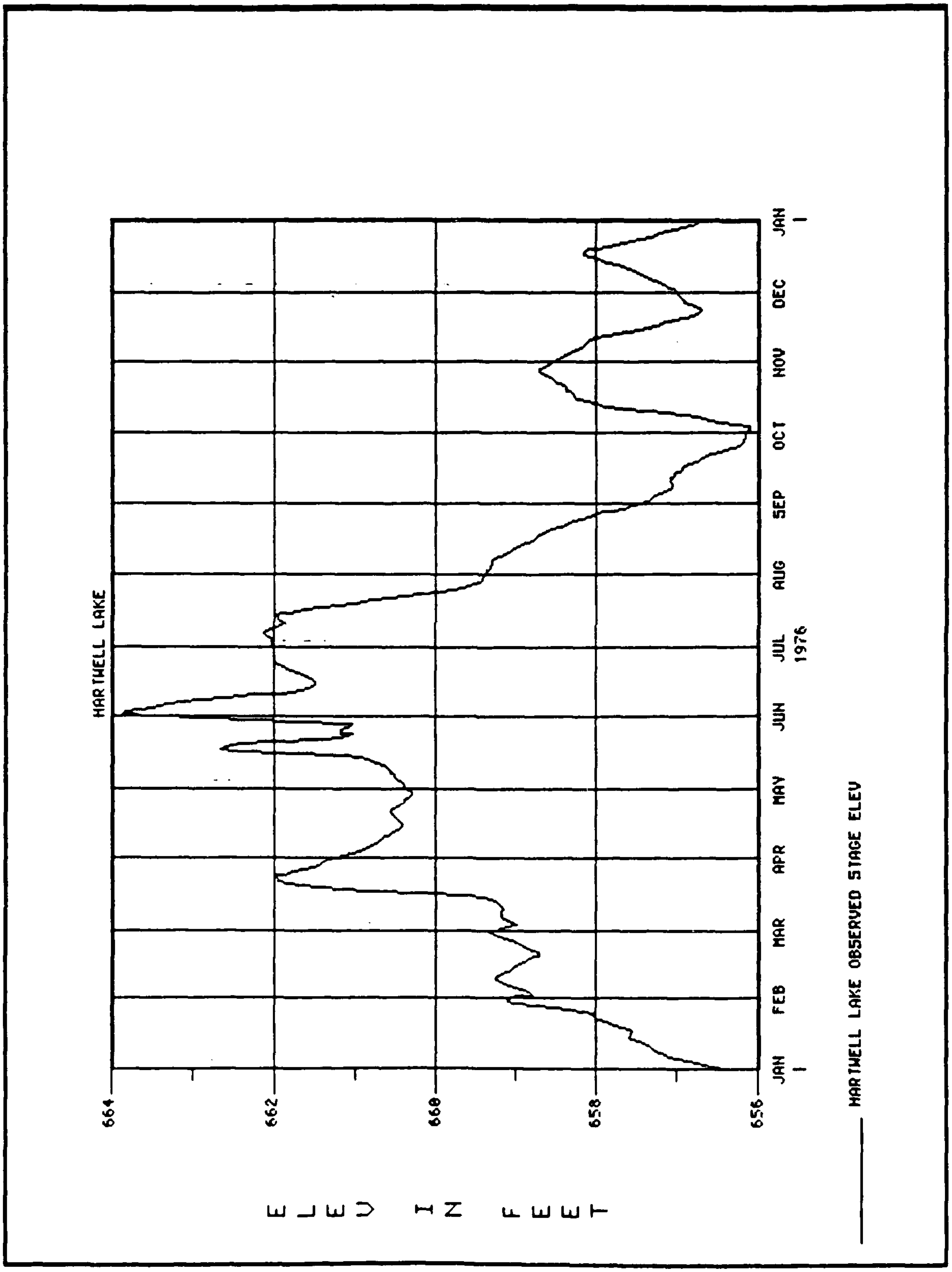
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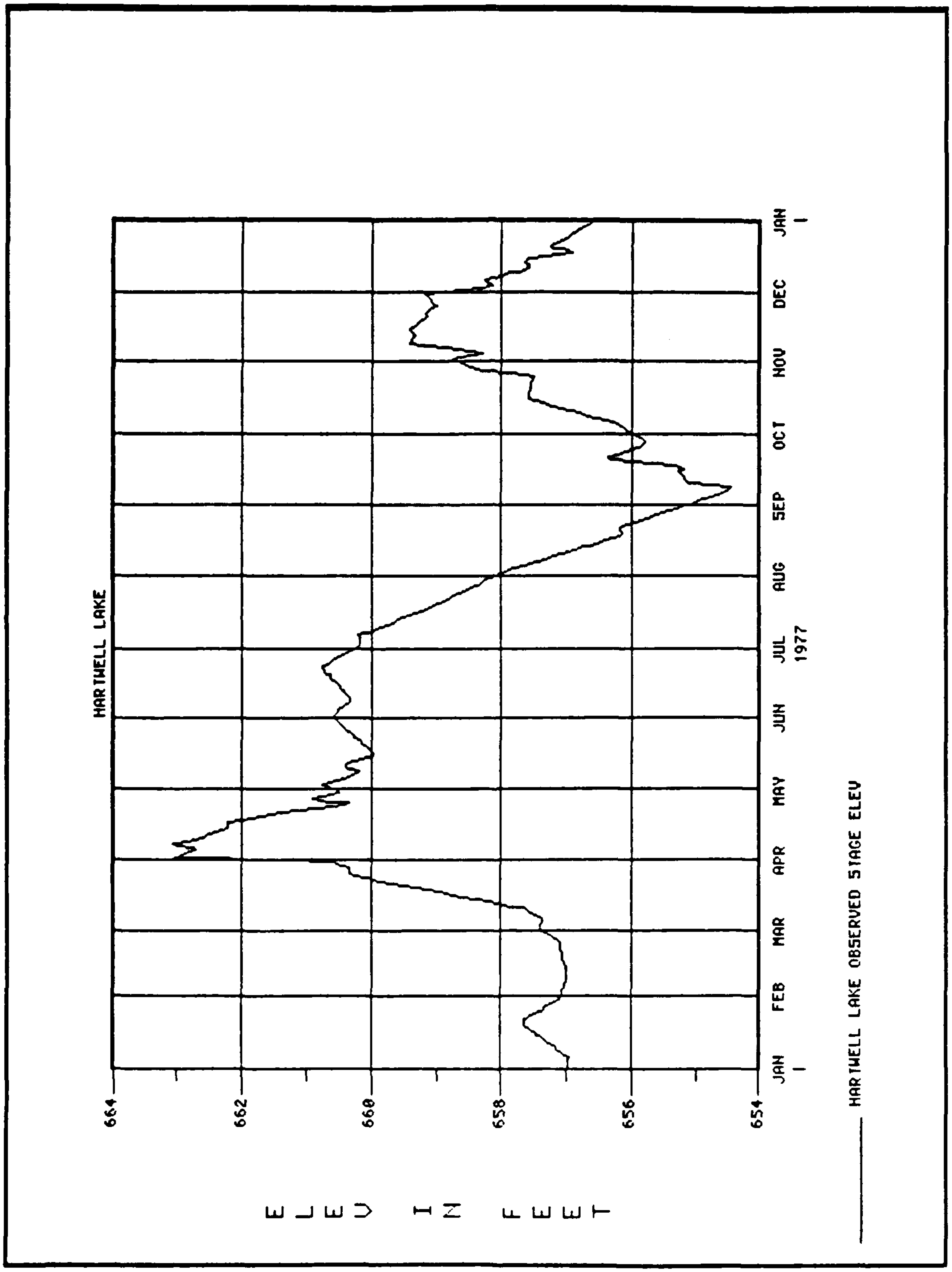
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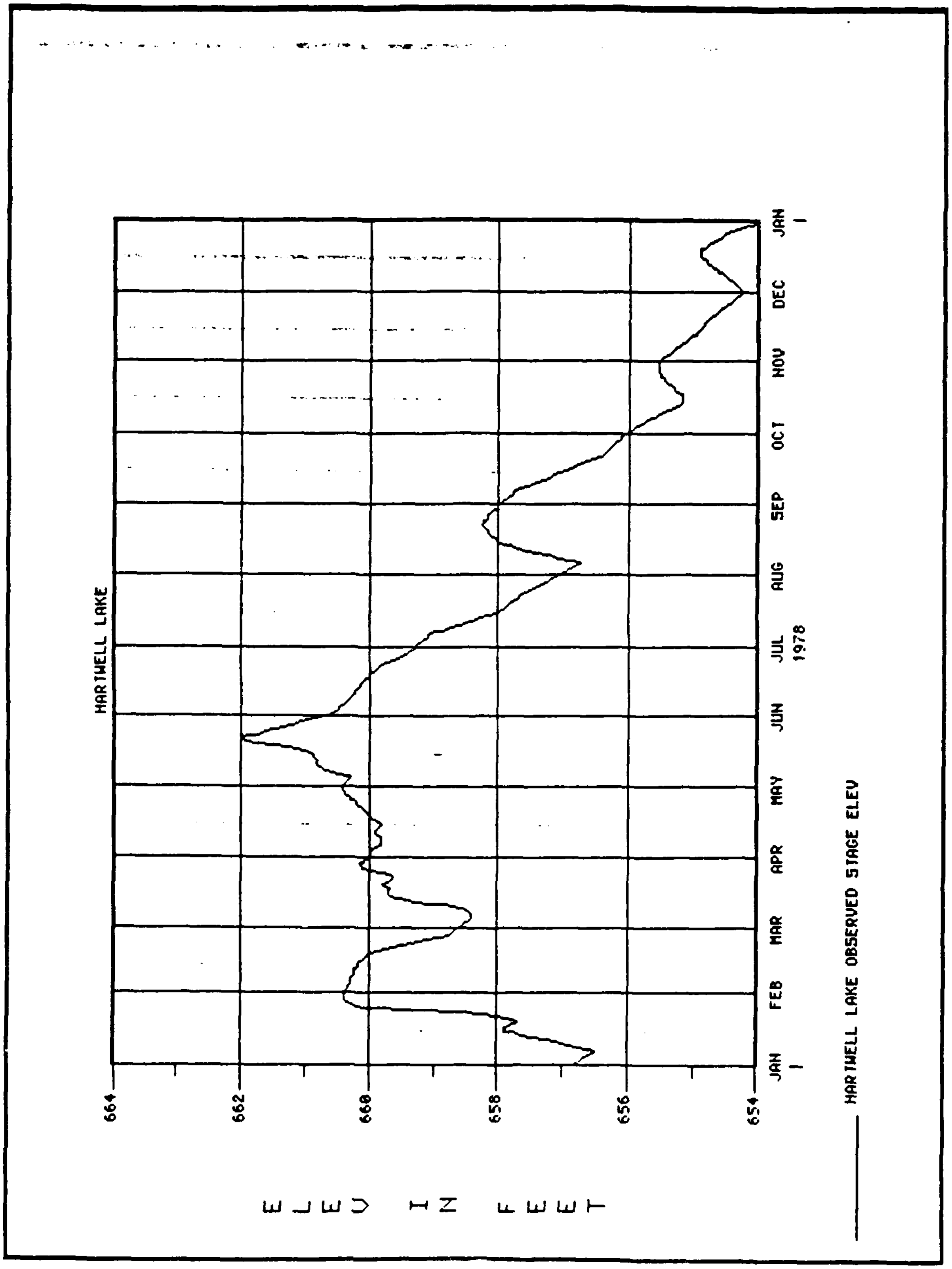
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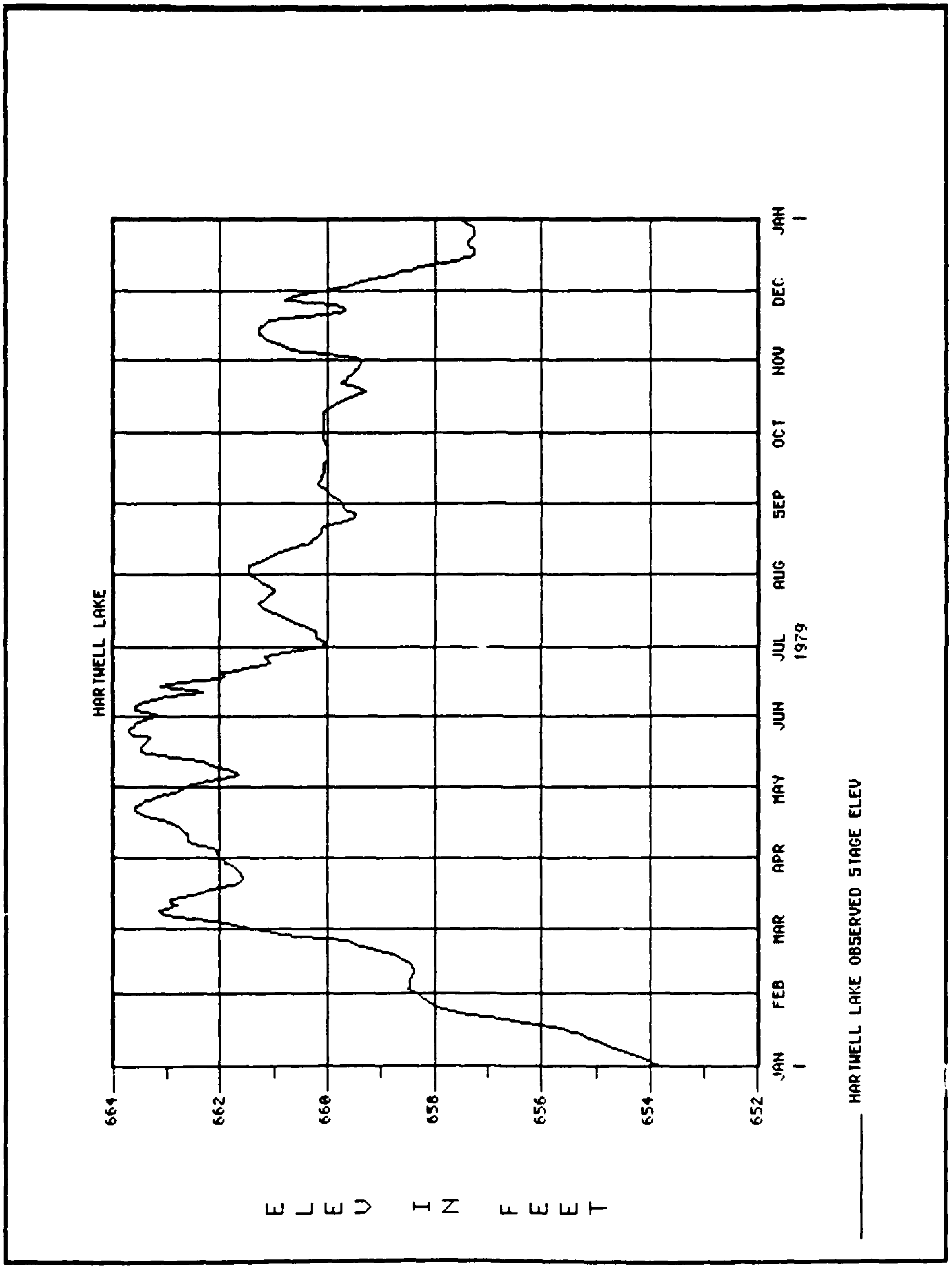
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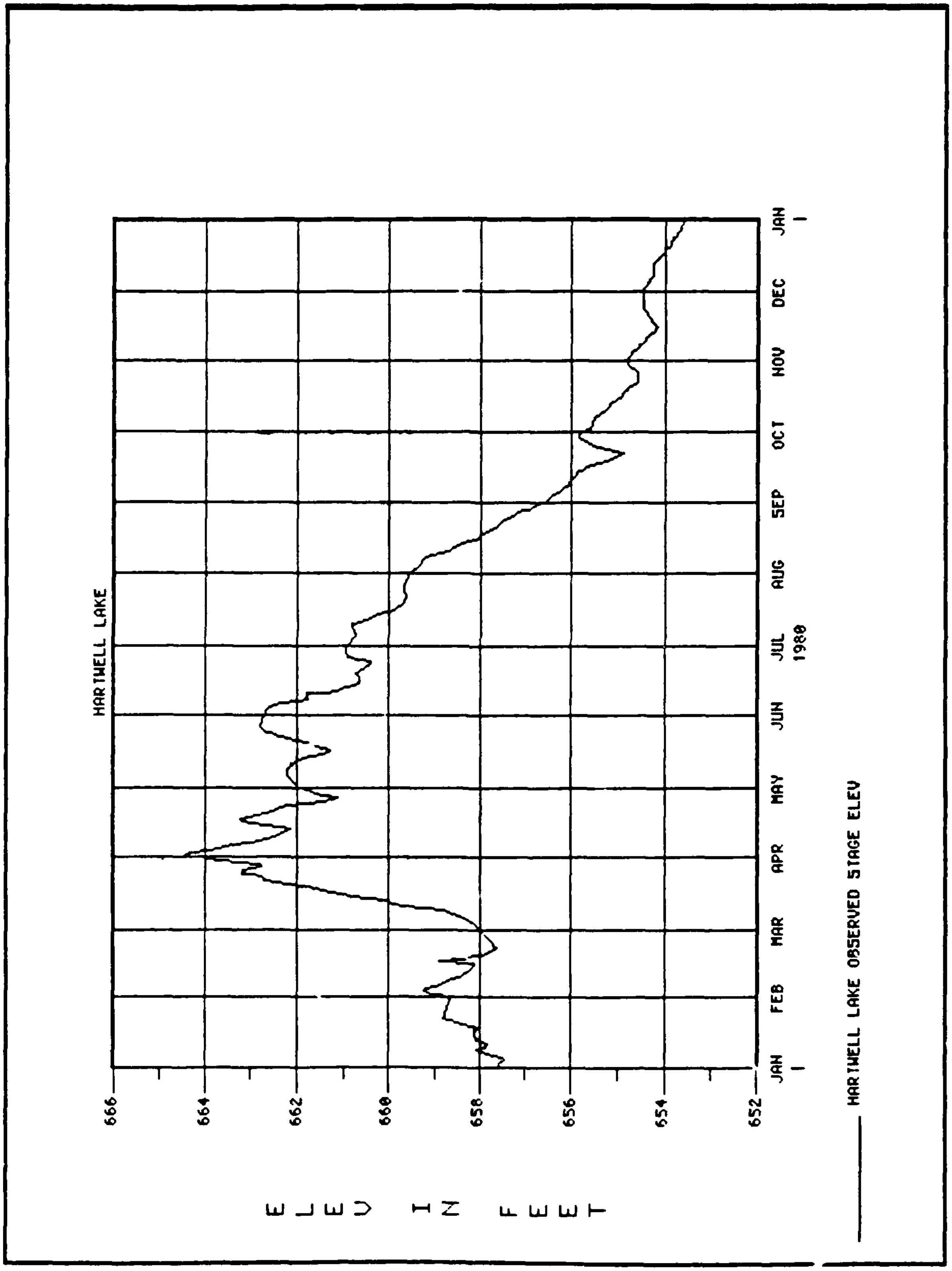
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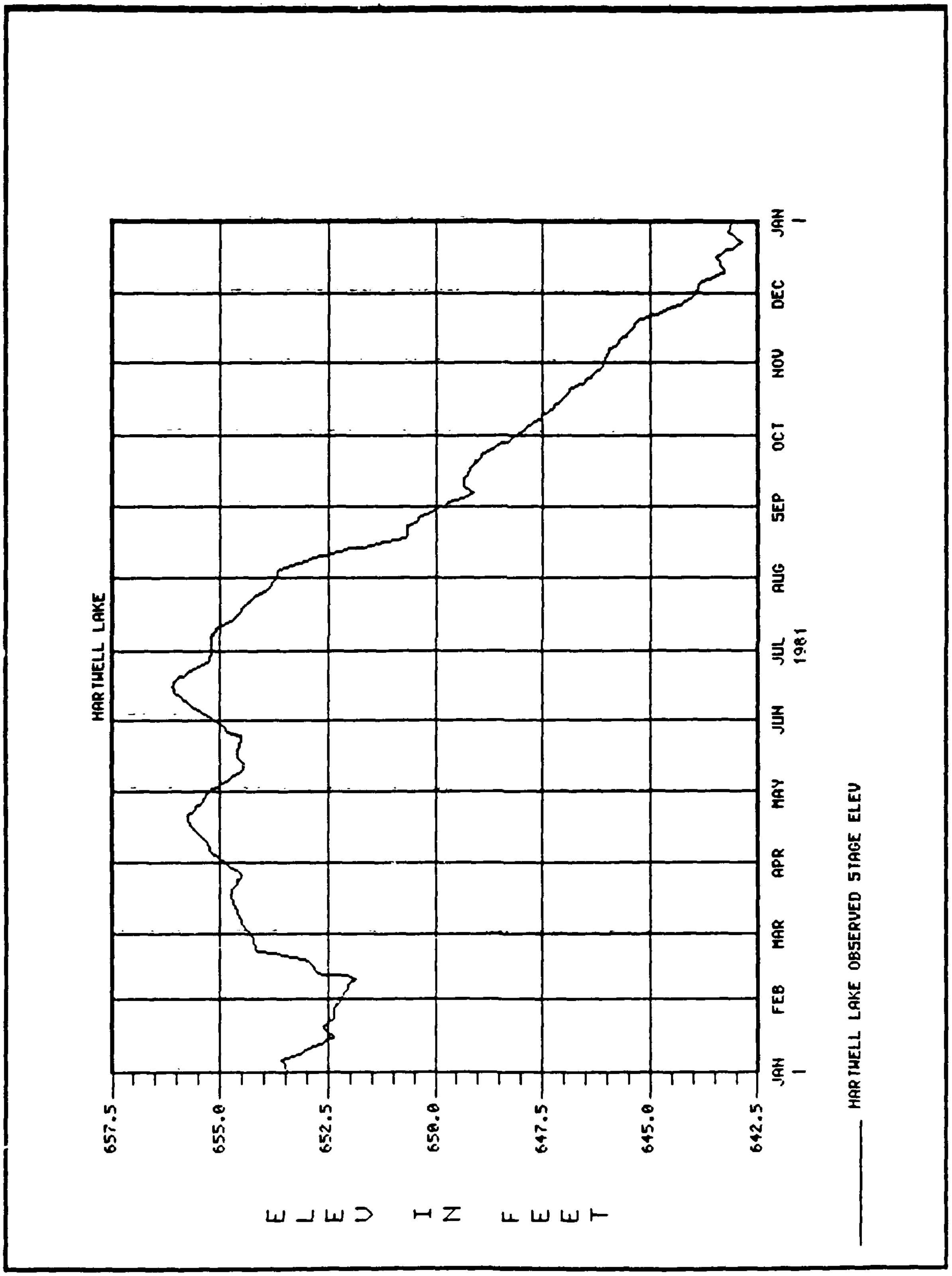
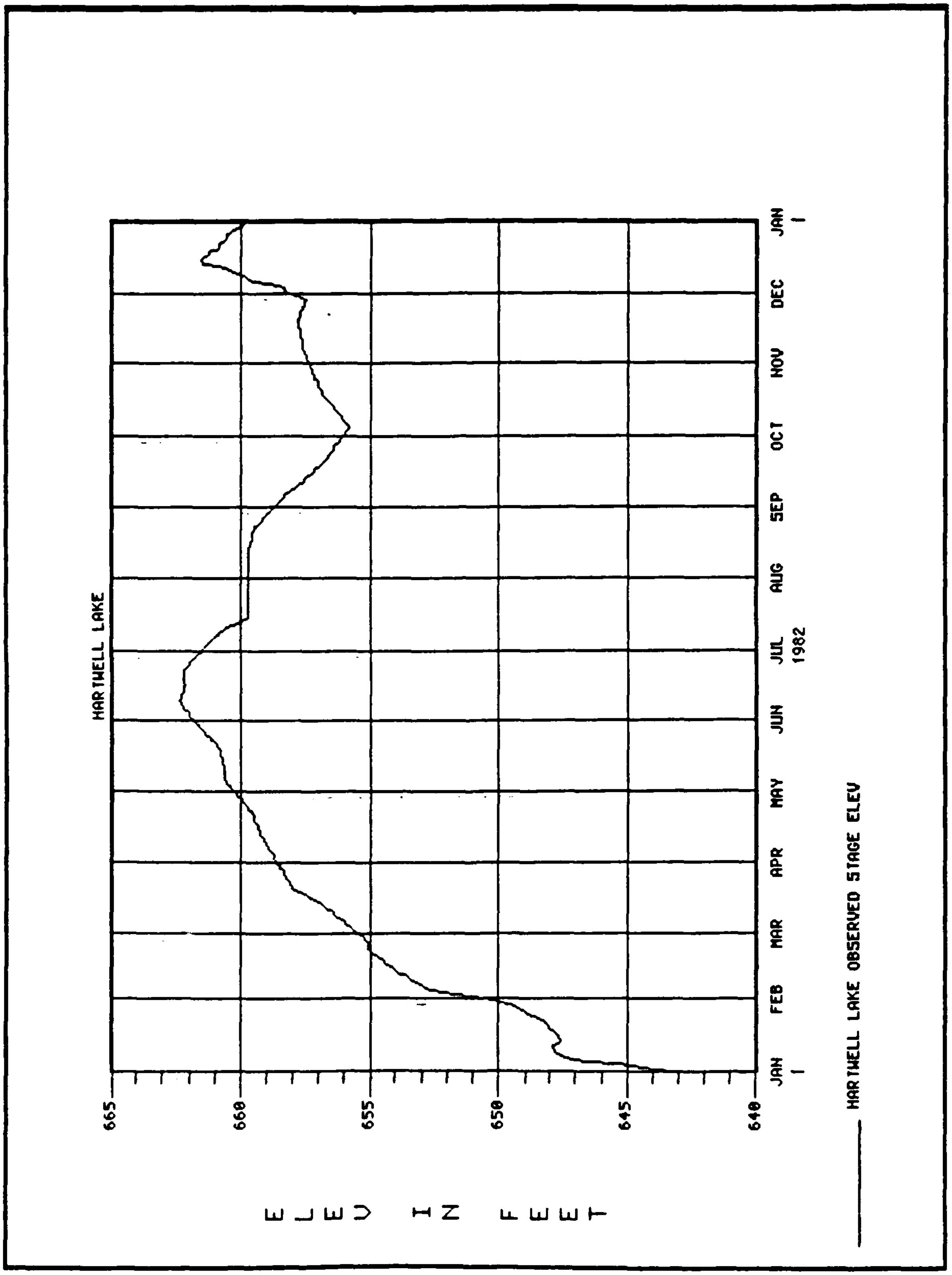

HARTWELL LAKE
ELEV IN FEET
657.5
655.0
652.5
650.0
647.5
645.0
642.5
JAN 1
FEB
MAR
APR
MAY
JUN
JUL 1981
AUG
SEP
OCT
NOV
DEC
JAN 1
HARTWELL LAKE OBSERVED STAGE ELEV


HARTWELL LAKE
665
660
655
650
645
640
ELEV IN FEET
JAN 1
FEB
MAR
APR
MAY
JUN
JUL
1982
AUG
SEP
OCT
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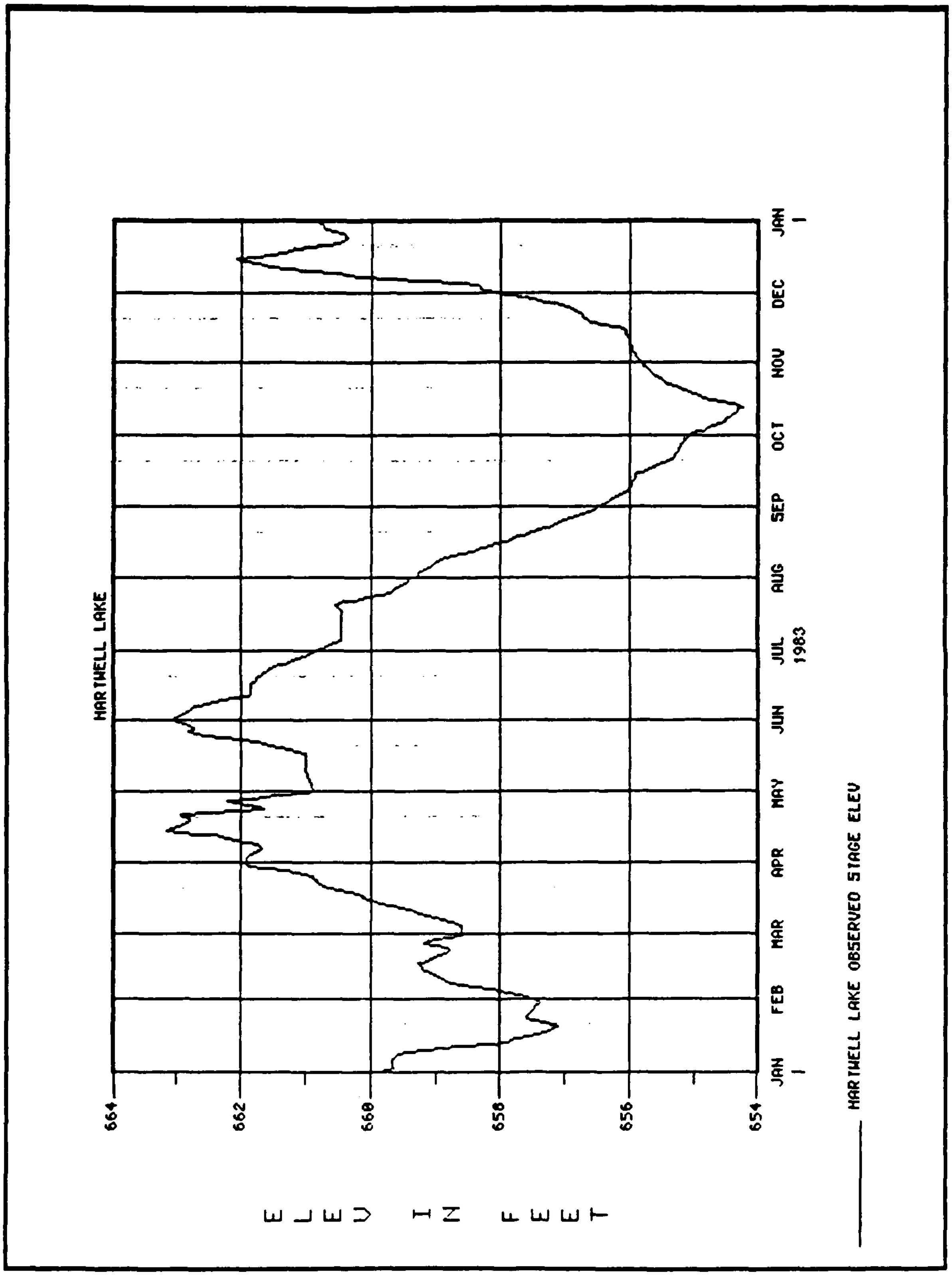
DEC
JAN 1
HARTWELL LAKE OBSERVED STAGE ELEV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ELEV IN FEET
664
662
660
658
656
654
JAN 1
FEB
MAR
APR
MAY
JUN
JUL
1983
AUG
SEP
OCT
NOV
DEC
JAN 1
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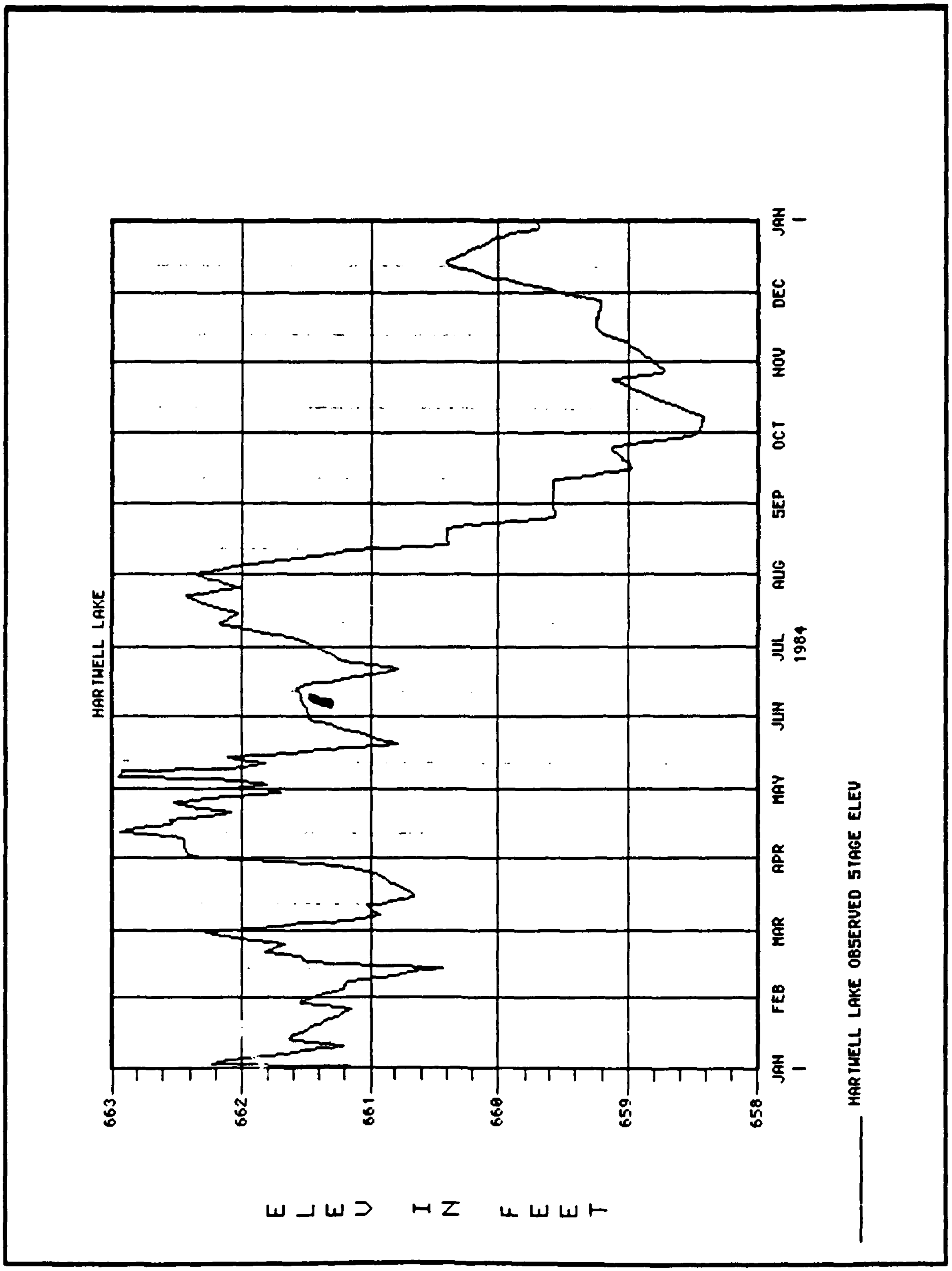
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ELEV IN FEET
663
662
661
660
659
658
JAN
FEB
MAR
APR
MAY
JUN
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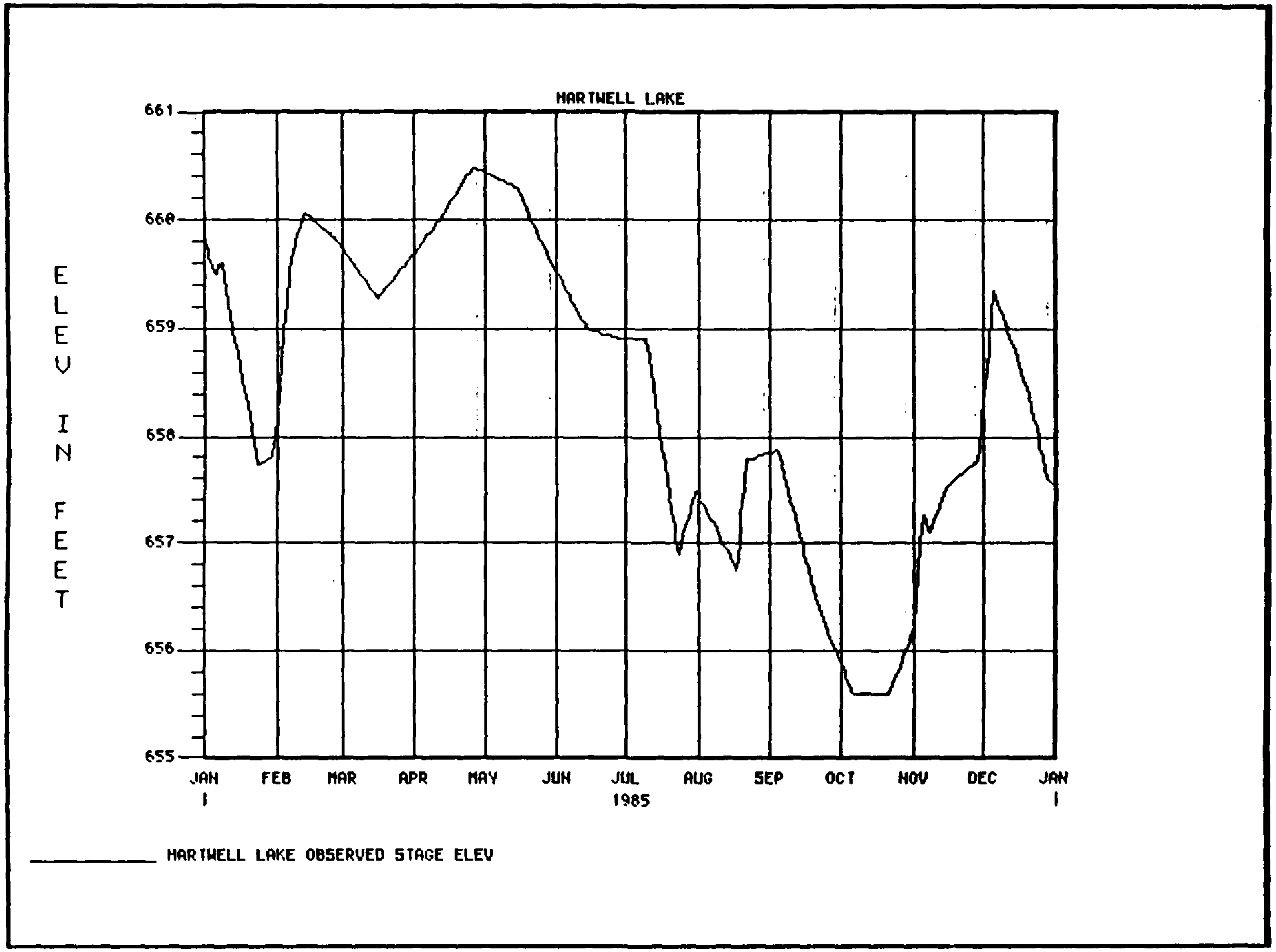
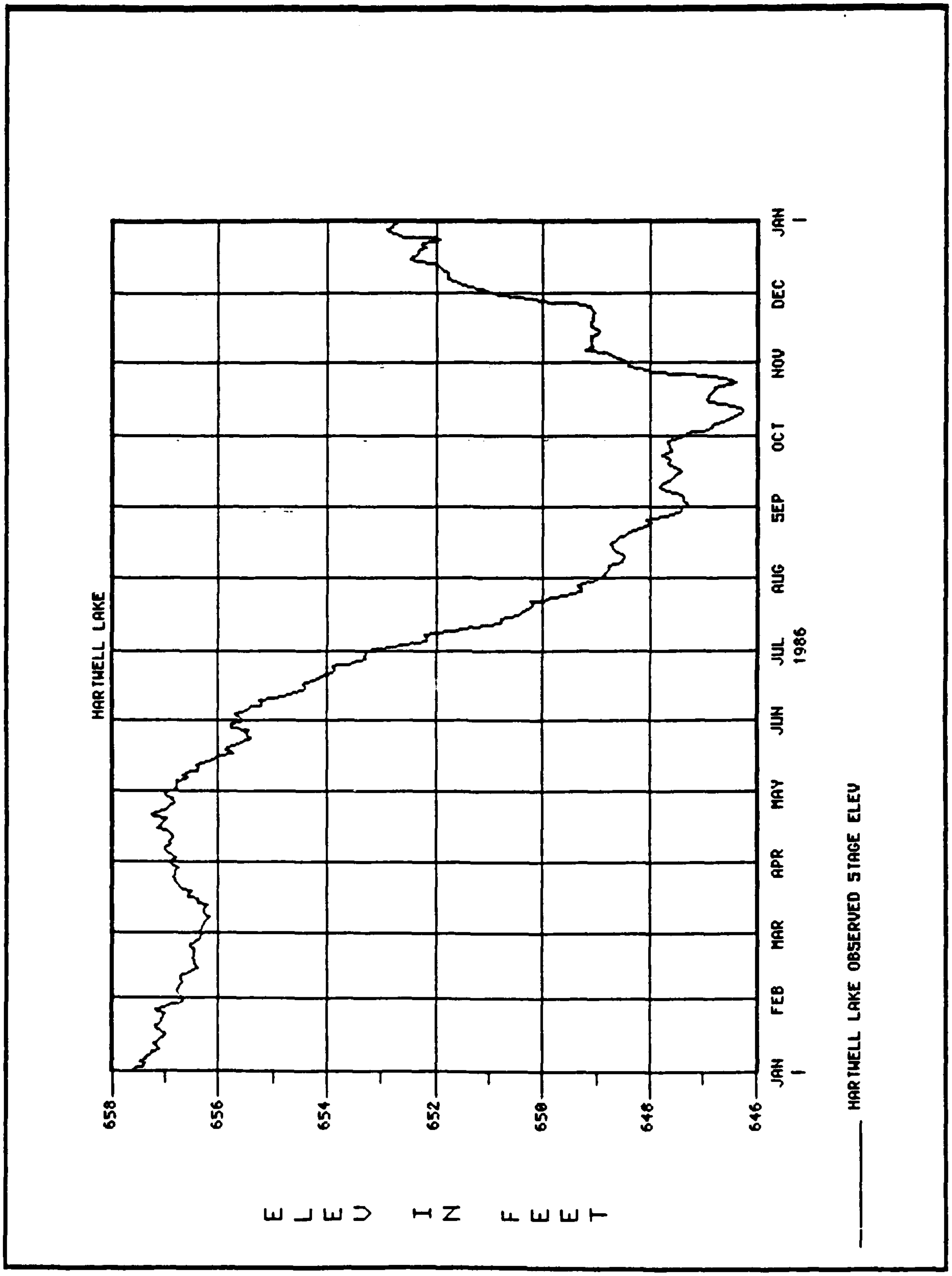
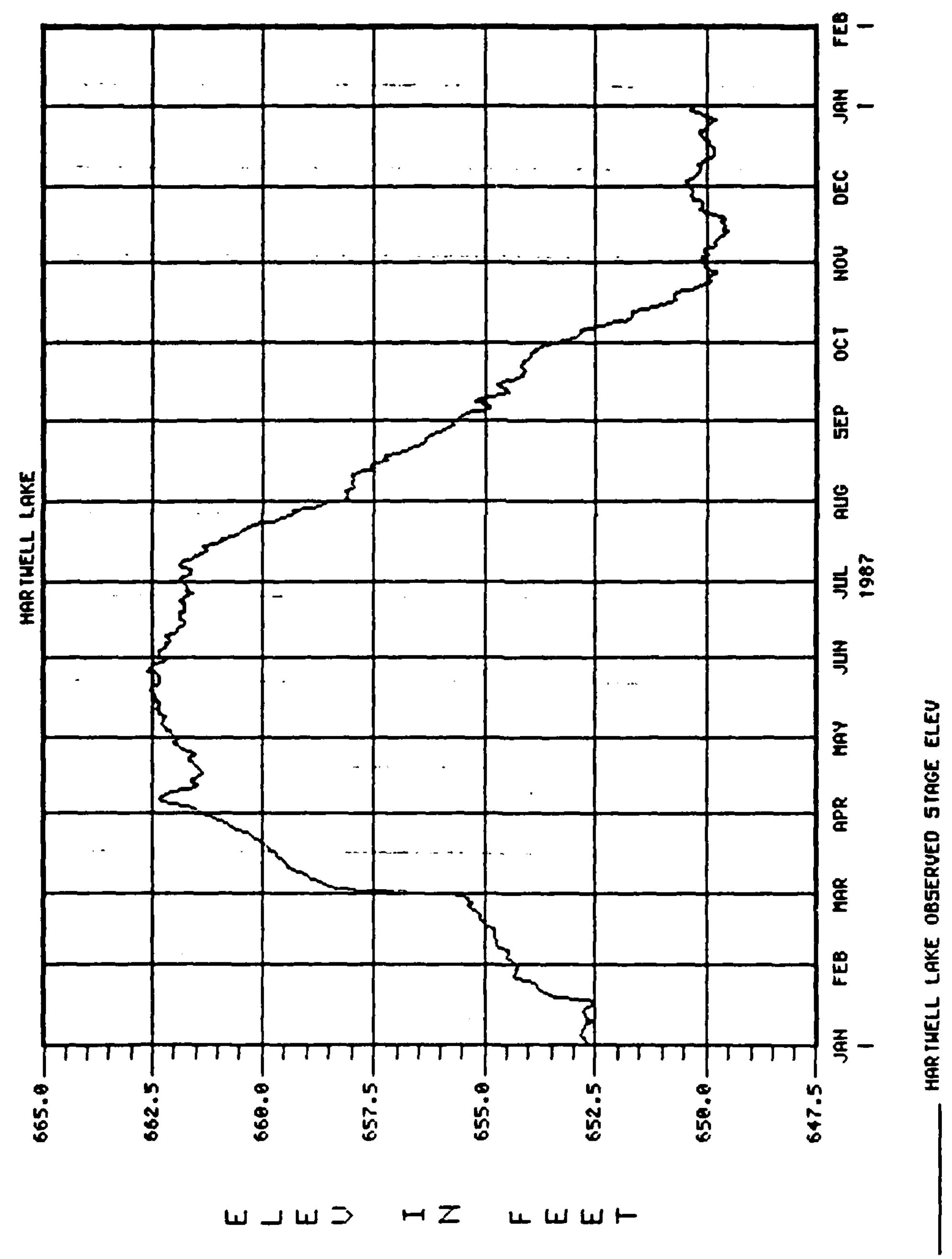
AUG
SEP
OCT
NOV
DEC
JAN
1984
HARTWELL LAKE OBSERVED STAGE ELEV


HARTWELL LAKE
661
660
659
658
657
656
655
ELEV IN FEET
JAN 1
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN 1
1985
HARTWELL LAKE OBSERVED STAGE ELEV



HARTWELL LAKE
ELEV IN FEET
658
656
654
652
650
648
646
JAN 1
FEB
MAR
APR
MAY
JUN
JUL
1986
AUG
SEP
OCT
NOV
DEC
JAN 1
HARTWELL LAKE OBSERVED STAGE ELEV


HARTWELL LAKE
ELEV IN FEET
665.0
662.5
660.0
657.5
655.0
652.5
650.0
647.5
JAN 1
FEB
MAR
APR
MAY
JUN
JUL
1987
AUG
SEP
OCT
NOV
DEC
JAN 1
FEB 1
HARTWELL LAKE OBSERVED STAGE ELEV

APPENDIX E

Trip Report on Union County Earthquake

by Jack M. Keeton

(from U.S. Army Corps of Engineers, 1983)

SASEN-FG 20 February 1980

SUBJECT: Trip Report - Union County Earthquake

MEMORANDUM FOR RECORD:

1. DATE: 11-14 February 1980

2. PURPOSE: Research newspaper reports of the Union County earthquake of January 1, 1913.

3. PERSON MAKING TRIP:

Jack M. Keeton, SASEN-FG

4. PERSONS CONTACTED:

Mrs. Phillip Flynn, Union, SC resident
Various library, archival, and newspaper people

5. BACKGROUND:

It was requested that I research appropriate newspapers to help determine the intensity of the Union County earthquake of January 1, 1913.

6. OBSERVATIONS:

a. I researched the following newspapers:

Aiken, JOURNAL AND REVIEW
Barnwell, PEOPLE SENTINEL
Beaufort, GAZETTE
Bennettsville, PEE DEE ADVOCATE
Charleston, EVENING POST
Chester, LANTERN
Columbia, STATE
Conway, HORRY HERALD
Darlington, NEWS AND PRESS
Dillion, HERALD
Greenville, DAILY NEWS
Greenwood, INDEX
Hartsville, MESSENGER
Lexington, DISPATCH-NEWS
Newberry, OBSERVER
Orangeburg, TIMES AND DEMOCRAT
Rock Hill, EVENING HERALD
Rock Hill, RECORD
Spartanburg, HERALD

Union, PROGRESS
Walterboro, PRESS AND STANDARD
Salisburg, EVENING POST (North Carolina)
Charlotte, DAILY OBSERVER (North Carolina)

b. Most of these newspapers are on microfilm at the South Carolina Library in Columbia, SC. I had copies made of the following:

Columbia STATE
GREENVILLE DAILY NEWS
ROCK HILL EVENING HERALD
Rock Hill RECORD
SPARTANBURG HERALD
Union PROGRESS
CHARLOTTE DAILY OBSERVER
SALISBURY EVENING POST

These are on file in the Geology Section.

c. I visited the following places:

Columbia, SC
Newberry, SC
Union, SC
Rock Hill, SC
Charlotte, NC
Salisburg, NC
Ashboro, NC

d. Inclosure 1 is a summation of what appeared in the newspaper at the time of the earthquake.

7. CONCLUSIONS:

a. In trying determine [illegible] this quake should be assigned an intensity of VII, I have listed each descripter of a VII on the modified Mercalli intensity scale and made observations to each as follows:

Based on my newspaper research.

(1) "Frightened all - General alarm."

OBSERVATION: Many persons were quite terrified. Quite a few people were alarmed.

(2) "All ran outdoors."

OBSERVATION: Houses and stores were soon emptied of most occupants.

(3) "Some, or many, found it difficult to stand."

OBSERVATION: There was no mention of anyone finding it difficult to stand during the quake.

(4) "Noticed by persons driving motor cars."

OBSERVATION: There was no mention of anyone driving a motor car during the quake.

(5) "Trees and bushes shaken moderately to strongly."

OBSERVATION: There was no mention of trees and bushes being shaken.

(6) "Waves on ponds, lakes, and running water."

OBSERVATION: There was no mention of waves on ponds, lakes, or running water.

(7) "Water turbid from mud stirred up."

OBSERVATION: There was no mention of turbid water.

(8) "Incaving to some extent of sand or gravel stream banks."

OBSERVATION: There was no mention of incaving.

(9) "Rang large church bells, etc."

OBSERVATION: There was no mention of ringing church bells, large or small.

(10) "Suspended objects made to quiver."

OBSERVATION: Some light fixtures did sway.

(11) "Damage negligible in buildings of good design and construction, slight to moderate in well-built, ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc."

OBSERVATION: There was no mention of considerable damage to any buildings, poorly built or otherwise. There was cracking in the old jail wall at Union, SC; however, this jail was built in 1823.

(12) "Cracked chimneys to considerable extent, walls to some extent."

OBSERVATION: There was mention of considerable chimney damage in some areas. It must be pointed out that we do not know the condition of these chimneys before the quake. Many of the chimneys that were damaged may have been in bad shape before the quake.

(13) "Fall of plaster in considerable to large amount, also some stucco."

OBSERVATION: The "Rock Hill Evening Herald" did mention that "the plastering in many places was knocked down."

(14) "Broke numerous windows, furniture to some extent."

OBSERVATION: There was no mention of either broken windows or furniture. Windows were said to have rattled.

(15) "Shook down loosened brickwork and tiles."

OBSERVATION: The only bricks said to have fallen were from chimneys, and it is not known if they were loose before the quake or not.

(16) "Broke weak chimneys at the roofline (sometimes damaging roofs)."

OBSERVATION: There was no mention of roofs being damaged. We do not know what chimneys were "weak" and were not "weak" before the quake.

(17) "Fall of cornices from towers and high buildings."

OBSERVATION: There was no mention of cornices or towers in the newspapers that were researched.

(18) "Dislodged bricks and stones."

OBSERVATION: See descripter number 15 above.

(19) "Overturned heavy furniture, with damage from breaking."

OBSERVATION: There was no mention of furniture being damaged.

(20) "Damage considerable to concrete irrigation ditches."

OBSERVATION: There was no mention of concrete irrigation ditches.

b. It is my opinion that the Union County earthquake of January 1, 1913,

SASEN-FG 20 February 1980
SUBJECT: Trip Report - Union County Earthquake

should have a modified Mercalli intensity of VI assigned to it.

8. RECOMMENDATIONS:

No recommendations are made.

2 Incl
as

JACK M. KEETON
Geology Section

FROM NEWSPAPER REPORTS OF THE UNION COUNTY EARTHQUAKE OF JANUARY 1, 1913

LOCATION	TIME	DURATION	DAMAGE
SOUTH CAROLINA			
Union	1:28	20 sec	Chimneys partially shaken down, buildings rocked and swayed, houses and stores were emptied of most occupants, ornaments and other things rattled, cracks in new court house, wall of the old jail was cracked, the motion appeared to be from northwest and southeast, houses and stores were emptied of most occupants.
Colerain			Chimneys were shaken down.
Cross Keys			Chimneys were shaken down.
Monarch			Chimneys were shaken down.
West Springs			Chimneys were thrown down, a pig killed by falling brick.
Pacolet Mills			Chimneys demolished.
Gaffney	1:28	10 sec	Chimneys fell.
Chester	1:35		2 shocks, 1:35 and 2:00 PM, linotype machine moved
Columbia			Was felt but no damage was reported.
Spartanburg	1:25	6 sec	Chimneys were damaged, buildings were shaken.
Enoree	1:25		Chimneys were damaged.
Rock Hill	1:32	5 sec	Dishes and windows rattled, electric light fixtures swayed, the vibrations were in the direction of east to west
Newberry			Dishes rattled, houses swayed.
Greenville	1:20		Vases were thrown from mantles.
Edgefield	1:30		Was felt very perceptibly.
Asheville	1:30		The vibration was brief, but quite perceptible.
Campobello			The shock at this place was distinct.
NORTH CAROLINA			
Charlotte	1:28	30 sec	Buildings trembled, but no damage was reported.
Salisbury	1:30		Numbers of citizens reported as having felt the quake, but no damage was reported.
Greensboro	1:30		Was felt, but no damage was reported.

APPENDIX F

Recommended Accelerograms and Response Spectra

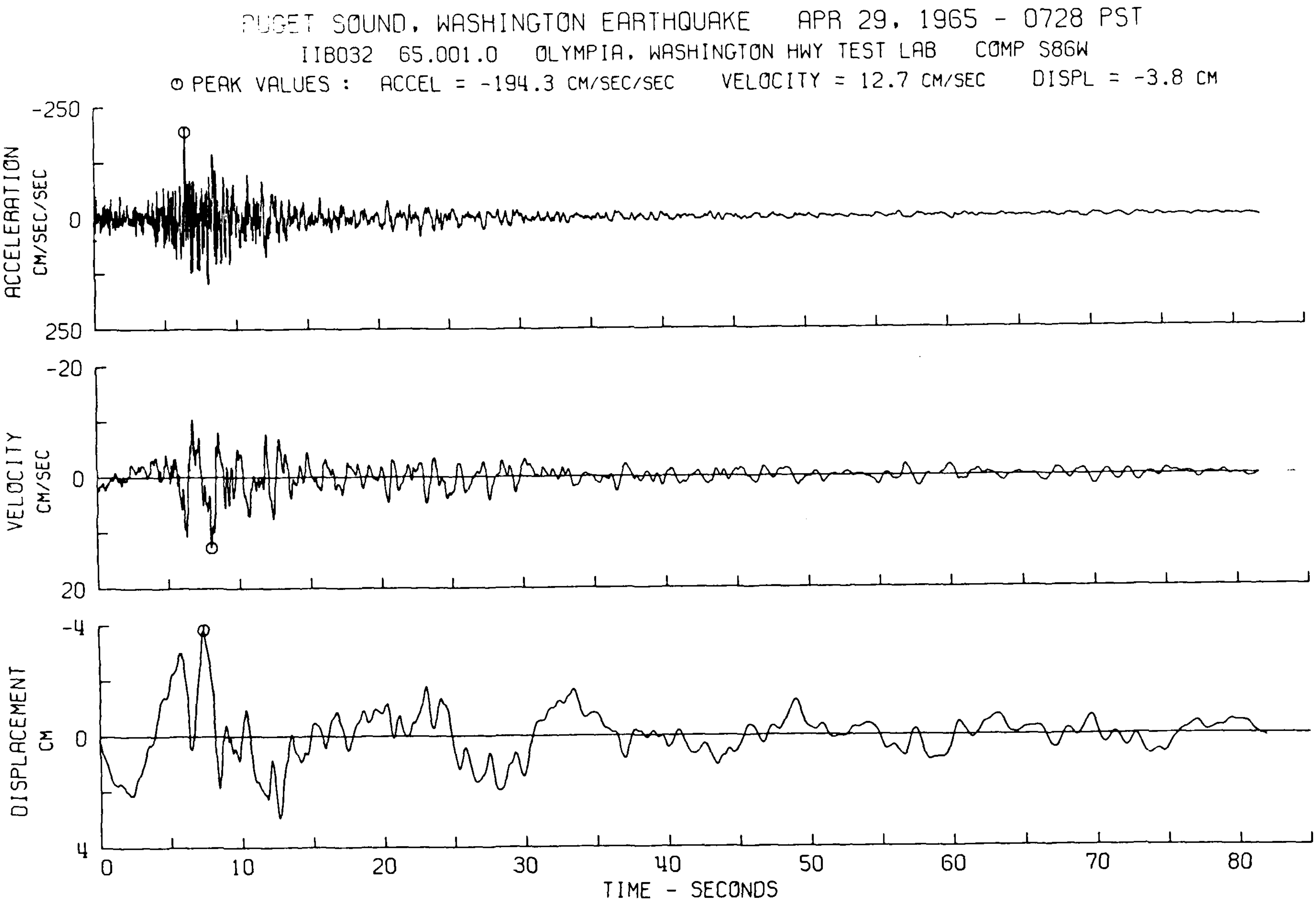
From California Institute of Technology,
Strong Motion Earthquake Catalogue, 1971 to 1975

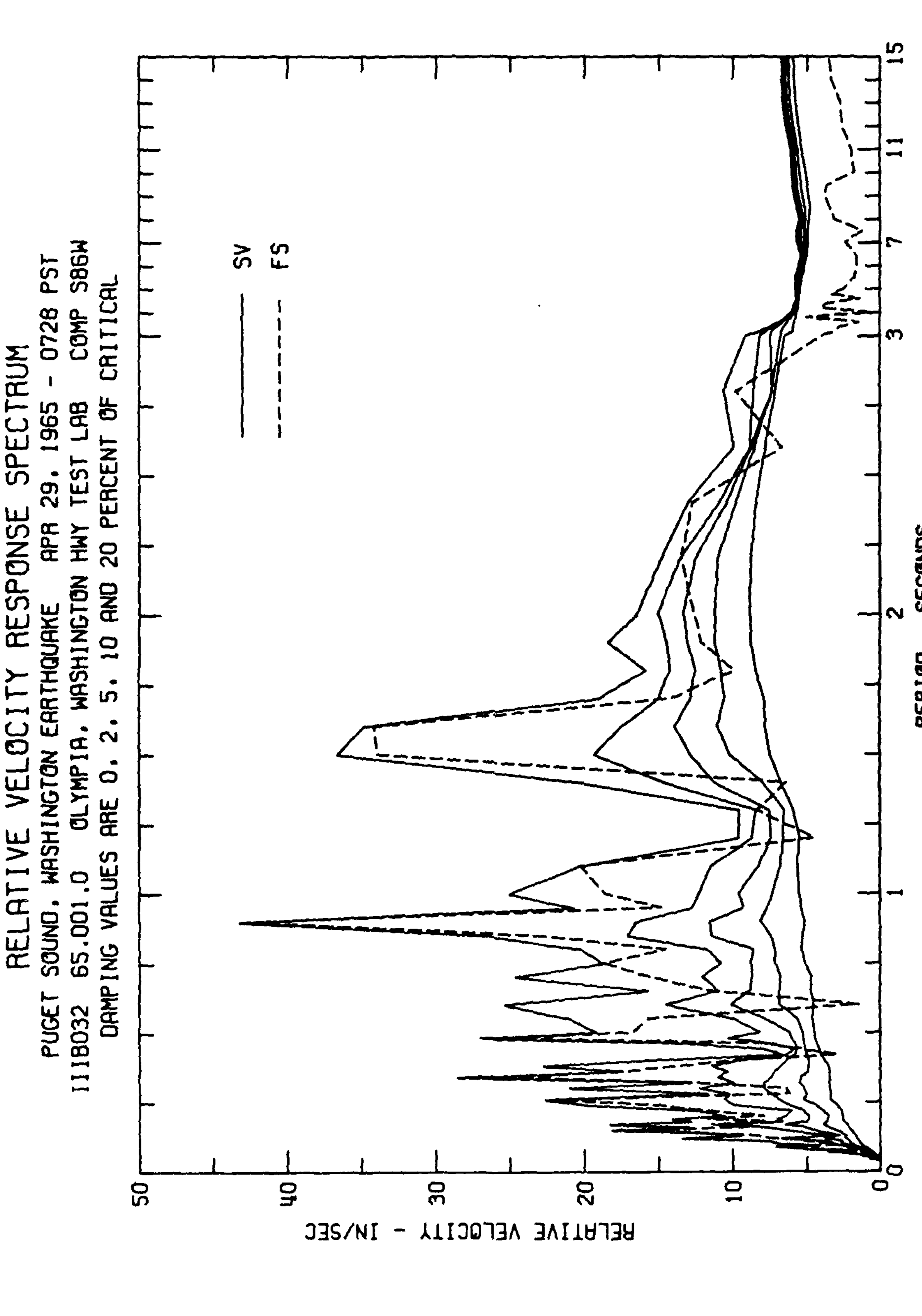
Record B032: Olympia HIghway Test Lab
Puget Sound, Washington
Component: S86W

Record Q233: 14724 Ventura Boulevard
San Fernando, Los Angeles
Component: N78W

Record 0198: Griffith Park Observatory
San Fernando, Los Angeles
Component: S00W

Record 0198: Griffith Park Observatory
San Fernando, Los Angeles
Component: S90W


PUGET SOUND, WASHINGTON EARTHQUAKE APR 29, 1965 - 0728 PST
IIB032 65.001.0 OLYMPIA, WASHINGTON HWY TEST LAB COMP S86W
⊙ PEAK VALUES : ACCEL = -194.3 CM/SEC/SEC VELOCITY = 12.7 CM/SEC DISPL = -3.8 CM
ACCELERATION
CM/SEC/SEC
-250
0
250
VELOCITY
CM/SEC
-20
0
20
DISPLACEMENT
CM
-4
0
4
0
10
20
30
40
50
60
70
80
TIME - SECONDS

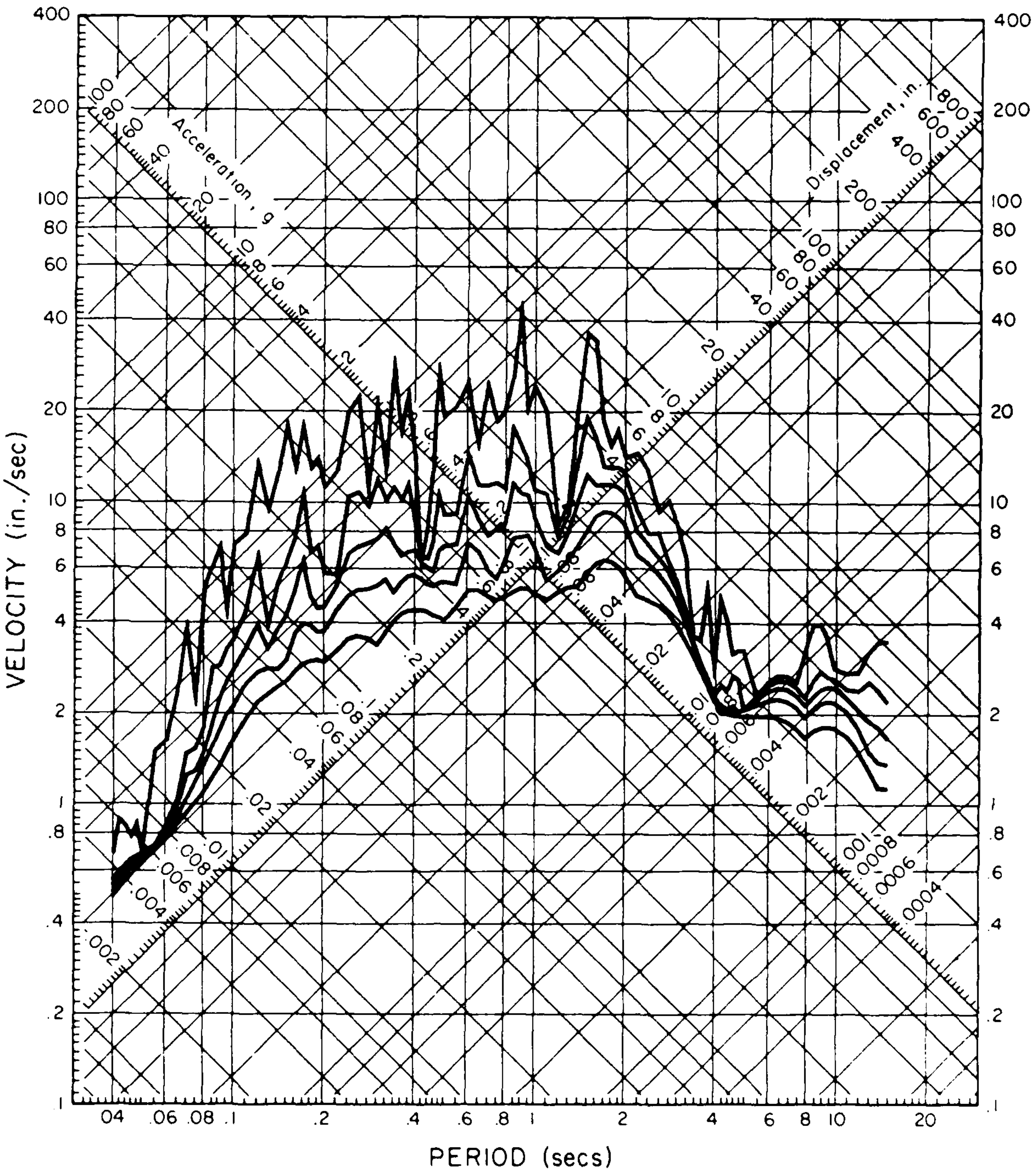

RELATIVE VELOCITY RESPONSE SPECTRUM
PUGET SOUND, WASHINGTON EARTHQUAKE APR 29, 1965 - 0728 PST
IIIB032 65.001.0 OLYMPIA, WASHINGTON HWY TEST LAB COMP S86W
DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL
SV
FS
RELATIVE VELOCITY - IN/SEC
0
10
20
30
40
50
PERIOD - SECONDS
0
1
2
3
7
11
15

RESPONSE SPECTRUM

PUGET SOUND, WASHINGTON EARTHQUAKE APR 29, 1965 - 0728 PST

IIIB032 65.001.0 OLYMPIA, WASHINGTON HWY TEST LAB COMP S86W

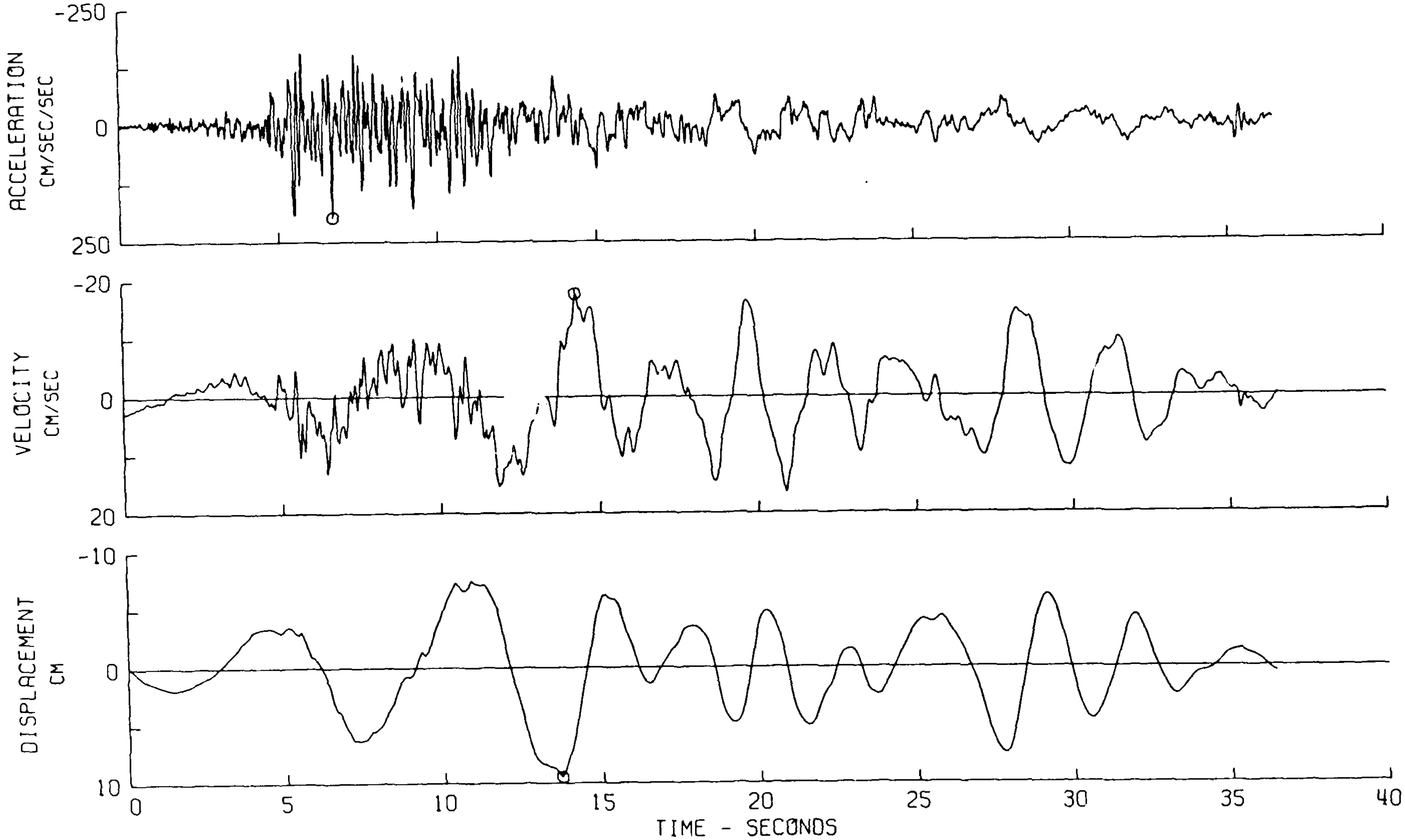
DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL



SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIQ233 71.162.0 14724 VENTURA BOULEVARD, 1ST FLOOR, LOS ANGELES, CAL. COMP N78W

⊙ PEAK VALUES : ACCEL = 197.0 CM/SEC/SEC VELOCITY = -17.6 CM/SEC DISPL = 9.5 CM

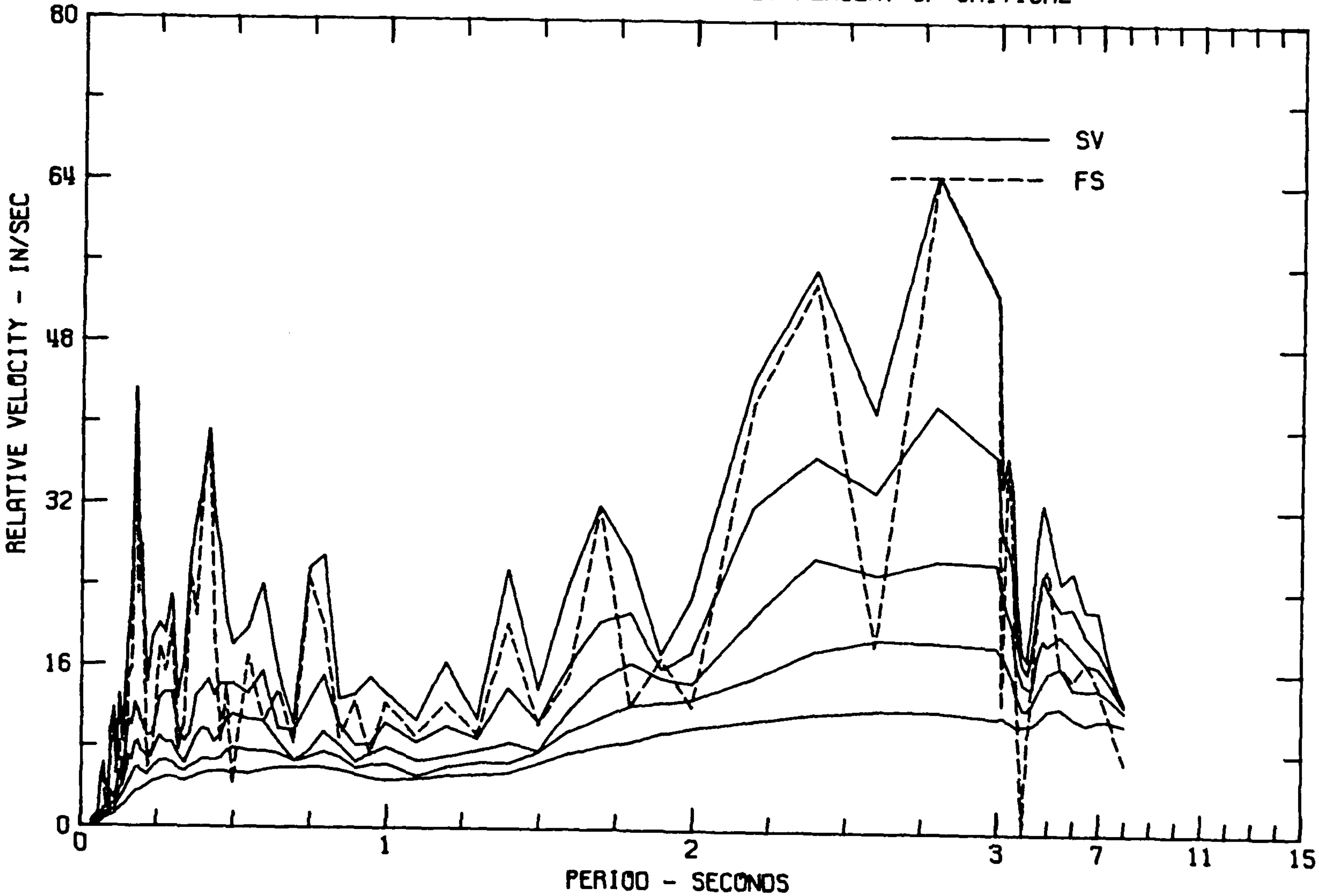


RELATIVE VELOCITY RESPONSE SPECTRUM

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

III0233 71.162.0 14724 VENTURA BOULEVARD, 1ST FLOOR, LOS ANGELES, CAL. COMP N78W

DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL

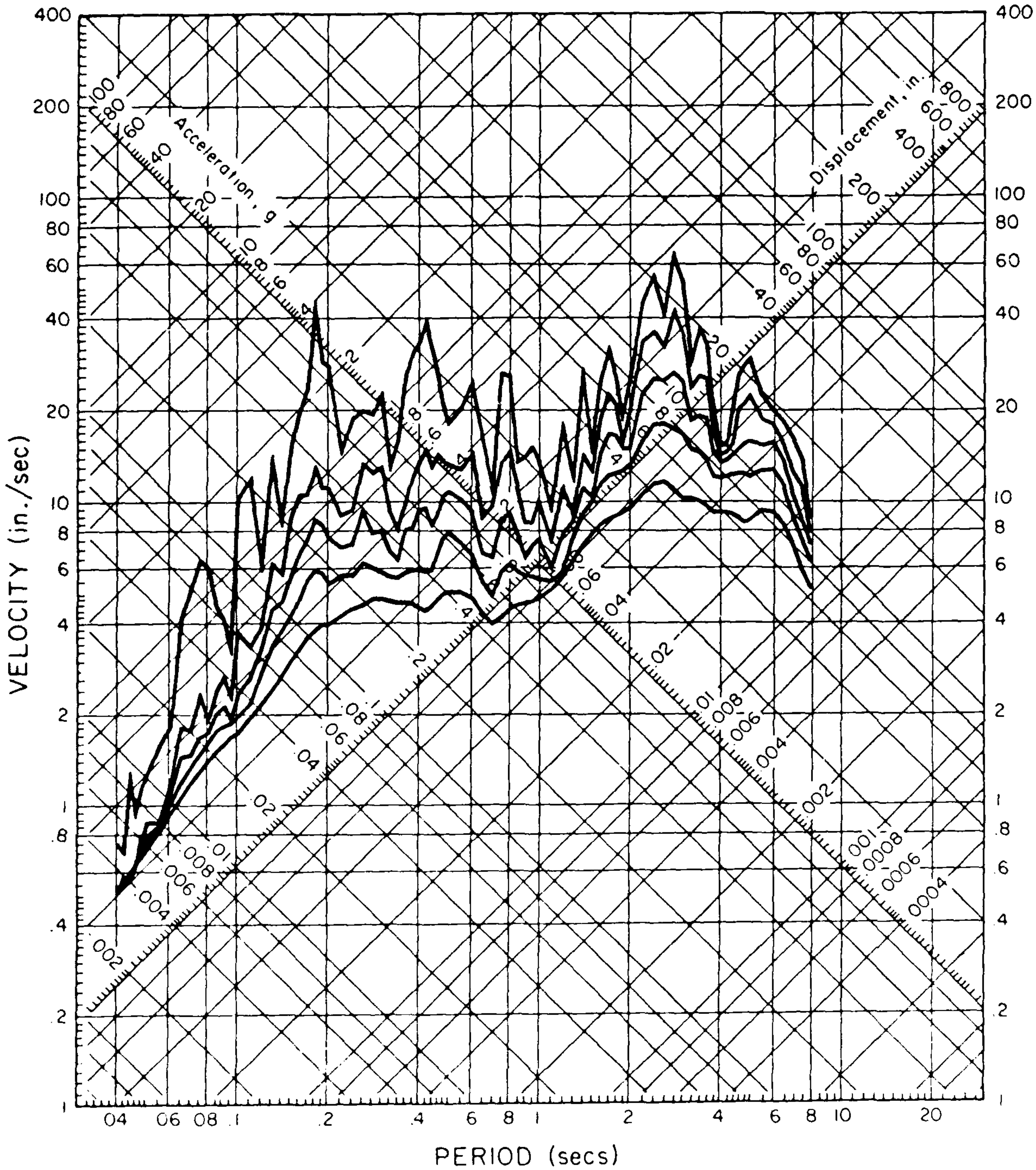


RESPONSE SPECTRUM

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIIQ233 71.162.0 14724 VENTURA BOULEVARD, 1ST FLOOR, LOS ANGELES, CAL. COMP N78W

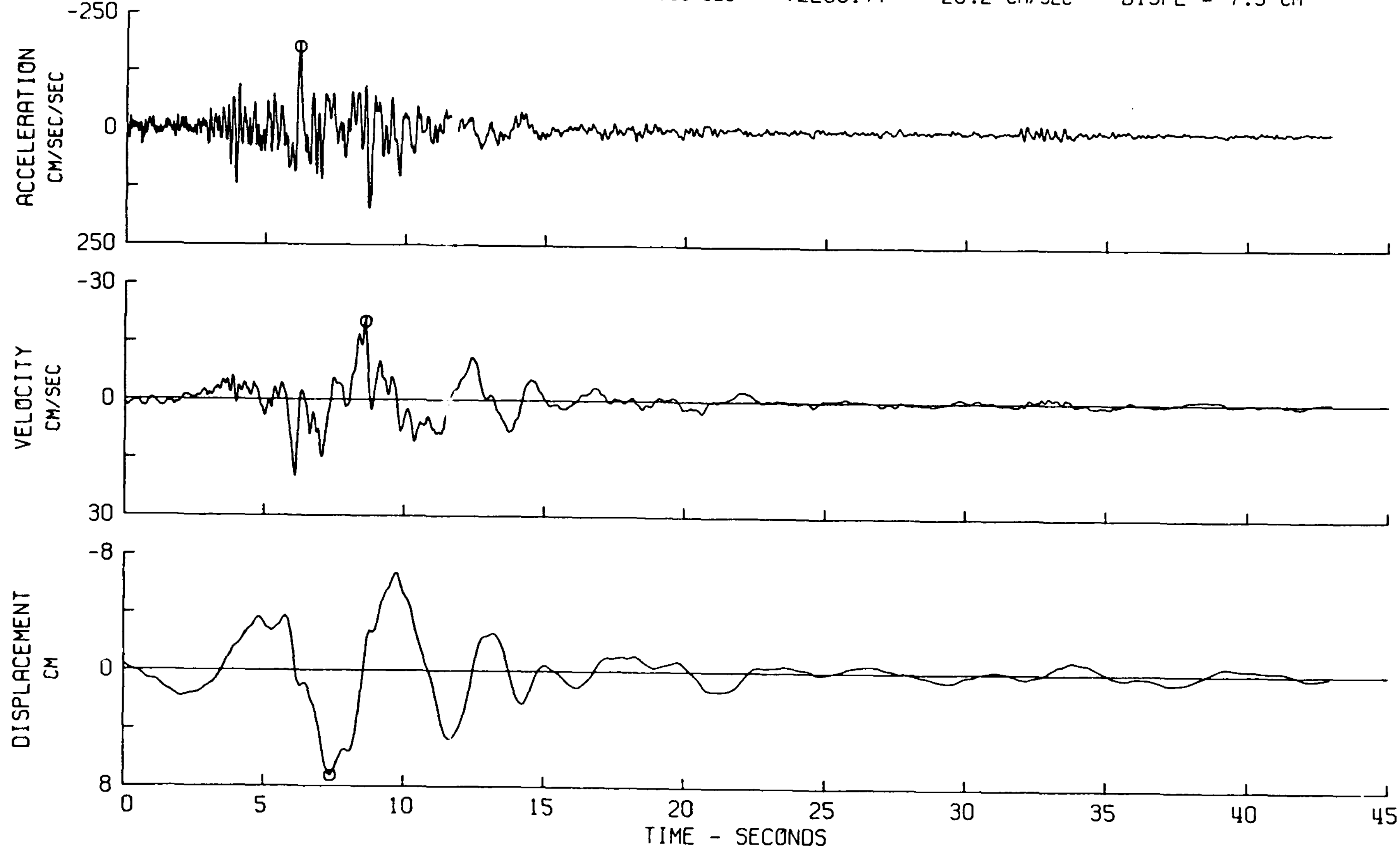
DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL

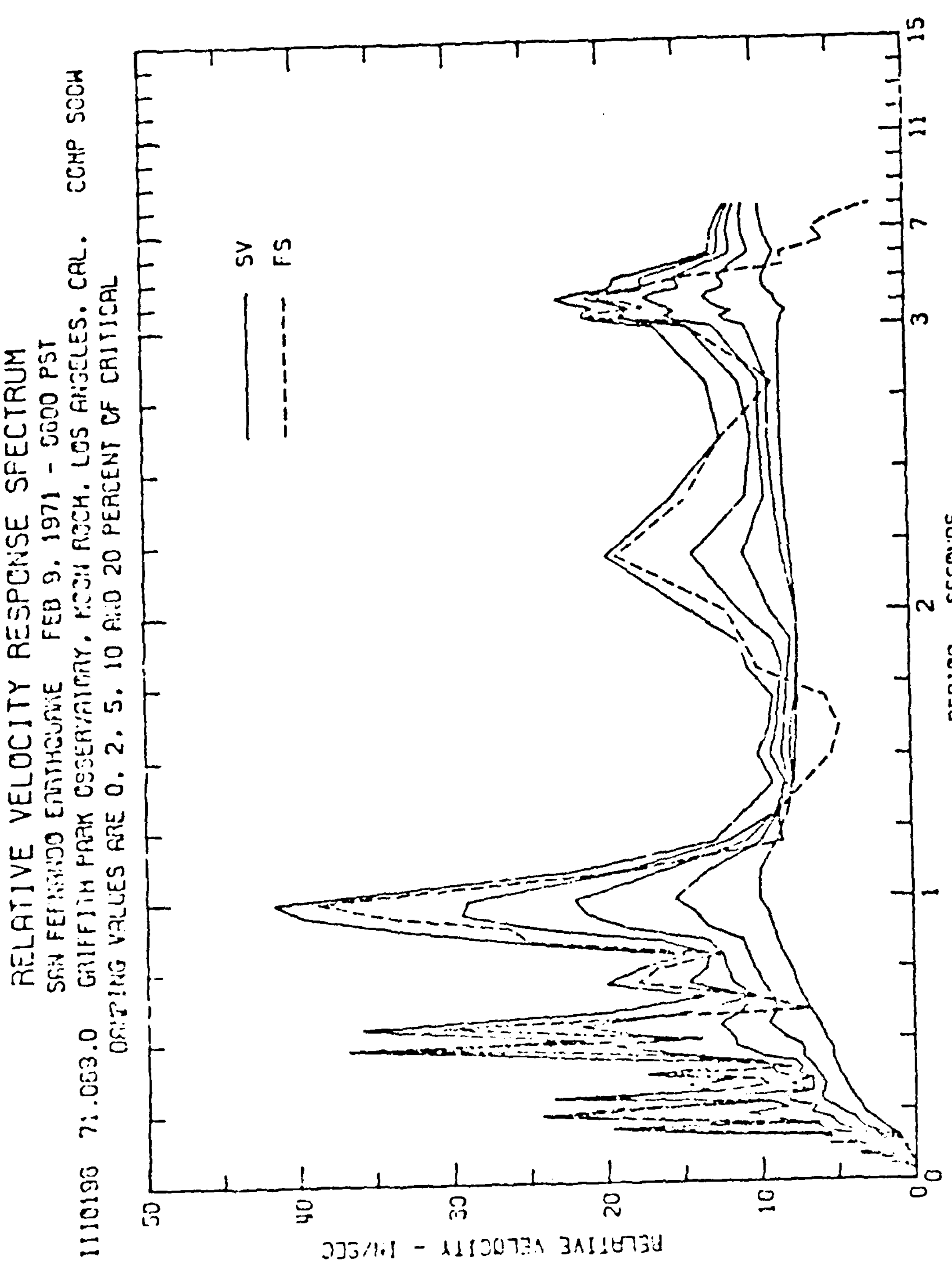


SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

II0198 71.069.0 GRIFFITH PARK OBSERVATORY, MOON ROOM, LOS ANGELES, CAL. COMP S00W

⊙ PEAK VALUES : ACCEL = -176.9 CM/SEC/SEC VELOCITY = -20.2 CM/SEC DISPL = 7.3 CM



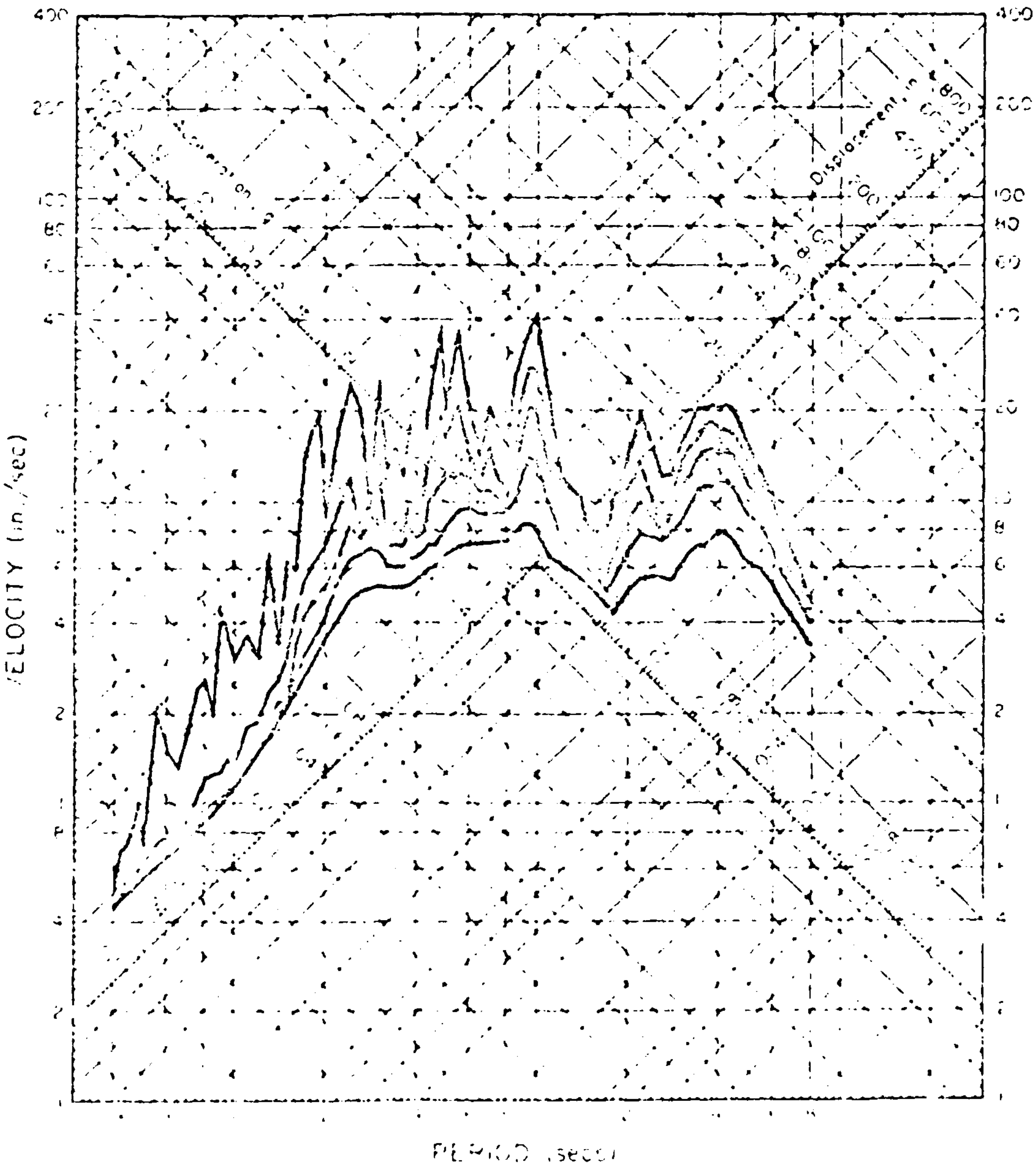

RELATIVE VELOCITY RESPONSE SPECTRUM
SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST
GRIFFITH PARK OBSERVATORY, MOON ROOM, LOS ANGELES, CAL. COMP S00W
DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL
SV
FS
RELATIVE VELOCITY - IN/SEC
PERIOD - SECONDS
0
10
20
30
40
50
1
2
3
7
11
15

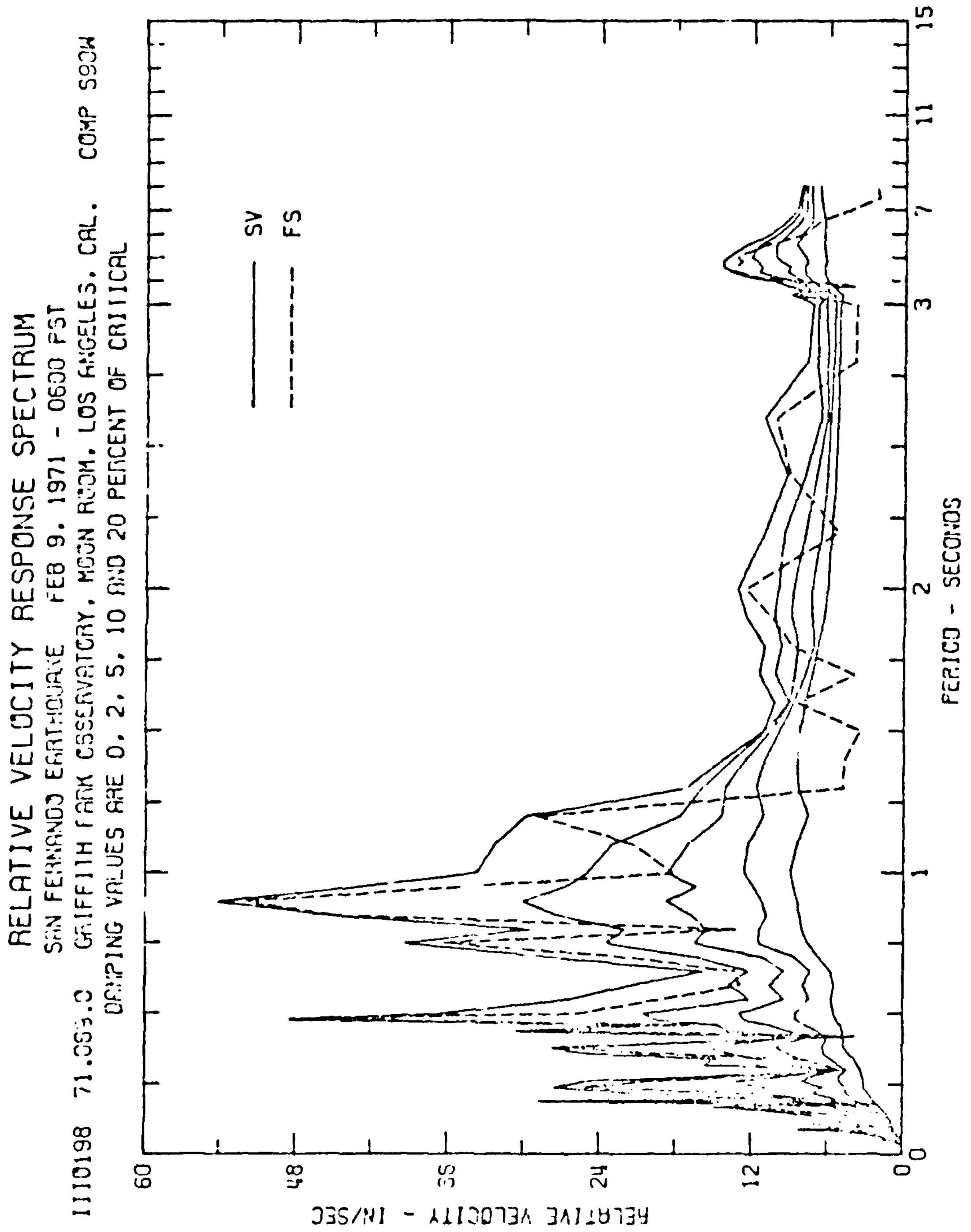
RESPONSE SPECTRUM

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIIC198 71.059.0 GRIFFITH PARK OBSERVATORY, MOON ROOM, LOS ANGELES, CAL. COMP SOOW

DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL




III0198 71.033.0
RELATIVE VELOCITY RESPONSE SPECTRUM
SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST
GRIFFITH PARK OBSERVATORY, MOON ROOM, LOS ANGELES, CAL. COMP S90W
DAMPING VALUES ARE 0, 2, 5, 10 AND 20 PERCENT OF CRITICAL
SV
FS
RELATIVE VELOCITY - IN/SEC
0
12
24
36
48
60
PERIOD - SECONDS
0
1
2
3
7
11
15

APPENDIX G

Glossary of Earthquake Terms

GLOSSARY

Accelerogram. The record from an accelerometer presenting acceleration as a function of time.

Attenuation. Characteristic decrease in amplitude of the seismic waves with distance from source. Attenuation results from geometric spreading of propagating waves, energy absorption and scattering of waves.

B-line. The slope of a straight line indicating frequency of occurrence of earthquakes versus earthquake magnitude.

Bedrock. A general term for any hard rock where it is not underlain by unconsolidated materials.

Design Spectrum. A set of curves used for design that shows acceleration velocity, or displacement (usually absolute acceleration, relative velocity, and relative displacement of the vibrating mass) as a function of period of vibration and damping.

Duration of Strong Ground Motion. The length of time during which ground motion at a site has certain characteristics. Bracketed duration is commonly the time interval between the first and last acceleration peaks that are equal to or greater than 0.05 g. Bracketing may also be done at other levels. Alternatively, duration can be a window in which cycles of shaking are summed by their individual time intervals between a specified level of acceleration that marks the beginning and end.

Earthquake. A vibration in the earth produced by rupture in the earth's crust.

1. Maximum Credible Earthquake. The largest earthquake that can be reasonably expected to occur.

2. Maximum Probable Earthquake. The worst historic earthquake. Alternatively it is (a) the 100-year earthquake or (b) the earthquake that by

probabilistic determination of recurrence will occur during the life of the structure.

3. Floating Earthquake. An earthquake of a given size that can be moved anywhere within a specified area (seismotectonic zone).

4. Safe Shutdown Earthquake. That earthquake which is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. These structures, systems, and components are those necessary to assure: (a) the integrity of the reactor coolant pressure boundary; (b) the capability to shut down the reactor and maintain it in a safe shutdown condition; or (c) the capability to prevent or mitigate the consequences of accidents which could result in potential offsite exposures comparable to the guideline exposures of this part. (Nuclear Regulatory Commission: Title 10, Chapter 1, Part 100, 30 April 1975. Same as Maximum Credible Earthquake.)

5. Operating Basis Earthquake. The earthquakes for which the structure is designed to remain operational. Its selection is an engineering decision.

6. Floating Earthquake. An earthquake of an assigned size that may occur anywhere within an area specified as the earthquake source zone.

Effective Peak Acceleration. A time history after the acceleration has been filtered to take out high frequency peaks that are considered unimportant for structural response.

Epicenter. The point on the earth's surface vertically above the point where the first earthquake ground motion originates.

Fault. A fracture or fracture zone in the earth along which there has been displacement of the two sides relative to one another.

1. Active Fault. A fault, which has moved during the recent geologic past (Quaternary) and, thus, may move again. It may or may not generate earthquakes. (Corps of Engineers: ETL 1110-2-301, 23 April 1983.)

2. Capable Fault. An active fault that is judged capable of generating felt earthquakes.

Focal Depth. The vertical distance between the hypocenter or focus at which an earthquake is initiated and the ground surface.

Focus. The location in the earth where the slip responsible for an earthquake was initiated. Also, the hypocenter of an earthquake.

Free Field. A ground area in which earthquake motions are not influenced by topography, man-made structures or other local effects.

Ground Motion. Numerical values representing vibratory ground motion, such as particle acceleration, velocity, and displacement, frequency content, predominant period, spectral values, intensity, and duration.

Hard Site. A site in which shear wave velocities are greater than 400 m/sec and overlying soft layers are less than or equal to 15 m.

Hot Spot. A localized area where the seismicity is anomalously high compared with a surrounding region.

Intensity. A numerical index describing the effects of an earthquake on man, on structures built by him and on the earth's surface. The number is rated on the basis of an earthquake intensity scale. The scale in common use in the U.S. today is the modified Mercalli (MM) Intensity Scale of 1931 with grades indicated by Roman numerals from I to XII. An abridgement of the scale is as follows:

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeable indoors, especially on upper floors of buildings, but many people may not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration can be estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks.

XI. Few structures remain standing. Unreinforced masonry structures are nearly totally destroyed. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Liquefaction. The sudden, total loss of shear strength in a soil as the result of excess pore water pressure. The result is a temporary transformation of unconsolidated materials into a fluid.

Magnitude. A measure of the size of an earthquake related to the strain energy. It is based upon the displacement amplitude and period of the seismic waves and the distance from the earthquake epicenter.

1. Body Wave Magnitude (m_b). The m_b magnitude is measured as the common logarithm of the maximum displacement amplitude (microns) of the P-wave with period near one second. Developed to measure the magnitude of deep focus earthquakes, which do not ordinarily set up detectable surface waves with long periods. Magnitudes can be assigned from any suitable instrument whose constants are known. The body waves can be measured from either the first few cycles of the compression waves (m_b) or the 1 second period shear waves (m_{b1g}).

2. Local Magnitude (M_L). The magnitude of an earthquake measured as the common logarithm of the displacement amplitude, in microns, of a standard

Wood-Anderson seismograph located on firm ground 100 km from the epicenter and having a magnification of 2,800, a natural period 0.8 second, and a damping coefficient of 80 percent. Empirical charts and tables are available to correct to an epicentral distance of 100 km, for other types of seismographs and for various conditions of the ground. The correction charts are suitable up to epicentral distances of 600 km in southern California and the definition itself applies strictly only to earthquakes having focal depths smaller than about 30 km. The correction charts are suitable up to epicentral distances of about 600 km. These correction charts are site dependent and have to be developed for each recording site.

3. Surface Wave Magnitude (M_S). This magnitude is measured as the common logarithm of the resultant of the maximum mutually perpendicular horizontal displacement amplitudes, in microns, of the 20-second period surface waves. The scale was developed to measure the magnitude of shallow focus earthquakes at relatively long distances. Magnitudes can be assigned from any suitable instrument whose constants are known.

4. Richter Magnitude (M). Richter magnitude is nonspecified but is usually M_L up to 6.5 and M_S for greater than 6.5.

5. Seismic Movement (M_o). Seismic moment is an indirect measure of earthquake energy.

$$M_o = G\ A\ D$$

where

G = rigidity modulus

A = area of fault movement

D = average static displacement

The values are in dyne centimeters.

6. Seismic Moment Scale (M_w). Expresses magnitude based on the concept of seismic moment:

$$M_w = \frac{2}{3} \log M_o - 10.7$$

7. <u>Comparison of Magnitude Scales</u>. Table 7-1 presents a comparison of values for m_b , M_L , M , $\log M_o$, M_w and M_S .

Table 7-1. Comparison between m_b , M_L , M , $\log M_o$, M_w and M_S scales.

m_b Body-Wave	M_L Local	M Richter	Log M_o (dyne-cm) Seismic Moment	M_w Moment	M_S Surface-Wave
5.0	5.4	5.4	24.2	5.4	5.0
5.5	5.9	5.9	25.0	6.0	5.8
6.0	6.4	6.7	26.1	6.7	6.7
6.5	6.9	7.5	27.3	7.5	7.5
7.0	7.5	8.3	28.6	8.4	8.3

<u>Particle Acceleration</u>. The time rate of change of particle velocity.

<u>Particle Displacement</u>. The difference between the initial position of a particle and any later temporary position during shaking.

<u>Particle Velocity</u>. The time rate of change of particle displacement.

<u>Response Spectrum</u>. The maximum values of acceleration, velocity, and/or displacement of an infinite series of single-degree-of-freedom systems, each characterized by its natural period, subjected to a time history of earthquake ground motion. The spectrum of maximum response values is expressed as a function of natural period for a given damping. The response spectrum acceleration, velocity, and displacement values may be calculated from each other by assuming that the motions are harmonic. When calculated in this manner these are sometimes referred to as pseudo-acceleration, pseudo-velocity, or pseudo-displacement response spectrum values.

Saturation. Where those measures of earthquake motions (acceleration, velocity, magnitude, etc.) do not increase though the earthquakes generating them may become larger.

Scaling. An adjustment to an earthquake time history or response spectrum where the amplitude of acceleration, velocity, and/or displacement is increased or decreased, usually without change to the frequency content of the ground motion.

Seismic Hazard. The physical effects of an earthquake.

Seismic Risk. The probability that an earthquake of or exceeding a given size will occur during a given time interval in a selected area.

Seismic Zone. A geographic area characterized by a combination of geology and seismic history in which a given earthquake may occur anywhere.

Soft Site. A site in which shear wave velocities are less than 400 m/sec in a surface layer 16 or more m thick.