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Tectonic Environment of the 1892 Vacaville/Winters Earthquake, and the Potential for Large Earthquakes Along the Western Edge of the Sacremento Valley, California

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I. Introduction

The May 2, 1983 M6.7 Coalinga earthquake has renewed concern over the possibility of large earthquakes elsewhere along the western edge of the Great Valley. That earthquake occurred on a hidden thrust fault related to the development of folds in the Great Valley sediments along the Coast Range/Great Valley (CR/GV) boundary (Eaton, 1985a). A similar process was responsible for the M5.7 North Kettleman earthquake that occurred 2 years after and 17 km southeast of the Coalinga main shock (Eaton 1985b). In the Coalinga/Kettleman region the upper crust beneath the eastern Coast Ranges is being shoved eastward above a zone of decoupling 12-15 km deep and thrust eastward over the basement beneath the western edge of the Great Valley (Eaton, 1985c; Wentworth and others, 1984). From a variety of geological and geophysical evidence, Wentworth and others (1984) conclude that Franciscan rocks of the Coast Ranges are being driven eastward in a tectonic wedge above the Great Valley basement and beneath the Great Valley formation and younger sedimentary rocks of the Great Valley. Folding and reverse faulting in the compressed sediments above the advancing wedge produce rows of hills in the Valley parallel to and east of the GV/CR boundary. Movement on the basal thrust fault and related reverse faults in brittle rocks beyond the eastern edge of the transform zone beneath the Coast Ranges can produce large earthquakes like the 1983 Coalinga event. A review of the pattern of seismicity in the southern Coast Ranges for the interval Jan. 1972-Apr. 1983, carried out after the Coalinga earthquake (Eaton, 1985c; Eaton and Rymer, in press), suggested that the process that generated the Coalinga earthquake, as well as likely sites for such an earthquake, could have been deduced from analyses of the seismicity and geology of the region before the earthquake.

A situation like that at Coalinga prior to the 1983 quake now appears to exist along the CR/GV boundary north of San Francisco Bay. A tectonic model for the CR/GV boundary along the west side of the Sacramento Valley, based on an analysis of geology and seismic reflection profiles across the boundary, is similar to that for the Coalinga region (Wentworth and others, 1984). A tectonic wedge of Franciscan rocks driven eastward above the Great Valley basement is peeling up the Great Valley formation and younger rocks along the GV/CR boundary. Moreover, the part of this boundary between Vacaville and Winters did experience an M6.5$\pm$ earthquake and several large aftershocks in 1892. Although the 1892 quake has not been placed on a known fault, reanalysis of the felt report data (Toppozada and others, 1981) strongly suggests that the 1892 quake and its large aftershocks occurred beneath the western edge of the valley several km east of the Coast Range front. This location is analogous to those of the Coalinga and Kettleman quakes. The purpose of this report is to examine the patterns of seismicity in the northern Coast Ranges and adjacent Sacramento Valley to gain insight into the cause of the 1892 earthquake and the possibility of future large earthquakes beneath the western edge of the Sacramento Valley.

II. Development of the seismic network

The development of the USGS seismic network north of San Francisco Bay got underway in 1970; but the net remained fragmentary until 1975, when the number of stations in the northern Coast Ranges was increased from 20 to 39 and the Oroville network, with 15 stations, was set up in the Sierra foothills in the Oroville region. The Sierra foothills network was augmented to 41 stations in 1976, with the addition of stations in the Auburn and Lassen regions. A further improvement occurred in 1979, with the addition of 14 stations that extended the Coast Range network to Cape Mendocino. From 1980 onward the net in the northern Coast Ranges and Sierra Foothills remained almost unchanged, with about 77 stations in the northern Coast Ranges and 48 stations along the Sierran Foothills from Sacramento to Lassen. Location of earthquakes at the northern end of the Sacramento Valley was further improved by the addition of 8 stations around Shasta Lake in 1983.

Locating earthquakes beneath the Sacramento Valley has been and remains a special, difficult task for several reasons:

1) adequate sites for seismic stations are rare because of extensive farming activities in the valley;
2) stations that have been established are noisy;
3) there are large lateral variations in crustal structure a) at the CR/GV boundary, b) from west to east across the valley, and c) at the foothill belt/Sierra Nevada boundary.

The seismicity map that we shall present includes all earthquakes from the standard CALNET catalogs for the years 1972 through 1985 that satisfy the following criteria: magnitude 1.5 or greater, seven or more stations used in hypocenter determination, root mean square of traveltime residuals less than 0.5 sec, and distance to nearest station less than 50 km. Because of the stepwise improvement of the network outlined above, the "completeness" of the map varies considerably from place to place. Coverage of the Coast Ranges has been good southeast of Clear Lake since 1972 and northwest of Clear Lake since 1975. Coverage of the Sacramento Valley was extremely weak prior to 1976; and it remains poor to this date, particularly along the CR/GV boundary north of Clear Lake. For earthquakes beneath the valley, the determination of focal depths is particularly difficult. This problem is probably most serious for shallow events (say < 10 km), for which direct wave arrivals are generally lacking.

III. Seismicity pattern: 1972-1985

In spite of the uneven coverage noted above, several clear features are apparent on the 1972-1985 seismicity map (figure 1). North of San Francisco Bay there are two prominent linear zones of earthquakes in the Coast Ranges that trend parallel to the San Andreas fault but lie about 35 km and 70 km, respectively, east of it. The western zone follows the Rogers Creek/Maacama fault trend from San Pablo Bay to Laytonville. The eastern zone begins along the Green Valley fault at the west end of Suisuin Bay and runs northwestward along the west side of Lake Berryessa, past the east side of Clear Lake, and on to Round Valley. The northern part of this feature has been called the Bartlett Springs fault zone (Herd, 1983; McLaughlin and Nilsen, 1983). In the 1972-1985 data, the western zone is almost continuous but the eastern zone is broken by gaps at the north end of Lake Berryessa and northeast of Clear Lake.

Further east, a third less well-defined zone in the seismicity pattern runs northward from Antioch (east end of Suisuin Bay), along or just east of the CR/GV boundary to the Dunnigan hills, and then on northward to the prominent north-south alignment of deep earthquakes beneath the center of the valley near Butte City, west of Oroville. (The CR/GV boundary lies along the broad strip of Great Valley formation (GVF) shown on figure 1.) This third zone of seismicity is composed of isolated clusters of earthquakes with calculated depths of 10 km and greater (down to 20 or 30 km), and it appears to mark a region across which the density of epicenters decreases sharply from west to east. This zone is probably poorly represented on the map because small earthquakes ($M < 2$) were not recorded as a consequence of inadequate station density and telemetry performance in this region.

Imperfect as they may be, however, these data may shed light on the processes and structures associated with large earthquakes in the region, such as the 1892 event.

The strongest clusters of earthquakes along the Antioch/Butte City zone are just north of Antioch, near Williams, and at Butte City. Calculated focal depths of the Antioch events and the Butte City events are in the ranges 15 to 25 km and 15 to 40 km, respectively. Calculated focal depths for events in the clusters near Williams are in the range 10 to 25 km. Although it appears quite certain that earthquakes in these 3 regions are deeper than the 12 to 15 km maximum for Coast Range earthquakes, the sparse network and uncertain velocity model in this region undermine confidence in the calculated depths.

The region between Antioch and Williams is marked by scattered events along the CR/GV boundary and by modest clusters of events north of Winters and near Dunnigan. Events in these clusters appear to be shallower than those in the more prominent clusters described above. The cluster north of Winters is interesting because it contains the largest event (M 4.3) during 1972-1985 between the Antioch and Williams clusters. This earthquake appears to have been caused by movement of a S-W dipping low angle thrust fault about 11 km deep (figure 2). It lies about 8 km north of the inferred epicenter of the largest aftershock (M 6^+) of the 1892 earthquake. The inferred epicenters of the 1892 M 6.4 earthquake and its M 5^+ aftershocks lie along the Antioch/ Butte City zone between Vacaville and Madison (Ellsworth and others, 1981) figure 1. That part of the zone has been relatively quiet since 1972, perhaps because of the strain release associated with the 1892 events.

Additional features of the seismicity pattern that should be noted are:

1) a southwest-northeast trending transverse alignment of earthquake clusters at the Geysers (induced), at the south end of Clear Lake, north of Wilbur Springs, and northwest of Williams;

2) a sharp change in strike of the Rogers Creek/Maacama fault zone, from about N 35°W on the south to about N 23°W on the north, at the southwest end of the transverse zone of earthquake clusters noted under item 1;

3) a sharp change in strike of the Green Valley-Bartlet Springs zone at Lake Berryessa, from N 18°W on the south to N 30°W on the north;

4) a 15 to 20-km-wide band of low seismicity extending northweastward from Clear Lake to Butte City along the northwest edge of the transverse zone of earthquake clusters;

5) a dense cluster of events due to mine blasts just east of station NMT (20 km NNW of Lake Berryessa), and about 10 events probably caused by seismic refraction shots along a line from Lake Berryessa to just north of Dunnigan.

Eberhart-Phillps (in press) suggests that the Maacama fault may connect with the Green Valley fault zone along the line of epicenters extending southeastward from the southeast end of the mapped trace of the Maacama fault (figure 1).

IV. Structure along the west side of the Sacramento Valley between Vacaville and Williams.

Seismicity along the Antioch/Butte City zone may also be related to a system of ridges projecting southeastward into the Sacramento Valley south of Williams. The most prominent of these ridges lies just east of Capay Valley, which separates it from the higher ridge formed by the sharply upturned Great Valley formation (GVF) that marks the eastern edge of the Coast Ranges along most of the length of the Sacramento Valley (figure 1). The broad northeastern flank of the Capay Hills (delineated by the contact between eastward-tilted Pliocene rocks (T) and flat-lying Qal of the Sacramento Valley floor) trends N 30°W and extends as far north as Williams. South of Capay Valley, the belt of eastward-tilted Pliocene rocks east of the Coast Range front trends about N 10°W and is 5 to 7 km wide.

East of the Capay Hills, the Dunnigan Hills lie 10 to 12 km farther out in the valley. Their trend is also about N 30°W. Near their southern end, west of Woodland, the Dunnigan Hills are replaced by the low north-trending Monument Hills for another 8 km farther south. Five to 10 km still farther south, just southwest of the Winters/Davis airport, a 10-km-long northwest-southeast trending zone of elevated ground with windows of Pliocene rocks protruding through the Qal cover reveals another ridge in the valley sediments. Twenty five km farther south (10 km east of Vacaville) isolated patches of Pliocene rocks protruding through the Qal cover suggest another zone of slight uplift of the valley sediments. Outlines of these last two regions of Pliocene outcrops are shown with dotted lines in figure 1. The Dunnigan Hills and the uplifted areas to the south just enumerated all lie along the eastern edge of the Antioch/Butte City seismic zone.

We presume that the foothills along the west side of the Sacramento Valley between Williams and Vacaville as well as the Dunnigan Hills and uplifted regions to the south have been formed by a process like that in the Coalinga/Kettleman region. Northeastward encroachment of the Coast Ranges against the west side of the Sacramento Valley is peeling up the rocks above the valley basement and driving them northeastward over the basement along a zone 10 to 15 km deep (Wentworth and others, 1984). At such depths beneath the Coast Ranges (and above the Pacific/N. America transform zone) decoupling in the lower crust permits the upper crust to be driven northeastward without earthquakes (Eaton and Rymer, in press). Colder, more brittle rocks at these depths beneath the valley do not permit silent decoupling. There, displacement occurs in the stick-slip mode as the upper crust is thrust northeastward; and earthquakes, including some very large ones are produced.

V. The 1892 Vacaville/Winters earthquakes

From what we can judge from the historical records of the 1892 earthquake sequence (Toppozada and others, 1981; Ellsworth and others 1981), the main shock was about the same size as the 1983 Coalinga main shock (M $6.5^{\pm}$ vs M 6.7). The inferred locations of the mainshock and its two largest aftershocks (figure 1) suggest that the size of the 1892 aftershock zone was also comparable to that of the Coalinga sequence. It appears that the main shock occurred beneath the English Hills about 10 km south of Winters and that the aftershock zone extended 10 km or more toward the north, east, and south. Thus, the 1892 sequence appears to have involved only the southern one third (perhaps 30 km) of the 90-km-long zone of foothills and adjacent valley ridges between Vacaville and Williams. Simple arithmetic suggests that the northern 2/3 of this region could produce additional earthquakes as large as that of 1892.

The foregoing analysis is admittedly superficial, and the recent seismicity data for the west side of the Sacramento Valley is not up to modern standards. Nonetheless, reconsideration of the long-neglected 1892 sequence in the light of the well-studied Coalinga sequence and the limited recent seismic data that are available for the region north of San Francisco Bay shows that additional M 6.5$\pm$ earthquakes along the west side of the Sacramento Valley between Vacaville and Williams are likely. Which section of that zone might break next, and when, is beyond our present ability to determine.

IV. Improved seismic hazard assessment of the west side of the Sacramento Valley.

The epicenters of the 1892 earthquake deduced from intensity data lie a few km west of I-505 about midway between Vacaville and Winters. This location is about 14 km southeast of Monticello Dam and very near the main Putah South Canal that carries water from the dam to the Vacaville-Fairfield area. The I-505 corridor between Vacaville and Winters, which is undergoing rapid urbanization, is contained mostly within the probable aftershock region of the 1892 earthquake.

Better evaluation of seismic hazards in this region, as well as throughout the Antioch-Butte City seismic zone, will require a better understanding of active tectonic structures and processes in the region than is now available. Fortunately, considerable groundwork applicable to the Vacaville-Winters region has been laid by studies of the CR/GV boundary some distance north and south of the region (Wentworth and others, 1984). Additional critical information can be obtained from the instrumental record of microearthquakes. Because of the relatively low current rate of seismicity in the region, it is important to reinforce the seismic network to accelerate the accumulation of a sufficient seismic record to identify active seismic structures and to obtain focal mechanisms of earthquakes that occur on them. Two objectives with somewhat different network requirements should be considered:

1) the region around Lake Berryessa and Monticello Dam and the region of the 1892 sequence and its possible northward extension should be covered by a network sufficient to provide reliable recording of earthquakes larger than M 1.3. A local net of about 8 additional stations to supplement 5 existing stations should fullfill this need.

2) The regional network should be supplemented very selectively to provide better definition of the Bartlett Springs fault zone and the Antioch/Butte City seismic zone. For this purpose an additional 8 stations are needed. Some of these may be obtained by relocating existing stations. The required stations are widely dispersed, and some of them can be added to existing telemetry circuits at low cost.

These two groups of proposed stations are shown in figure 1. For maximum cost effectiveness and scientific usefulless, any additional stations should be of the standard USGS design and their records should be analyzed in conjunction with the rest of the northern California network.

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Figure 1. Seismicity of the northern Coast Ranges, 1972-1985. The Coast Range/Great Valley boundary is along the easternmost major outcrop of the Great Valley Formation (GVF). Deformation along the west side of the Great Valley is outlined by the contact between flat-lying Great Valley sediments (Qal) and the deformed older sediments (T, Qc) below them. Epicenters of large historic earthquakes along the CR/GV boundary are indicated by large, heavy circles with labels showing magnitudes and dates of occurrence.

Figure 2. First motion plot and fault plane solution for the M 4.3 earthquake northeast of Winters on September 9, 1978.

Dot = compression

Circle = dilation

P = P axis

T = T axis

F

MONTICELLO 1972-1985

RMS<0.50 NSTA>7 MAG>1.5 DMIN<50 ERH<20

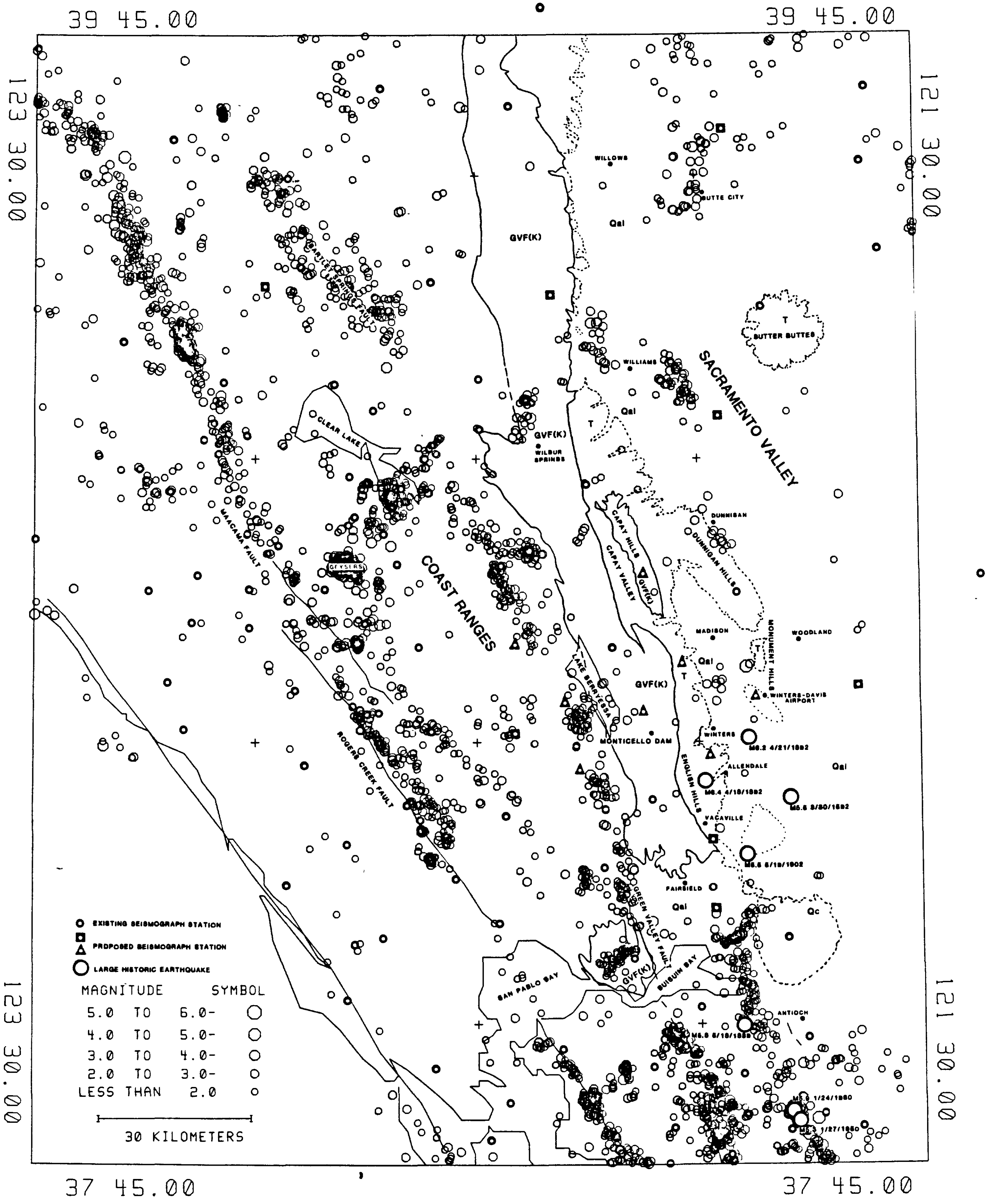

Figure 1

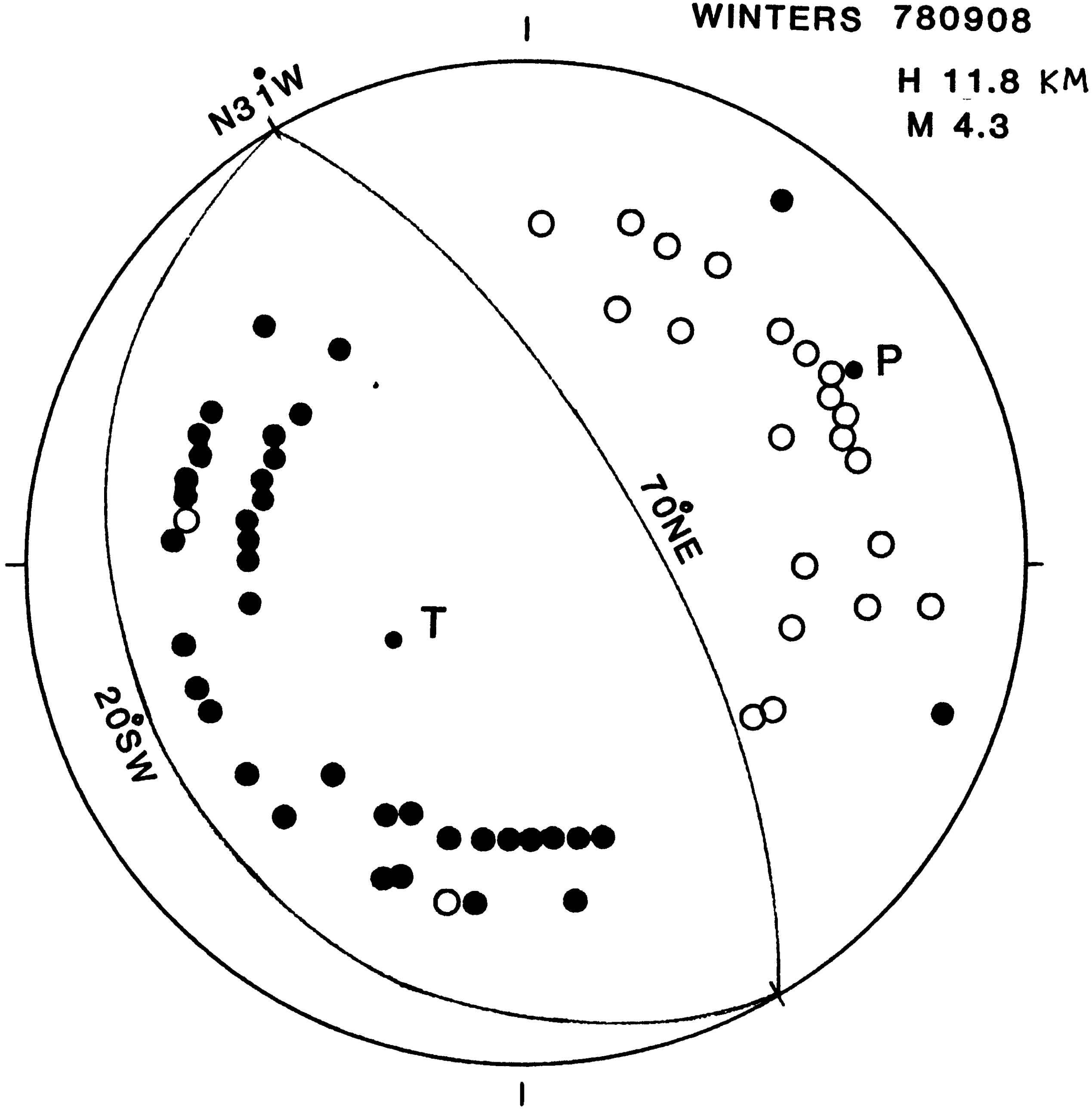

Figure 2