Circular 210

Earthquake catalogs for New Mexico and bordering areas: 1869–1998

Allan R. Sanford, Kuo-wan Lin,
I-ching Tsai, and Lawrence H. Jaksha
Geophysical Research Center and Department of Earth and Environmental Science
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801

New Mexico Bureau of Geology and Mineral Resources

A Division of New Mexico Institute of Mining and Technology

Socorro 2002

Earthquake catalogs for New Mexico and bordering areas: 1869–1998

Copyright © 2002 by
The New Mexico Bureau of Geology and Mineral Resources
A Division of New Mexico Institute of Mining and Technology
801 Leroy Place
Socorro, NM 87801
(505) 835-5420
http://geoinfo.nmt.edu
Excerpts of this publication may be reproduced for educational purposes.

Project Editor
Nancy Gilson

Layout
Nancy Gilson

Cartography
Karl Frisch
Kathryn E. Glesener

Editorial Assistance
Gina D´Ambrosio
Elizabeth Campbell
Jane A. Calvert Love
L. Greer Price

Library of Congress Cataloging-in-Publication Data
Sanford, Allan R.
Earthquake catalogs for New Mexico and bordering areas—1869–1998 / by Allan R. Sanford, Kuo-wan Lin, I-ching Tsai, and Lawrence H. Jaksha
p. cm.
Includes bibliographical references.
ISBN 1-883905-13-3
1. Earthquakes—New Mexico—Observations. 2. Earthquakes—New Mexico—History—20th century. I. Sanford, Allan R., 1927- II. Circular (New Mexico. Bureau of Geology and Mineral Resources) ; 210.
TN24.N6 A235 no. 210
[QE535.2.U6]
553'.09789 s--dc21
[551.22/097
2002009690
CIP

Published by authority of the State of New Mexico, NMSA 1953 Sec. 63-1-4
Printed in the United States of America
First Printing

Summary

Records of earthquakes for a specific area over a given period of time are significant sources of data for researchers of earthquake activity. Such records allow researchers to evaluate seismic hazards and make more accurate predictions concerning the likely location—and magnitude—of future earthquakes. The catalogs presented here represent more than 40 years of research, provide an accurate historical record of earthquakes in New Mexico, and document a number of trends. A disproportionate number of earthquakes are centered in the Rio Grande valley near Socorro, New Mexico, in a tight cluster of earthquakes known as the Socorro Seismic Anomaly. The enhanced seismic activity of this region is believed to be the result of the stretching of the earth's crust over a large body of magma that exists at a depth of 12 miles below the region. This anomaly occupies less than 1% of the study area but accounts for 23% of the earthquakes of magnitude 2.0 or greater. Two parallel east-northeast trends are also apparent: an alignment the authors call the Socorro fracture zone and, to the north, the Jemez lineament, a large-scale fracture zone that extends from southwest of Grants, New Mexico, to Los Alamos, Española, and beyond to the northeast corner of the state. Surprisingly, with the exception of the Socorro Seismic Anomaly, no discernable trend is apparent for the Rio Grande rift, a major flaw in the earth's crust that bisects the state north to south and along which the Rio Grande flows. Data from the catalogs can be downloaded at http://geoinfo.nmt.edu/publications/earthcat/

COVER: A probabilistic seismic hazard map for New Mexico based on earthquake data from the catalogs in this publication. Seismic hazard maps commonly show the expected geographic distribution of maximum ground motion from earthquake activity. They are constructed for different percentages of probability over a specified time period. The map on the cover shows expected maximum or peak horizontal ground accelerations (PGA) that have a 10% probability of being equaled or exceeded in a 50-yr period. The colors and contours on the hazard map are scaled to ground acceleration as a fraction of the earth's gravity g. The highest predicted PGA, ~0.18 g, is located ~40 km (~25 mi) north of Socorro. A PGA of ~0.2 g is considered the acceleration level at which considerable damage can begin to occur to weakly built or designed structures—masonry structures of adobe and adobe and stone, for example. With the exception of the Socorro area, predicted PGAs on the hazard map are much less than 0.2 g. However, this map is based on instrumental earthquake data collected from 1962 through 1998, a very short time period to characterize the long-term seismicity of a region like New Mexico. Therefore this map has a fairly high degree of uncertainty.

For technical details on how the hazard map was constructed, see: Lin, K. W., 1999, Probabilistic seismic hazard in New Mexico and bordering areas: Unpublished Ph.D. dissertation, New Mexico Institute of Mining and Technology, New Mexico, 194 pp.

Other less detailed descriptions of the technical details of the hazard map can be obtained from New Mexico Tech geophysics open-file reports available at http://dutchman.nmt.edu/~nmquakes/

Table of Contents

PREFACE . . . vi
INTRODUCTION . . . 1
GENERATION OF THE NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY CATALOGS . . . 1
CATALOGS OF OTHER ORGANIZATIONS . . . 1
PROCEDURES . . . 1
Earthquake magnitudes . . . 1
Earthquake epicenters . . . 1
Accuracy of epicenters . . . 3
THE CATALOGS . . . 4
GEOGRAPHIC DISTRIBUTION OF EARTHQUAKES . . . 6
TEMPORAL VARIATION OF EARTHQUAKE ACTIVITY . . . 8
SUMMARY AND CONCLUSIONS . . . 8
ACKNOWLEDGMENTS . . . 9
REFERENCES . . . 9
APPENDICES . . . 11
I. Earthquake catalogs for New Mexico and bordering areas—1962–1995, moment magnitude ≥ 1.3 . . . 11
II. Earthquake catalogs for New Mexico and bordering areas—1962–1998, moment magnitude ≥ 2.0 . . . 59
III. Earthquake catalogs for New Mexico and bordering areas—1962–1998, moment magnitude ≥ 3.0 . . . 83
IV. Listings of magnitude differences between New Mexico Institute of Mining and Technology and contributing institutions . . . 89
V. Seismograph station locations . . . 97

Tables

1—Magnitude adjustments for events from contributing institutions . . . 2
2—Strongest earthquakes in New Mexico, 1869–1998 . . . 5

Figures

1—Seismicity of New Mexico and bordering areas from 1962 through 1995, moment magnitudes of 1.3 or greater . . . 2
2—Seismicity of New Mexico and bordering areas from 1962 through 1998, moment magnitudes of 2.0 or greater . . . 3
3—Seismicity of New Mexico and bordering areas from 1962 through 1998, moment magnitudes of 3.0 or greater . . . 4
4—Strongest New Mexico earthquakes from 1869 through 1998, moment magnitudes of 4.5 or greater . . . 6
5—Temporal seismicity for the Socorro Seismic Anomaly and the remainder of New Mexico and bordering areas from 1962 through 1998, moment magnitudes of 2.0 or greater . . . 8
Appendix V-1—Locations of seismograph stations in operation from 1962 through 1972 . . . 99
Appendix V-2—Locations of seismograph stations in operation from 1973 through 1982 . . . 100
Appendix V-3—Locations of seismograph stations in operation from 1983 through 1998 . . . 101

Preface

The earthquake catalogs, maps, and discussion we present here are the outcome of 40 years of seismological research at New Mexico Institute of Mining and Technology (NMIMT) and elsewhere in New Mexico and west Texas. Research at NMIMT was started in 1958 when I learned from publications, primarily by Stuart A. Northrop and H. F. Reid, that, based on felt earthquakes, the Socorro area had a history of strong earthquake swarms and was probably the most active region in New Mexico. In a short 3-day period of instrumental recording in the fall of 1959, 49 microearthquakes were detected, 40 within 20 km (12.4 mi) of Socorro. This was a strong indication that research based on seismograph recordings would be productive. At the end of 1960 we had a suite of instruments operating in an abandoned mine at the foot of Socorro Mountain. Through the years, NMIMT seismograph stations have increased to 16, the number currently in operation.

Although our research program has emphasized earthquake activity within the Socorro area, beginning in 1962 we were able to locate earthquakes throughout New Mexico and bordering areas using data from NMIMT instruments in conjunction with stations throughout the region. This report would not have been possible without seismograms or readings from (1) stations operated by the Air Force Technical Applications Center, (2) U.S. Geological Survey (USGS) stations at Albuquerque and elsewhere in the region, (3) a seismograph network operated for a number of years by Los Alamos National Laboratory, and (4) university stations at University of Texas at El Paso, University of Texas at Austin, and Texas Tech University. Individuals who made particularly significant contributions by providing station readings and earthquake locations and magnitudes were Ken Olsen, Dan Cash, and Leigh House at Los Alamos National Laboratory and Diane Doser and G. Randy Keller at the University of Texas at El Paso.

This report would also not have been possible without the contributions of a long line of talented undergraduate and graduate research assistants at NMIMT. They helped maintain instruments in the field and in the recording observatory. They also interpreted the seismograms, often completing special studies as well as routine determinations of the strengths and locations of earthquakes throughout the region.

An important aspect of the data presented here is that they establish average rates of activity. For the Socorro area (~5,000 km^2; ~ 1,900 mi^2), the expected numbers of earthquakes on average is 5.8/yr, moment magnitude 2.0 or greater and 1.0/yr, moment magnitude 3.0 or greater. For the remainder of New Mexico and bordering areas (700,000 km^2; 270,000 mi^2), the average rates are 19.1/yr, moment magnitude 2.0 or greater and 4.3/yr, moment magnitude 3.0 or greater. As will be shown, earthquakes of magnitude 1.3 and greater occurred throughout New Mexico and bordering areas from 1962 through 1998; however, with a few exceptions, the level of activity has been low compared to regions like California.

Data from the catalogs can be downloaded at http://geoinfo.nmt.edu/publications/earthcat/

Allan R. Sanford
September 2002

Introduction

Starting in July 1960 and continuing through 1998, New Mexico Institute of Mining and Technology (NMIMT) generated files on all earthquakes they were able to locate in New Mexico and bordering areas. These files provided a starting point for generating the comprehensive and consistent catalogs presented here and were ultimately the source of 84% or more of the earthquakes in these listings. The event locations in the NMIMT files used phase readings from many organizations. For the period from 1962 through 1972, the principal contributing organizations were the U.S. Geological Survey (USGS), the Air Force Office of Scientific Research (Air Force Technical Applications Center), and universities (Texas Tech University [TTU] and University of Texas at El Paso [UTEP]). For the period from 1973 through 1982, the principal contributing organizations were the USGS, universities (UTEP and TTU), and Los Alamos National Laboratory (LANL). From 1983 through 1998, the principal contributing organizations were LANL, the USGS, and UTEP.

Generation of the New Mexico Institute of Mining and Technology catalogs

An initial problem with the earthquakes on file at NMIMT was that different procedures were used to locate and assign magnitudes during different periods from 1960 through 1998. Therefore our first step was to relocate and reassign magnitudes for all events in the NMIMT files using the SEISMOS location program (Hartse, 1991) and a New Mexico duration magnitude scale (Newton et al., 1976; Ake et al., 1983). All known explosions from open-pit copper mines in southwestern New Mexico and southeastern Arizona, open-pit coal mines in northwestern New Mexico and northeastern Arizona, and miscellaneous explosions from quarry operations and road construction were eliminated from the NMIMT data.

At this stage of the study, a decision was made to divide the NMIMT data into two catalogs of earthquakes with duration magnitudes of 1.3 or greater; one for a 5,000 km^2 (1,900 mi^2) region surrounding Socorro that we have designated the Socorro Seismic Anomaly (SSA), the other for the remainder of New Mexico and bordering areas (RNM). The SSA occupies 0.7% of the total study area but accounts for ~29% of the earthquakes in our most comprehensive catalog ($M_d \geq 1.3$). The division was made not only because of the seismological importance of the SSA but also because the procedures followed were somewhat different for the SSA and the RNM.

The principal characteristics of these initial NMIMT catalogs were: (1) an increase in the number of earthquakes with time because of an increase in the number of stations with a more favorable geographic distribution for location of events in New Mexico and bordering areas and (2) a bias toward earthquakes with locations near Socorro because of the geographic distribution of seismograph stations operated by NMIMT. Because of the temporal and spatial distribution of seismograph stations (see Appendix V), the catalogs generated for magnitude 1.3 or greater shocks were temporally and spatially biased. We realized that these problems could be removed by determining the lowest magnitude at which the data are complete throughout the study area. However, before testing for completeness, we wanted to have as complete catalogs as possible at the magnitude 1.3 or greater level. This meant searching for missing events using catalogs from other organizations.

Catalogs of other organizations

The only organization cataloging earthquakes in New Mexico and bordering areas for the entire 1962–1998 period was the USGS. Their listings were particularly helpful in providing missing events at the outer margins of the study area that occurred from 1962 through 1980. From 1981 through 1998, all earthquakes cataloged by the USGS were also located by NMIMT.

The NMIMT catalogs were cross-checked with LANL catalogs for the period from 1 December 1972 through 31 December 1981. These catalogs filled gaps in the NMIMT catalog, particularly in the north-central area of New Mexico. The LANL catalogs were biased toward that area because of the distribution of stations in their network.

The NMIMT catalogs were cross-checked with UTEP catalogs for the period from 1 December 1976 through 30 April 1978. These catalogs provided missing events in southeastern New Mexico and bordering west Texas at a time when NMIMT was not adequately monitoring that area.

In the process of cross-checking catalogs, we identified a substantial number of NMIMT cataloged earthquakes that were also located by the USGS, LANL, and UTEP. On the basis of these co-located events, we were able to establish magnitude adjustments to the missing events added to the NMIMT catalog from the USGS, LANL, and UTEP listings (see Appendix IV).

Procedures

Earthquake magnitudes

A major effort was made to have all magnitudes in our catalogs based on or tied to a New Mexico duration magnitude scale (Newton et al., 1976; Ake et al., 1983). For determining magnitudes the relation

$$M_d = 2.79 \log \tau_d - 3.63$$

was used, where τ_d is the duration in seconds. This relation was first developed by Dan Cash at LANL (Newton et al., 1976) for earthquakes in northern New Mexico. Later an essentially identical relation was derived at NMIMT (Ake et al., 1983). The basic data for the NMIMT duration magnitude equation were 64 Wood–Anderson seismograph recordings of earthquakes in New Mexico and bordering areas. Local magnitudes (M_l) calculated from the amplitudes on the Wood–Anderson seismograms (Richter, 1958) were linearly related to the logarithm of τ_d measured on seismograms from the Albuquerque (ALQ) station of the World Wide Seismograph Network (WWSN). Hanks and Kanamori (1979) have demonstrated that local magnitude (M_l) is equivalent to moment magnitude (M).

All duration magnitudes calculated by NMIMT were based on τ_d measurements on ALQ–WWSN seismograms or on seismograms produced by instruments with similar responses and magnifications. For a small fraction of events in the NMIMT catalogs, duration magnitudes could not be calculated but magnitudes from the USGS, LANL, UTEP, or Albuquerque Seismic Laboratory (ASL, a USGS facility) were available. To obtain consistency in magnitudes, we established magnitude adjustments based on differences in magnitudes for events co-located by NMIMT and the USGS, LANL, UTEP, and the ASL (see Appendix IV for detailed listings). Table 1 summarizes the adjustments. The hierarchy adopted when magnitudes were available from two or more organizations was NMIMT, USGS, LANL, ASL, and UTEP.

Earthquake epicenters

Most locations of earthquakes within the SSA were obtained from the inverse method program SEISMOS (Hartse, 1991) designed to incorporate crustal reflections into the location process. A relatively complex and tightly constrained crustal structure obtained from inversion of reflection data was used with the SEISMOS program in the SSA (Hartse et al., 1992).

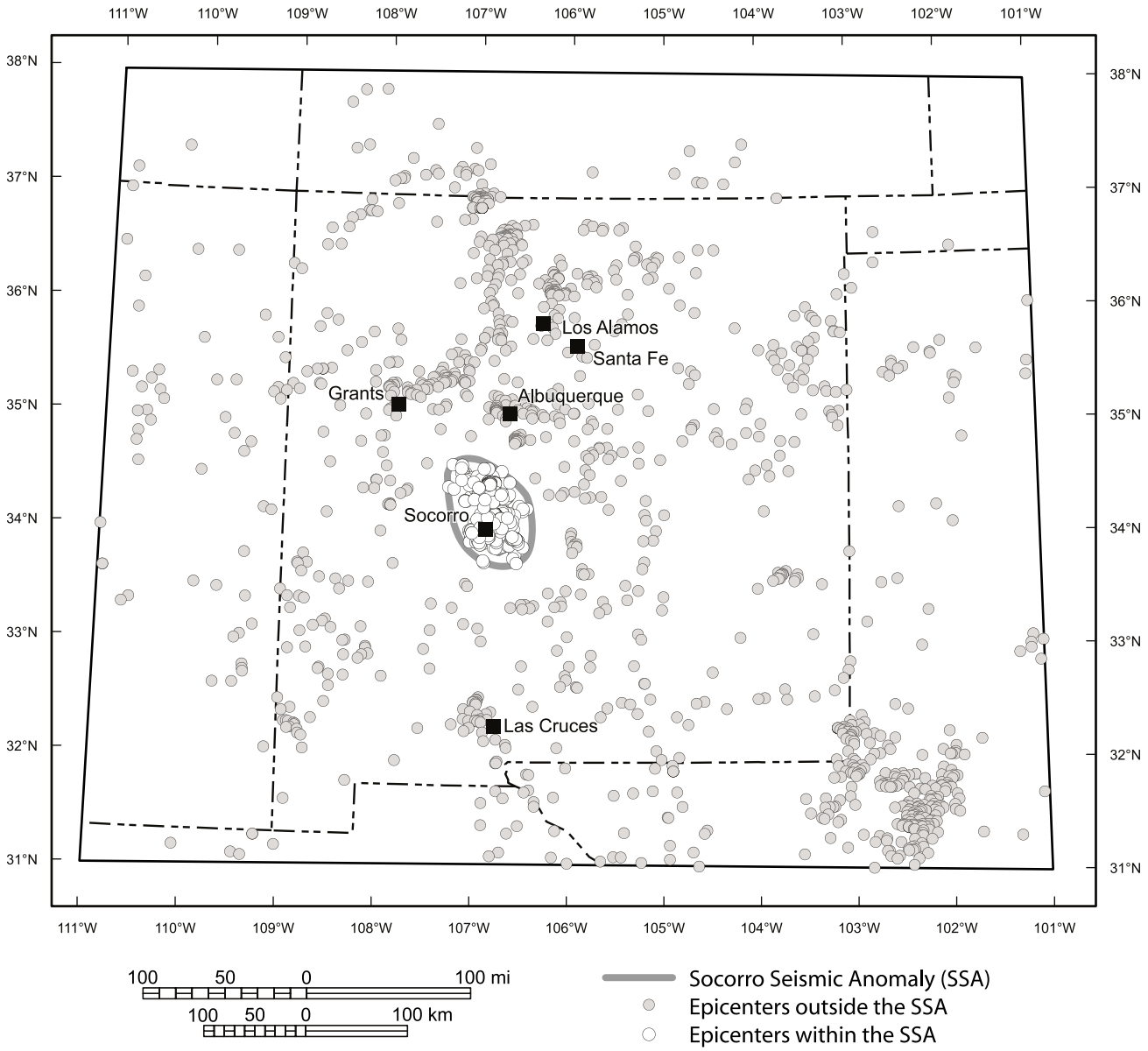

FIGURE 1—Seismicity of New Mexico and bordering areas, from latitude 31° to 38° and longitude 101° to 111°, during the time period 1962–1995 with moment magnitudes of 1.3 or greater. A total of 1,794 earthquakes are plotted on this map, 572 of which are inside the Socorro Seismic Anomaly (SSA; see black circle above and in Figs. 2, 3). An additional 206 earthquakes beyond the map boundary are included in Appendix I for a total of 2,000.

Epicenters for the earthquakes everywhere in the state and bordering areas (RNM) except the SSA were obtained from the SEISMOS program modified to locate regional earthquakes. SEISMOS, like other inverse method location programs, e.g. HYPO71 (Lee and Lahr, 1975) and HYPOELLIPSE (Klein, 1978), fails to obtain reliable locations for regional events whose epicenters may be far outside small aperture networks. For the 37 yrs of New Mexico instrumental recording, this was a common occurrence. Lin (1994) and Lin and Sanford (2001) solved this problem by developing a fuzzy logic algorithm that obtains a highly reliable initial estimate of the epicenter for input into the SEISMOS program. An important step in the generation of the NMIMT catalogs was relocation of nearly all of the earthquakes using SEISMOS modified to include the fuzzy logic algorithm. The reason for relocation using a single location program was to obtain a more uniform set of epicenters. Also, locations in many cases were improved by combining readings from two or more organizations.

TABLE 1—Magnitude adjustments for events from contributing institutions.

Institute	Magnitude adjustment	First standard deviation	Number of events compared
USGS	-0.185	0.395	182
LANL	0.104	0.332	28
UTEP	-0.453	0.409	7
ASL	0.397	0.275	7

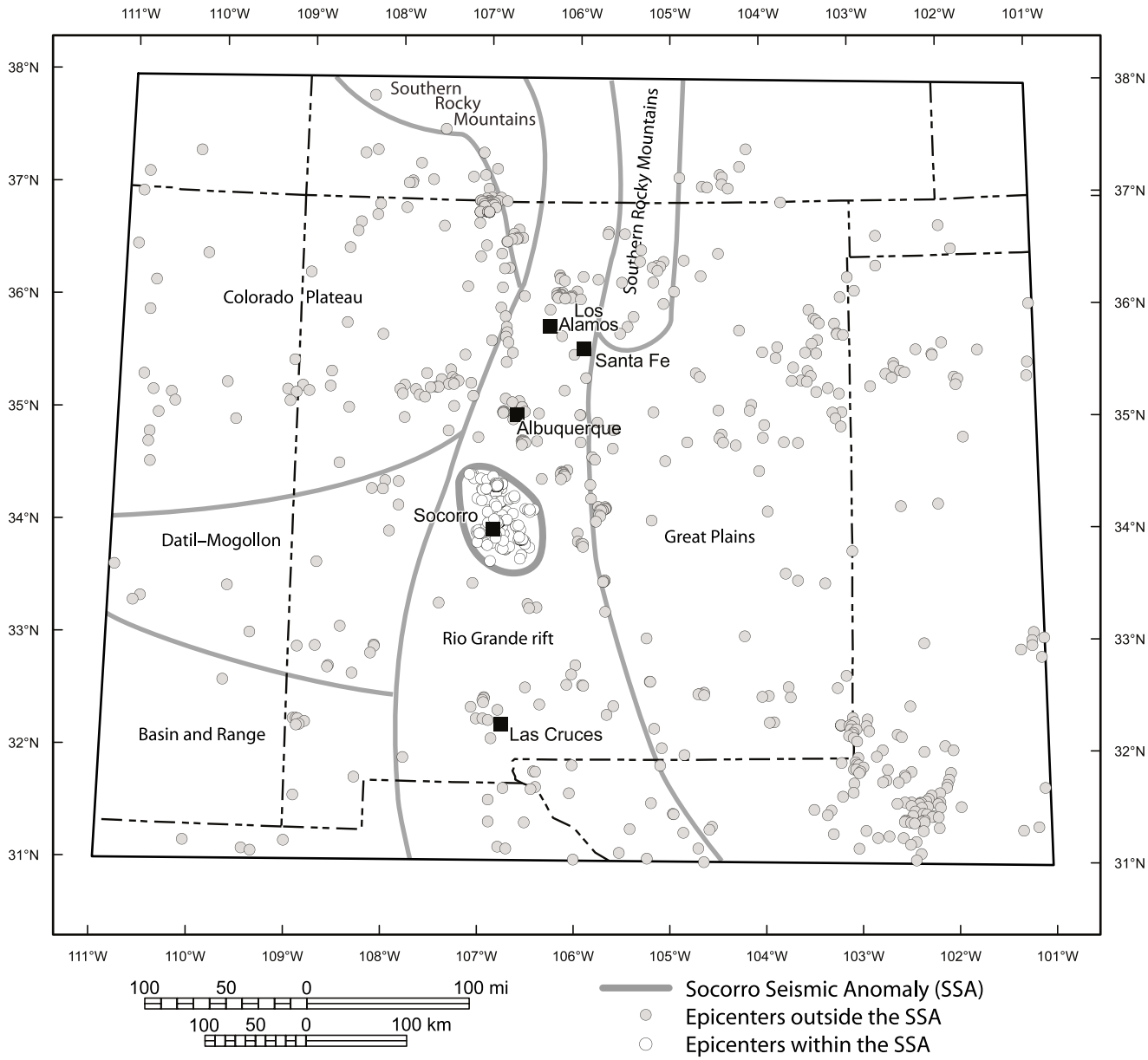

FIGURE 2—Seismicity of New Mexico and bordering areas, from latitude 31° to 38° and longitude 101° to 111°, during the time period 1962–1998 with moment magnitudes of 2.0 or greater. A total of 789 earthquakes are plotted on this map, 215 of which are inside the Socorro Seismic Anomaly (SSA; see black circle above and in Figs. 1, 3). An additional 134 earthquakes beyond the map boundary are included in Appendix II for a total of 923.

The velocity model used with SEISMOS to locate earthquakes outside the SSA was a simple half-space crustal model with a velocity of 6.15 km/sec and a Poisson's ratio of 0.25. Because of this crustal model, only Pg and Sg arrival times were used in the location process. With this procedure, finding reasonable epicenters for the largest number of earthquakes was possible. Many tests on the locations of known mining operations using this procedure indicated that for a significant fraction of New Mexico earthquakes, it may produce the most accurate locations.

For 10.9% of the events in our most comprehensive RNM catalog ($M \geq 1.3$), it was necessary to use locations obtained by the USGS (3.5%), LANL (6.8%), and UTEP (0.6%). We do not know the procedures used by these organizations to obtain earthquake locations.

Accuracy of epicenters

We define accuracy as how close the locations calculated by SEISMOS are to the true epicenters. A primary factor influencing accuracy is how close the adopted crustal velocity model matches the true velocity structure. For the Socorro Seismic Anomaly (SSA), the match is close and the recording distances for most events short. For the remainder of New Mexico and bordering areas (RNM) the adopted half-space crustal model is an average for the entire study area. Some epicenters will not be accurate because all paths to recording stations for a given event are through crust that has a velocity different from the average. Recording paths for many events are long, which can increase the error arising from crustal velocities different than the adopted model.

Other factors influencing accuracy of the epicenters are:

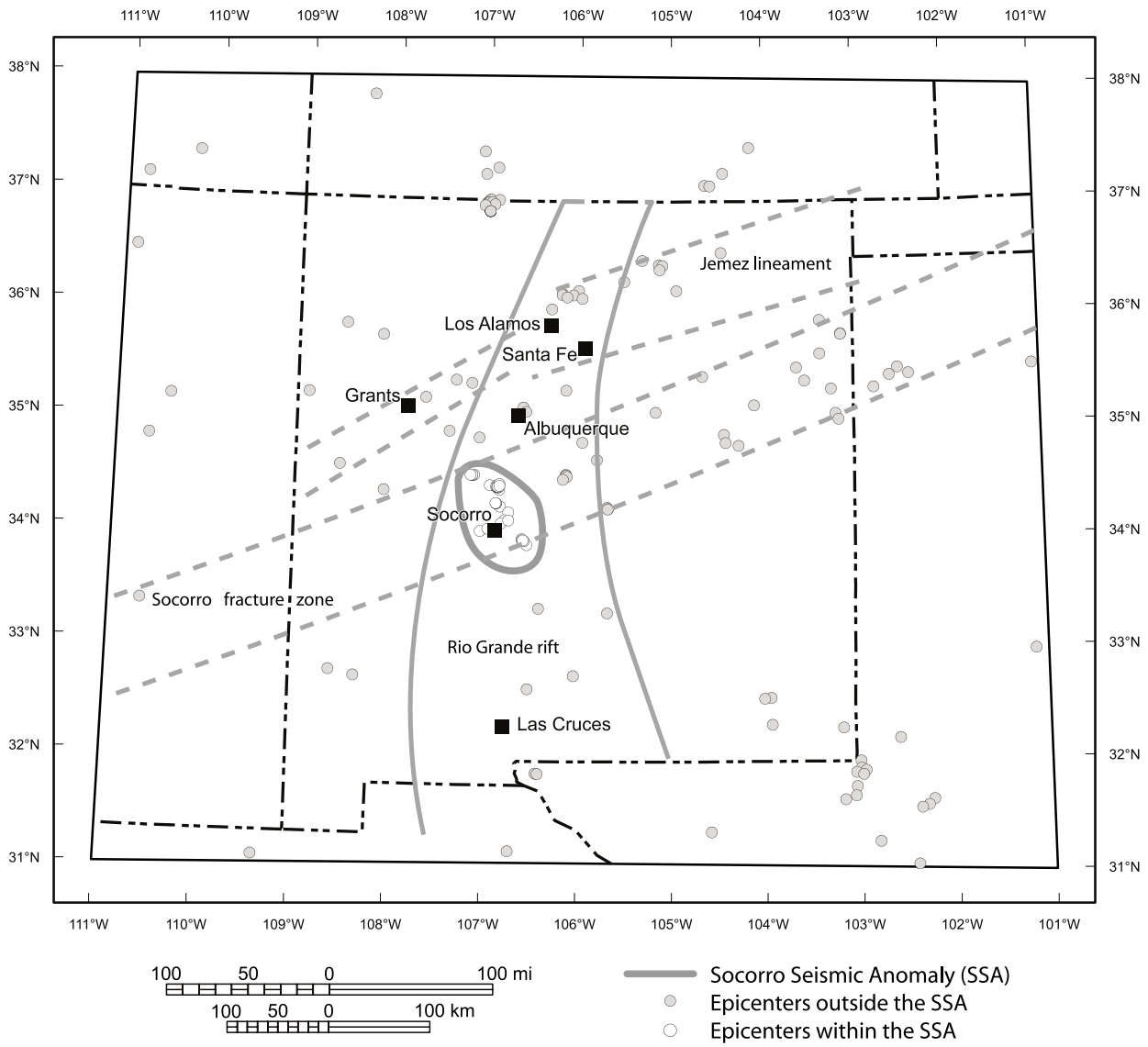

FIGURE 3—Seismicity of New Mexico and bordering areas, from latitude 31° to 38° and longitude 101° to 111°, during the time period 1962–1998 with moment magnitudes of 3.0 or greater. A total of 155 earthquakes are plotted on this map, 36 of which are inside the Socorro Seismic Anomaly (SSA; see black circle above and in Figs. 1, 2). Thirty-nine earthquakes that occurred beyond the map boundary are nonetheless included in Appendix III for a total of 194. Thirty events outside of the SSA fall within the Socorro fracture zone. The approximate boundaries of the Rio Grande rift and the Jemez lineament are also shown.

(1) number of stations, (2) geographic distribution of stations, (3) quality of P and S phase arrivals, and (4) number of paired P and S phase arrivals. Quantifying the effect of these factors on the accuracy of epicenters is difficult or impossible for about 23% of the events in the catalogs ($M \geq 1.3$) because one or more of the four factors is not known. However, the following generalizations about accuracy of locations in the catalogs can be made: (1) accuracy improves with time because of an increase in number of stations with geographic distributions favorable for location of earthquakes in the region (see Appendix V for tables and figures showing temporal changes in numbers and distributions of seismograph stations); (2) accuracy improves with an increase in the magnitude of an event; and (3) accuracy is highest for events located near seismograph networks operated by NMIMT (west-central NM and southeast NM), LANL (north-central NM), and UTEP (southeast NM and adjacent areas of west Texas).

The catalogs

The first pair of catalogs (Appendix I) are for earthquakes with moment magnitudes of 1.3 or greater for the period 1962–1995. Separate listings are given for the SSA and the RNM. Percentage contributions by organizations to the 2,000 locations in Appendix I are: SSA (572 locations)—

TABLE 2—Strongest earthquakes in New Mexico, 1869–1998. Data from Sanford and Lin (1998a)

No.	Date	Origin time hr	min	secs	Approximate location lat (°N)	long (°W)	Maximum intensity (modified Mercalli)	Estimated M	Nearby city
1.	1869				34.1	106.9	VII	5.2	Socorro
2.	Sep. 7, 1893				34.7	106.6	VII	5.2	Belen
3.	Oct. 31, 1895	12			34.1	106.9	VI	4.5	Socorro
4.	1897				34.1	106.9	VI	4.5	Socorro
5.	Sep 10, 1904				34.1	106.9	VI	4.5	Socorro
6.	Jul. 2, 1906	10	15		34.1	106.9	VI	4.5	Socorro
7.	Jul. 12, 1906	12	15		34.1	106.9	VII to VIII	5.5	Socorro
8.	Jul. 16, 1906	19			34.1	106.9	VIII	5.8	Socorro
9.	Nov. 15, 1906	12	15		34.1	106.9	VIII	5.8	Socorro
10.	Dec. 19, 1906	12			34.1	106.9	VI	4.5	Socorro
11.	May 28, 1918	11	30		35.5	106.1	VII to VIII	5.5	Cerrillos
12.	Feb. 5, 1931	4	48		35.0	106.5	VI	4.5	Albuquerque
13.	Feb. 21, 1935	1	25		34.5	106.8	VI	4.5	Bernardo
14.	Dec. 22, 1935	1	56		34.7	106.8	VI	4.5	Belen
15.	Sep. 17, 1938	17	20		33.3	108.5	VI	4.5	Glenwood
16.	Sep. 20, 1938	5	39		33.3	108.5	VI	4.5	Glenwood
17.	Sep. 29, 1938	23	35		33.3	108.5	VI	4.5	Glenwood
18.	Nov. 2, 1938	16	0		33.3	108.5	VI	4.5	Glenwood
19.	Jan. 20, 1939	12	17		33.3	108.5	VI	4.5	Glenwood
20.	Jun. 4, 1939	1	19		33.3	108.5	VI	4.5	Glenwood
21.	Nov. 6, 1947	16	50		35.0	106.4	VI	4.5	Albuquerque
22.	May 23, 1949	7	22		34.6	105.2	VI	4.5	Vaughn
23.	Aug. 3, 1955	6	39	42	37.0	107.3	VI	4.5	Dulce
24.	Jul. 23, 1960	14	16		34.4	106.9	VI	4.5	Bernardo
25.	Jul. 3, 1961	7	6		34.2	106.9	VI	4.5	Socorro
26.	Jan. 23, 1966	1	56	39	37.0	107.0		4.8	Dulce
27.	Jan. 5, 1976	6	23	29	35.9	108.5		4.7	Gallup
28.	Nov. 29, 1989	6	54	39	34.5	106.9		4.7	Bernardo
29.	Jan. 29, 1990	13	16	11	34.5	106.9		4.6	Bernardo
30.	Jan. 2, 1992	11	45	35	32.3	103.2		5.0	Eunice

NMIMT (99.6%), LANL (0.4%) and RNM (1,428 locations)—NMIMT (89.1%), USGS (3.5%), LANL (6.8%), UTEP (0.6%). A map of epicenters for earthquakes in Appendix I is presented in Figure 1. Because of the distribution of seismograph stations (Appendix V) and the low cut-off magnitude, the seismicity for this data set is biased toward the western two-thirds of New Mexico.

Tests on a catalog covering a slightly smaller region than shown in Figure 1 indicated that the earthquake data were only complete over that area at magnitude of 2.0 or greater (Lin, 1999). For our second pair of catalogs (Appendix II), the same cut-off was adopted, although we realized that there was a chance that we may have missed some magnitude 2.0 earthquakes at the outer limits of the study area. The time period for this second pair of catalogs is extended to 37 yrs (1962–1998). In Appendix II, separate listings are presented for the SSA and the RNM. Percentage contributions by organizations to the 923 locations in Appendix II are: SSA (215 locations)—NMIMT (99.5%), LANL (0.5%) and RNM (708 locations)—NMIMT (86.5%), USGS (8.2%), LANL (4.2%), UTEP (1.1%). A map of epicenters for earthquakes in Appendix II is presented in Figure 2.

The third pair of catalogs (Appendix III) are for earthquakes with moment magnitudes of 3.0 or greater. As before separate listings are presented for the SSA and the RNM. Percentage contributions by organizations to the 194 locations in Appendix III are: SSA (36 locations)—NMIMT (100%) and RNM (158 locations)—NMIMT (83.6%), USGS (16.4%), LANL (0%), UTEP (0%). A map of epicenters for earthquakes in Appendix III is presented in Figure 3.

A final catalog (Table 2) is presented for the strongest earthquakes within the borders of New Mexico from 1869 through 1998. Earthquakes documented by felt reports before 1962 are incorporated into this listing. The record of historical seismicity for New Mexico begins in the mid-nineteenth century. Although settlement by the Spanish began in 1598, little is known of earthquake activity in the state before it became a territory of the United States in 1848. No doubt, reports of earthquakes exist in Spanish and Mexican archives; such information, however, is difficult to extract, and to our knowledge no such attempt has been made. The earliest report after U.S. occupation is the description of a swarm of shocks in the Rio Grande valley at Socorro by a U.S. Army surgeon (Hammond, 1966). No shock in this 22-event swarm from 11 December 1849 through 8 February 1850 was felt at distances greater than 25 km (16 mi), an indication that these earthquakes did not exceed magnitude 3.5. Similar sequences of shocks located away from population centers in the state could easily have gone unreported before the start of instrumental studies in 1962.

Before 1962 the strengths of nearly all earthquakes were expressed in terms of the maximum intensity, I_o, a quantity assigned on the basis of what people observe during an earthquake and damage to structures. The scale used for ranking earthquake intensity in the United States is the Modified Mercalli–Revised 1931 (Richter, 1958). An empirical relation between maximum intensity and duration magnitude (equivalent to moment magnitude) has been derived by Sanford (1998) for New Mexico earthquakes:

$$M = 0.5 + \tfrac{2}{3} I_o.$$

This equation was used to convert maximum observed intensities for shocks before 1962 into magnitudes in order

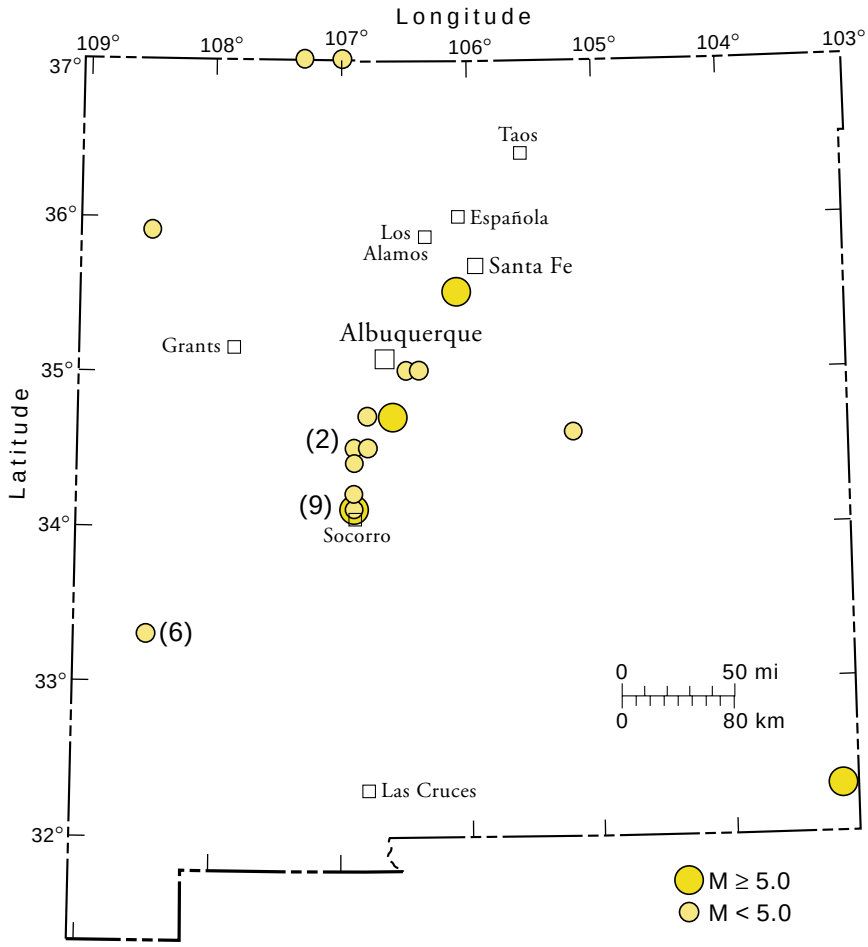

FIGURE 4—Strongest New Mexico earthquakes during time period 1869–1998 with moment magnitudes of 4.5 or greater. The number in parenthesis indicates multiple events at that location.

to obtain a list of strongest earthquakes with the same measure of strength.

The difficulty with using maximum intensity reports as a measure of the strength of an earthquake is that it implies the presence of people and/or structures directly at the epicenter of the shock. Therefore the reliability of the reports is dependent on population density, which was very low for nearly all of New Mexico before 1962. To reduce but not eliminate any population density problems, we have restricted our list of strongest earthquakes for the period before 1962 to shocks with maximum reported intensities of VI or greater. This places a lower limit of about moment magnitude 4.5 on the list of strongest earthquakes. Locations of the 30 earthquakes equaling or exceeding magnitude 4.5 from 1869 through 1998 are mapped in Figure 4.

Geographic distribution of earthquakes

The most striking feature of the seismicity in Figures 1 and 2 is the tight cluster of earthquake activity in the Rio Grande valley near Socorro. This Socorro Seismic Anomaly (SSA) occupies only 0.7% (~5,000 km^2; ~1,900 mi^2) of the total area of the figures but accounts for 23% of the earthquakes of magnitude 2.0 or greater. The SSA is believed to be the result of crustal extension over an inflating mid-crustal magma body. The magma body is ~150 m (~500 ft) thick, ~19 km (~12 mi) deep, and has a lateral extent of ~3,400 km^2 (~1,300 mi^2; Ake and Sanford, 1988; Hartse et al., 1992; Balch et al., 1997). Level-line data indicate that the surface above the magma body is undergoing uplift at a maximum rate of ~1.8 mm/yr (~0.071 inch/yr; Larsen et al., 1986) presumably because of injection of new magma into the thin, extensive mid-crustal chamber. Stresses in the upper crust generated by an inflating magma body at a depth of 19 km (12 mi) are expected to extend over a larger region than the lateral extent of the magma body (~3,400 km^2; ~1,300 mi^2).

In Figures 1 and 2, the pattern of seismicity outside the SSA is diffuse and occurs in all physiographic provinces including the presumably tectonically stable Colorado Plateau and Great Plains provinces. Well-defined seismic trends are not apparent. However, on the map of magnitude 3.0 or greater shocks (Fig. 3), an interesting alignment of shocks does appear. Extending east-northeast from the SSA into the Great Plains of eastern New Mexico and west Texas is a band of epicenters that straddles the trace of a prominent topographic lineation identified by Thelin and Pike (1991) on a digital shaded relief map they generated for the conterminous United States. The lineation, a possible fracture zone of Precambrian origin, extends 1,400 km (870 mi) east-northeast from southwestern Arizona to the Texas Panhandle–Oklahoma border (Sanford and Lin, 1998b). The ~85 km (~53 mi) wide track of this feature is defined by a lineation of many features such as rivers, elongate depressions, faults, and the historical seismicity in Figures 2 and 3. We have designated this feature the Socorro fracture zone. Using Monte Carlo techniques, we have tested the possibil-

ity that the alignment of epicenters overlying the topographic lineation is accidental. The earthquakes of magnitude 3.0 or greater outside the SSA were randomly distributed over the region nearly 1,000 times without reproducing the band of seismicity extending east-northeast from the SSA—a band that occupies 7% of the total area of the region but produces 19% of the earthquakes of magnitude 3.0 or greater outside the SSA.

A large fraction of the earthquakes in northern New Mexico appear to be related to the Jemez lineament (Aldrich and Laughlin, 1984), a fracture zone that extends from southwest of Grants to Los Alamos and Española in the Rio Grande valley and then continues on along an east-northeast track to beyond the northeast corner of the state (Fig. 3). The Jemez lineament is a 50–80 km (30–50 mi) wide leaky fracture zone defined by many hundreds of magmatic eruptive centers, including the very large aseismic Jemez volcanic complex just west of Los Alamos (Sanford et al., 1991). Other areas (Figs. 1, 2) where there appears to be an association between volcanism and seismicity are: (1) near the Albuquerque volcanoes, 35.1°N and 106.8°W (Jaksha et al., 1981), and (2) near the vents for the Carrizozo flow, 33.9°N and 106.0°W (Sanford et al., 1991), which has an eruption date of 5,200 ± 700 yrs ago (Dunbar, 1999).

Perhaps the most unusual characteristic of earthquake activity from 1962–1998 is its failure to define the Rio Grande rift, a major continental rift extending north–south through the state from north of Taos to south of Las Cruces (Chapin, 1971, 1979). The overwhelming majority of Quaternary faults in New Mexico (Machette et al., 1998) fall within the boundaries of the Rio Grande rift, shown in Figure 3, and yet earthquakes are absent or nearly so over much of its extent; for example, from just south of Socorro to just north of Las Cruces (Figs. 1, 2).

The 30 largest earthquakes for the period 1869–1998 (Fig. 4) appear more concentrated along the rift than the weaker shocks (Figs. 1–3). However, because of the very low population density over most of the region east and west of the rift, there is a good possibility that events with maximum intensities of VI–VII (Modified Mercalli–Revised 1931, Richter 1958) may have gone unreported in the period before the start of instrumental recording in the early 1960s. Note that 14 of the 30 strongest earthquakes in New Mexico (Table 2) had epicenters within the SSA. Five of these 14 earthquakes occurred during a prolonged earthquake swarm that began in July 1906 and extended into 1907 (Sanford et al., 1991). The two strongest earthquakes in New Mexico from the mid-1800s to the end of the millennium took place during this swarm.

Off the southeastern corner of New Mexico in the Great Plains is an extensive cluster of earthquake activity. In this area the spatial distribution of epicenters appears to correlate with locations of oil and gas fields, taking into account uncertainties in epicenters. Published studies (Sanford et al., 1980) and ongoing research strongly suggest that a large fraction of activity in southeastern New Mexico and adjacent areas of west Texas is induced by production, secondary recovery, or waste injection within this petroleum and natural gas province.

Temporal variation of earthquake activity

The number of events versus time for the Socorro Seismic Anomaly (SSA) and the remainder of New Mexico and bordering areas (RNM) is presented in Figure 5. The earthquakes considered are magnitude 2.0 or greater, and the area covered for the RNM is slightly smaller than in Figures 1–3. For the period 1962–1998, the seismicity of both source zones was temporally irregular at short and long intervals. For example, there were periods as long as 2 yrs without a magnitude 2.0 or greater shock within the SSA. The number of recorded events within the SSA for the 17-yr period 1982–1998 was 147, which is significantly higher than the 68 shocks in the 20-yr period 1962–1981. For the RNM, there were no very long term variations such as were observed for the SSA, but intermediate term variations with periods of ~ 5 yrs were recorded. The temporal variations illustrate the danger of using short term histories of earthquake activity to estimate long-term hazard. The sharp peaks in the temporal seismicity for the two seismic source zones are the result of earthquake swarms and mainshock-aftershock sequences.

Summary and conclusions

Catalogs and maps of the seismicity for New Mexico and bordering areas based on instrumental data are presented for the time period from 1962 through 1998. An important consideration in the generation of the catalogs was to maximize uniformity in the magnitudes and epicenters by using a single magnitude scale (100% of the time) and a single location program (89% of the time; Ake et al., 1983; Hartse, 1991). The largest catalog, which contains 2,000 earthquakes of magnitude 1.3 or greater, is temporally and spatially biased because of an increase with time in the number of stations with a more favorable geographic distribution for location of events in the New Mexico region. Two additional catalogs have cutoff magnitudes of 2.0 and 3.0. Respectively, they are temporally and spatially almost complete to complete over the entire region for the entire 37-yr interval. The final catalog presented is for the strongest earthquakes in New Mexico for the time period 1869–1998. This catalog uses felt reports of earthquakes having maximum intensities of VI or greater (Modified Mercalli–Revised 1931, Richter 1958) before 1962, and is probably incomplete before that date.

The catalogs document a long known feature of the seismicity of the New Mexico region—a disproportionate fraction of the activity is occurring in the middle of the Rio Grande rift at Socorro. A 5,000 km^2 (1,900 mi^2) area surrounding this community is contributing 23% of the earthquakes of magnitude 2.0 or greater. The enhanced seismicity over this small area is believed to be the result of crustal extension arising from inflation of a thin (~150 m; ~500 ft), extensive (~3,400 km^2; ~1,300 mi^2) magma body at a depth of ~19 km (~12 mi; Ake and Sanford, 1988; Hartse et al., 1992; Balch et al., 1997).

The catalogs also document the existence of earthquakes in all physiographic provinces of the region including those considered tectonically stable, such as the Colorado Plateau and the Great Plains, as well as the Rio Grande rift. A somewhat surprising observation is that the rift is not clearly defined by the seismicity although this province contains nearly all faults with evidence of Quaternary movement (Machette et al., 1998).

Perhaps the most important outcome of our compilations is that they establish average rates of activity for the anomalous Socorro area (SSA) and for the remainder of New Mexico and bordering areas (RNM). For the SSA, the expected number of earthquakes of moment magnitude 2.0 or greater is 5.8 each year, and for moment magnitude 3.0 or greater it is 1.0 each year. For the RNM, the expected number of earthquakes of moment magnitude 2.0 or greater is 19.1 each year, and for moment magnitude 3.0 or greater it is 4.3 each year. The latter are modest rates of activity for such a large region, and the resulting earthquake hazard is for the most part low. On the other hand, the rate of activity per square kilometer is relatively high for the SSA, and con-

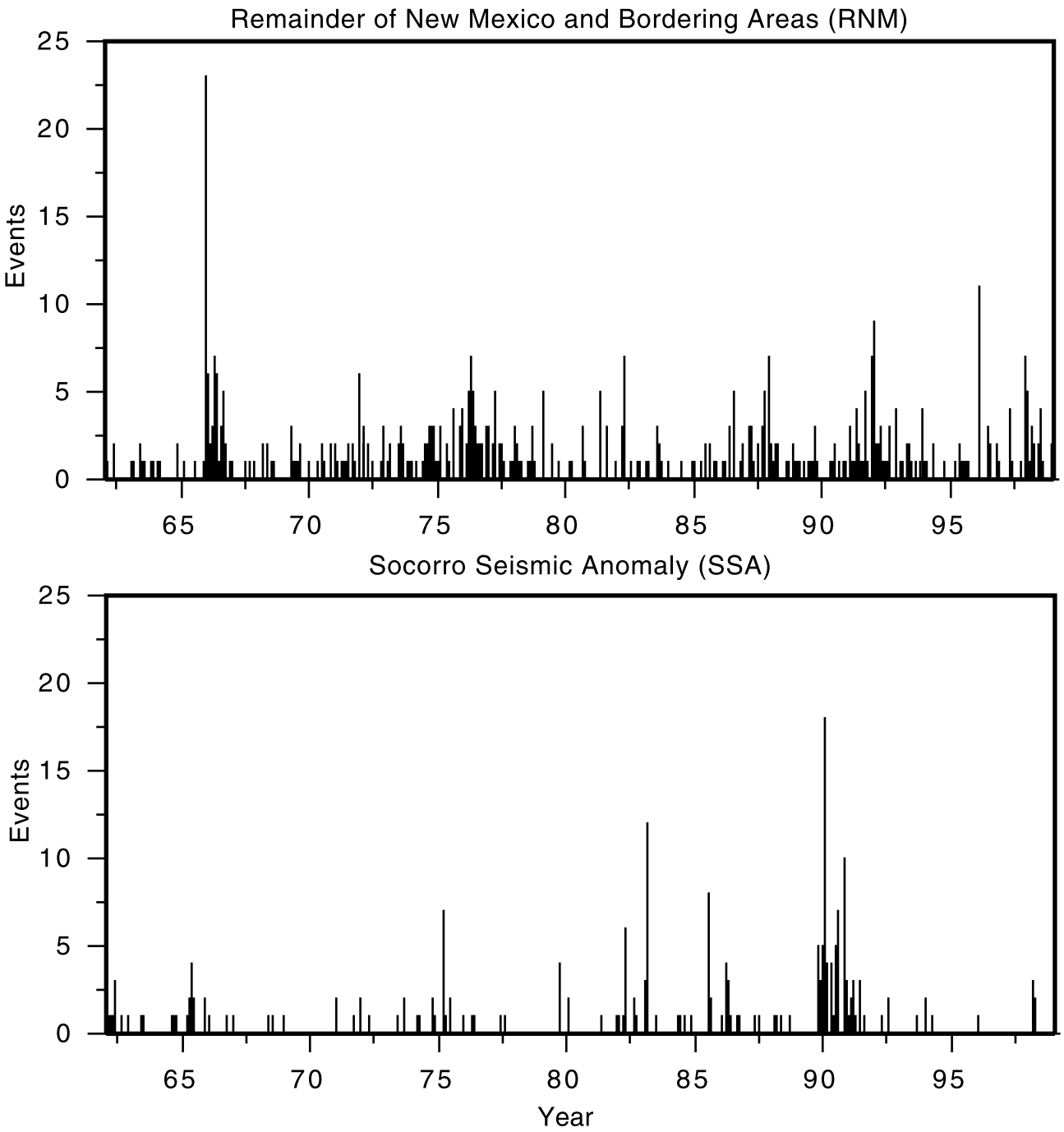

FIGURE 5—Temporal seismicity for the Socorro Seismic Anomaly (SSA) and the remainder of New Mexico and bordering areas (RNM) during time period 1962–1998 with moment magnitudes of 2.0 or greater. A total of 215 events are plotted for the SSA (bottom) and 492 for the RNM (top). In this case the area covered by RNM is smaller than in Figures 1–3. The sharp peaks in the temporal seismicity for the two seismic source zones are the result of earthquake swarms and mainshock-aftershock sequences.

sequently the resulting hazard is considerably higher but still quite moderate when compared with most areas of California.

Acknowledgments

The authors are grateful to Leigh House, Diane Doser, and Noel Barstow for their many useful comments and suggestions on the text accompanying the catalogs of this publication.

References

Ake, J. P., and Sanford, A. R., 1988, New evidence for existence and internal structure of a thin layer of magma at mid-crustal depths near Socorro, New Mexico: Bulletin of the Seismological Society of America, v. 78, pp. 1335–1359.

Ake, J. P., Sanford, A. R., and Jarpe, S. J., 1983, A magnitude scale for central New Mexico based on signal duration: New Mexico Institute of Mining and Technology, Geophysics Open-file Report 45, 26 pp.

Aldrich, M. J., Jr., and Laughlin, A. W., 1984, A model for the tectonic development of the southeastern Colorado Plateau boundary: Journal of Geophysical Research, v. 89, pp. 10,207–10,218.

Balch, R. S., Hartse, H. E., Sanford, A. R., and Lin, K. W., 1997, A new map of the geographic extent of the Socorro midcrustal magma body: Bulletin of the Seismological Society of America, v. 87, pp. 174–182.

Chapin, C. E., 1971, The Rio Grande rift—Part 1, modifications and additions; *in* James, H. L. (ed.), San Luis Basin, Colorado: New Mexico Geological Society, Guidebook 22, pp. 191–201.

Chapin, C. E., 1979, Evolution of the Rio Grande rift: A summary; *in* Riecker, R. E. (ed.), Rio Grande rift: Tectonics and magmatism: American Geophysical Union, Washington, D.C., pp. 1–5.

Dunbar, N. W., 1999, Cosmogenic ^{36}Cl-determined age of the Carrizozo lava flows, south-central New Mexico: New Mexico Geology, v. 21, no. 2, pp. 25–29.

Hammond, J. F., 1966, A surgeon's report on Socorro, New Mexico, 1852: Stagecoach Press, Santa Fe, NM, 47 pp.

Hanks, T. C., and Kanamori, H., 1979, A moment magnitude scale: Journal of Geophysical Research, v. 84, pp. 2348–2350.

Hartse, H. E., 1991, Simultaneous hypocenter and velocity model estimation using direct and reflected phases from microearthquakes recorded within the central Rio Grande rift: Unpublished Ph.D. dissertation, New Mexico Institute of Mining and Technology, Socorro, 251 pp.

Hartse, H. E., Sanford, A. R., and Knapp, J. S., 1992, Incorporating Socorro magma body reflections into the earthquake location process: Bulletin of the Seismological Society of America, v. 82, pp. 2511–2532.

Jaksha, L. H., Locke, J., and Gebhart, H. J., 1981, Microearthquakes near the Albuquerque volcanoes, New Mexico: Geological Society of America, Bulletin, v. 92, pp. 31–36.

Klein, R. W., 1978, Hypocenter location program HYPOINVERSE Part I—Users guide to versions 1, 2, 3 and 4: U.S. Geological Survey, Open-file Report 78–694, 114 pp.

Larsen, S., Reilinger, R., and Brown, L., 1986, Evidence for ongoing crustal deformation related to magmatic activity near Socorro, New Mexico: Journal of Geophysical Research, v. 91, pp. 6283–6292.

Lee, W. H. K., and Lahr, J. C., 1975, HYPO71 (Revised)—A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes: U.S. Geological Survey, Open-file Report 75–311, 59 pp.

Lin, K. W., 1994, Regional earthquake hypocenter location using a fuzzy logic algorithm enhanced SEISMOS program: New Mexico Institute of Mining and Technology, Geophysics Open-file Report 74, 82 pp.

Lin, K. W., 1999, Probabilistic seismic hazard in New Mexico and bordering areas: Unpublished Ph.D. dissertation, New Mexico Institute of Mining and Technology, Socorro, 195 pp.

Lin, K. W., and Sanford, A. R., 2001, Improving locations of regional earthquakes using a modified G matrix and fuzzy logic: Bulletin of the Seismological Society of America., pp. 82–93.

Machette, M. N., Personius, S. F., Kelson, K. I., Haller, K. M., and Dart, R. L., 1998, Map and data for Quaternary faults and folds in New Mexico: U.S. Geological Survey, Open-file Report 98–521, 443 pp.

Newton, C. A., Cash, D. J., Olsen, K. H., and Homuth, E. F., 1976, LASL seismic programs in the vicinity of Los Alamos, New Mexico: Los Alamos Scientific Laboratory, Informal Report LA–6406–MS, 42 pp.

Richter, C. F., 1958, Elementary seismology: W. H. Freeman, San Francisco, 768 pp.

Sanford, A. R., 1998, An empirical relation between magnitude and maximum intensity for New Mexico earthquakes: New Mexico Institute of Mining and Technology, Geophysics Open-file Report 86, 4 pp.

Sanford, A., Sandford, S., Wallace, T., Barrows, L., Sheldon, J., Ward, R., Johansen, S., and Merritt, L., 1980, Seismicity in the area of the Waste Isolation Pilot Plant (WIPP): Sandia National Laboratories, SAND 80–7096, 74 pp.

Sanford, A. R., Jaksha, L. H., and Cash, D. J., 1991, Seismicity of the Rio Grande rift in New Mexico; *in* Slemmons, D. B., Engdahl, E. R., Zoback, M. D., and Blackwell, D. D. (eds.), Neotectonics of North America: Geological Society of America, Decade map, v. 1, pp. 229–244.

Sanford, A. R., and Lin, K. W., 1998a, Strongest earthquakes in New Mexico—1860 to 1998: New Mexico Institute of Mining and Technology, Geophysics Open-file Report 87, 4 pp.

Sanford, A. R., and Lin, K. W., 1998b, Evidence for a 1,400 km long Socorro Fracture Zone: New Mexico Institute of Mining and Technology, Geophysics Open-file Report 89, 18 pp.

Thelin, G. P., and Pike, R. J., 1991, Landforms of the conterminous United States—a digital shaded-relief portrayal: U.S. Geological Survey, Miscellaneous Investigation Series Map I-2206, 1:3,500,000, 16 pp. text.