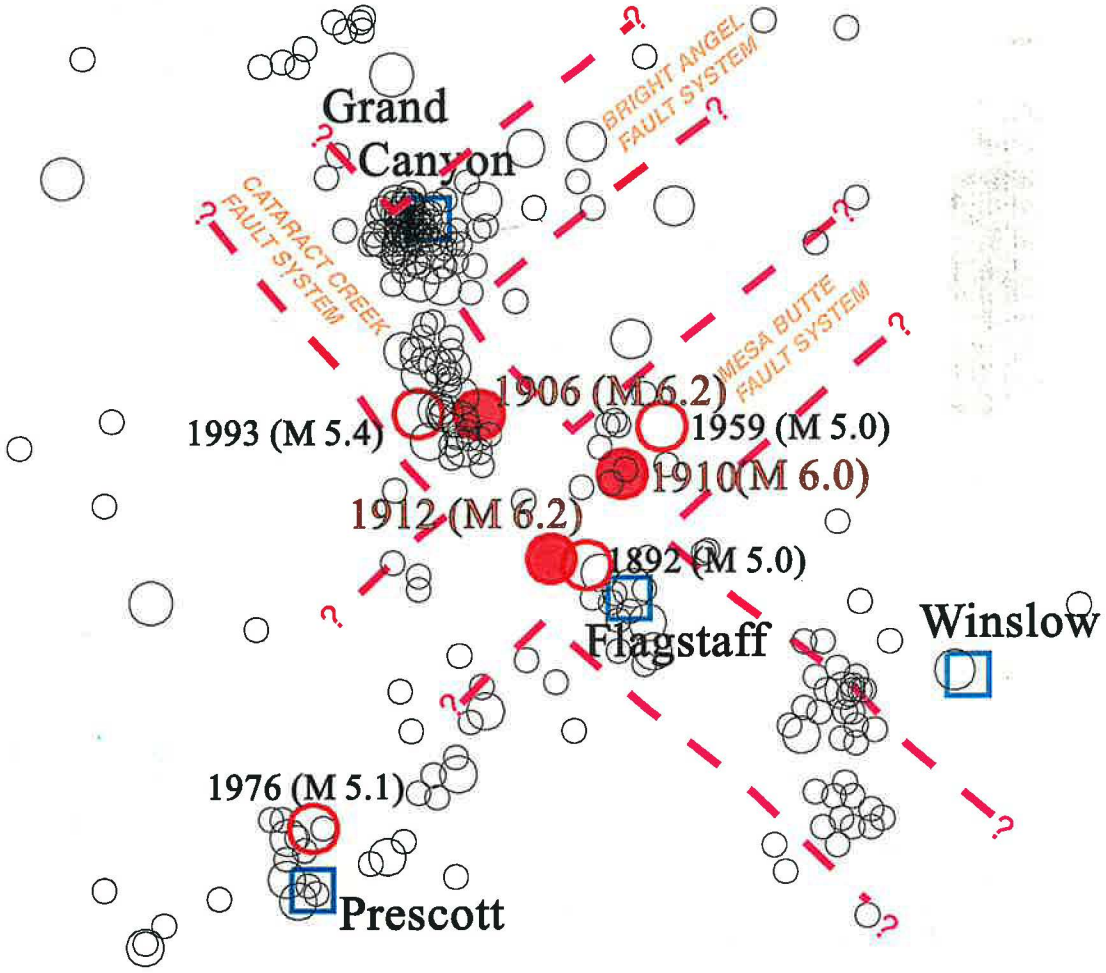
Ivan Wong

RELOCATION STUDY OF EARLY ARIZONA EARTHQUAKES:
EVENTS OF 1906, 1910, and 1912



Prepared for:
The Arizona Division of Emergency Management, Earthquake Program

Supported by:
Federal Emergency Management Agency and the Arizona Earthquake Information Center

LEGEND

M < 3.0

M 3.0-5.0

M > 5.0

NEW LOCATIONS OF STUDY EARTHQUAKES

1910 (M 6.0)
date and (magnitude)

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Executive Summary

The Scope of Work for this study was performed by the Arizona Earthquake Information Center (AEIC) in the Northern Arizona University (NAU) Geology Department. The Scope of Work extended for twelve (12) months pursuant to ARS 35-148(A) agreement with the Arizona Division of Emergency Management.

Purpose - The purpose of this study was to gather and analyze previously unused data that led to improved locations for the 1906 (M_S 6.2), 1910 (M_S 6.0) and 1912 (M_S 6.2) northern Arizona earthquakes. Both ground shaking intensity patterns and instrumental data were used. The objective is to provide epicenter locations accurate enough to allow planners to decide what ground acceleration levels are most appropriate for northern Arizona. The results can make the difference between UBC Zones 2, 3 or 4 for the region.

Work Performed Under this Agreement Consisted of:

First Quarter:

- task 1- Library/archive research for intensity of ground shaking data at Arizona repositories.
- task 2- Trip to National Archives in Denver to search for early seismograms, microfilm, logbook copies of events.
- task 3- Send out letters of inquiry to locate non-archival material held privately.
- task 4- Trip to Tucson to Arizona Heritage Center Library.
- task 5- Gather data on potential calibration events (4-29-93; 2-4-76; 7-21-59).

Second Quarter:

- task 6- Evaluation of intensity data; assignment of intensities to locations, and contouring of improved isoseismal maps.
- task 7- Use of the 1993 Cataract Creek data to generate travel times for phases, wave velocities along specific paths (e.g. BRK, TUO, DEN etc.)
- task 8- Evaluation of parameters (origin time, location) of 2-04-76 and 7-21-59 northern Arizona earthquakes, for use as potential master/calibration events.
- task 9- Analysis/evaluation of S-P times and application where possible to locations.
- task 10- Preparation of semi-annual report.

Third Quarter:

- task 11- Local time contouring for all events, correlation of aftershock reports.
- task 12- Cross correlation of calibration event seismograms with those of 1906, 1910, 1912, where available.
- task 13- Analyze results, integrate results from all data sources, interpret results.

Fourth Quarter:

- task 14- Write papers, give talks on findings.
- task 15- Write final report.

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1.0 INTRODUCTION

Prior to beginning this study the state-of-knowledge concerning northern Arizona earthquakes can be summarized as follows:

- The region between Flagstaff and the Arizona-Utah border has produced seven $M \geq 5.0$ historic earthquakes.
- The three largest occurred within a six year period (1906-1912).
    - 1906, January 25, M_S 6.2
    - 1910, September 24, M_S 6.0
    - 1912, August 18, M_S 6.2
- No $M > 5.0$ earthquake has occurred within 25 miles of a population center since 1912.
- Most well-instrumentally located earthquakes have occurred within a northwesterly trending belt of seismicity beginning southeast of Flagstaff, trending through the Grand Canyon, and apparently joining with a northward trending belt of seismicity at the Arizona-Utah border. This has been termed the Northern Arizona Seismic Belt (NASB) (Brumbaugh, 1987) (Figure 1).
- Two of the three historic earthquakes (1910 and 1912) were located by DuBois and others (1982) within a region of sparse instrumentally located activity between 10 and 30 miles northeast of the NASB (Figure 1).

The Primary Study Goals Include:

- To better constrain the location of the three largest historic Arizona earthquakes.
- To evaluate likely fault system(s) to which these earthquakes might belong.
- To assess new locations in terms of earthquake hazards in northern Arizona.

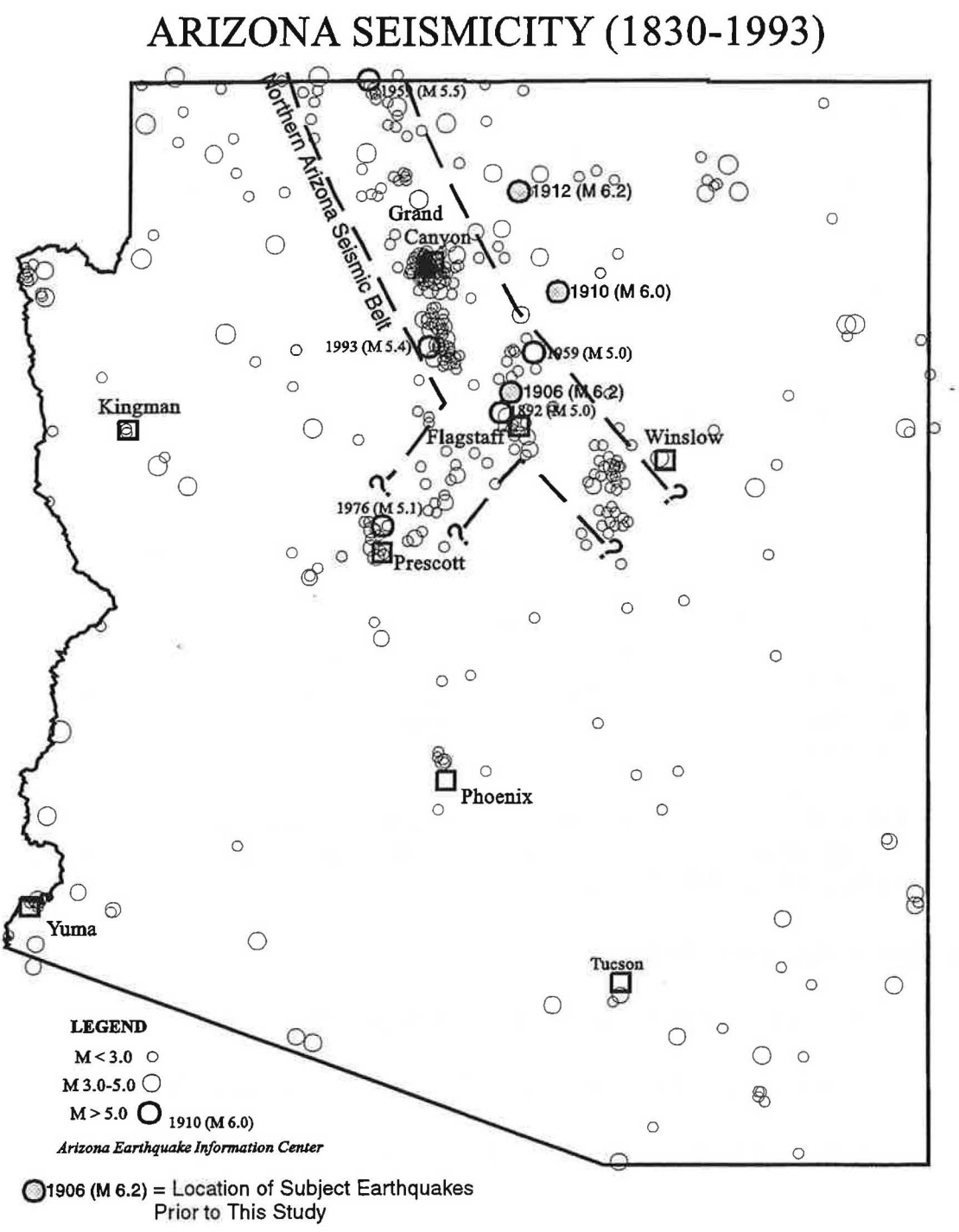

Figure 1 *- Arizona seismicity, illustrating locations for the 1906, 1910, and 1912 earthquakes prior to this study and the Northern Arizona Seismic Belt (NASB).*

2.0 INTENSITY AND MAGNITUDE

This study incorporates historic intensity data and early instrumental data from the few seismic stations in operation early this century. The intensity data are collected from records of personal observations of earthquake effects. An introduction of earthquake processes and their relationship to intensity and magnitude is provided below.

2.1 Earthquakes

Earthquakes occur when stresses within the earth's crust are relieved by slippage along rupture surfaces known as faults. The rupture process generates waves that radiate from the fault source, affecting people and structures on the surface of the earth. Although the process is conceptually simple, the factors controlling the precise nature of an earthquake are not completely understood. Ongoing geological and seismological research is continuing to assess where and when earthquakes will occur in the future, as well as how large they are likely to be, and to anticipate the probable effects on various types of man made structures.

The focus, or hypocenter, of the earthquake is the point within the earth's crust where the initial rupture of the rocks occurs and where the elastic waves from the earthquake are first released. The majority of earthquakes recorded in the United States have had shallow focal depths; 15 km or less; and have occurred in regions containing faults outcropping at the surface. In other regions, however, earthquakes occur at deeper locations within the earth's crust, so that a surface rupture is not often observable in the field. The later process is perhaps the most common within the study area. Relatively deep earthquakes often exceeding 15 km are recorded for the Colorado Plateau (AEIC Catalog of Earthquakes, Wong and Chapman, 1986). In addition, no surface rupturing events associated with Colorado Plateau earthquakes have been observed during historic time.

In summary, three *primary* factors determine what is felt in an earthquake: 1) earthquake magnitude; 2) distance from the fault; and 3) local soil conditions. In addition to these primary factors, a discussion of secondary factors that may be applicable to these historical earthquakes are provided below.

2.1.1 Determining Epicenters:

The epicenter of an earthquake is the projection of the focus up on to the earth's surface. In the absence of instrumental data, epicenters have often been established on the basis of felt reports and the damage that is observed as in this study. However, epicenters are now typically located by the relative arrival times of seismic wave components received at various instruments operating within a seismograph network. In Arizona, there are twelve seismic stations located throughout the state at Tucson, Yuma, Phoenix, Flagstaff, Williams, Jerome, Sunset Crater, Blue Ridge Reservoir, Pipe

Springs National Monument and the south and north rims of the Grand Canyon (Figure 2). However, in view of Arizona's earthquake risk and size, this is considered sparse seismic station coverage. Historically, seismic station coverage for Arizona is considered very sparse. The earthquake risk to the state can best be determined by adequate seismic station coverage that collects and processes accurate earthquake data. The accuracy of epicenter and hypocenter locations depends upon: (1) The number of reliable recording stations; (2) geologic interpretations of crustal structures; and (3) knowledge of local earthquake wave propagation velocities in various areas.

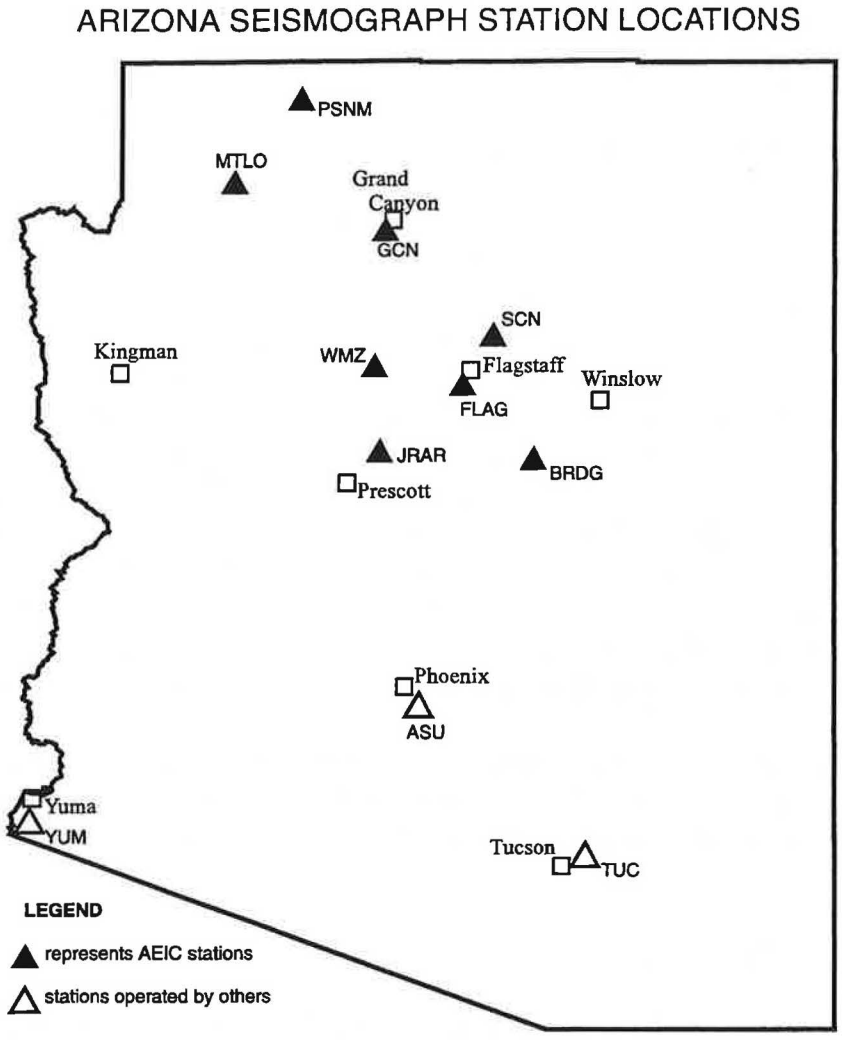

Figure 2 *- Locations of seismograph stations within Arizona. Stations maintained by the AEIC are shown by open triangles, and include remote analog stations PSNM and SCN operated by the National Park Service, and JRAR operated by the State Parks service. Other operators in Arizona include: Arizona State University (ASU), Caltech (YUM), and University of Arizona (TUC).*

2.1.2 Earthquake Magnitude:

The magnitude of an earthquake is intended to be a measurement of its size, independent of the place of observation. It is calculated from measurements on seismographs. Physically, the magnitude can be correlated with the energy released by an earthquake, as well as with the fault rupture length and the maximum fault displacement. At present, at least four different magnitudes are in common use for classifying earthquakes: (1) local magnitude (M_L), the classic Richter magnitude based on peak response of a Wood-Anderson torsion seismometer 100 km from the epicenter; (2) body-wave magnitude (m_b), based on the response amplitude of the primary (P-wave) body-wave; (3) surface wave magnitude (M_S), based on the response amplitude of long-period surface waves; and (4) the moment magnitude (M_W), which is the most complete measure of earthquake size. Moment magnitude (M_W) is directly based on the amount of energy released during an earthquake and can be measured by a geologist in the field examining the fault geometry, as well as by a seismologist studying the digital waveforms. Each of these magnitudes are used in this report, and are derived from a well-calibrated instrument, knowledge of the characteristics of the rock through which the seismic waves must travel and the local conditions at the seismograph station.

Earthquakes are normally classified as to severity according to their magnitude (usually using the Richter scale), or their seismic intensity. Richter magnitude is a logarithmic measure of the maximum motions of the seismic waves as recorded by a seismograph. Because this size classification is based on a logarithmic scale, a magnitude 8 earthquake is not twice as big as a magnitude 4 earthquake, but rather, 10,000 (i.e. 10^4 or 10x10x10x10) times larger. More recently, seismologists have shown that magnitude is also proportional to the energy released during an earthquake, but at a level 32 times greater between earthquake magnitudes (e.g. a magnitude 6 earthquake releases 32 times the energy as a magnitude 5 earthquake).

2.1.3 Earthquake Intensity:

In the absence of instrumental recordings of ground motion, seismologists have described the ground movement by assigning intensity numbers according to subjective intensity scales (Table 1). Following an earthquake, the assignment of an intensity to a given location is based on interviews with inhabitants of the area and on observations of damage in the area. Assigned intensity values from different locations are then combined to formulate a map containing a series of isoseismals, contours that separate regions of successive intensity rating. The shape and extent of the isoseismals are influenced by the tectonic features of the area, indicating predominant directions along which seismic waves are transmitted and the manner in which the earthquake originates (NUREG, 1975). In addition, several other factors influence the felt intensity of an earthquake, including: population density, local geology, shallow ground water, and building type.

The destructiveness of an earthquake at a particular location is commonly reported using the Modified Mercalli Scale of seismic intensity. Seismic intensities are subjective classifications based on reports of ground shaking and damage caused by past earthquakes. There are several seismic intensity scales; the one used most often is the Modified Mercalli Intensity (MMI) scale. The MMI scale was modified in the 1930's to address construction practices and affects on new inventions such as automobiles, and the scale is undergoing modification during the writing of this report to address modern construction practices, such as steel frame buildings. This scale has 12 levels of intensity; the higher the number, the greater the ground shaking intensity and/or damage.

Earthquakes have only one magnitude, but they have variable intensities that generally decrease with increasing distance away from the source. However, other factors such as local geology, shallow ground water and building type affect the intensities of earthquakes at a site. For example, greater intensities are associated with poorly consolidated alluvial soils, high ground water levels, poor construction practices and unreinforced masonry structures. Certain soils greatly amplify the shaking in an earthquake. Seismic waves travel at different speeds in different types of rock, and when seismic waves pass from rock to soil they generally slow down and get bigger. The looser and thicker the soil is, the greater the amplification will be. For example, ground motion that damaged regions underlain by poorly consolidated sediment in the Loma Prieta earthquake were 10 times greater than neighboring regions. In addition, earthquakes such as Northridge 1994 and Kobe 1995 have demonstrated the influence of fault rupture directivity on intensity distribution. When the earthquake rupture moves along the fault, it focuses energy in the direction it is moving so that a site in that direction will receive more shaking than a site the same distance away but in the opposite direction.

TABLE 1 - ABRIDGED MODIFIED MERCALLI INTENSITY SCALE

Intensity Value and Description		*Average peak velocity (centimeters per second)*	*Average peak acceleration (g is gravity = 9.80 meters per second squared)*
I.	Not felt except by a very few under especially favorable circumstances (I Rossi-Forel scale)		
II.	Felt only by a few persons at rest, especially on upper floors of high-rise buildings. Delicately suspended objects may swing. (I to II Rossi-Forel scale)		
III.	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration estimated. (III Rossi-Forel scale)		
IV.	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like a heavy truck striking building. Standing automobiles rocked noticeably. (IV to V Rossi-Forel scale)	1-2	0.015g-0.02g
V.	Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel scale)	2-5	0.03g-0.04g
VI.	Felt by all, many frightened and run outdoors. Some heavy furniture moved, a few instances of fallen plaster and damaged chimneys. Damage slight. (VI to VII Rossi-Forel scale)	5-8	0.06g-0.07g
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 cars. (VIII Rossi-Forel scale)	8-12	0.10g-0.15g
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, and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving cars disturbed. (VIII+ to IX Rossi-Forel scale)	20-30	0.25g-0.30g
IX.	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+ Rossi-Forel scale)	45-55	0.50g-0.55g
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, slopped over banks (X Rossi-Forel scale)	More than 60	More than 0.60g
XI.	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.		
XII.	Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown into air.		

3.0 LOCATION ANALYSIS USING INSTRUMENTAL DATA

3.1 Methodology

Principal problems to be overcome in locating early instrumental earthquakes are acquisition of sufficient sources of data, and determination of the accuracy of timing data. Early mechanical seismographs had low magnification and the arriving earthquake phases were often incorrectly identified. For example, because of low gain, the P-wave would frequently not be recorded. In addition, the S-wave and on occasion the Surface waves would be identified as the P-wave (Figure 3).

Timing was also a serious concern. Many early seismograph systems operated at drum speeds less than that used today, so that records were usually read down to 0.1 minute (6 seconds). This limits the accuracy of determination of arrival times, and thus locations. Clock calibration adds to this concern about timing. So some consideration must be instituted in studies such as this one to evaluate phase picks, and the timing of phase arrivals.

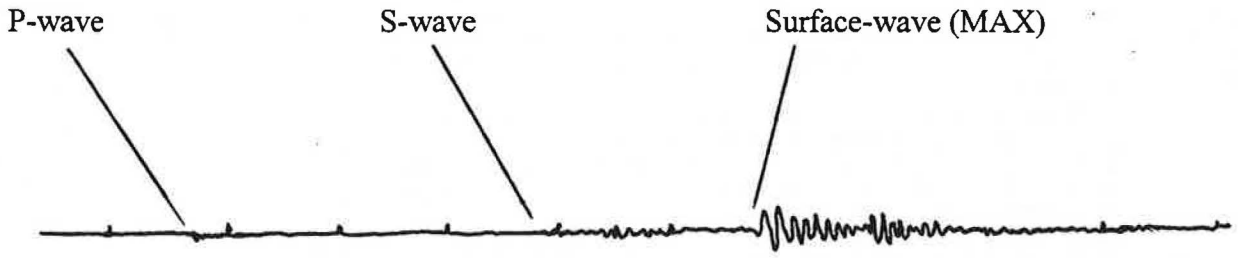

Figure 3 - Recording at SLM (Saint Louis, Missouri) of 1912 earthquake.
(time marks are at one-minute intervals)

3.1.1 Data Search

The two primary sources of data were early seismograms and station logbooks. Data sources included the AEIC archives, Stanford University Library, NOAA Geophysical Data Center, Denver National Archives, the National Earthquake Information Center, Saint Louis University, University of California Berkeley seismograph stations, and the Geological Survey of Canada.

During the time period 1900-1912 several networks useful to this study were in operation: the Milne worldwide network, the association of Jesuit seismograph stations, and the Canadian government network. There were also a number of independent stations (e.g. Berkeley) associated with universities and stations operated by the U.S. government usually at magnetic observatories such as Tucson (Figure 4). Data search of the available sources resulted in both original seismograms and logbook data for the three Arizona earthquakes (Tables 2 and 3).

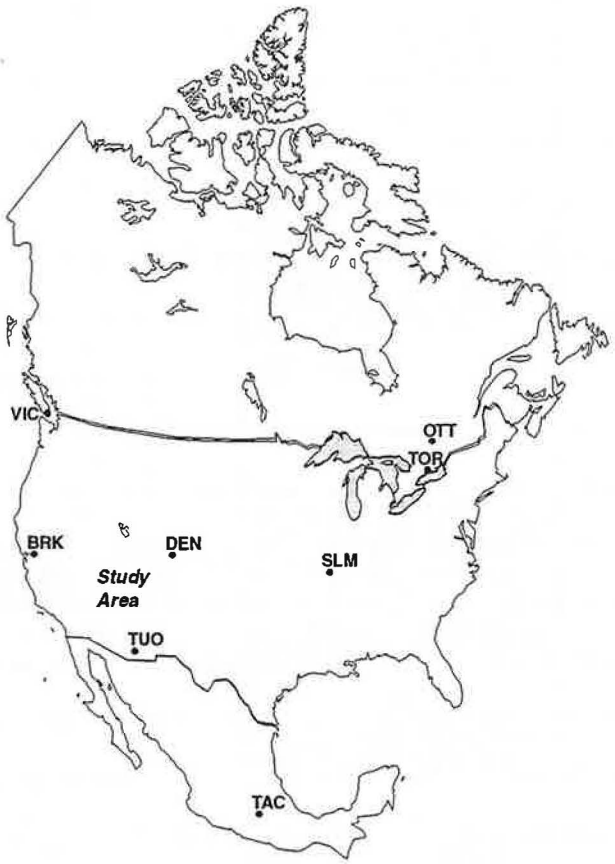

***Figure 4** - Location of seismograph stations from which data were gathered for this study.*

3.1.2 Calibration Events

The research plan was to try to evaluate the data gathered for the three northern Arizona earthquakes by comparing them to well constrained and documented data from modern analogues. Thus data were gathered for modern earthquakes occurring in northern Arizona, a principal data source being the April 29, 1993 Cataract Creek tremor (M_W 5.3).

TABLE 2 - POTENTIAL INSTRUMENTAL DATA SOURCES			
STATION	**1906**	**1910**	**1912**
STR	X	X	X
TAC	X	X	X
BRK	X	X	X
BUF		X	X
CLE	X	X	X
CLH	X	X	X
DEN		X	X
FOR		X	X
GEO		X	X
HON	X		
MHC	X	X	X
NOL		X	X
REN			X
SCL		X	
SEA	X	X	X
SLM		X	X
TOR	X	X	X
TUO		X	X
VIC	X		X
WAS		X	X

Choice of modern analogues were governed by events that had waves that traveled paths similar or identical to those traveled by waves from the early 1900 Arizona earthquakes. Since few modern analogues exist for events occurring in northern Arizona, events occurring elsewhere and recorded in northern Arizona at stations FLG and FLAG were also used. For example, tremors that occurred close to stations BRK, VIC, and DEN, and were well recorded at the Flagstaff stations were especially useful in this study.

TABLE 3 - ARRIVAL TIMES				
1906				
STATION	**P**	**COM**	**S**	**MAX**
HON	---	205318	---	205648
STR	211600	---	211932	212132
TAC	204027	---	---	204317
TOR	---	---	---	204918
VIC	---	---	---	204054
1910				
OTT	042047	---	042300	042342
SLM	041500	---	041630	041718
TOR	---	041300	---	042200
TUO	040603	---	---	040723
VIC	---	041418	---	---
1912				
BRK	211230	---	---	211509.6
DEN	211200	---	---	211400
HON	211230	---	---	211248
OTT	212018	---	---	212900
SLM	211536	---	211848	---
TOR	---	212154	---	212648
TUO	211129	---	---	211221

Key to abbreviations used above: *P=p-wave arrival time, COM=commencement arrival time, S=s-wave arrival time, MAX=maximum amplitude arrival time.*

Of special interest was the travel time of the maximum amplitude surface wave, which was usually noted on the horizontal component. Not only should this wave have a relatively constant velocity for a given path, or in some cases in a given region, but was often the phase of highest amplitude reported in early logbooks and thus the most accurately timed arrival. Plots of the maximum phase, as it was usually termed, show velocities that cluster around 3.0 to 3.1 km/sec (Figure 5).

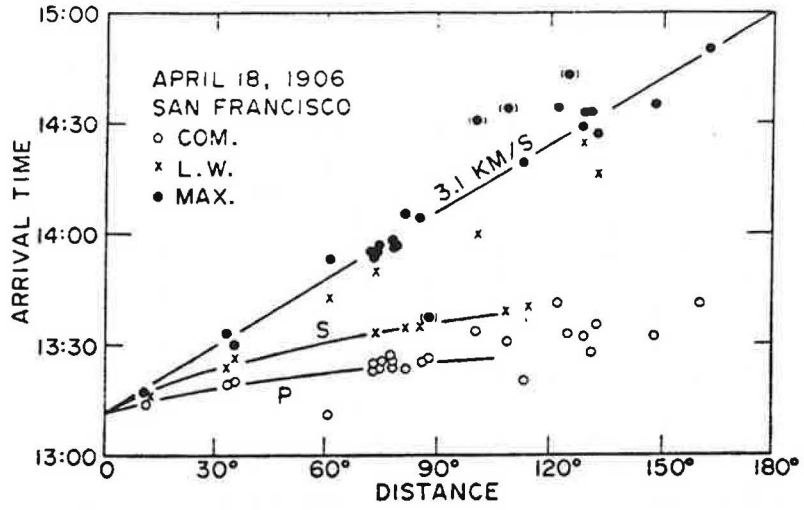

***Figure 5** - Arrival times for the San Francisco earthquake of 1906. (MAX.=maximum amplitude surface wave; COM.=commencement; L.W.= long wave)*

Travel times of phases for modern events along paths identical or parallel and close to paths for waves from the early 1900 tremors, were used to evaluate phase identification and arrival times from logbook entries. One example was timing for the 1912 Arizona earthquake at station VIC (Victoria) in British Columbia. Here the modern analogue was an earthquake that occurred in northwest Washington state on 5-28-81. This event had a magnitude of m_b 4.8 and was well recorded at Flagstaff, Arizona (FLAG). The path for this event was very close to that of the early Arizona events. The path velocity for the maximum phase determined from the seismogram was 3.15 km/second. Given a distance of 1,760 kilometers between the Flagstaff area (35.00N x 111.30W) and the VIC station, the predicted arrival time for the maximum phase would be 21:18:51.7. The only phase reported for the 1912 tremor arrived at 21:19:06 and was identified as the P-wave. This was instead clearly the surface wave.

Path velocities for the maximum phase were calculated for northern Arizona to Denver, Victoria, Berkeley, Saint Louis, Ottawa, Toronto, Tacubaya, Strassburg, Tucson and Honolulu (Table 4).

TABLE 4 - SURFACE WAVE VELOCITIES				
STATION	**FROM-TO**	**DISTANCE**	**EVENT**	**VELOCITY**
BRK	Livermore-FLAG	998 km	1-27-80	2.96 km/sec
DEN	Denver-FLG	796 km	4-10-67	3.00 km/sec
OTT	Northridge-OTT	4,332 km	1-17-94	3.16 km/sec
SLM	Northridge-CCM	2,513 km	1-17-94	2.99 km/sec
	Cat. Creek-SLM	1,977 km	4-29-93	3.00 km/sec
STR	Cal.-OTT-Greece	7,620 km	4-18-28	3.08 km/sec
TAC	Mex.City-FLAG	2,071 km	10-25-81	2.94 km/sec
TOR				
TUC(TUO)	NAz-Tucson	367 km	10-13-59	3.20 km/sec
VIC	Wash.-FLAG	1,500 km	5-28-81	3.15 km/sec

3.1.3 Analysis of Instrumental Data

Good origin times are essential to location. This is perhaps the most difficult parameter to evaluate. Fortunately for the early Arizona earthquakes constraints are available from locally observed times. Careful observers were available in Flagstaff from the astronomers at Lowell Observatory where accurate timing was an essential scientific attribute. Also, the local weather station meteorologist was able to provide onset times accurate to one-half minute. These data are supplemented by onset times published in the local newspapers throughout northern Arizona.

Origin times were calculated by several methods. This included the use of S-P times, use of constraints supplied by aftershock reports, and use of surface wave data. Once again, however, the data must also be tested to preclude errors in clock calibration and arrival times. Reid (1979) calculated the origin time for the 1912 tremor from analysis of the Tucson records as 21:12:00 GMT. This origin time appears to be in error for the following reasons. The time gap between the P-wave arrival and the Surface wave time is 54 seconds for the north component and the same for the east component. This gives a distance of 4.2 degrees, and is equivalent to a distance of 467 kilometers. This calculated distance is far to the northwest of the region of intense ground shaking. Furthermore, if we use the arrival times and travel times for the P-wave we find that we have for origin times:

Reported Arrival Times at TUO	Travel Time	Calculated Origin Times
North: 21:11:45	-(67 seconds)	21:10:38
East: 21:11:29	-(67 seconds)	21:10:22

Reids' origin time estimate in the literature is 21:12:00. This agrees with neither of the estimates above. Nor do any of the three estimates agree with the local onset times reported. Observers in Williams, Winslow, and Flagstaff all gave onset times of 21:10:00. This includes the on duty astronomer at Lowell Observatory. A report of 21:11:00 came from farther east, at Holbrook, Arizona. The latest reported onset time was from the far north of the state, at Tuba City, which gave 21:15:00. Although some of these times may be passed off as inaccurate, it is difficult to see how they could all be within one minute of agreement and also in error when compared to Reids' estimate by as much as two to three minutes.

Using the reported onset times as a guide, instrumental data was sought to corroborate. The data chosen was that from station BRK (Berkeley) which is about 10 degrees from the region of strong ground shaking for the 1912 tremor. The January 27, 1980 M 5.8 Livermore, California tremor was the modern analogue used. The distance between this epicenter and BRK is 40 kilometers, so the wavepath is nearly identical over the distance in question. The maximum phase (Surface wave) velocity calculated from the Flagstaff records for this path is 2.96 km/second. Reasonable phase velocities and travel times were also calculated for P and S. Comparing the modern times to the 1912 earthquake logbook entries, the logbook times for P, S, and Surface wave maximum phases are all close to what would be predicted, and are thus not grossly in error.

An origin time was calculated for the 1912 tremor using the Surface-P-wave time interval for Berkeley and was found to be 21:09:36. This seems reasonable considering the onset times of 21:10:00 reported in northern Arizona. The Berkeley station times and time keeping appear quite impressive for this early time period. By 1912 the Berkeley station had 25 years of time keeping experience upon which to rely. Clocks were calibrated daily and time keeping was considered accurate to within ±0.1 minute of standard time.

Another piece of independent data which is important in epicentral location is the report of aftershocks felt. Aftershocks should lie within the mainshock rupture volume, and also have a certain maximum magnitude in relation to the main shock. These two factors also help constrain the location of the main shock. The August 18, 1912 northern Arizona tremor has a reported instrumental magnitude of M_S 6.2 (Brumbaugh, 1991). The largest aftershock would likely be no larger than 1.2 units less, or M_S 5.0. Such an event has a felt radius of about 120 km, based on data from previous events in northern Arizona. For the 1912 event, the same aftershock with a similar felt intensity was reported in Flagstaff, as well as Williams. A conservative estimate then would place the largest of these aftershocks no further than 120 km from Flagstaff or Williams (Figure 6). The aftershock volume of an M_S 6.2 tremor would have a radius of about 15 km. Thus the main

shock should lie no further than 135 km from Flagstaff, and likely less than this distance. Such a restriction on location also restricts origin time. Given the onset time at Flagstaff of 21:10:00 as approximately correct, and a P-wave velocity of 6.25 km/second, then for a radius of 135 kilometers, an earliest estimated origin time would be 21:09:38.4. Of course the reported onset time is probably not correct to the second, but the agreement of this line of reasoning is encouraging when compared to the estimated origin time of 21:09:36 based on the S-P time gap as reported in the BRK logbook.

The next step in location is to use the reported local times, estimated maximum radius of main shock from Flagstaff, and the intensity map for 1912 to set up distance grids in northern Arizona for each station recording the tremor.

Having a fairly accurate origin time for 1912, independently checked, and path velocities for the Maximum Phase (Surface wave) from modern events, and finally an evaluation of the accuracy of the Maximum Phase arrival times, the distance grid for each station allows evaluation of locations. Each latitude/longitude point on the grid is associated with a travel time and distance that can be compared to those calculated for each station. This comparison for all stations will yield best-fit arcs for these stations. The intersection of these wave fronts yields an estimated location of the epicenter. This is an areal grid approach to the classical circle intersect technique of epicenter location. Very few S- and P-wave arrivals were available to apply to locations, so the majority of arc positions were estimated using Maximum Phase (Surface wave) arrival data.

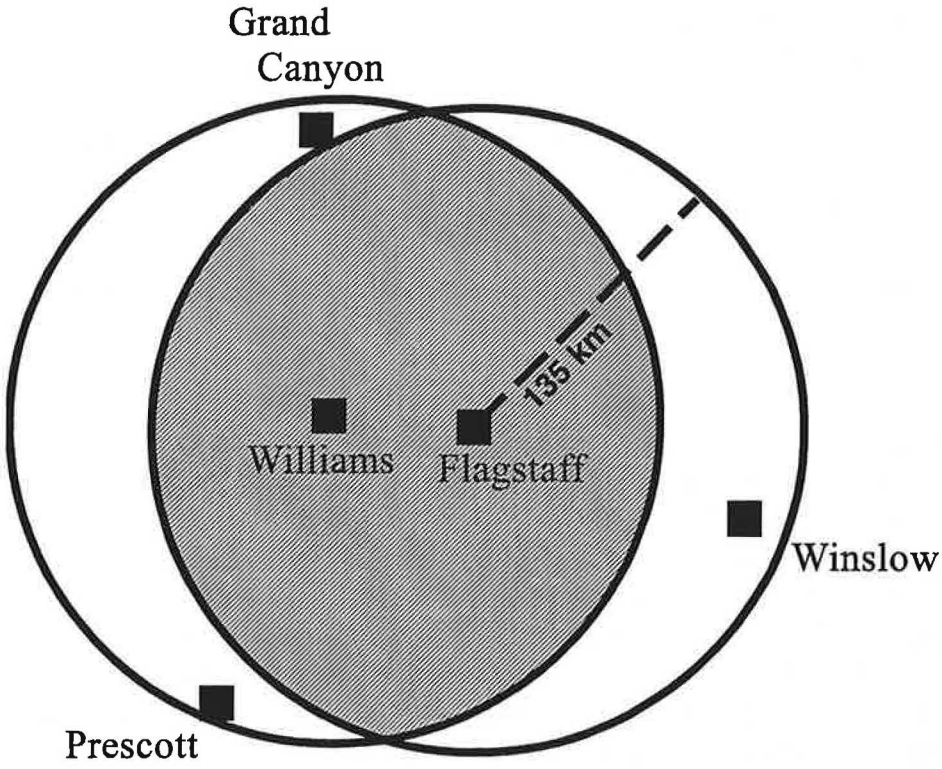

Figure 6-Constraints on Epicentral Location Utilizing Aftershock Data

An aftershock of the August 18, 1912 tremor occurring during the early morning hours of the following day were felt at Flagstaff and Williams, and reported as "a slight shock" at both locations. The following methodology were used to estimate the maximum distance of the aftershock from Flagstaff and Williams:

1. Estimate of maximum aftershock size: Based on similar size earthquakes, the largest aftershock should be no more than 1.2-1.4 magnitude units less than the main shock. Thus for the August 18, 1912 tremor *M 6.2-1.2 = M 5.0.*
2. Estimate, using results of 1), the felt radius of an M 5.0 event: Based on tremors that have occurred in Arizona, and their felt radii, a magnitude 5.0 should have a felt radius of about 120 kilometers.
3. The 5.0 aftershock should lie within the aftershock volume, which for a 5.0 is estimated by: *log V=9.58 + 1.47(5.0) or V = 1.82 x 10^3 cm or 14.76 km*
4. Thus a conservative estimate for the maximum distance from Flagstaff of the main shock would be: *120 km + 14.76 km = 134.76.*
   (note: A similar methodology is used for the aftershocks of the 1906 event.)

4.0 SUMMARY OF INTENSITY DATA

4.1 Earthquake of January 25, 1906, Thursday, 1:32:30 p.m. (local time), M_S 6.2

Angel **MMI VII**

At Angel, the force of the quake was greater than here (Flagstaff). In the house of the railroad agent furniture was moved (The Coconino Sun, 1/27/06).

Flagstaff **MMI VII**

An interesting observation of the damage reports for Flagstaff are that the reports of building damage are all within the "new town" site rather than the "old town" region. Perhaps the difference is related to the basaltic bedrock foundation of the old town site compared to the alluvial soils that underlie new town about one mile to the east. As a trained and experienced observer, the observations reported by A.E. Hackett (Flagstaff Weather Bureau), we feel should be given greater consideration. As described below, a few chimneys thrown down and panic stricken persons fall within MMI category VII.

- A severe earthquake shock was felt at 1:32:30 p.m. The wave apparently came from the NNW and its duration was about 20 seconds several persons report having heard a rushing or roaring sound for a few moments preceding the shock. A few chimneys were shaken down, plastering was shaken from ceilings, crockery was thrown from shelves and clocks were stopped. At the public school the children were thrown into a panic and school was dismissed for the day (A.E. Hackett, Flagstaff Weather Bureau).

- At 1:33 today the people of this city were thrown into a panic by a terrific shock of an earthquake that threw down chimneys, cracked the walls of buildings and shook the plastering from ceilings (The Arizona Republican, 1/26/06).

- The seismic wave came from the largest of these craters in the San Francisco peaks and the rushing grinding sound of its approach was heard for several seconds before it reached the city (The Arizona Republican, 1/26/06).

- As it passed beneath the city, buildings rocked and swayed and crockery and bric-a-brac were thrown to the floor and people rushed into the street fearing that walls were falling (The Arizona Republican, 1/26/06).

- At the public school, a two-story brick building, the children were panic stricken and rushed to the stairways and but for the coolness and presence of mind of the teachers, some of the smaller children would have been trampled to death (The Arizona Republican, 1/26/06).

- Many persons in the city experienced a feeling of seasickness so great was the rocking motion of the earth (The Arizona Republican, 1/26/06).

- Advices from the neighboring towns indicate that Flagstaff was near the center of the disturbance. The vibrations continued for about 30 seconds and the motion seemed to be from northwest to southeast and the wave traveled at the rate of 180 miles per hour (The Arizona Republican, 1/26/06). (note: we do not know where this rate (180 mph) came from, but it is far slower than either the speed of earthquakes waves or sound.)

- People fled in terror to the streets. Two distinct shocks were felt (The Coconino Sun, 1/27/06).

- The quake was of less than a minute's duration, but that was long enough to satisfy everyone (The Coconino Sun, 1/27/06).

- Slight damage was done by the tremor which seemed to come from east to west and extended from Seligman to Gallup (The Coconino Sun, 1/27/06).

- The people were panic stricken and rushed from stores, public buildings and residences, to the streets (The Coconino Sun, 1/27/06).

- At the public school the shock was severely felt, the teachers and pupils making a hasty exit from the building, but fortunately none were injured in the scramble to get out. The plastering in every room of the building was cracked (The Coconino Sun, 1/27/06).

- At the court house, a portion of the plastering fell from the ceiling of the clerks office (The Coconino Sun, 1/27/06).

- The chimney at Heller's blacksmith shop fell and the chimney on the Santa Fe bunk house (The Coconino Sun, 1/27/06).

- A stone fell from the kitchen door of the old Bank hotel (The Coconino Sun, 1/27/06).

- At the hardware department of Babbitt's store, glassware was thrown from the shelves and bottles were dislodged from the shelves in each of the drug stores (The Coconino Sun, 1/27/06).

- The clock at Lowell observatory was stopped, and in one instance, a clock that had not run for months, was started (The Coconino Sun, 1/27/06).

- Buildings rocked, chimneys fell, plaster was loosened from the ceiling and goods were jarred off the shelves of stores (The Tucson Citizen, 1/27/06).

- Naturally, the shaking of the earth frightened the people of Flagstaff and people ran out of their houses panic stricken. The force of the shock was from east to west (The Tucson Citizen, 1/27/06).

- At Flagstaff chimneys fell down, bottles and crockery crashed to the floor, and pupils in the public school fled in terror from the building. They were so frightened that it was impossible to resume school that day (Arizona Weekly Miner, Prescott, 1/31/06).

- Received the heaviest shock of any place where the tremblings were perceptible (Winslow Mail, 1/27/06).

- A couple of chimneys being demolished and merchandise precipitated to the floor (Winslow Mail, 1/27/06).

- At this place plastering was cracked on a couple of buildings, and nearly every person that was indoors when the shaking commenced made a bee-line for the street (Winslow Mail, 1/27/06).

- While we were away Flagstaff entertained a large-sized earthquake, which put the fear of the Lord into a large part of my family. It was a very severe shake-up, some chimneys being knocked down, and altogether, there was a feeling that the old peaks were about to resume operations. It did no damage to us in any way, except to scare up the children for a considerable time (M.J. Riordian, letter to sister, Feb. 5, 1906).

- Charles Babbitt ran across Cherry Ave. to the Catholic School and helped to evacuate the pupils, including his children. Based on Charles Babbitt's recollection to his son, the ground shaking lasted the entire duration of the evacuation (James Babbitt, personal communication, 1996).

- At 1:37 today the severest earthquake of years was witnessed here. Buildings rattled for more than half a minute and seemed they would certainly fall. Bottles and other goods on shelves in businesses fell to the floor (Williams News, 1/27/06).

- The brick chimney on the Santa Fe section house was shaken down and pieces of plaster fell from the Coconino county hospital. Every one rushed out of buildings and congregated in the streets in great fear (Williams News, 1/27/06).

- The force seemed to come from north to south, with great quivering. No material damage done (Williams News, 1/27/06).

Bellemont **MMI VII**

- At Bellemont, the shock was severe enough to break the ice in the ponds (The Coconino Sun, 1/27/06).

- At Bellemont, ice was broken to pieces in the pond and the water was disturbed into waves by the temblor (Arizona Weekly Miner, Prescott, 1/31/06).

San Francisco Peaks **MMI VII**

- Stones and dead trees are said to have been shaken down the mountains (DuBois and others, 1982).

Williams **MMI VI**

- This section was visited by a severe earthquake, which caused a shaking of homes and rattling of goods upon the shelves (Williams News, 1/27/06).

- No damage, however, was done to property (Williams News, 1/27/06).

- At Williams, the shock was felt, causing the buildings to tremble, and shaking glasses and bottles from shelves. The duration was about three seconds and seemed to extend from west to east (The Coconino Sun, 1/27/06).

- Severe shock. Williams was also shaken up (Arizona Weekly Miner, Prescott, 1/31/06).

Grand Canyon **MMI VI**

- Felt (The Coconino Sun, 1/27/06).

- Strong here. Caused buildings to tremble and lamps hung from the ceiling to swing to and fro (Williams News, 1/27/06).

Seligman **MMI V**

- At Seligman, the depot and other buildings trembled perceptibly, and those in the company reading room ran out of the building terror-stricken. The force seemed to come from west to east (The Coconino Sun, 1/27/06).

Prescott **MMI V**

- Genuine earthquake shocks this city (Arizona Weekly Miner, Prescott, 1/31/06).

- One peculiar freak of the temblor was that it affected only the eastern part of town, the shock being quite marked in that section east of Cortez street (Arizona Weekly Miner, Prescott, 1/31/06).

- Many persons felt the shock yesterday. Allen Hill stated, "A little after 1:30 p.m. I was sitting in the chair in front of my desk talking to a friend when I felt a rocking sensation. I saw the pictures on the walls move, in fact quite noticeably. The building trembled, the windows rattled, and I believe that the shock lasted from 15 to 20 seconds. I thought when I felt the first trembling movement that a boiler had exploded in the neighborhood or that perhaps the chimney had fallen from the building." (Arizona Weekly Miner, Prescott, 1/31/06)

- H. Wm. Stevens, who was visiting in the offices of R.E. Morrison *(located in the second story of the Electric Light building)*, said, "I have felt earthquakes in Los Angeles and San Francisco, but I have never experienced one of such duration as this one. The chandeliers in the Morrison offices moved. I rocked in the chair that I was seated in, the pictures moved on the walls, and the windows rattled perceptibly. I later called into the offices occupied by Mr. Job in the same building, and the stenographer there stated that she plainly felt the earthquake, but did not realize what was the cause of the shaking." (Arizona Weekly Miner, Prescott, 1/31/06).

- Not felt (The Coconino Sun, 1/27/06). *(Note: This obviously erroneous report helped to prevent previous researchers from uncovering the pertinent felt report data for Prescott outlined above.)*

Jerome **MMI V**

- On Thursday Jerome experienced an earthquake, two distinct shocks being plainly felt by many persons (Jerome Mining News, 1/27/06).
- The oscillation was from east to west. It occurred at 1:29 in the afternoon, and shook heavy buildings in a manner which caused some alarm (Jerome Mining News, 1/27/06).
- Not felt (The Coconino Sun, 1/27/06).

Winslow **MMI VI**

- At Winslow, the shock was distinctly felt for half a minute, the force coming from east to west (The Coconino Sun, 1/27/06).

Holbrook **MMI VI**

- A very perceptible earthquake shock occurred here today, causing people to rush excitedly from buildings. No damage (Williams News, 1/27/06).

Fort Defiance **MMI IV**

- Buildings received a strong shaking, but no damage was done (Williams News, 1/27/06).

St. Michaels **MMI IV**

- Buildings received a strong shaking, but no damage was done (Williams News, 1/27/06).

Gallup, New Mexico **MMI IV**

- At Gallup, the shock was distinct and it seemed to be traveling from west to east. Buildings shook, desks and tables were moved about, the large pendulum of the clock at the depot was stopped (The Coconino Sun, 1/27/06).
- Quite a sharp earthquake occurred here at 1:27 p.m., that shook buildings and broke windows (Williams News, 1/27/06).

Ash Fork **MMI III**

- Slightly felt here (Williams News, 1/27/06).

Phoenix **MMI III**

- Marked tremors and rocking motion (DuBois and others, 1982).

Needles, California **MMI III**

- Felt (Winslow Mail, 1/27/06).

Kanab, Utah **MMI III**

- Felt (DuBois and others, 1982).

Hite, Utah **MMI III**

- Felt (DuBois and others, 1982).

Anith, Utah **MMI III**

- Felt (DuBois and others, 1982).

Fruitland, New Mexico **MMI III**

- Felt (DuBois and others, 1982).

Albuquerque, New Mexico **MMI III**

- Felt (Winslow Mail, 1/27/06)

4.1.1 **Aftershocks of 1906 Event**

Flagstaff

The lack of a significant number of aftershocks reported (three are described below) may indicate that the epicenter was at least not directly within Flagstaff. Our recent experience with northern Arizona earthquakes indicates that events down to magnitude 2.0 are felt by persons within the immediate vicinity of the epicenter and that numerous aftershocks are typical following northern Arizona earthquakes. However, the intensities described above do indicate that Flagstaff was the closest population center.

- Other slight shocks were felt at 6:36:40 p.m. and 7:31 p.m., Thursday, January 25, 1906 (A.E. Hackett, Flagstaff Weather Bureau).

- A very slight shock of earthquake was felt at 10:15:30 a.m. Friday, January 26, 1906 (A.E. Hackett, Flagstaff Weather Bureau).

- Another shock, but not near so violent, was felt the same evening, and none since (The Coconino Sun, 1/27/06).

- Later in the evening there was another slight shock, which was followed by a third quake Friday morning (The Tucson Citizen, 1/27/06).

- A second shock was felt at 6:36 and a third at 7:32 p.m. but these were much lighter than the first (The Arizona Republican, 1/26/06).

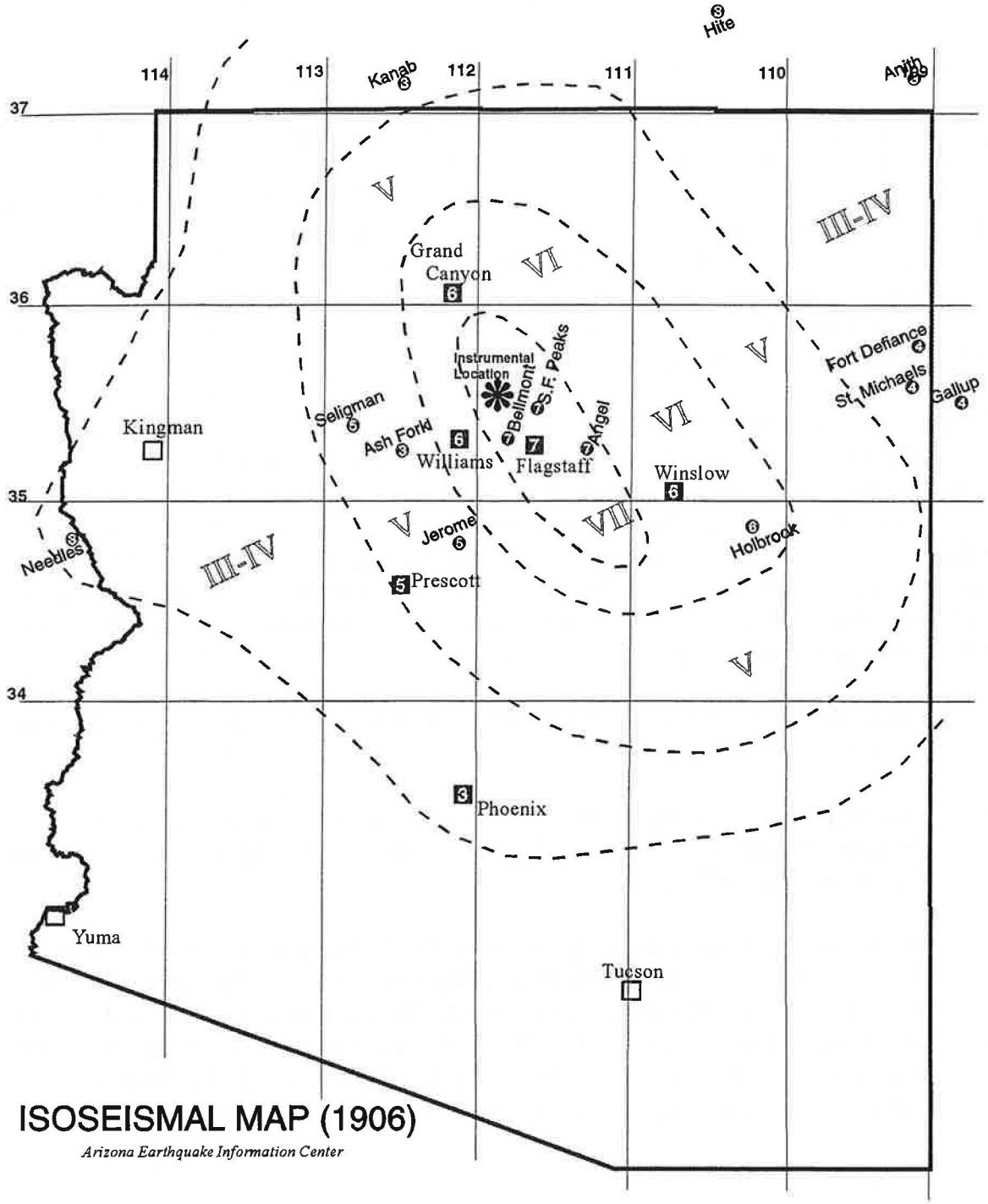

Figure 7 *- Isoseismal Map of 1906 Earthquake.*

4.2 Earthquake of September 23, 1910, Friday, 9:06 p.m. (local time), M_S 6.0

North of San Francisco Peaks **MMI VIII**

It is difficult to determine the exact location(s) of these felt reports. The Coconino Sun mentions 50 miles north of Flagstaff, which is at the latitude of Cameron, while the Tucson Citizen describes a site "45 miles from here." Other reports that describe the region as the "foothills" of the San Francisco mountains, and the report of the "Experts Visit the Earthquake Area" indicates a site 20 miles north of Flagstaff. The later report describes a vehicle trip by Dr. Percival Lowell, assistant Mr. Lampland, Weather Clerk Hackett and Ray Babbitt where they try to reach the "earthquake country" but miss the turn at the forks at Dead Man's Wash. These forks are on the road to Tuba City approximately 20 miles NNE of Flagstaff.

Work crews building a dam north of the peaks reported very severe effects and feeling numerous foreshocks and aftershocks. The dam site could be any of the numerous tanks located north of the peaks. The work crews describe feeling 52 shocks on Saturday the 10th, thirteen days prior to the main shock. These felt reports indicate that they were very close to the epicentral region, and perhaps at a location that may trap seismic energy, such as along a fracture system. We feel the most likely location for the crew is about 35 miles north of Flagstaff, which is a region that can be reached by turning at the forks of Dead Man wash, includes numerous small dams, and is underlain by the Mesa Butte fracture system.

- Succession of disturbances north of peaks cause fright and people rush into Flagstaff (The Coconino Sun, 9/30/10).

- The real full grown earthquake disturbances have occurred about fifty miles north of Flagstaff on the opposite side of the San Francisco mountains among the foothills (The Coconino Sun, 9/30/10).

- A gang of workmen under the foremanship of Mr. C. Michaels, who were constructing a dam for Campbell and Francis in that region, broke camp during Friday night and came home. Mr. Michaels stated that shock after shock was felt there and the final violent one threw them into a panic and they got away in the night without bothering to load up any of their belongings. Things were shaken up vigorously, and Mr. Michaels was thrown from his bed and back onto it again by the same jolt (The Coconino Sun, 9/30/10).

- The disturbances seem to extend from directly north of Flagstaff nearly through to Grand Canyon, a distance of 40 to 50 miles. There are dozens of old volcano craters in that region, but none of them have shown any indication of activity (The Coconino Sun, 9/30/10).

- Old crater near Flagstaff active. An old crater, 45 miles from here *(Flagstaff)* is showing signs of activity since the earthquake a few days ago. A crew of men working on a dam in the vicinity, was forced to stop operations on account of the violence of the shocks and the rumblings from the crater. Last Friday 52 earthquakes were counted by the men. They feared that the old volcano might deliver an eruption, and lost no time in getting to Flagstaff (The Tucson, Citizen, 9/27/96).

- He *(Sheriff John Francis)* also says that the zone where the trouble originated and has its base of violent action, the reports are that the country is unquestionably passing through a system of temblors without parallel in earthquake records, the ground vibrating at all times, and in some instances disturbing the topographic makeup of the land embraced and which lies close to the center that seems to be the generating source (Arizona Weekly Miner, Prescott, 10/5/10).

- Seven members of a dam construction gang arrived tonight with a story that they had been driven away from their work near an extinct volcano in Coconino forest, forty-five miles from this place by a series of fifty-two violent earthquakes last Friday night (Holbrook News, 9/30/10).

- C. McNichols, the foreman, told a story which was corroborated by all his men. He said the shocks began on the night of September 10. The first were slight but became stronger each day and night until the final on Friday (Holbrook News, 9/30/10). *(Note: Although the Coconino Sun reports the foreman's name as Michaels, the work crew referenced here appears to be the same.)*

- Territory depopulated. A territory fifty miles square and extending from here to the Grand canyon of the Colorado river tonight stands practically depopulated because of earthquakes and rumblings, which, beginning Saturday steadily increasing in magnitude and violence (Holbrook Argus, 10/4/10).

- Indians, of whom there are many in the region fled when the quakes began, terrified by sinister imports which they imagined to be contained in the cracking of the solid ground, tribal tales of the ancient activity of the now burned out craters, of which there are more than fifty in the region, hastened their flight (Holbrook Argus, 10/4/10).

- The whites remained until their houses fell about their ears. B. Chavez, the first of the refuges to reach Flagstaff, reported that his adobe house had cracked open before he left (Holbrook Argus, 10/4/10).

- The zone of the quake, according to reports reached from the Colorado river to the Grand Canyon (Williams News, 10/1/10).

J.P. Chavez Ranch **MMI VIII**

The location of the Chavez Ranch as reported by the Williams News is as `living at Cedar Wash.' An online search of the historical geographical place names for Chavez results in 12 feature records for the area, including Chavez Tank about 22 miles NNE of Flagstaff (35° 29.30'N x 111° 34.25'W) within the O'Leary Peak quadrangle. A database search and a map review for Cedar Wash, however, indicate a wash that extends from 35° 32.50'N x 111° 47.50'W within the Chapel Mountain quadrangle to a location of 35° 48.29'N x 111° 30.16'W. At the southwesternmost extent are the buildings and tanks of Cedar Ranch that is bounded to the south by mesas that appear similar to those described by Mr. Chavez. Therefore we assign a location of approximately 40 miles due north of Flagstaff.

- J.P. Chavez, the well known stockman, brought his family in the first of the week and told a story that was even more alarming. The chimney was jarred from his house and a small house near by was moved from the foundation, the chimney shaken off, and the corner of the building badly cracked (The Coconino Sun, 9/30/10).

- Mr. Chavez also stated that huge lava stones weighing many tons, were torn from the old lava beds and rolled down the mountainside. He was afraid to stay there and brought his family to town. Several others from that region have told substantially the same story, and so far as known the disturbances still continue (The Coconino Sun, 9/30/10).

- Mr. Chavez stated that his attention was first attracted to the phenomena in seeing large boulders rolling down the sides of a knoll, that projected from the plateau a few hundred feet, and in a few seconds there was a violent shock. Mr. Chavez became frightened, and going to his house was again startled by seeing practically it wrecked (*as reported by E.S. Clark to the* Arizona Weekly Miner, Prescott, Arizona, 10/5/10)

- J.P. Chaves (sic), a well known stockman, living at Cedar Wash, has brought in his family, and others have since followed, all much alarmed (The Williams News, 10/1/10).

- Chaves' adobe house was shaken from its foundation, a corner was cracked and the chimney toppled off. Lava stones weighing many tons were torn from the lava bed and hurled down the mountainside (The Williams News, 10/1/10).

Summit Ranch **MMI VIII**

- At 9:15 p.m. we had an earthquake shock lasting about 2 minutes (G. Hochderffer's, Summit Ranch Daily Log, 9/23/10). George Hochderffer's Summit Ranch, for which the daily entry describes an earthquake shock "lasting 2 minutes" is located 13 miles NNW of Flagstaff on the northwest flank of the San Francisco peaks.

Flagstaff **MMI VI**

- A slight earthquake shock was felt at 9:06 p.m. (A.E. Hackett, Flagstaff Weather Bureau, 9/23/10).

- The earthquake last Friday evening stirred up the students *(at the Normal School, now Northern Arizona University)* even quicker than a rising bell can (The Coconino Sun, 9/30/10).

- Last Friday night about 9:06 o'clock a distinct earthquake jar was felt in Flagstaff, but it was too slight to cause any particular commotion (The Coconino Sun, 9/30/10).

- At the Emerson school house a small patch of plastering was jarred loose, and the telescope at Lowell observatory showed signs of disturbance (The Coconino Sun, 9/30/10).

- A slight earthquake shock was felt here, at Jerome, Williams, Flagstaff, and Kingman at 9:06 o'clock tonight. No damage was reported (The Arizona Republican, 9/24/10).

- Sheriff John Francis of Coconino county passed through Prescott yesterday afternoon from Flagstaff, and imparted the interesting information that of Friday night that city experienced three distinct earthquake shocks, without damage resulting to property, or any alarm over the recurrence of the seismic disturbances that seem to be going on every day at points north (Arizona Weekly Miner, Prescott, 10/5/10).

- The arrival in that city of several scientific men, with the coming from Washington of the Geological Survey, are features that may lead to a solution of the frequent disturbances (Arizona Weekly Miner, Prescott, 10/5/10). *(Note: We requested any information pertaining to this potential investigation from the information resources division of the U.S. Geological Survey. A search of the USGS database using the keywords 'Arizona' and 'earthquake' did not retrieve any documents that could be related to a field investigation during this time period.)*

- Advices have been received in Flagstaff that the Geological Survey at Washington will send several of its members immediately to visit the field and to make observations. This body will be composed of at least a dozen members, and a large number of Eastern papers will accompany them (Arizona Weekly Miner, Prescott, 9/28/10). *(see note on previous entry)*

- Residents were alarmed at an earthquake shock tonight. The jar was felt at 9:08 o'clock. No damage was done, although many frame buildings were believed at first to have been badly shaken (Arizona Weekly Miner, Prescott, 9/28/10).

Williams **MMI VI**

- Tremblors felt in this section. A severe earthquake shock which from all accounts was general throughout northern Arizona, was felt in Williams last Friday night at 9:06 o'clock (Williams News, 10/1/10).

- Windows rattled in many frame buildings and electric lights in residences and stores swung like pendulums (Williams News, 10/1/10).

- At the Parlor Barber shop, where the shock was felt more, and where several were playing pool, the balls on the tables rolled as though being shot around by the players, and picture frames on the walls were all shaken out of position (Williams News, 10/1/10).

- No one was injured, but quite a number of our timid citizens were badly frightened (Williams News, 10/1/10).

- At 9:08 o'clock tonight a tremblor was felt here, lasting several seconds. Windows rattled in all the buildings and many of the frame structures were badly shaken. No damage was done (Arizona Weekly Miner, Prescott, 9/28/10).

- It is learned the earthquake reached as far west as Williams (The Arizona Republican, 9/24/10).

- A slight earthquake shock was felt here, at Jerome, Williams, Flagstaff, and Kingman at 9:06 o'clock tonight. No damage was reported (The Arizona Republican, 9/24/10).

Grand Canyon **MMI VI**

- The rumblings seem to come from the direction of the Grand Canyon and cover an area of forty or fifty miles along the mountains (Williams News, 10/1/10).
- Remarkable disturbances of the earth continue north of Flagstaff, extending through to the Grand Canyon (Williams News, 10/1/10).
- Grand Canyon and the Colorado River are reported to have been in the immediate zone of the quake (Williams News, 10/1/10).

Skull Valley **MMI VI**

- At Skull Valley the 'quake was reported at 9:05 o'clock, while operators at Williams, Flagstaff, and Kingman gave the time at 9:08 o'clock (Arizona Weekly Miner, Prescott, 9/28/10). *While the times reported for Williams, Flagstaff, and Kingman may be correct, the Skull Valley reported time is much too early to agree with the felt report data.*
- At 9:05 o'clock tonight an earthquake shook the buildings here, alarming many of the occupants. The railroad depot rolled as if falling from its foundation. Women residents were particularly alarmed, many calling to their husbands. Many in the depot report that the building rumbled and rattled as if hit by a locomotive running at high speed, and several rushed outside to inquire into the cause of the strange disturbance (Arizona Weekly Miner, Prescott, 9/28/10).

Winslow **MMI V**

- A slight shock of an earthquake was felt here last Friday evening about nine o'clock (Winslow Mail, 10/1/10).
- While not very severe, it was quite enough to have people hurrying from their homes to see what was going on (Winslow Mail, 10/1/10).

- A few people were awakened from their sleep while numerous others on the streets and at home failed to feel the jar at all (Winslow Mail, 10/1/10).

- The Ladies of the Maccabees were having a social session in the Elks Hall and they got the full effect of the shock. While some of them were a trifle alarmed there was nothing in the nature of a stampede (Winslow Mail, 10/1/10).

- No harm was done at Winslow, or at any other point the shaking not being severe enough to cause any damage (Winslow Mail, 10/1/10).

- Winslow was given an unusual scare this evening by a very lively sort of an earthquake. No one was hurt but people from the second stories of houses came rushing down stairs and into the open (The Arizona Republican, 9/24/10).

Cedar Glade **MMI V**

- An earthquake caused some alarm here tonight at 9:06 o'clock, but no damage was done. The depot building rolled and windows rattled, alarming several in the waiting room. The jar was distinctly felt for several seconds (Arizona Weekly Miner, Prescott, 9/28/10).

Jerome **MMI V**

- Inhabitants of this place were alarmed tonight, at 9:06 o'clock by the rumblings of an earthquake. The shock was distinctly felt for several seconds. Many buildings were shaken badly (Arizona Weekly Miner, Prescott, 9/28/10).

- At the Boyd Hotel the plaster of the walls and ceilings of the second and third floors was cracked in many places, some falling to the floor. No damage is reported at the United Verde smelters or other mines in this vicinity, although the shock was general throughout the Verde district (Arizona Weekly Miner, Prescott, 9/28/10).

- Felt south to Jerome (Winslow Mail, 10/1/10).

- A slight earthquake shock was felt here, at Jerome, Williams, Flagstaff, and Kingman at 9:06 o'clock tonight. No damage was reported (The Arizona Republican, 9/24/10).

Kingman **MMI IV**

- A severe earthquake shock was felt here tonight at 9:08 o'clock. Buildings shook several seconds and windows rattled, alarming many, but no damage was done (Arizona Weekly Miner, Prescott, 9/28/10).

- The quake was also felt has far west as Kingman (Winslow Mail, 10/1/10).

- A slight earthquake shock was felt here, at Jerome, Williams, Flagstaff, and Kingman at 9:06 o'clock tonight. No damage was reported (The Arizona Republican, 9/24/10).

Prescott **MMI V**

Data pertinent to mapping ground shaking differences throughout the city are presented within the felt reports below. Similar to felt report differences in the 1906 earthquake, these data can be useful in forecasting ground shaking hazards for the Prescott community.

- A slight earthquake shock was felt here, at Jerome, Williams, Flagstaff, and Kingman at 9:06 o'clock tonight. No damage was reported (The Arizona Republican, 9/24/10).

- At six minutes past 9 o'clock, last night an earthquake was felt in this city and many places throughout northern Arizona (Arizona Weekly Miner, Prescott, 9/28/10).

- By far the most violent shock in this city was reported from the S.F.,P. & P. storehouse, near the railroad depot. The building is reported to have been badly shaken, jarring supplies from the walls. Peculiar as it may seem, no shock was felt in the depot, only a short distance away. This it is believed is due to the fact that the depot is of reinforced concrete construction, the walls being reputed strong enough to support the heaviest engine on the Santa Fe lines. Not even the slightest tremble was felt in the train dispatcher's office, in the second story (Arizona Weekly Miner, Prescott, 9/28/10).

- Residents of Nob Hill report that they were attracted by a vibration in their homes, that dishes rattled in their pantries, and windows in particular, jarred perceptibly. No chimneys are reported to have fallen, although the plaster of walls and ceilings cracked in many places (Arizona Weekly Miner, Prescott, 9/28/10).

- Residents of the Thumb Butte section, arriving late last night, report that they felt no tremblor in that district and that the shock did not disturb that Locality (Arizona Weekly Miner, Prescott, 9/28/10).

- The 'quake was not felt in any of the large brick or stone buildings of the city. None of the inmates of the Hotel St. Michael, Prescott, Head or Schuerman hotels were cognizant of the temblor until informed later by the occupants of other buildings (Arizona Weekly Miner, Prescott, 9/28/10).

- A slight flicker of the electric lights was noticeable all over the city the time of the 'quake, but this did not attract any unusual attention in places where the shock was not felt (Arizona Weekly Miner, Prescott, 9/28/10).

Walker **MMI IV**

- Telephone advices received from Walker state that buildings of the town were perceptibly shaken by the earthquake, and that many sitting at their porches were alarmed at the rumbling sound of the tremblor. No damage is reported (Arizona Weekly Miner, Prescott, 9/28/10).

Poland Junction **MMI IV**

- The 'quake is reported to have awakened several residents of Poland Junction who had retired for the night. The jar was felt several seconds (Arizona Weekly Miner, Prescott, 9/28/10).

Fort Wingate, New Mexico **MMI III**

- Felt east to Fort Wingate (Winslow Mail, 10/1/10).

Phoenix **MMI II**

- Phoenix, which but rarely indulges in earthquakes, at least is not habitually addicted to them, pleads guilty of having felt a little touch of the Winslow jar last night. The only place it was reliably reported from was the Arizona club where the shock was felt perceptibly by several gentleman present at the time, among them Governor Sloan, Colonel McClintock and Dr. G.W. Vickers. No one thought to look at the clock at the time but later it was guessed that the hour was about 9:15 (The Arizona Republican, 9/24/10).

Fossil Creek **MMI I**

- Telephone advises from Fossil Creek over the Arizona Power company's lines are that the tremblor was not felt there (Arizona Weekly Miner, Prescott, 9/28/10).

4.2.1 Foreshocks and Aftershocks of 1910 Event

North of Peaks

- According to his *(Mr. C. Michaels)* story the disturbances began there the night of Saturday, September 10 *(thirteen days prior to the mainshock)*, when there were 52 shocks in succession. Since that time they have continued intermittently night and day (The Coconino Sun, 9/30/10).

- Last Friday *(same day of mainshock or seven days prior to the mainshock)* 52 earthquakes were counted by the men (The Tucson Citizen, 9/27/10).

- Saturday, Sunday, and Monday *(probably 9/24-9/26, according to J.P. Chavez)* the earth trembled almost continuously, with an occasional severe shock (The Coconino Sun, 9/30/10).

- The rumblings seem to come from the direction of the Grand Canyon and cover an area of forty or fifty miles along the mountains (Williams News, 10/1/10).

The shaking appears to have lasted from September 10th through the 26th. Fifty-two foreshocks were recorded prior to the mainshock on the evening of the 23rd, as well as "continuous" aftershock activity lasting for three days.

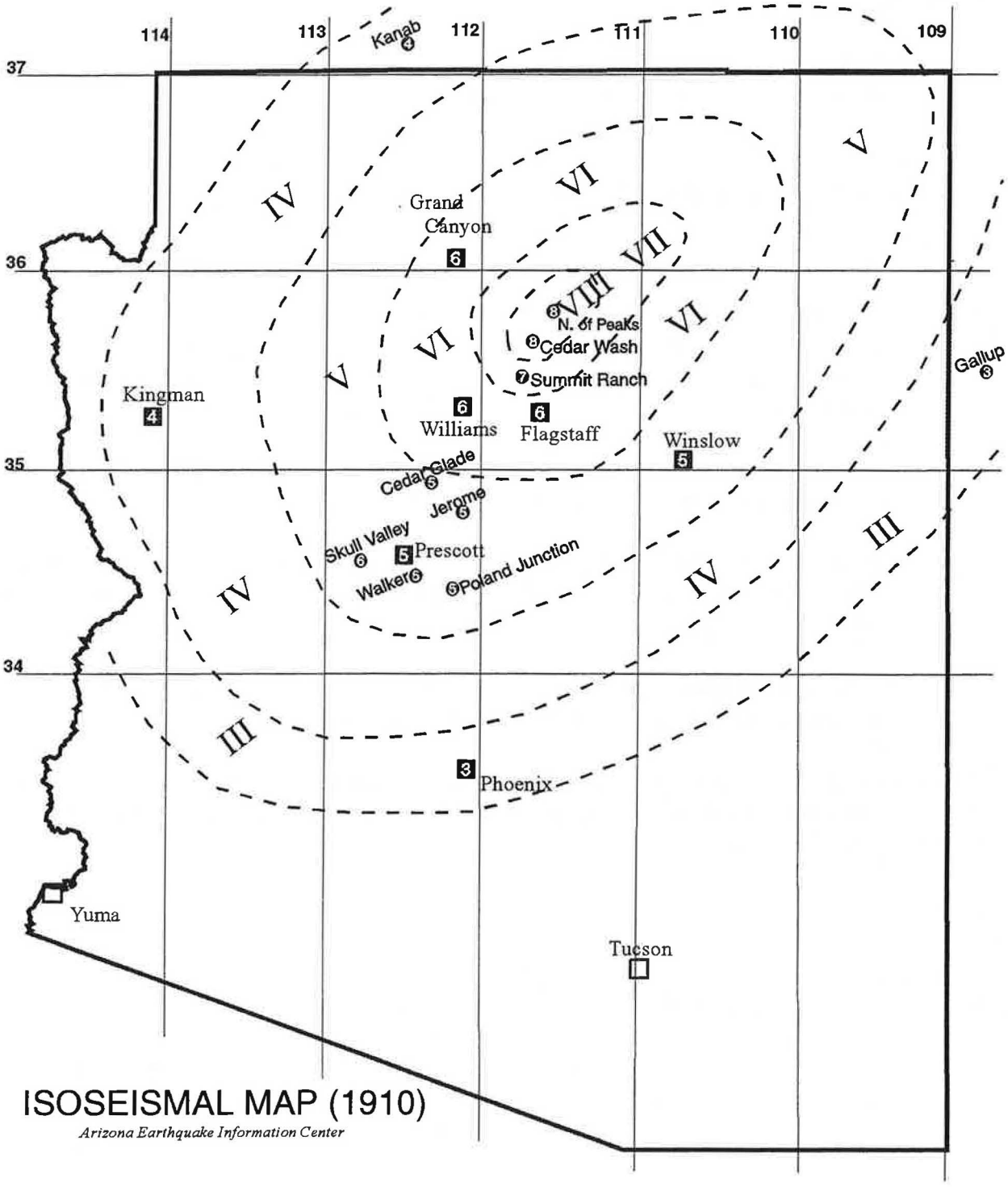

***Figure 8** - Isoseismal Map of the 1910 Earthquake*

4.3 Earthquake of August 18, 1912, Sunday, 2:12 p.m. (local time), M_S 6.2

Lockett Tanks **MMI VII**

The felt report from this location indicates the most severe effects from the earthquake. However, the effects represent those reported by a single observer, and no substantiation was found. In addition, the observer appears to exaggerate throughout his report including a claim of 'a rent in the earth 30 miles in length' and 'rocks sent up in the air.' Reports of smoke and fire may be related to the typical late-Summer monsoon season lightning. The Coconino Sun published the article containing the report from the Lockett Tanks area twelve days after the earthquake. For these reasons we assign only a MMI VII to this report, whereas if the account is taken verbatim, the MMI may be greater.

There are two Lockett Tanks in the region, one is 5 miles south of Williams and the other is 40 miles north of Flagstaff within Cedar Wash, a region described in the 1910 earthquake. Based on the observer's descriptions, the Lockett Tank referred to in the felt report below is likely the one north of Flagstaff. The northern Lockett Tanks are located within Cedar Wash, as with the 1910 earthquake the populated region that includes ranch homes and other development are within the northern foothills of the Peaks. Therefore, the location of this felt report is assigned the same map location as the 1910 Cedar Wash report.

- Volcanic eruption reported by Indians. Earthquake in Lockett Tank Country made a rent in earth for thirty miles--black smoke and steam arise from interior of earth (The Coconino Sun, 8/30/12).

- Considerable excitement was caused last Friday by the report brought in by a Navajo Indian named Tsi-ma-li from the Lockett Tank Country, that at the time of the earthquake a huge volume of black smoke and fire Came up out of a rent in the earth. He reported that rocks were sent up in the air and that boulders were shaken from the cliffs to go crashing down into canyons. The rent in the earth he said was from a few inches to a foot wide, extending from Lockett Tanks to Coconino Mountain a distance of over thirty miles. Where the earth shook and made waves like the sea, Tsi-ma-li said "Indian's hearts died in them and they left." (The Coconino Sun, 8/30/12).

- The same smoke was reported earlier in the week by W.W. Durham and Cumberland Michael who were within about ten miles of the place *(near O'Leary Peak)* (The Coconino Sun, 8/30/12).

- Sunday a party went to the top of the San Francisco Peaks, saw smoke off in that direction in three places, but this was afterward claimed to be small forest fires (The Coconino Sun, 8/30/12).

O'Leary Peak

- W.W. Durham and Cumberland Michael came in from the north-east Tuesday and reported seeing a large volume of black smoke rising and falling in the cinder country near O'Leary Peak, resembling the smoke of a volcano. The smoke arose in a black cloud from the ground about six miles from them and they could not distinguish the cause, but believed that it might be the eruption of a small volcano (The Coconino Sun, 8/23/12).

- The smoke seemed to come from the earth would rise in black clouds, then lower and turn white into what appeared to be a vapor. The smoke may have been caused by other means, but both first thought of a volcano. No one has been near enough to the place to see smoke since. Autoist (sic) are figuring on making a trip in that direction to investigate (The Coconino Sun, 8/23/12).

Williams **MMI VII**

- Heap big scare, no damage done. Last Sunday afternoon about 2:30 p.m., this vicinity was startled by a severe earthquake, which lasted fully 30 seconds and was accompanied by a distinct rumbling noise (The Williams News, 8/24/12).

- The shock was one of the most violent, according to the older residents--who have experienced several in times past--of any that has occurred in this section (The Williams News, 8/24/12).

- Windows were rattled, small articles on shelves in many houses were tumbled to the floor and shattered, which added to the confusion occasioned by the tremor (The Williams News, 8/24/12).

- No damage has been reported as a result of the quake. The inhabitants of the Mexican quarters were badly frightened, many of whom rushed out of their houses and sought safety in the streets (The Williams News, 8/24/12).

- The tremor was of an easterly and westerly direction and was unusually rapid (The Williams News, 8/24/12).

- According to a special dispatch received here this evening, Williams, Arizona, four hundred miles west of here, was severely shaken by an earthquake shock this afternoon. The shock lasted from 2:05 to 2:10 p.m. Buildings were rocked to their foundations and windows and crockery were broken. The inhabitants were greatly frightened. It is believed that no lives were lost (The Arizona Republican, A.P. dispatch from Albuquerque, 8/19/12).

- Vague reports from Williams and other towns along the Santa Fe railroad give varied reports of heavy damage to property that occurred, but were not substantiated (Arizona Weekly Miner, Prescott, 8/28/12).

Flagstaff **MMI VI**

- A severe earthquake shock was felt in Flagstaff at 2 p.m. Sunday, which lasted about ten seconds. The quake did no damage other than startling the people for the time being. So far as learned the shock did not extend from north to south (The Coconino Sun, 8/23/12).

Ash Fork **MMI VI**

- W.E. Henning of Detroit, who arrived Monday afternoon from Ash Fork, stated that he was in the Escalante and two distinct shocks were felt. The glass windows rattled, and between the first and second vibrations but a few seconds intervened. *Two shocks are commonly reported for single earthquakes, which indicates that the observers may be reporting the effects of the two primary earthquake waves, the P- and the S-wave.* In the railroad offices employees had their attention directed to the occurrence, but the slight disturbance did not occasion any alarm (The Weekly Miner, Prescott, 8/28/12). *(Note on 'Escalante': A geographic names search did not indicate an 'Escalante' near Ash Fork, however, the interpretation by DuBois and others (1982) that the Escalante referred to is in Utah is likely incorrect. In addition, the article states that Mr. Henning arrived from Ash Fork, not Utah. Traveling from Utah to Prescott in less than 24 hours was probably not practical in 1912.)*

Tuba City **MMI VI**

The report from Tuba City describes 'two distinct shocks,' however, no mention of the amount of time between the two shocks is made. Two shocks are commonly reported for single earthquakes, which indicates that the observers may be reporting the effects of the two primary earthquake waves, the P- and the S-wave.

- Earthquake felt at Tuba, Sunday afternoon at 2:15 o'clock, this region experienced two distinct earthquake shocks, the last one of half a minute duration, following one of half that time. The first shock was slight, but the second resulted in considerable rocking of the group of Indian School buildings, although no damage was done (The Coconino Sun, 8/23/12).

- The place being so isolated advices cannot be had from surrounding points as to whether or not the tremor was purely local in its character, or whether it extended into other sections of the state. Old residents state that this was the strongest shock ever experienced in this district (The Coconino Sun, 8/23/12).

Seligman **MMI V**

- J.W. Sullivan, who arrived yesterday morning from Seligman, says that when he arrived in that town on Sunday afternoon from his range, ten miles to the south, Mike McBride and other residents were somewhat excited over the seismic disturbance, and all were absorbed in discussing the temblor and the general shakeup that followed. The glass windows gave the first warning in being almost shaken from their casing, and the buildings also rocked to and fro. Every building in the town was affected but not damaged (The Weekly Miner, Prescott, 8/28/12).

Grand Canyon **MMI V**

- At Grand Canyon the quake was for hours the topic of conversation among the eastern tourists, who had never experienced an earthquake. At this point the tourists who were seated in rocking chairs at the El Tovar rocked back and forth and the rumbling noise was distinctly audible, while tourists seated along the rim were in ignorance of the quake until the excited guests hurriedly vacated the piazzas of the hotel (The Williams News, 8/24/12).

Kirkland Valley **MMI IV**

- L.J. Hasefield, who returned yesterday to Kirkland valley, stated that at 2 o'clock on Sunday afternoon his merchandise store and hotel building at that place were shaken up like dice in a box, and the rumbling of the glass in the windows, with the buildings moving perceptibly, was conclusive evidence of the earthquake reaching that place (Arizona Weekly Miner, Prescott, 8/28/12). *(Note: It appears from these reports that Mr. Hasefield was not actually in Kirkland Valley at the time of the earthquake on Sunday, the effects to his buildings must have been reported to him by another party.)*

Winslow **MMI IV**

- The shock was felt as far west as Winslow, a hundred miles (Arizona Republican, 8/19/12).

Holbrook **MMI IV**

- The shock was felt as far east as Holbrook (The Williams News, 8/24/12).
- The severest earthquake ever felt here occurred shortly after two o'clock this afternoon. The shock lasted fifteen seconds. No damage was done (The Arizona Republican, Associated Press dispatch from Holbrook, 8/19/12).
- Sunday afternoon at 2:10 o'clock an earthquake was distinctly felt here and it lasted for about fifteen seconds and appeared to move east and west. The shock was quite a severe one and was plainly felt by several persons eating dinner at the Cottage Hotel (The Holbrook Argus, 8/20/12; and The Winslow Mail, 8/24/12).

Kingman **MMI III**

- The shock was felt as far west as Kingman (The Williams News, 8/24/12).

Gallup, New Mexico **MMI III**

- Felt (The Arizona Republican, 8/19/12).

Needles, California **MMI III**

- Felt (The Coconino Sun, 8/23/12).

Albuquerque, New Mexico **MMI III**

Although the Flagstaff paper indicates that the earthquake was felt 'as far east as Albuquerque, the Associated Press dispatch from Albuquerque as reported in the Arizona Republican (8/19/12) indicates that the 'shock was felt as far west as Winslow.'

- Felt (The Coconino Sun, 8/23/12).

4.3.1 Aftershocks of the 1912 Event

Figure 6 and associated text provides an analysis of these aftershock reports and the constraint they may place on the location of the mainshock.

Williams

- During the night *(early Monday)* another slight shock was felt, but was not so violent as the first one (The Williams News, 8/24/12).

Flagstaff

- A slight shock was also felt early Monday morning for a couple seconds (The Coconino Sun, 8/23/12).

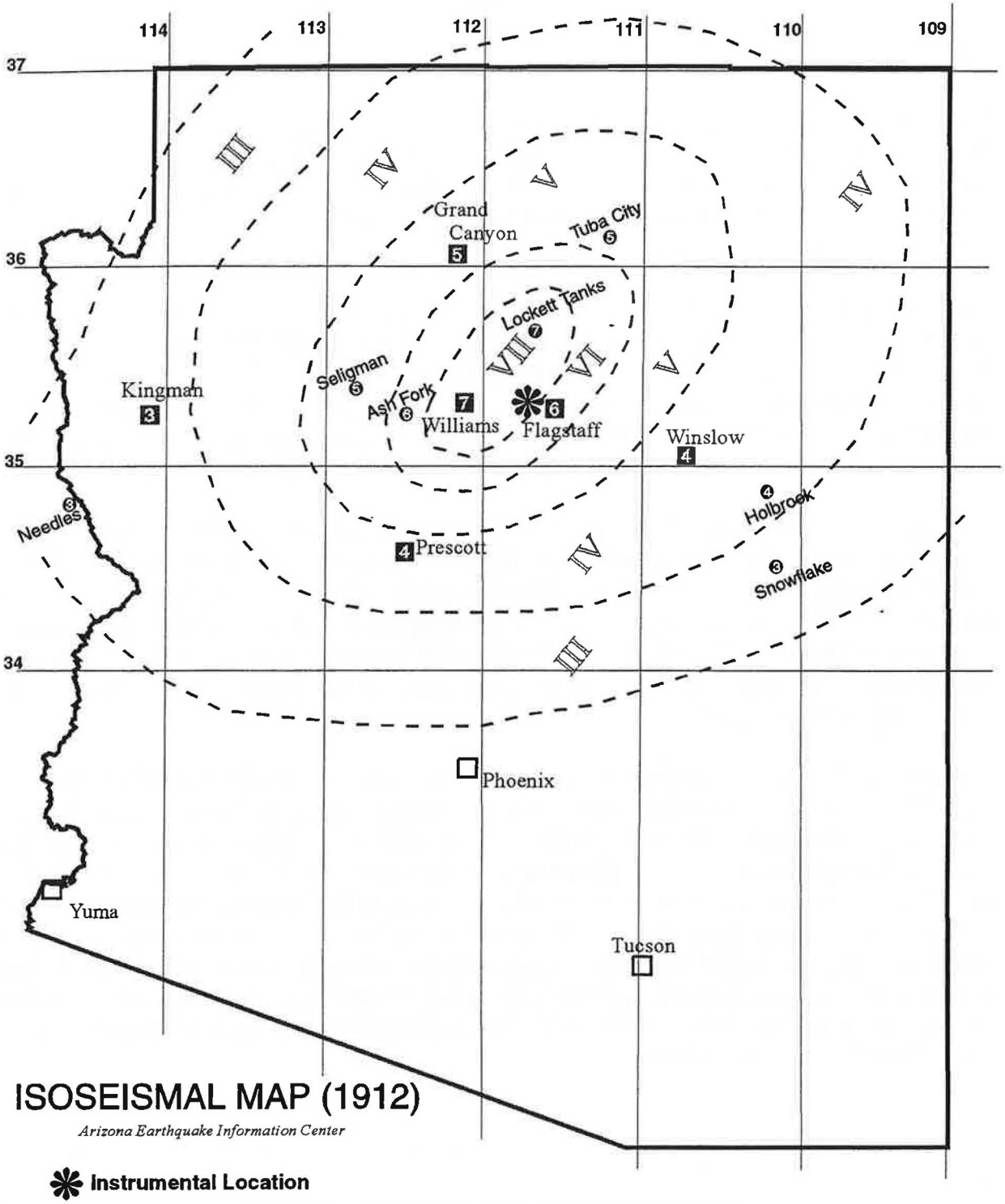

***Figure 9** - Isoseismal Map of 1912 Earthquake*

5.0 ANALYSIS OF INSTRUMENTAL DATA

5.1 January 25, 1906

Five seismograph stations reported this tremor as a logbook entry (Table 4). Neither of the two Milne stations (VIC, TOR) had arrival times that gave locations within the grid area in northern Arizona. Possibly this lack of correlation was a result of poor clock calibration or confusion with another event. The U.S. magnetic observatory at Honolulu (HON) also had arrival times that were not close to predicted ones for the phases reported.

The remaining two stations were Strassburg (STR) and Tacubaya (TAC) and both had useful data. The reported P-wave arrival for TAC is the S-wave instead, while for STR the P- arrival is clearly the surface wave. Given the distance of STR (8,000 km) and the size of the event (M_S 6.2), as well as the sensitivity of the early seismographs it is easy to see how the surface wave could be misidentified as the P-wave. The later phases at STR (S, Surface) attributed to this event likely belong to another tremor which was widely recorded in Europe, possibly from central Asia.

The onset time reported locally by the Flagstaff meteorologist for the 1906 tremor gives a latest origin time limit of 20:32:30. As the only reported aftershocks were felt at Flagstaff the aftershock radius approach may be used here. Based on this approach the main shock had to be located no further than 135 km from Flagstaff, and using a P-wave velocity of 6.25 km/second this gives the earliest origin time of 20:32:10. Thus initial estimates of origin time from non-instrumental sources ranges from 20:32:30 to 20:32:10. This helps constrain possible epicentral locations when combined with instrumental data.

The analysis map shows locations from the intersection of the STR and TAC best-fit arcs that vary from 35.49 x 111.52 (30 on map, Figure 10) corresponding to an origin time of 20:32:30, to a maximum to the northwest of 35.81 x 112.93, corresponding to the earliest origin time of 20:32:10. The fact that the Flagstaff meteorologist reported the sound (P-wave) advancing from the northwest at 20:32:30 eliminates all origin times later than 20:32:25, and all locations due north or northeast of Flagstaff. The isoseismal map further constrains location. Ideally an epicenter should locate inside of the highest level Modified Mercalli intensity contour. This eliminates northwest locations beyond 112.00 degrees longitude, and origin times earlier than 20:32:20. Thus a reasonable range in locations would be 35.60 x 112.00 to 35.57 x 111.86 and would correspond to origin times of 20:32:20 to 20:32:25, respectively.

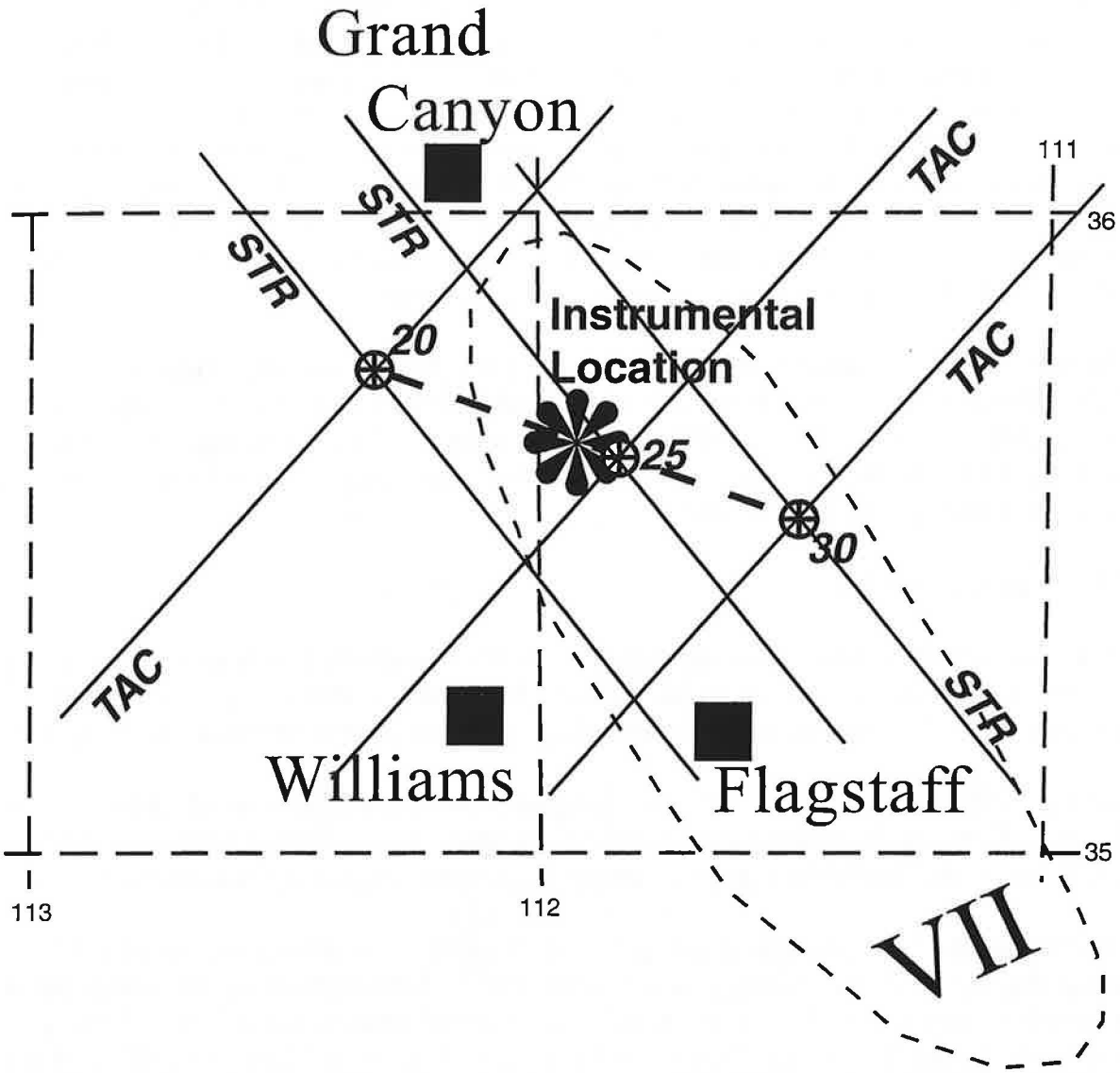

Figure 10 *- Estimated range of locations for the January 25, 1906 earthquake. (30= 20:32:30 origin time location; 25= 20:32:25 origin time location; 20= 20:32:20 origin time location.)*

5.2 September 23, 1910

Logbook data were acquired for five stations for this tremor. However, analysis of phase identifications and arrival times yield a location which is far removed from the highest ground shaking intensity region.

Logbook data were acquired for OTT, SLM, TOR, TUO and VIC. The arrival time for VIC yielded distances outside of the isoseismal area by over 100 kilometers. This suggests an error in arrival time for the phase reported. There were no reported S and P phases to check this discrepancy against for distance. The best-fit arc for SLM was also considerably distant, in this case well to the southwest of the inner isoseismals. The remaining three stations gave a good intersection of best fit arcs at 34.39 x 112.46, which however was 187 kilometers from the area of most intense ground shaking. This discrepancy is difficult to explain unless the isoseismal location is the result of high intensity produced by a combination of wide angle mantle reflections, directivity and/or topographic enhancement. The other possible explanation is poor instrumental data.

The most difficult parameter to evaluate for the 1910 tremor was origin time. Local onsets of 04:06:00 were reported from Flagstaff, Williams, and Prescott, while the earliest reported onset was farther north at Coconino Forest at 04:05:00. These reports would seem to support a location closer to Cedar Wash. On the other hand sound at Williams was reported moving from west to east, and at Cedar Wash (?) from north to south.

5.3 August 18, 1912

Data existed for this tremor for eight stations. Three of these which were also among the closest stations had the most useful data: BRK, DEN, SLM. Both the BRK and DEN arrivals correlated well with those of modern events for the same wave paths, suggesting the times were fairly accurate.

The arrival time of P and S for SLM were not good, however, examination of the S-P time gap in the logbook and confirmation from reading the SLM seismogram indicated that the clock calibration was the problem. The S-P time gap was correct for an event originating in northern Arizona.

Constraints on origin time for this event were available from written reports of the Flagstaff meteorologist, Lowell Observatory, and newspaper reports from northern Arizona communities (see Appendix). Flagstaff, Williams, and Winslow all reported onset times of 21:10:00 that gives an approximate latest origin time. Because of the number of onsets at 21:10:00 it is likely that these times were accurate to within a minute. Especially the report from the Lowell Observatory astronomer and the Flagstaff meteorologist. These persons are trained scientific observers, and especially in the case of the astronomer (Lampland), since accurate time was very important in astronomical research. Conversations with Lowell Observatory astronomers indicate that accuracy during this time period of absolute reported times was controlled by a calibrated observatory clock.

As indicated previously, estimates of origin time for the 1912 tremor discussed include 21:09:36 and 21:09:38.4. These two origin times resulted from S-P time difference and aftershock felt analysis, respectively. The SLM S-P time indicated a distance of 1,945 kilometers to epicenter. This distance

would place a best fit arc through the Flagstaff area. Using this location and surface wave velocities for the Maximum phase, an origin time of 21:09:33 was estimated. Locations for the 1912 tremor were thus calculated for the three origin times. The result are three closely clustered locations that fall very close to Flagstaff (Figure 11). The origin time of 21:09:33 yields the best result. Four stations (BRK, DEN, SLM, VIC) have best-fit arcs that intersect in a relatively small area to the west northwest of Flagstaff (Figure 11). Three of the arcs intersect at 35.25N x 111.72W, which is preferred as the location of the epicenter. This location is approximately 11 kilometers northwest of Flagstaff.

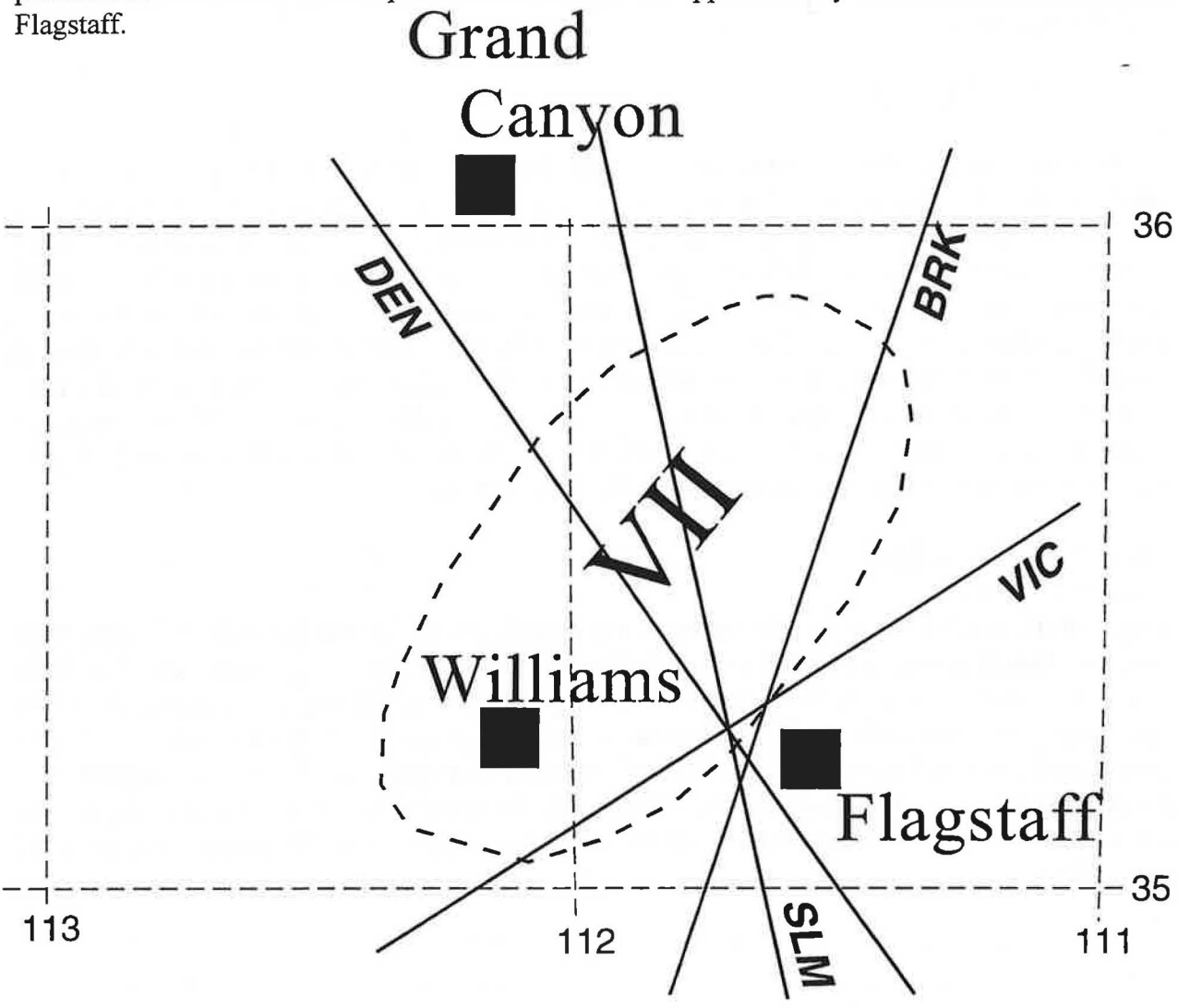

***Figure 11** - Instrumental location for the August 18, 1912 earthquake: 35.25N x111.72W. This corresponds to an origin time of 21:09:33. (BRK=Berkeley best-fit arc; DEN=Denver best-fit arc; SLM=Saint Louis best-fit arc)*

5.4 Analysis of Error in Instrumental Locations

The sources of error for location in this study consist of inaccurate determination of origin time, arrival time, wave velocities and phase type. Gross errors were eliminated for all four sources by comparison to modern event analogues for the same or nearly identical wave paths and distances. Because of this approach the greatest confidence and least error can be attributed to phase identification and wave velocities. The largest amount of error can be attributed to 1) arrival time and 2) origin time.

5.4.1 Arrival Time Error

Arrival time error can be attributed to two causes. First clock calibration, which varied widely in quality during the early 1900s. Usually gross errors in clock calibration were easy to determine by comparison to modern analogues. Smaller calibration errors or clock drift could be occasionally detected by cross checks with S-P time gaps. This was the case for SLM and DEN for 1912. Rarely, as with SLM, the error was indicated on the record (5 seconds). The second source of error in arrival time was often because of the low magnification of the early mechanical seismograph systems. Therefore arrival times for higher amplitude phases from closer stations were likely the most accurate, and barring clock calibration errors were probably usually accurate to within 6 seconds (0.1 minute). Given the velocities of the Maximum Phase Surface wave (approximately 3.0-3.1 km/second) this gives an error in location of 18-19 kilometers.

5.4.2 Origin Time Error

The greatest error in location can be attributed to estimation of origin time. For example for the 1906 event a change in origin time of five seconds results in a change of epicentral location of 33 kilometers. So the change in origin time results in a potential error twice that from arrival time. The only way to evaluate such errors is by independent checks. Independent checks consisted of onset times, aftershock radius/volume, direction of estimated sound, and origin times calculated from phase arrival times of modern events. All four checks were available to evaluate origin time estimates for the 1906 tremor, whereas all but sound direction were used to cross check the 1912 origin time.

6.0 FINDINGS

6.1 Revised Locations

Figure 12 has been prepared to illustrate the old (DuBois and others, 1982; Reid, 1979) and the new (this study) locations for the study earthquakes. The revised earthquake locations are between 40 to 140 km from their original locations, and are now located within the region of most instrumentally recorded earthquakes (Figure 13). The reason(s) for the location changes were primarily a combination of:

- Analysis of instrumental data obtained from early world-wide seismograph stations. Including phase arrival times and assessment of propagation velocities and origin times.
- Additional felt report data. Including a thorough review of diaries and letters of the Northern Arizona University Special Collections.
- Incorrect location assignment for felt reports (e.g. 'Escalante Country' assigned to Utah, rather than the Ash Fork area).

6.1.1 Revised Location of the 1906 Earthquake

The revised epicenter of the M_S 6.2 1906 earthquake is 40 km northwest of the original location (Figure 12). The new location is within the region of the 1993 m_b 5.4 Cataract Creek earthquake sequence. The 1993 sequence was northern Arizona's largest in the last 38 years and is discussed in additional detail in a later section of this report. The primary reason for the revised location is based upon the instrumental data. Both the revised and original location fall within the innermost isoseismal contour (MMI VII), however, the instrumental location is approximately 40 km northwest of the center of the MMI VII region (Figure 12).

6.1.2 Revised Location of the 1910 Earthquake

The revised epicenter of the M_S 6.0 1910 earthquake is 50 km southwest of the original location (Figure 12). The revised epicenter places the event within the Northern Arizona Seismic Belt (NASB) at the tectonic boundary of the Colorado Plateau as defined by Brumbaugh (1987) (Figure 13). The former location was within a region of relatively low seismicity. The new epicenter is about 45 km from Flagstaff, whereas the former location was about 90 km to the northeast. The revised location is based entirely upon felt report data, unfortunately the instrumental data were too poor to constrain the location of the event. The primary reasons for the change in location include:

1) An additional MMI VIII felt report from George Hochderffer's Summit Ranch Daily Log;

2) Through the Geographic Names Information System (GNIS), more accurate locations for the workcrew north of the peaks and the ranch of J.P. Chavez were obtained; and

3) Additional felt reports from the Prescott-Jerome region, primarily from local newspapers, indicated greater intensities than previously reported.

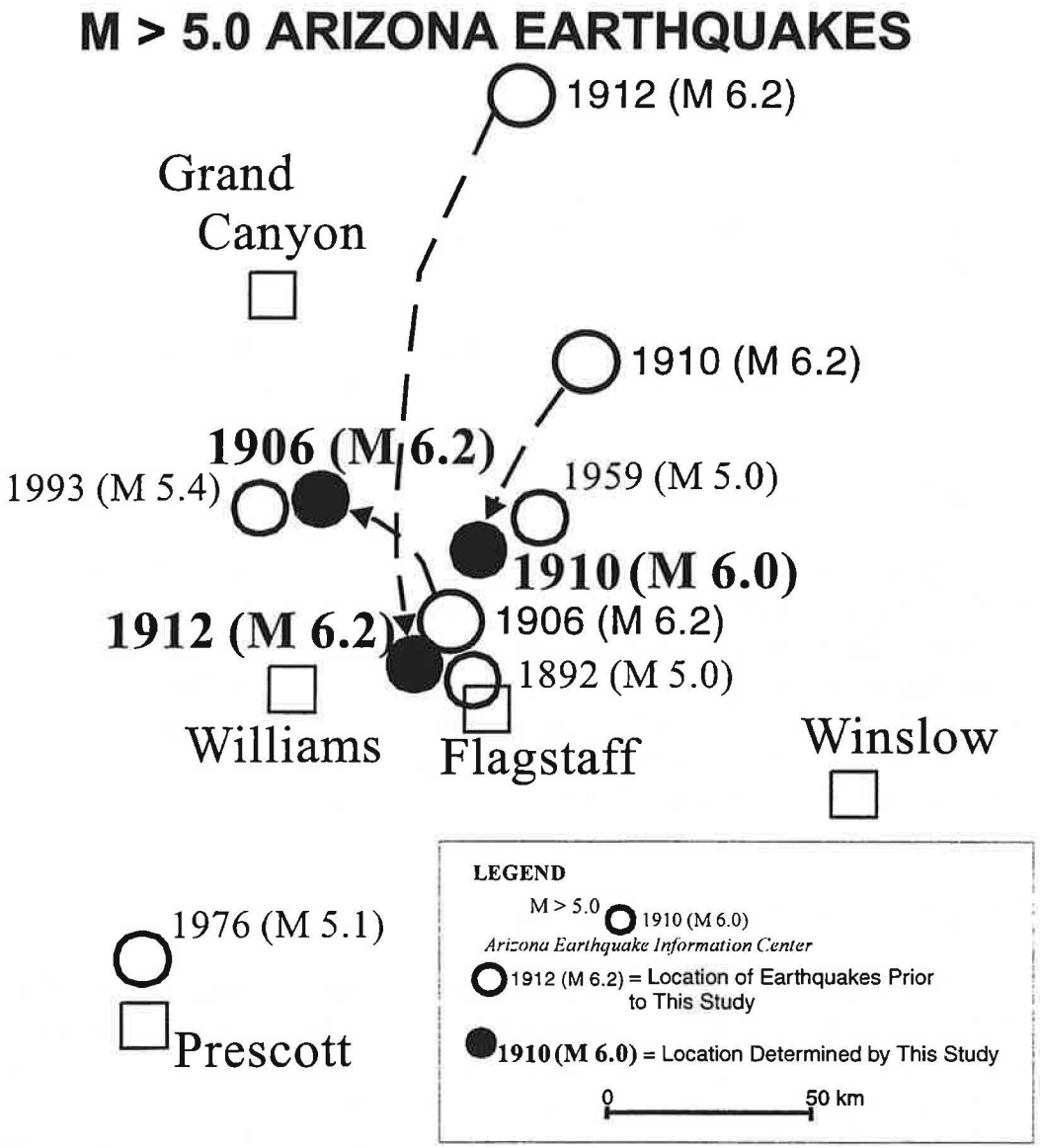

***Figure 12** - Former and revised epicenters of study earthquakes, as well as the locations of significant (M > 5.0) regional earthquakes.*

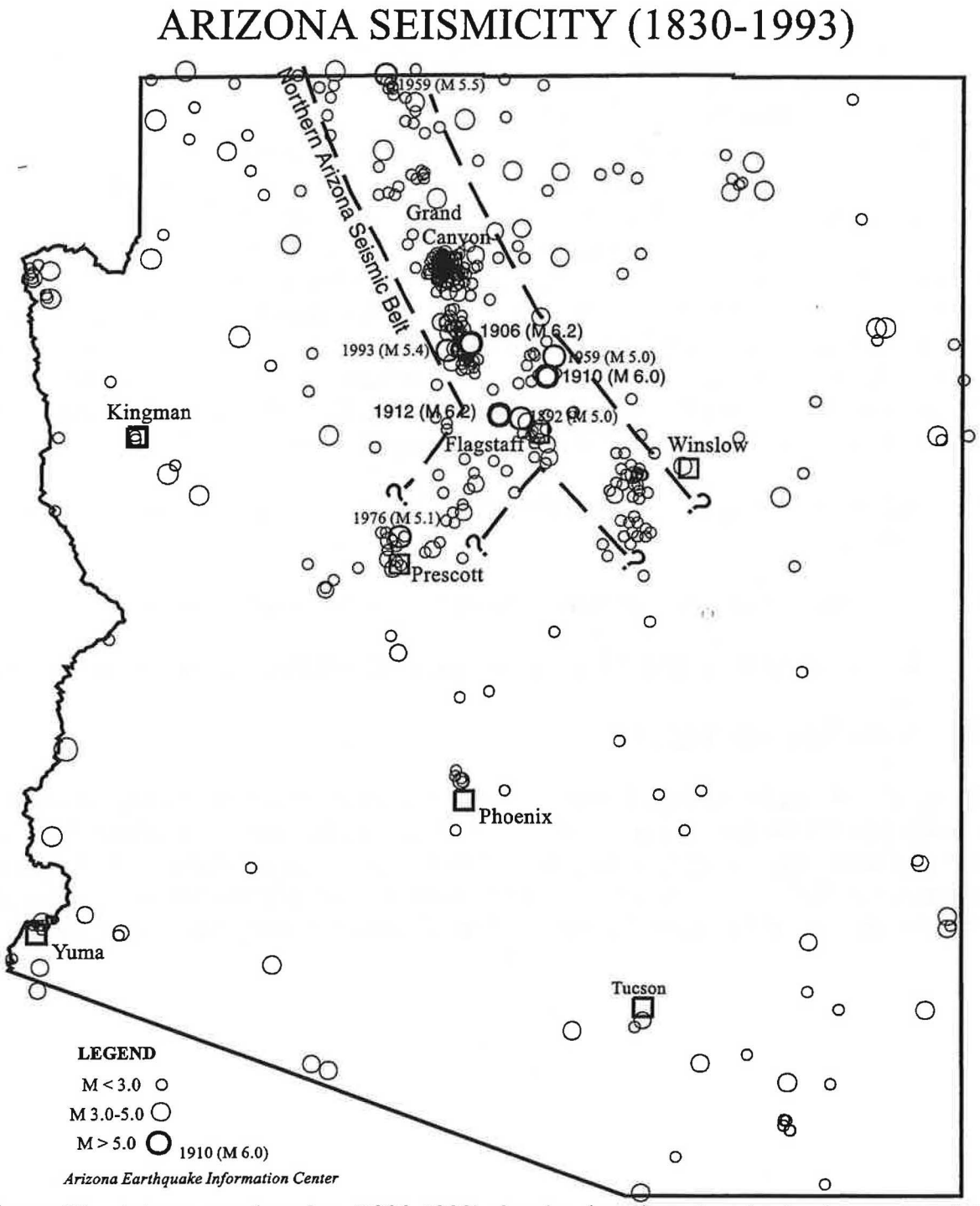

Figure 13 *- Arizona earthquakes (1830-1993) showing location of revised epicenters and the Northern Arizona Seismic Belt (NASB).*

6.1.3 Revised Location of the 1912 Earthquake

The revised epicenter of the M_S 6.2 1912 earthquake moved the greatest of any of the three study earthquakes. The new location is 140 km south-southwest of the original location (Figure 12). The revised epicenter also places the event within the NASB at the tectonic boundary of the Colorado Plateau. The new epicenter is only 20 km northwest of Flagstaff, while the former location was about 150 km to the northeast. The revised location is based on a relatively significant number of instrumental recordings and additional felt report data. The instrumental location is based on the convergence of waveform and origin time data from four stations (Berkeley, CA; Victoria, Canada; Denver, CO; and Saint Louis, MO). In addition, much of the new felt report data support the instrumental location. The instrumental location is at the eastern edge of the innermost MMI VIII isoseismal (Figures 9 and 11), rather than the middle. An unusual aspect of the event is that it was felt more strongly at Williams than Flagstaff, yet located closer to Flagstaff. This may be a result of the effects of rupture directivity and/or depth, as discussed in Section 2, on the intensity pattern of this earthquake. New felt report data obtained during this study included:

1) Additional felt report data from the local Williams newspaper that indicated MMI VIII shaking;

2) A revised interpretation and location for the Lockett Tanks felt report; and,

3) Through the GNIS, a more realistic interpretation of the felt report from 'Escalante Country.'

6.2 Probable Fault System(s)

The impact to the regional seismic hazard of the revised epicenters depends mostly on which fault system(s) underlie the new locations. That is, which new fault(s) are now considered active and capable of producing damaging earthquakes. The revised locations indicate activity along the Cataract Creek fault system (Figure 14). The revised epicenter of the 1910 earthquake is at the juncture of the northwest trending Cataract Creek and northeast trending Mesa Butte fault systems.

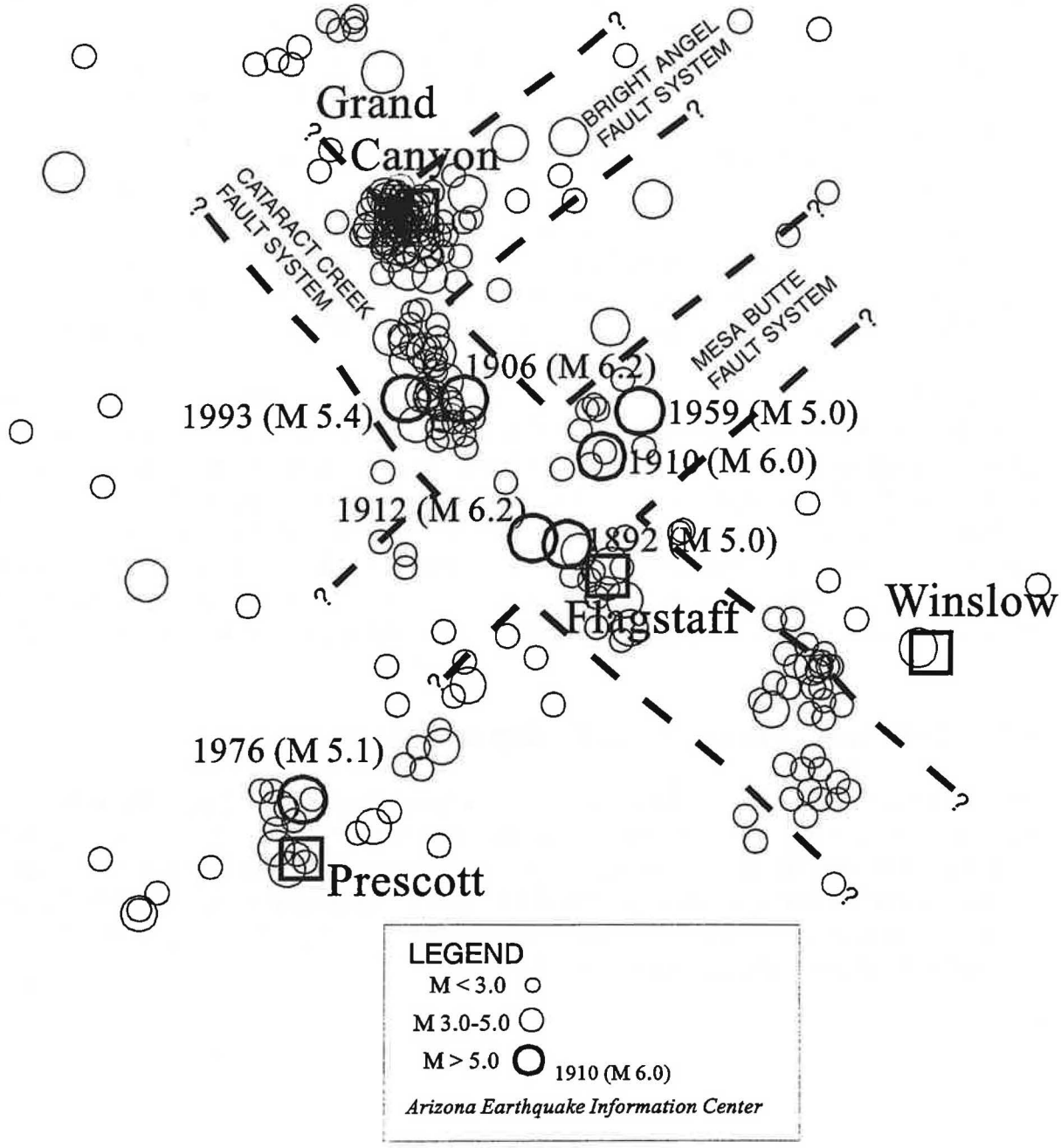

Figure 14 *- Northern Arizona seismicity and fault systems.*

6.2.1 Cataract Creek Fault System

Northern Arizona experienced m_b 4.9 and 5.4 earthquakes on April 25 and 29, 1993, respectively. These events occurred within a sparsely populated region approximately 3 miles northwest of Valle, Arizona (pop. 75). The revised epicenter of the 1906 earthquake co-locates with these significant and well-located Arizona earthquakes (Figure 14). The location of these events are within the Cataract Creek fault system. The Cataract Creek fault system consists of a 200 km long group of northwest trending high angle faults extending from the western Grand Canyon region southeastward to the Mogollon Plateau of Arizona. Age of faulting is difficult to estimate for most of the faults of the system because the surface traces cut eroded Paleozoic rocks and lack younger dateable deposits. No historic surface rupture has been identified with any of the faults, but study of historic seismicity indicates that at least some of the faults of the system are active. This would include the Cataract Creek fault proper, as well as the Chavez Mountain fault and the Lake Mary fault near Flagstaff.

A study of first motion readings for the m_b 4.9 and m_b 5.4 events resulted in similar solutions, both indicating predominantly normal faulting (Bausch and Brumbaugh, 1994). Of the resulting nodal planes, preference is given to the northwesterly oriented planes, parallel to the known fractures of the Cataract Creek fault system. These results are compatible with results of waveform modeling techniques (Lay and others, 1994) of these two earthquakes. An aftershock study of the 1993 earthquake sequence indicated northwest trending locations for three days following the main shock, while later events appeared to follow a northeasterly trend (Sanders, 1996). This may indicate a migration of activity onto the northeasterly trending Bright Angel fault system (Figure 14).

6.3 Impacts to Northern Arizona Earthquake Hazard

Data obtained by this study appear to increase the seismic hazard for northern Arizona by elevating the risk to its major population center. The revised epicenters are much closer to Flagstaff than originally believed, which may indicate that the seismogenic sources nearer Flagstaff are more active. Additional data obtained regarding the pattern of local ground shaking in both Flagstaff and Prescott during these historic earthquakes may be useful in mapping predicted ground shaking intensities for future earthquakes affecting those cities.

6.3.1 Impact of Revised Locations to Flagstaff

All three study events are now believed to have occurred within 40 km of Flagstaff. Indicating seismogenic sources, such as the Cataract Creek fault system, nearer Flagstaff, have historically been relatively active. Of course this only suggests that they will remain active in the future. However, research evidence from major fault systems throughout the world have shown a strong correlation between earthquake hazard and fault activity (e.g. it is the proximity and the scale of the fault that most controls the earthquake hazard. These data are further indicative of the hazard to northern Arizona from the Cataract Creek fault system. This system is long enough and active enough to produce damaging earthquakes in northern Arizona. Most critical is the fact that this system underlies Flagstaff and its largest segments, the Lake Mary faults, are within a few kilometers of the city limits.

Information uncovered during this study concerning the damage pattern and felt intensity of the 1906 earthquake for the developed portions of Flagstaff could potentially be valuable in producing hazard maps for the City. Regions of greater intensity shaking and damage may indicate the areas of the city that are most susceptible to damaging ground shaking in future earthquakes. The City of Flagstaff is a rapidly growing community of currently about 51,000 persons, almost double the population of ten years ago. While the city has enforced Uniform Building Code (UBC) Seismic Zone 2b construction practices for the last seven years, a number of older unreinforced masonry buildings (URMs) are located within downtown Flagstaff. Several of these structures were damaged by the 1906 earthquake. In addition, many remodels have produced a "soft-story" on the ground floor, and the freeze-thaw cycle has undoubtedly contributed to a weakening of the URMs during their 100+ year lifetimes.

6.3.2 Probabilistic Acceleration Mapping

The National Hazard Maps and subsequently the Uniform Building Code, which is based upon the national maps prepared periodically by the U.S. Geological Survey, are a result of probabilistic acceleration mapping. The construction of probabilistic acceleration maps are a result of three types of basic input parameters:

1) Attenuation of ground shaking with distance from the earthquake source;

2) Frequency of earthquakes within an area or region, termed recurrence; and

3) The character and extent of regions and faults that generate earthquakes.

Several probabilistic assessments have been performed for the study area (Table 5).

FLAGSTAFF	*TABLE 5 - AVERAGE PEAK GROUND ACCELERATION*		
	50 YEAR	**100 YEAR**	**250 YEAR**
Arizona Earthquake Information Center (Bausch and Brumbaugh, 1994)	11	17	26
Arizona Department of Transportation (Euge and others, 1992)	20	N/A	42
Building Seismic Safety Council (Algermissen and others, 1990)	8	N/A	N/A
1996 National Seismic Hazard Maps (Frankel and others, 1996)	10	N/A	N/A
Arizona Geological Survey (Pearthree and others, 1996)	11	N/A	N/A
Accelerations are expressed as a percent of gravity at bedrock, based on 90% non-exceedance.			

The effect of the revised epicenters on these probabilistic acceleration values depends on the methodology incorporated by the individual study. The studies listed above utilized several different methods in determining the probabilistic accelerations for northern Arizona. Bausch and Brumbaugh (1994), Euge and others (1992), and Pearthree and others (1996) all represent regional reports, while Algermissen and others (1990) and Frankel and others (1996) represent the national mapping of the U.S. Geological Survey. The regional reports all utilized the computer program SEISRISK III (Bender and Perkins, 1987), and include line sources (faults), as well as historic seismicity. However, the only study to utilize smaller faults, such as Lake Mary, as line sources, rather than only major Arizona faults, was that by Pearthree and others (1996). They found that the influence of these smaller sources, due mostly to their low Maximum Credible Earthquakes, were a negligible contribution to the acceleration values. The high values obtained by Euge and others (1992) are a result of defining a relatively small San Francisco Volcanic Field Source Zone with a relatively high rate of seismicity that included the three study earthquakes. However, the results of this study indicate at least two of the events (1906 and 1912) did not occur within their defined source zone, and therefore, new acceleration values would be lower. The revised epicenter locations would not affect the values obtained by Bausch and Brumbaugh (1994) Their study placed the earthquakes within a Southwest Plateau Transition Zone, which defines an area that includes the revised epicenter locations.

A new method of determining probabilistic accelerations was utilized during preparation of the most recent national maps by Frankel and others (1996). Rather than defining seismogenic source zones, this method moves a one-square kilometers grid across the historic seismicity database, thereby providing a running average of the occurrence values for the region. The primary advantage of this method is in eliminating the uncertainties in defining source zone boundaries. The revised epicenters would likely have the greatest affect on this method. For example, the near co-locations of the 1906 M 6.2 and the 1993 M 4.9&5.4; the 1910 M 6.0 and the 1959 M 5.0; and the 1912 M 6.2 and 1892 M 5.0 (Figure 14), would result in locally significant increases in acceleration values.

6.3.3 Impact on the Uniform Building Code

The seismic hazard zonation for the UBC has historically been defined by the Structural Engineers Association of Southern California (SEAOSC) based on the National Seismic Hazard Mapping of the U.S. Geologically Survey. The zoning for the north-central and -western portions of Arizona, including Flagstaff, are defined as Zone 2b, while the northeastern portion of the state is defined as Zone 1. The scale begins at 0 as the lowest and 4 as the highest seismic hazard. For the 1994 UBC, SEAOSC adopted a value of 20% g from the 50 year probabilistic maps as the division between Zone 2 and 3. Therefore, the impacts of the revised epicenters are uncertain, however, if they resulted in increasing the acceleration to above 20% g, one may surmise that the UBC Zonation should be increased. These revised epicentral locations are updated in the Catalog of Arizona Earthquakes, and will be provided to the U.S. Geological Survey. Any changes to the UBC as a result of this work would likely not be incorporated until the 2002 version of the UBC. However, local policies can be more restrictive and the next logical step would be to incorporate the results of this study into a Earthquake Hazard Evaluation for the Flagstaff Community.

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8.0 SUMMARY OF DESCRIPTIVE RECORDS REVIEWED
Northern Arizona University--Special Collections

Below is a summary of the abundant resources reviewed within the Northern Arizona University Library Special Collections. Materials found relating to the earthquakes were copied and are included within the Appendix.

Babbitt Brothers Trading Company Collection, Flagstaff, Arizona, N.A.U. Manuscript Collection #83: Financial records 1880-1970. Includes records of numerous Babbitt ranches and businesses in Flagstaff and throughout northern Arizona.

Mostly large financial ledgers. Review showed no mention of earthquakes.

Babbitt, Gertrude Collection, N.A.U. Manuscript Collection #179: Correspondence and files concerning George, David and Emma Babbitt, 1849-1929.

Family letters did not mention 1906 and 1910 events. Family was in France during 1912 event.

Babbitt, Joseph Robert, Sr. Collection, N.A.U. Manuscript Collection #68: Photocopied scrapbook belonging to Joseph R. Babbitt, Sr. Includes miscellaneous receipts, some Babbitt Bros. Trading Co. letters, letterheads, and information on different businesses in Arizona, 1884-1950.

Review showed no mention of earthquakes.

Bushman, John Collection, N.A.U. Manuscript Collection #174, John Bushman was a Mormon pioneer who settled in Joseph City along the Little Colorado River three miles south of Holbrook. Includes diaries and journals, 1871-1923.

Review showed no mention of earthquakes. Time gaps in diaries occurred during event times in 1906, 1910, and 1912.

Cline, Platt Collection, President of the Arizona Daily Sun, Flagstaff and local historian. N.A.U. Manuscript Collection #91: Historical files concerning Flagstaff and Coconino County. Includes pioneer reminiscence of Black Family, Babbitt Brothers Trading Co. records, correspondence and business papers of J. Gutherie Savage. Includes 1912 diary of Harold P. Blome of Flagstaff.

Review showed no mention of earthquakes. Time gap in 1912 Blome diary for time of event.

Flagstaff City--Coconino County Public Library Oral History Project Collection, N.A.U. Manuscript Collection #183: Interviews of 89 persons conducted with people that had been in the Flagstaff area at least prior to 1930.

Interviews were conducted in the 1970's, and a review of the persons ages indicated they were either too young or not born prior to the 1906-1912 time frame of interest.

Arizona Champion-Coconino Sun Newspaper Index Collection, NAU Manuscript Collection #189.

Contains a comprehensive name and subject index for the period 1883-1894. Therefore, does not include the time period of the subject earthquakes. Includes entry for 1892 Flagstaff earthquake on Feb. 4, 1892, and a reference to a story regarding 'land near Yuma changed because of earthquakes' on Aug. 22, 1891. The index is very comprehensive and further review should be undertaken as this index is updated.

Flagstaff Weather Bureau Collection, NAU Manuscript Collection #186: Includes 21 lineal feet of weather records for the time periods 1898-1991.

A review provided good descriptive accounts of the 1906 and 1910 earthquakes by an observational scientist. However, detailed record keeping other than general temperature and precipitation data ceased after March 1912, and missed the August 12, 1912 earthquake.

Frier, Thomas (1859-1942) and Della (1873-1959) Collection, NAU Manuscript Collection #119: Scrapbooks and photographs of Flagstaff and northern Arizona history.

Contains primarily post 1920 materials and no mention of the earthquakes were found.

Grand Canyon Pioneers Collection, NAU Manuscript Collection #242: Includes correspondence of northern Arizona businessman Ralph Cameron, legal and financial records, 1900-1917.

Predominantly legal documentation such as deeds and insurance documents. No descriptive journals or logs were found and no mention of the earthquakes are made.

Hochderffer Collection, George Sr., (1863-1955), NAU Special Collections: Includes several boxes containing scrapbooks and journals.

Scrapbooks contain mostly newspaper clippings and personal mementos. Although newspaper clippings concerning the earthquakes are included, there are none in addition to those on microfilm. The daily journal Hochderffer maintained for Summit Ranch, located north-northwest of the San Francisco Peaks, include an entry for the 1910 earthquake. It appears from the entries that Hochderffer was 'absent from ranch May '05-April '06' and 'In 1912 I removed East at Harvard University.'

Killebrew, Ernest Collection, NAU Manuscript Collection #104: Cottonwood, Arizona postal records, 1885-1912.

No mention of the earthquakes, contains mostly logbooks of packages, religious scrawl and envelopes.

Kolb, Emery Collection (1881-1976), NAU Manuscript Collection #197, Part 10: Includes photographs, correspondence, manuscripts, cameras and other objects of Emery and Ellsworth Kolb's photographic studio at the Grand Canyon from the early 1900's to 1976.

Contains 36 lineal feet of materials, with very few items from the time period of the earthquakes. No mention or records of the earthquakes were found.

Lowell Observatory Collection, NAU Manuscript Collection #194: Includes correspondences for the period 1894-1916.

Letters from Percival Lowell from MIT to his observatory during the period of the 1906 and 1910 earthquakes were reviewed, and no mention of the earthquakes were found. During the time of the 1912 event Lowell was very ill and correspondence were rare. A 1919 letter written by C.O. Lampland of the observatory that describes the 1912 earthquake was located and copied.

Navajo Trading Post Collection, NAU Manuscript Collection #260: Contains trading post journals from the Babbitt Brother's Trading Company.

Contains meeting minutes from the Kayenta Trading Post, and cash ledgers for the posts at Kayenta, Pine Springs, Kinteél, and Wide Ruins. A review of these records showed no mention of the earthquakes.

Nielson, Frihoff Godfrey Collection, NAU Manuscript Collection #172: Contains journal, autobiography and notes for Mormon Pioneer of Joseph City, Arizona.

Joseph City is along the Little Colorado River about 10 miles west of Holbrook. Materials describe early Morman pioneer life and dam building. Almost daily entries were made into journals, however, no mention of earthquakes were made including the entries of 1/25/06, 9/24/10 and 8/18/12.

Perrin, Edward Collection, NAU Manuscript Collection #87: Records of entrepreneur, rancher in Seligman and Williams, Arizona, 1873 to 1945.

Contains primarily business records concerning claims related to mining and ranching interests.

Riordan Letters, NAU Special Collections: Includes letter books of M.J. Riordan containing professional and personal letters compiled sequentially by date.

Includes letter to sister describing the 1906 earthquake, however, the letter indicates he was in California on business when the earthquake occurred and accounts are second hand through family members. Extensive correspondence relate to 1906 San Francisco earthquake was found, due to Riordan business interest (flour mill) in San Francisco that was destroyed. Letters indicate that he was in New York during the 1910 earthquake. No mention of the 1912 earthquake are made in his letters including several correspondence that are dated the following day.

Schuster, A&B Collection, NAU Manuscript Collection #86: Correspondence and financial records of the A&B Schuster Co. mercantile company in Holbrook, Arizona, 1890's-1950's (scattered).

Includes records of Navajo Trading Co. located in Na-ah-tee Canyon, correspondence with customers and suppliers. No mention of earthquakes were found.

Switzer Hardware Store Collection, NAU Manuscript Collection #178: Financial records and correspondence, 1906-1960, Flagstaff, Arizona.

No mention of earthquakes, primarily legal documents and business ledgers.

Tanner, George S. Collection, NAU Manuscript Collection #176: Records of Mormon settlement in northern Arizona, copies of numerous diaries, journals, correspondence, etc., 1876-1970.

Documents reviewed concerned primarily with colonization of Joseph City along Little Colorado River. The time periods 1870's and 1880's were extensively covered. Records include a diary of John H. Standifird, residing in the Alpine, Arizona region about 35 miles southwest of Holbrook during the time period of the earthquakes. The Standifird dairy contains entries related to Morman life on the days of the earthquakes, but do not include mention of the earthquakes.