

Global Seismicity: Three New Maps Compiled with Geographic Information Systems

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Abstract

This paper presents three new maps of global seismicity compiled from NOAA digital data, covering the interval 1963-1998, with three different magnitude ranges (m_b): > 3.5 , < 3.5 , and all detectable magnitudes. A commercially available geographic information system (GIS) was used as the database manager. Epicenter locations were acquired from a CD-ROM supplied by the National Geophysical Data Center. A methodology is presented that can be followed by general users. The implications of the maps are discussed, including the limitations of conventional plate models, and the different tectonic behavior of continental vs. oceanic lithosphere. Several little-known areas of intraplate or passive margin seismicity are also discussed, possibly expressing horizontal compression generated by ridge push.

Introduction

Seismology is one of the main foundations of modern tectonic theory. Its scope has expanded greatly in recent decades. This expansion has produced an array of data that now gives interpretive insight at greater scales. The new digital databases require new manipulation techniques due to increases in data size and attribution. A geographic information system offers the

Popular Summary

This paper presents three new maps showing earthquake locations for the entire planet during the period 1963 to 1998, a total of more than 350,000 earthquakes . The technique used was based on a commercially available geographic information system (GIS), with which events from the National Oceanographic and Atmospheric Administration (NOAA) digital data base were plotted. Unlike most earthquake maps, based on a Mercator Projection, this one uses the Robinson Projection, permitting plotting of events near the poles. One map shows earthquakes of all magnitudes, bringing out several little-known seismic zones, such as those west of the Norwegian coast. Another shows only events over body wave magnitude 3.5, eliminating most artificial sources such as quarry and mine blasts. These maps may be the most comprehensive modern earthquake compilations published to date, in terms of time span (35 years), areal coverage, and magnitude range. They bring out the diffuse nature of many plate boundaries, and show clearly the difference in tectonic activity between continental and oceanic crust.

appropriate algorithms for data manipulation and the ability to produce analytical outputs (Jensen, 1986). We have combined these developments to produce three new maps (Figs. 1, 2, and 3) of global seismicity covering the 35 year period 1963-1998. These maps are presented as examples of GIS applied to geophysics. A tectonic activity map (Fig. 4) has also been included. 2

The data was made available from the National Geophysical Data Center and National Earthquake Information Center in Boulder, Colorado. The availability of inexpensive computer hardware and relevant software allows research to be conducted from grade school to the professional level. We, therefore, present a detailed description of the equipment and software used, followed by a discussion of possible geological implications of the maps.

The three seismicity maps were compiled as part of a large program to develop a digital tectonic activity map (DTAM) of the world, to be presented at the 1998 meeting of the Geological Society of America (Yates et al., 1998). The DTAM is a completely new map, stimulated by an earlier map published in this journal (Lowman, 1982). The map presented here (Fig. 4) is a greatly revised version of the 1982 one, part of the revision being based on the seismicity maps presented in this paper.

Equipment and Software

All work was completed on a Silicon Graphic Indigo2 computer. The computer's CPU was a MIPS R4400 chip. The FPU was a MIPS 4000 floating point co-processor. The Indigo2 system contained 128 megabytes of RAM, 2 gigabytes hard disk, and peripherals that included: CD-ROM, tape reader, and 18 gigs external disk space. The commercially available GIS software called "ARCVIEW" (ESRI, 1996) was used for database management. The data, in the form of ASCII text files, was also manipulated by the UNIX commands: "awk," "cp," and "sed" (Gilly, 1992).

Data acquisition

The seismicity data was acquired via CD-ROM from the National Geophysical Data Center and the National Earthquake Information Center. The CD-ROM was volume 2 of global and regional data between the time periods of 2150 B.C. - 1996 A.D. Using the interface called, "GEOVU," contained on the disk, the preliminary determination of epicenters were extracted. Initially, there was a formatting problem because the column of data overlapped. This was corrected by acquiring the data for the center's FTP site. The commands used were:

```
>ftp ftp.ngdc.noaa.gov
>login: anonymous
>password: (your email address)
>cd pub
>cd pde
>get pdeto98.eq
>quit
```

The size of the data set was 24 megabytes. This is too large for standard spreadsheet programs. Also, all of the data was not needed. The data came in a column, tab-delineated format. The column headings were: Numeric month, Numeric day of the month, Numeric hour of the day, Numeric minute, Numeric second, Year, Latitude, Longitude, Depth, Magnitude, Local magnitude, Surface magnitude, Unspecified magnitude and Number of stations. These columns were numbered as fields 1 to 14, respectively. Using the UNIX command "cp," a copy was made of the original data:

```
cp pdeto98.eq Table 1
```

Table 1 is now the data set used. If it becomes corrupted in any way, work can begin from the original data set.

Methodology

The columns of data needed were: Longitude, Latitude, Year, Depth, and Magnitude. The following UNIX command, typed at the UNIX prompt,

was used to subset the text file to extract only the data identified as requisite for analysis:

```
awk '{print $8, $7, $6, $9, $10}' Table1 > Table2
```

"Table1" is an arbitrary name given to the data set only to show a starting point before a subset of the data was produced. The "\$ number" after the "print" parameter places the desired columns, in the order listed, in the newly created file called "Table2." It is important to note positions 8,7,6,9, and 10 are reflective of their positions in "Table1." They have acquired the new positions 1,2,3,4, and 5 in "Table2." Next, it was necessary to extract only the data that was between 1963 to 1998. The following conditional construct in "awk" was used:

```
awk '{ if ($3 > 1962) print $0}' Table2 > Table3
```

The "print \$0" means to print the entire record if the conditional statement is satisfied. As a result, from Table2, all records in which the year is greater than "1963" exist in text file called, "Table3." The same command was used to extract only the records, from Table3, with magnitudes greater than three:

```
awk '{ if ($5 > 3) print $0}' Table3 > Table4
```

The columns in Table4 have lost their "tab delineation." They are now separated by spaces. The ARCVIEW software accepts column data separated by commas, therefore, the following command was used to substitute the spaces with commas:

```
sed 's/ //g' Table4 > Table5
```

The result is now Table5 with the five columns: Longitude, Latitude, Year, Depth and Magnitude. There were a total of 200,855 records all with magnitude greater than 3 and between the years 1964 and 1998. Open Table5 in the system's text editor. The Silicon Graphics computer text editor is called, "jot." Once Table5 is open, add the following header to the file:

```
Longitude,Latitude,Year,Depth,Magnitude
```

It is important that spaces are not added between the commas. Save the file as "Table5.txt" with the new header. "Table5.txt" is now ready for

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importing into ARCVIEW. Open ARCVIEW. Once the interface has appeared, click on the word "Project" in the blue bar. In the menu that opens, click on "add table." Another interface will open. Under "List Files of Type:" click on the "Delineated Text (*.txt)." "Table5.txt" should appear. Click on it and press "OK." "Table5.txt" will appear with the column headings in place. Next, click on "new" in the untitled box. View1 will appear.

Under the word EDIT there is a gray box with a plus sign. That will add a new theme. Click the button and the interface will open to the ARCVIEW directory. This location contains base maps. Open the directory called MAPS, then WORLD. To the left, all available data sets will appear. Open the file "world30.shp" first, then open "cntry94.shp."

In the blue bar, execute the following pathway:

View -> Properties -> Projection -> Type -> Robinson

The Robinson Projection was chosen because the distortion in shape and area are low, and the scale is constant along latitudes. It also has utility as a "general use" map. The countries and ocean grid should have change shape into a Robinson projection. Next, in the blue bar execute the following pathway:

View -> Add Event Theme

Once the interface appears, load "Table5.txt" and click "OK." Table5.txt should be loaded with the world in Robinson projection and will appear as dots once the Table5.txt theme is turned on. The "information tool," (it looks like this I) can be used to discern any individual record. The query builder can utilize Boolean logic to accomplish spatial analysis for the whole data set. Each record will have five attributes. The attributes are the five columns established with the "awk" command. This procedure was repeated for magnitudes "less than or equal to three," and for "all magnitudes."

Tectonic Implications

Readers are invited, in fact urged, to make their own interpretations of the epicenter maps. The following section is intended to point out some

possible implications for global and regional tectonism. A few aspects of the epicenter maps should first be clarified, starting with the time and magnitude intervals chosen.

Instrumental seismology dates from the late 19th century, but it was the nuclear test ban treaty of 1963 that triggered development of the World Wide Standardized Seismograph Network (WWSSN). Since 1963, there have been available seismic records from this global array of three component, long and short period seismometers, and we accordingly start our epicenter compilation at this year. The long interval, 35 years, is greater than for any previously published map based on modern instrument networks, and brings out many obscure features to be discussed.

Three different magnitude (m_b) intervals have been chosen. The map showing all magnitudes (Fig. 1) is excellent for delineating areas of low level seismic activity, such as those along the Norwegian continental margin. However, areas such as Western Europe appears saturated with epicenters, many of which are undoubtedly quarry or mine blasts. Another example of such artificial sources is probably southern Africa at roughly 25 to 30 deg. S latitude, a major mining district with blasting and rock bursts in deep mines. To eliminate the majority of such non-tectonic sources, we have compiled a second map (Fig. 2) showing only magnitudes greater than 3.5.

This interval eliminates most, but not all non-tectonic events, as shown by the cluster of epicenters in Novaya Zemlya, a nuclear test site for the former Soviet Union (Bolt, 1976). Finally, for comparison (Fig. 3), we present a third map showing only magnitudes less than 3.5. The great majority of these small events are of course natural, following the well-known inverse frequency-magnitude relationship, but in densely populated areas such as Western Europe the number of artificial sources persists. Let us now discuss some possible tectonic implications of the three maps collectively, with reference to the 1998 tectonic and volcanic activity map (Fig. 4). (Note: the 1998 map uses a different projection from the seismicity maps)

The Plate Tectonic Model

The fundamental phenomena of plate tectonics - sea-floor spreading, subduction, and transform faulting - have been directly demonstrated by several independent lines of evidence (Lowman, 1996). There is little question that plate tectonic theory gives a coherent and basically correct explanation for ocean basin and active margin (e.g., Andean) tectonic activity. However, the seismicity maps presented here call for discussion of the question: How good a picture of the Earth's crust, and in particular its tectonic activity, do plate tectonic models (Fig. 5) such as NUVEL-1 (DeMets et al., 1990) give us?

There is no simple answer to this question. The NUVEL-1 model, and its predecessors (e.g., Minster and Jordan, 1978) have been shown not only self-consistent, but independently verified for at least the Pacific basin by space geodesy. One of the most surprising discoveries has been that spreading rates inferred from magnetic anomalies for the last 3.0 million years are very close to those directly measured by space geodesy methods, i.e., the present-day motions. However, the epicenter maps presented here show that the plate boundaries, in the continents, are far more diffuse than NUVEL-1.

This is hardly a new finding, workers such as Stein (1992) having pointed it out before. However, it implies that plate models are primarily valid only for ocean basins. A further implication is that continental stress patterns (e.g., Zoback, 1992) can not be interpreted in terms of "rigid" plate interaction. Plate-driving forces are clearly important in some areas, but continental geologic and seismic activities are far too complex to be explained by plate tectonic theory alone.

Intraplate Seismicity and Tectonism

The epicenter maps show a far greater number of intraplate events than commonly published maps of global seismicity, restricted in time or magnitude. Some of these intraplate events, such as the cluster around the Hawaiian Islands, are natural but volcanic, not tectonic, and many other

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events in volcanically active areas are presumably non-tectonic. However, there are still many areas of generally unknown intraplate seismicity, especially in North America.

The New Madrid zone is of course well-known, but few if any previous maps show the belt of epicenters running west from the Mississippi Valley. This belt appears related to the Anadarko Basin (King, 1976), which despite its age is either still active or reactivated. The St. Lawrence Valley, well-known to be seismically active, appears to extend well into the mid-continent region. The Appalachian chain, including the Appalachian Plateau shows a surprisingly coherent pattern of along-strike seismicity.

Australia shows widely-distributed seismic activity, much more so than adjacent oceanic and presumably intraplate areas. Some of this is associated with known tectonic features, such as the Darling Fault and the Lake Eyre Basin, but others have no obvious association. It appears that Australia, like other continents, is at present under strong horizontal compression as shown by the World Stress Map Project (Zoback, 1992). The concentration of the resulting seismicity in continents presumably reflects plate-driving forces, specifically ridge push.

On the other side of the Atlantic, there is a well-defined belt of epicenters west of the Norwegian coast, a supposedly passive margin. Previously published seismicity maps show no such belt, which has evidently been found by the relatively new Norwegian Seismic Array (NORSAR). A large number of epicenters appear to connect the Norwegian margin with the Mid-Atlantic Ridge north of Iceland, an area with no obvious fault zones.

These and other previously unmapped seismic zones clearly reflect the establishment of NORSAR and other new seismic networks. However, they raise the question of how well we actually know the seismicity of passive margins and plate interiors in areas such as West Africa, for which there are no new seismic arrays? Would a West African NORSAR or LASA find evidence of slow passive margin subduction (Lowman, 1991)?

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It seems safe to conclude that although the main tectonic features of the planet are well-expressed by seismicity maps, we are still limited by the distribution and density of global seismic stations. This argues for the continuance of seismic arrays such as NORSAR even in the post-Cold War era. It should be remembered that some of the most catastrophic earthquakes in recorded history happened in nominally intraplate (e.g., New Madrid) or passive margin (e.g., Lisbon) settings.

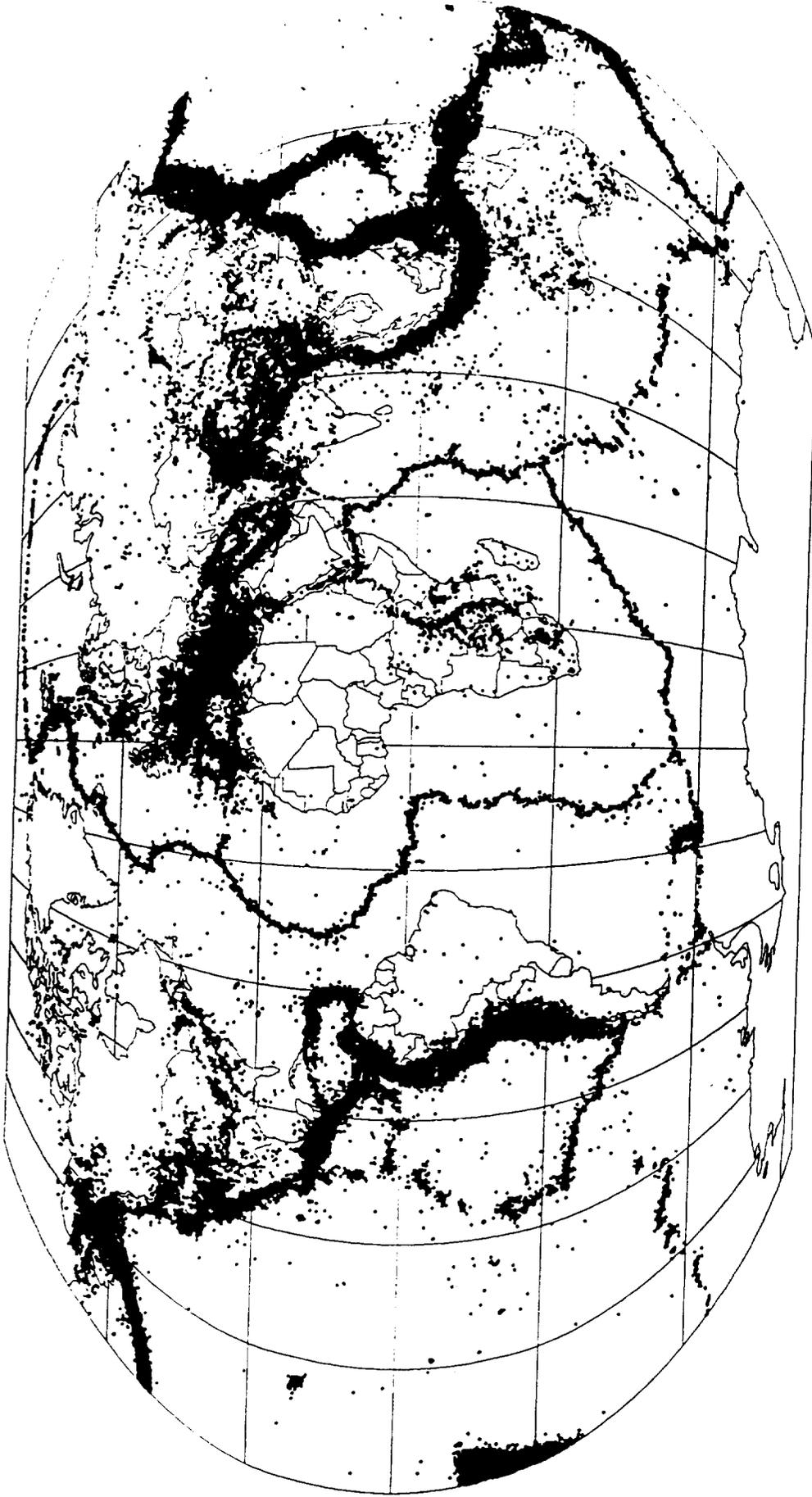
Summary and Conclusions

We have tried to demonstrate the power of modern computer data handling methods and the scope of digital databases. We stress that this demonstration gives only a general idea of possible new approaches to the use of seismic data. For example, using the same methods and data shown here, one could make a series of overlapping seismicity maps for much narrower magnitude intervals, varying focal depths, or intervals. In addition, seismicity maps focussed on specific regions, such as California, can easily be compiled. The surprising features of the three maps presented here suggest that there are innumerable opportunities for future research in theoretical seismology and tectonics.

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Preliminary Determination of Epicenters 358,214 Events, 1963 - 1998



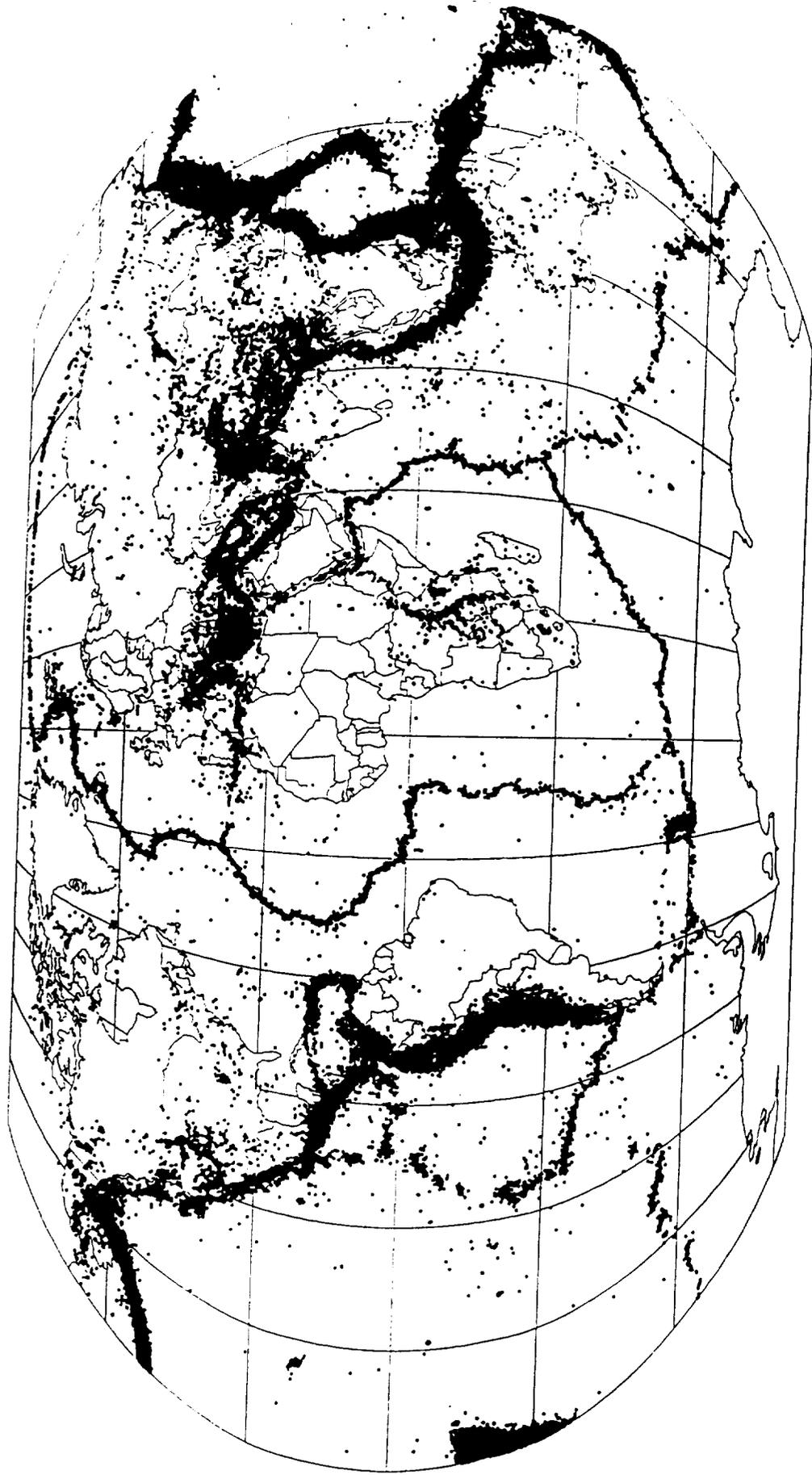
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Data Source:
Seismicity Catalogs
Volume 2 Global and Regional, 2150 B. C. - 1996 A. D.
The National Geophysical Data Center and
The National Earthquake Information Center

Map prepared in Robinson Projection
with all magnitudes.
August 12, 1998

Preliminary Determination of Epicenters 200,855 Events, 1963 - 1998



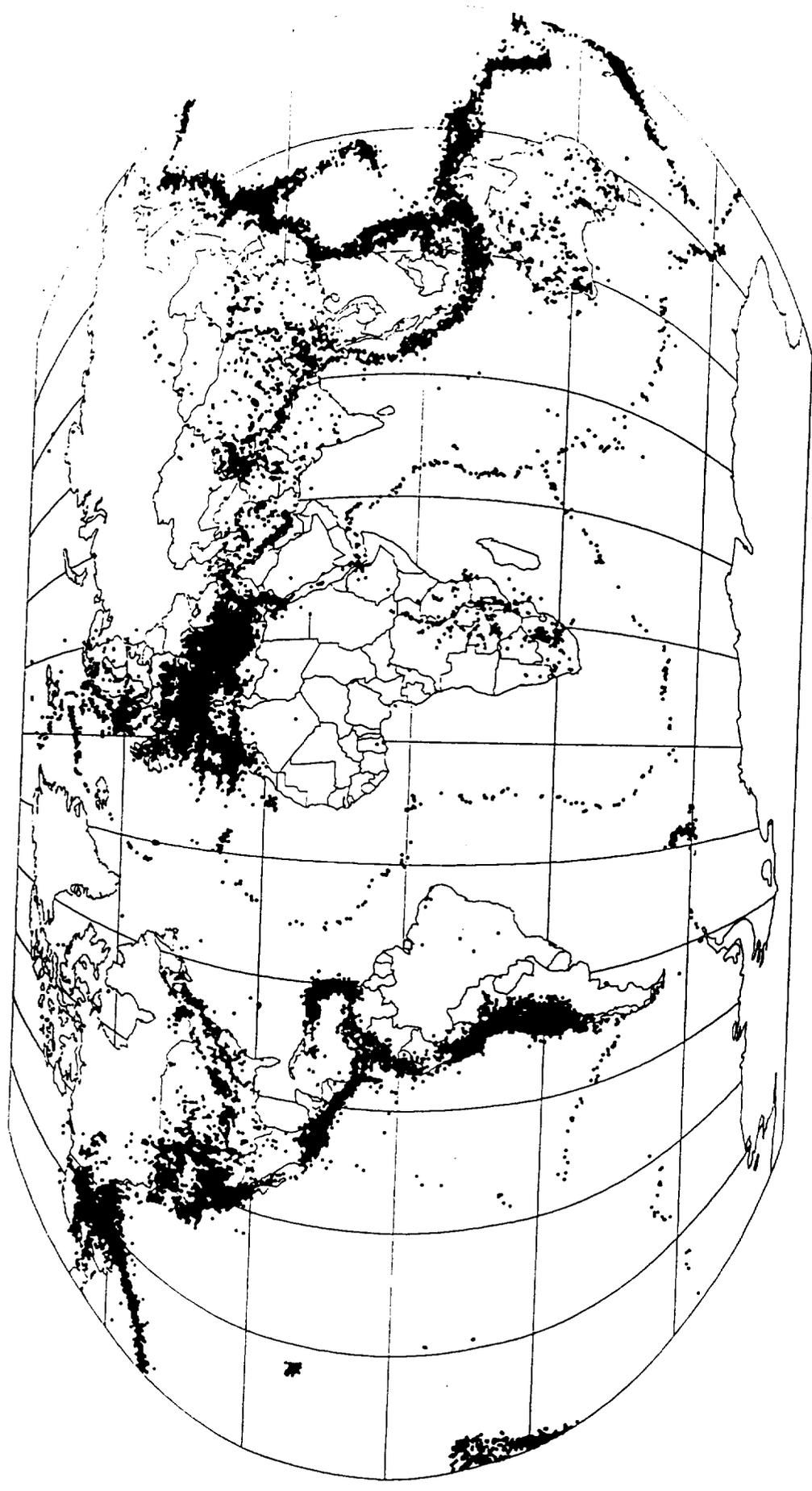
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Data Source:
Seismicity Catalogs
Volume 2 Global and Regional, 2150 B. C. - 1996 A. D.
The National Geophysical Data Center and
The National Earthquake Information Center

Map prepared in Robinson Projection
with magnitudes greater than 3.5.
August 12, 1998

Preliminary Determination of Epicenters 157,359 Events, 1963 - 1998

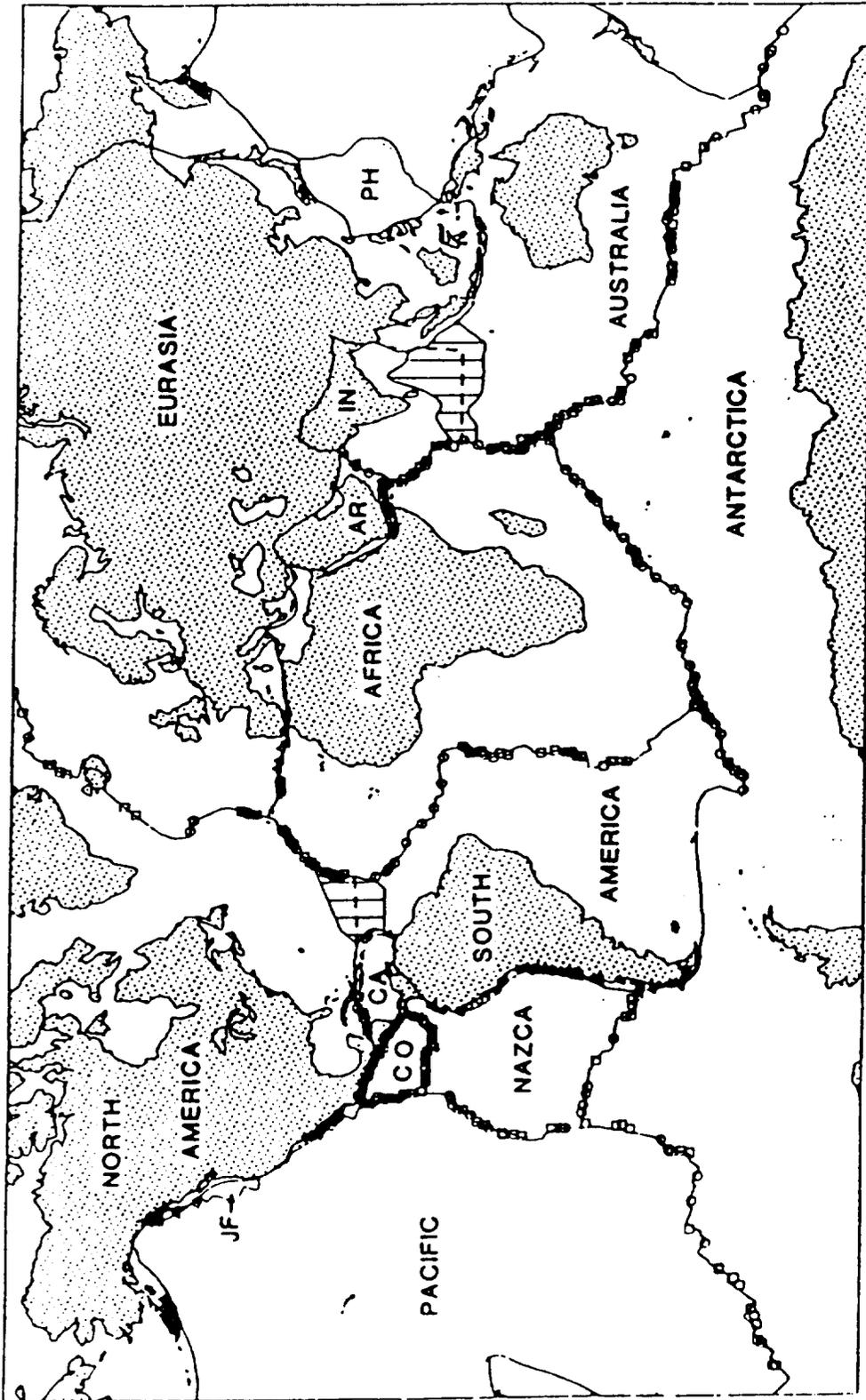


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Map prepared in Robinson Projection
with magnitudes less than 3.5.
August 12, 1998



NUVEL-1 (De Mets et al. 1990) Fig. 5