Geothermal Gradient Distribution in Indiana

Open File Study 03 - 02

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Introduction

During the late 1960s and continuing through the early 1970s, the American Association of Petroleum Geologists (AAPG) sponsored a project entitled “Geothermal Survey of North America.” The aim of this project was to collect temperature information from deep boreholes (predominantly oil and gas wells) in order to calculate the geothermal gradients in the uppermost part of the crust of North America. A portion of that national project targeted the states of Indiana and Illinois and resulted in the production of an unpublished map showing the distribution of the gradients in this region.

In the AAPG project, maximum recorded values for bottom-hole temperatures were used to calculate the gradient throughout the region. A wide variety of geophysical well logs were used, most of which had a temperature value reported for the bottom of the hole and for the surface. Numerous questions remain as to the compilers’ use of these data. Consideration of cooling or heating by the drilling process and any systematic processing of the reported values relative to those considerations is unknown.

The map produced for Illinois and Indiana contained more than 600 different data points, however, only about one-third were located in Indiana. The large number of data points outside Indiana undoubtedly exerted a significant influence on how the gradients were contoured for Indiana. Additionally, some “corrected” or inferred bottom-hole temperatures were used owing to a lack of measured down-hole temperature data for Indiana (Kehle and others, 1971; Keller, pers. comm., 2003). By basing geothermal gradient calculations on modified bottom-hole temperatures, the calculated gradients in some parts of the state may not be accurate. The purpose of this project was to collect new data and generate a new geothermal gradient map of the state, thus providing a more accurate representation of the geothermal gradients in Indiana.

Methods

New data was collected exclusively from Indiana to minimize inconsistencies resulting from previous compilations in which different criteria and methodologies were employed. A set of 192 borehole records and associated geophysical logs, collectively known as the “type log file”, was assembled at the Indiana Geological Survey (IGS). These records are considered to be the most representative of a particular area within the state. These logs are thought to best represent the structure and stratigraphy and to provide the most accurate data measurements. This file of “type logs” was augmented with data from additional selected wells to produce the new set of temperature values; from these, the new geothermal gradients were constructed, calculated, and mapped. Records were chosen from those wells that had the greatest depth, the most complete and up to date suite of geophysical logs, and geographically were the most representative.

In addition to using temperature data from the log headers of conventional geophysical logs, temperature logs were also employed to obtain information about the thermal gradient. Digital records from the Petroleum Well Database of the IGS were used to supplement the type log information. Because temperature logs record actual temperatures and the depth at which these temperature measurements were taken, they can be used to accurately calculate a geothermal gradient. Temperature logs are considered to be more accurate than temperatures recorded by the maximum set thermometers used with the other geophysical logs, and values from the temperature logs were preferred in most cases and used to calibrate values from other logs.

Once wells having optimum temperature data were identified and their corresponding records pulled, we compiled the appropriate data in an electronic relational database so that they could be easily accessed, manipulated, and exported to other programs. The most useful data from the "type log" files were bottom-hole temperature and the total depth drilled. The information compiled in the geothermal gradient database from the well log files included the drilling information (location, driller, lease name, well number, total depth, formation at depth, and date of log run), temperature data, the depth at which the temperature was recorded, and a calculated geothermal gradient.

Using data from vertically drilled boreholes allowed for a linear geothermal gradient calculation. We calculated the geothermal gradient using the formula: $T_{form} = T_{suf} + GX$, where T_{form} is the temperature at a specific depth (in many cases the total depth), T_{suf} is the average ambient surface temperature, G is the geothermal gradient, and x is the depth at which the temperature measurement was made (Geo Vista, 1999). The average total depth of a well was approximately 2,000 feet. The average ambient surface temperature in Indiana varies from north to south; when calculating the geothermal gradient, the amount of variance in the average temperature from the northern to southern part of Indiana is insignificant. A website devoted to Indiana climate (http://shadow.agry.purdue.edu/index.html) provided the information needed to make this assumption; it also provided the average surface temperatures required for the geothermal gradient calculations (Scheeringa, 1999).

Because the information gathered from various types of logs is so different, a different database structure must be used for each group of logs used. The database created for the temperature logs includes temperature measurements with corresponding depths, location information, and geothermal gradient calculations. For this database, the temperature measurements were recorded from the temperature log every 20 feet beginning at a depth of 100 feet (to eliminate for atmospheric fluctuations) to the total depth of the well (Guyod, 1946). Owing to the large amount of data, we calculated three geothermal gradients: from a depth of (1) 100 feet to the total depth, (2) 500 feet to total depth, and (3) 1,000 feet to total depth. These gradients were then compared to see which best accounts for the influence of surface temperatures. We noted that the geothermal gradient starting at 500 feet and continuing to depth typically was the most consistent with respect to normal crustal values. Gradients calculated from a depth of 100 feet proved to have extreme values (either unrealistically high or low) while gradients calculated from a depth of 1,000 feet proved to have very high values that we judged to be unrealistic. However, all the measurements and calculations were recorded in the database so that individuals could make their own inferences.

Displaying the data proved to be more challenging than finding and collecting it. A program was needed that would display data point locations as well as provide contouring algorithms to map the distribution of geothermal gradients. A GIS program, Environmental Systems Research Institute’s (ESRI) ArcGIS 8.2, was chosen initially to fulfill these requirements. While displaying locations and data quickly, easily, and correctly, the program did an unacceptably poor job of contouring the gradient data. Although the software contained a suite of contouring algorithms, it was difficult to change the algorithms’ properties. Many algorithms proved to be very neighbor-dependent, meaning that the points were excessively influenced by surrounding values. In a project such as this where there is a broad range of comparable data values, a less neighbor-dependent algorithm was needed. Altering the properties associated with these algorithms proved ineffective, as the patterns of the contours became more skewed from the anticipated logical pattern. ArcGIS 8.2 had serious difficulties contouring the information and rendering a reasonable representation of Indiana's geothermal gradients.

A different program, geoPLUS Corporation's PETRA, was more appropriate and useful for contouring the geothermal gradient data. Once the data was imported into PETRA, we tested several different contouring algorithms. Using the program's least neighbor-dependent algorithm, the data was contoured using all the points from the geothermal gradient databases. This produced a map of Indiana containing 219 data points; however, the first map produced included numerous closed contours, suggesting that some data points may have been inaccurate (fig. 1).

Figure 1 illustrates the problems that can arise when a data set is first manipulated. Several points may lie in close proximity to one another and have very different values. In this case, steep geothermal gradients occur that can be deemed inaccurate. In these instances, the points with extreme gradient values were removed to create smoother gradient contours and to eliminate very steep temperature gradients between adjacent points. Table 1 lists the data points that were removed from subsequent maps. In all, 18 maps were created using this method; each one has been captured as a digital image file (JPEG format) so that users can determine which map is most relevant to their own work. Using simple computer technology, this project (data and resulting maps) is readily accessible and can be formatted to fit within almost any project format.

Conclusions

Starting with a set of logs that have temperature and depth values, and enhancing that data with information that is representative of a given area, it is possible to improve upon the ”The AAPG Geothermal Survey of North America” from the 1970s. Using a database and appropriate computer applications to manipulate the data produced a better representation of present-day geothermal gradients in Indiana. It is much easier to manipulate our current data set into a format that is compatible with many users’ needs. In our project, we do not include locations with calculated bottom-hole temperatures or locations that project anomalous geothermal gradients into Indiana. These modifications, along with the speed and precision of present-day computers, have made it possible to provide an improved geothermal gradient map for the state of Indiana.

Products

We created 18 maps that show the distribution of the selected wells. The progression from the earliest map (fig. 1) through the final map (fig. 18) results from the removal of certain problematic points. Showing the steps involved in the creation of the geothermal gradient maps, it is easy to understand the reason for the removal of particular locations.

The data used for making these maps resides in a relational database; the data can be modified as more accurate computer applications are created. The AAPG map data resided in “a format of magnetic tapes and punched cards.” (Kehle et al., 1970). While this technology was the most advanced of its day, it is very difficult today to find a computer that can read the cards and tapes. Allowing for easier data manipulation and updating, the database format allows periodic updates that are quick and simple, and yet the current software will allow for easy upgrades as newer software is developed. This will in turn help avoid the problem of recollecting the data which was a major problem in previous projects.

Problems/ Recommendations

Questions that arose while collecting, working with, and interpreting the data used in this study included uncertainties associated with data accuracy and representativeness; accuracy is the greatest concern. However, it is not feasible to remeasure the temperature again at the hole in question or drill another hole nearby and record the temperature using more elaborate procedures. There are methods of checking the reliability of data. A practical method of checking the accuracy of bottom hole-temperature is reviewing the surrounding wells and checking their bottom-hole temperatures. If bottom-hole temperatures in adjacent wells are the same then the bottom-hole temperature in question is probably a derived value. It could be accurate but it probably is a calculated value and, therefore, not a lot of confidence should be placed in it. Furthermore, the hole often is not allowed to reach equilibrium before measurements are made, and therefore erroneous values may be recorded.

The absence of data in large areas is also a significant problem when creating contour maps. Even though the computer can infer values in areas that lack data, interpolated values may be grossly inaccurate. This problem will persist until new wells are drilled and new temperature data is collected. Even though little data exists for central Indiana with regards to the geothermal gradients, the contouring program produced an acceptable rendering of geothermal gradient distribution, given the data that was available

By placing confidence in wells that are deemed to be representative of a given area ("type logs") and using logs designed for this specific purpose (temperature logs are used to accurately calculate geothermal gradients), a data set is obtained that is accurate and inclusive. Keeping such data sets up-to-date is a challenge. Maintaining and updating the database will make it easier to re-contour and reevaluate the data as improved computer applications become available. We anticipate that this database will be periodically updated as new data becomes available and as methods for evaluating subsurface temperature data improve.

References:

Guyod, Hubert, 1946, Temperature well logging: Oil Weekly, v. 123, p. 47.

Kehle, R.O., Schoeppel, R.J., and Deford, R.K., 1971, The AAPG geothermal survey of North America [U.N. Symposium on the Development and Utilization of Geothermal Resources]: Geothermics, special issue no. 2, part 1, p. 358- 367.

GeoVista, 1999, News and views: http://geovista.co.uk/pages/news1b.htm, accessed on Feb 2, 2003

Scheeringa, K. L., 1999, Normals: Applied Meteorology Group: Dept. of Agronomy, School of Agriculture, Plant and Soils Lab, Purdue University. http://shadow.agry.purdue.edu/index.html, accessed on Feb. 2003.

Figure	No. of Wells	Wells Removed
1	219	None
2	196	2, 5, 24, 30, 62, 63, 64, 168, 174, 187, 216, 238, 125538, 125554, 134499, 134509, 134516, 134518, 13520, 134570, 134602, 157968, 159241
3	183	22, 31, 39, 40, 44, 46, 68, 69, 157, 239, 265, 144472, 152616
4	178	136060, 152516, 152612, 152613, 162610
5	173	117407, 118307, 121053, 123686, 135616
6	168	114480, 150140, 155582, 157484, 159764
7	164	143816, 144461, 159236, 159239
8	161	107782, 156866, 160109
9	155	135456, 135967, 142883, 156748, 157958, 158028
10	150	107208, 118667, 118712, 144519, 152608
11	146	114816, 117407, 155729, 157501
12	142	253268, 144526, 158069, 162029
13	139	126629, 135982, 147351
14	135	142024, 145894, 147784, 157741
15	131	122844, 150102, 157284, 158005
16	126	114705, 115438, 156327, 156370, 156904
17	122	124451, 158009, 158025, 160109
18	119	116844, 117254, 152652

Table 1: This table lists the contouring maps that were created, the number of wells that were used to create each map, and the specific wells that were removed in order to create the well selection list for each map. Not all well numbers are Indiana Geological Survey ID numbers.

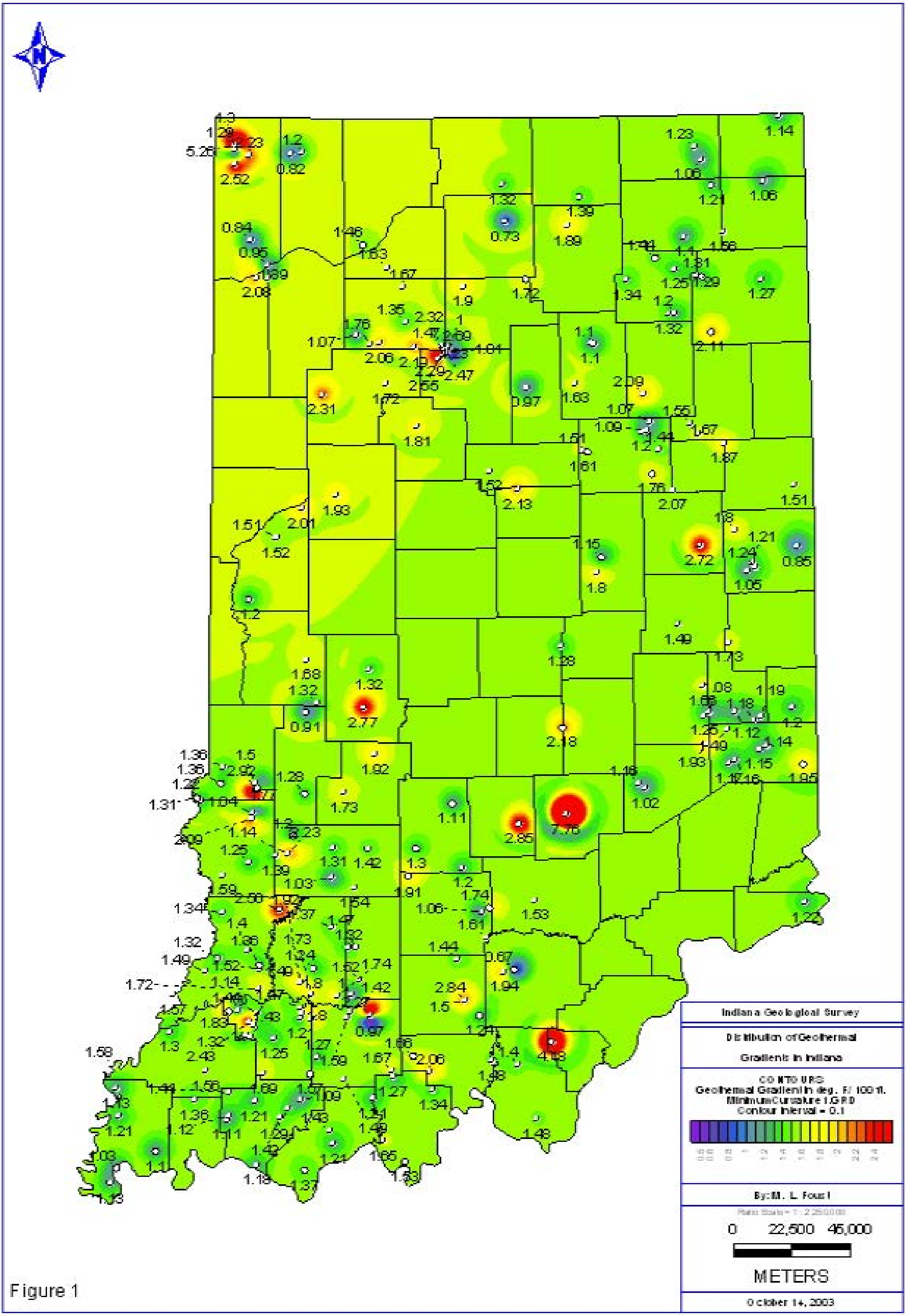

Figure 1

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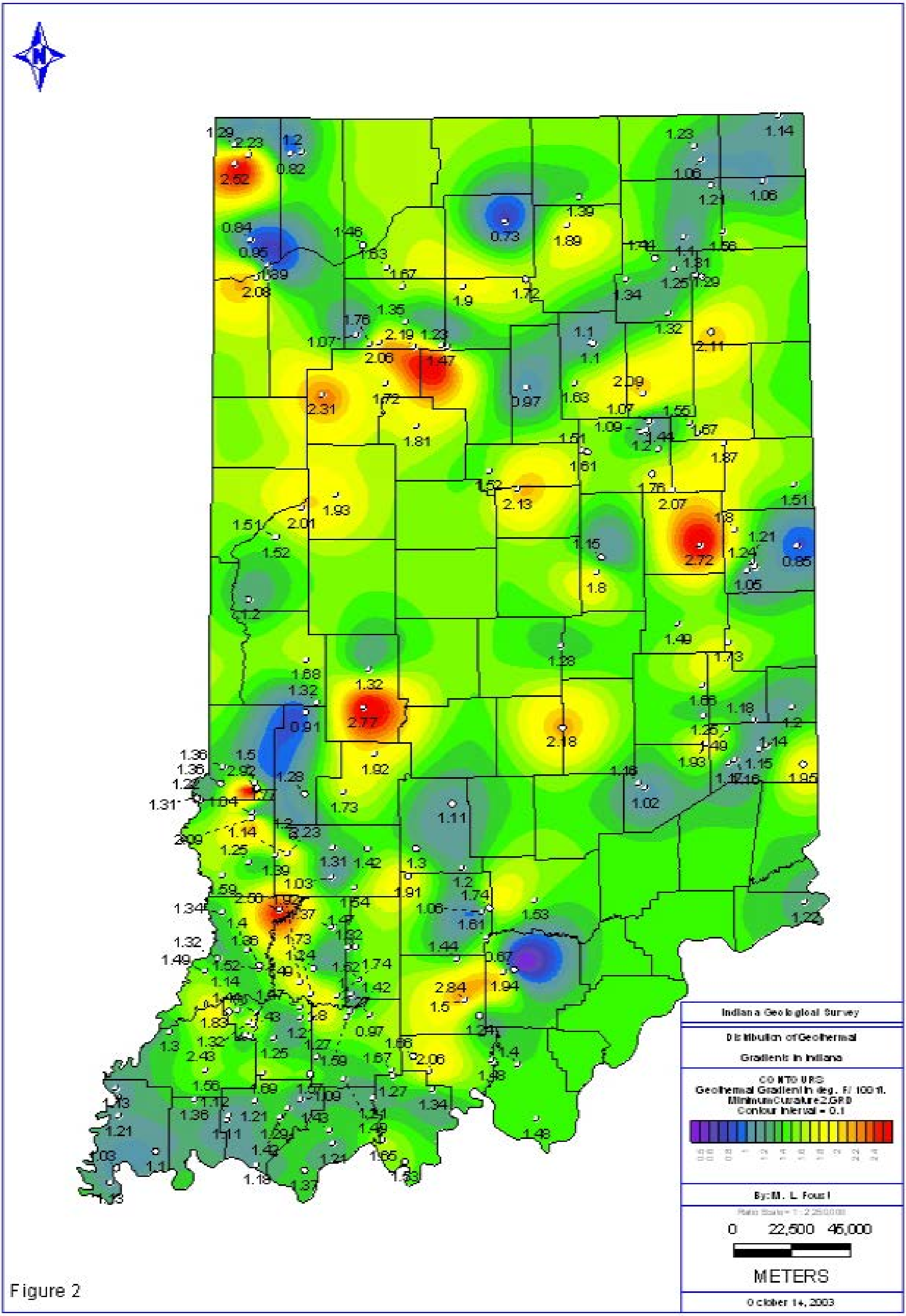

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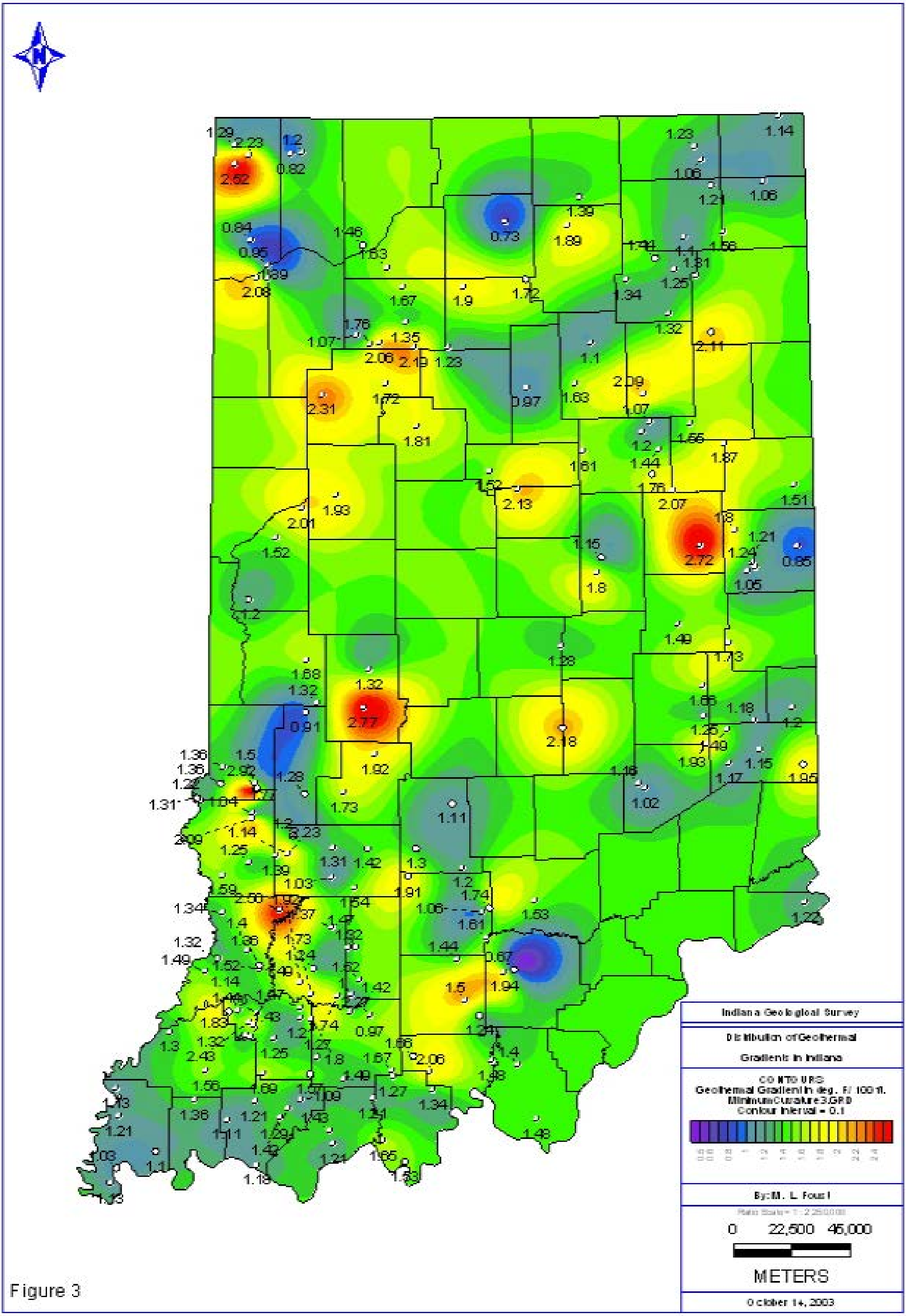

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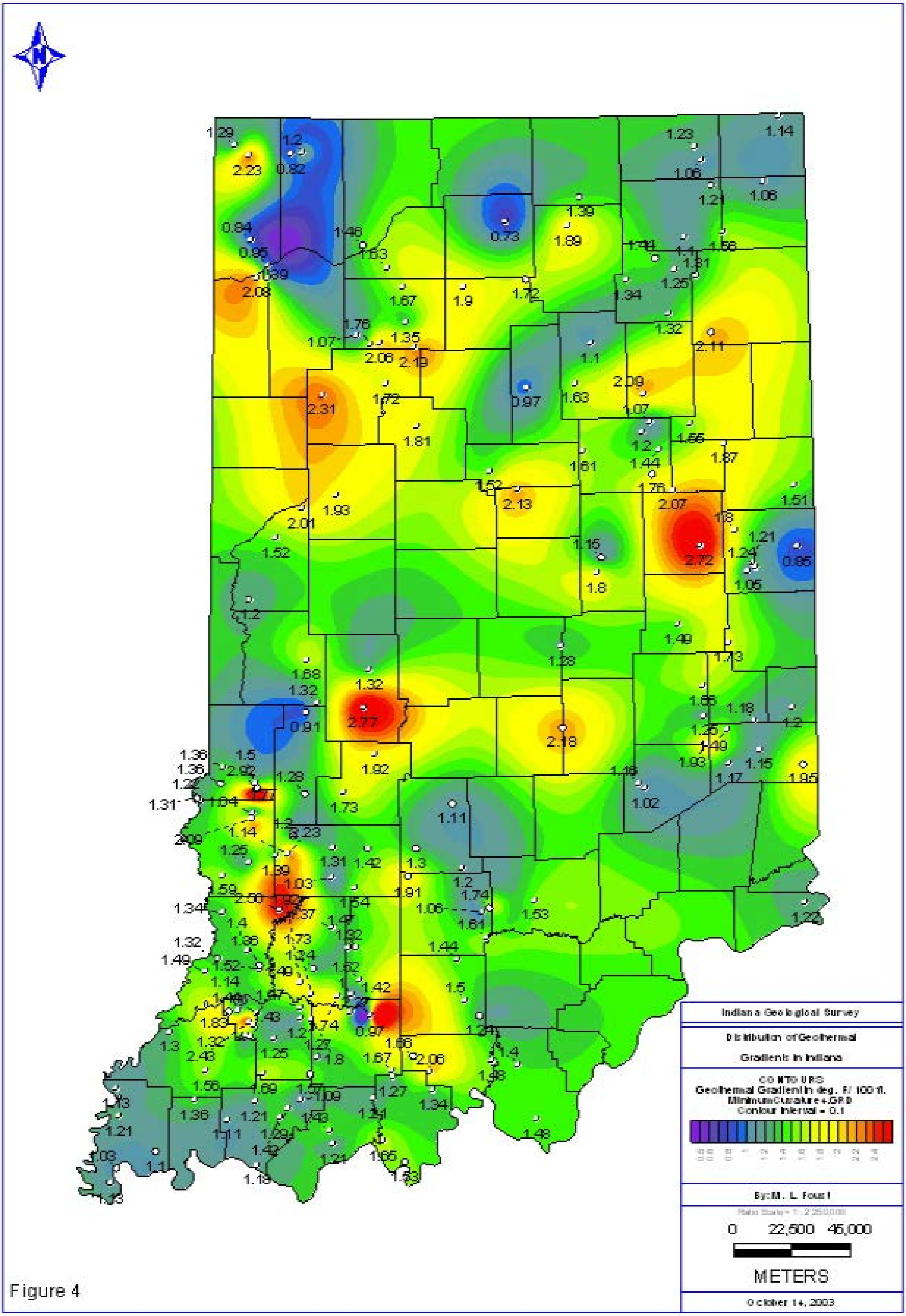

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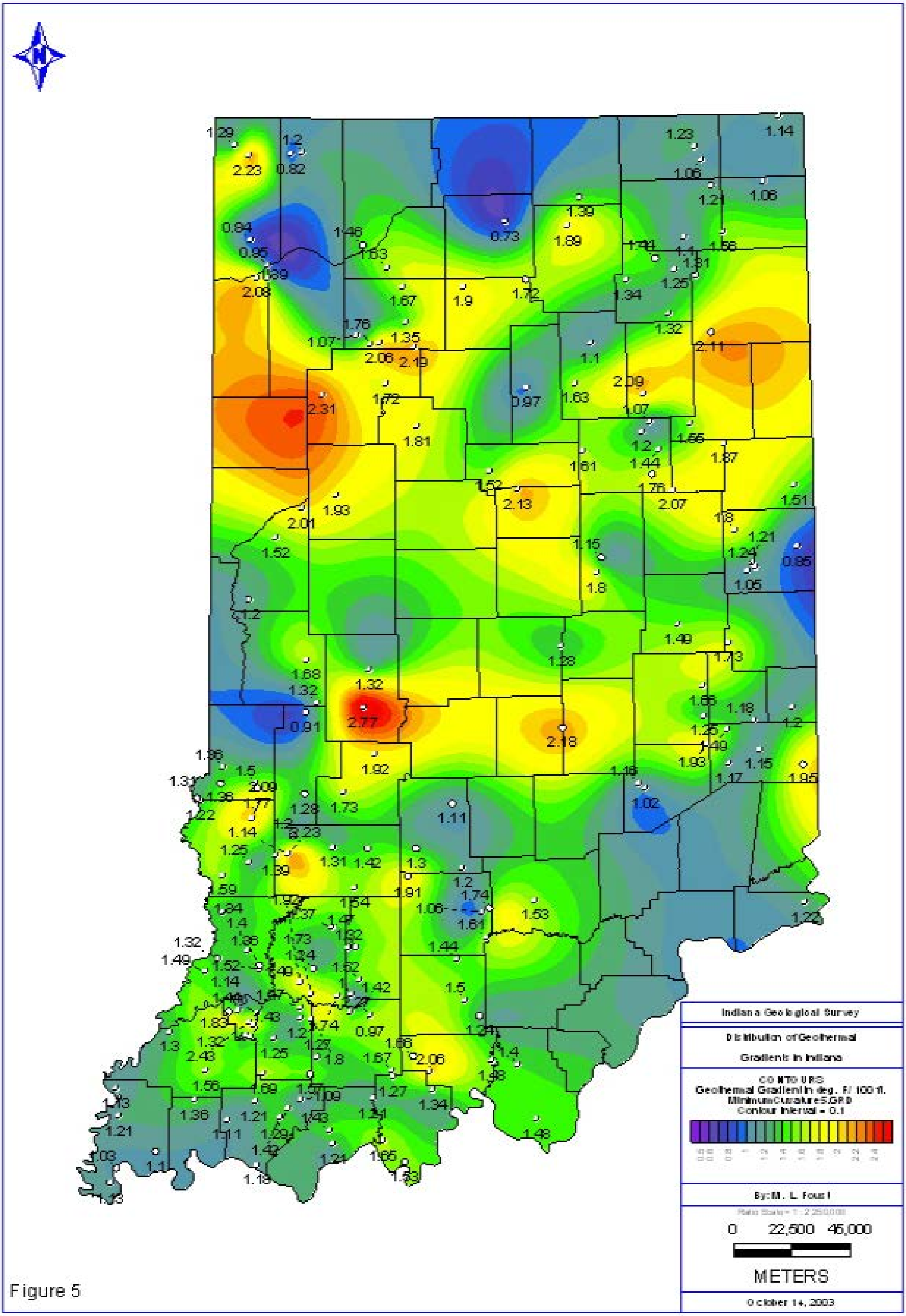
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Indiana Geological Survey
Distribution of Geothermal
Gradients in Indiana
CONTOURS
Geothermal Gradient in deg. F/ 100 ft.
MinimumCurvature5.GRD
Contour Interval = 0.1
By: M. L. Foust
Ratio Scale = 1 : 2,250,000
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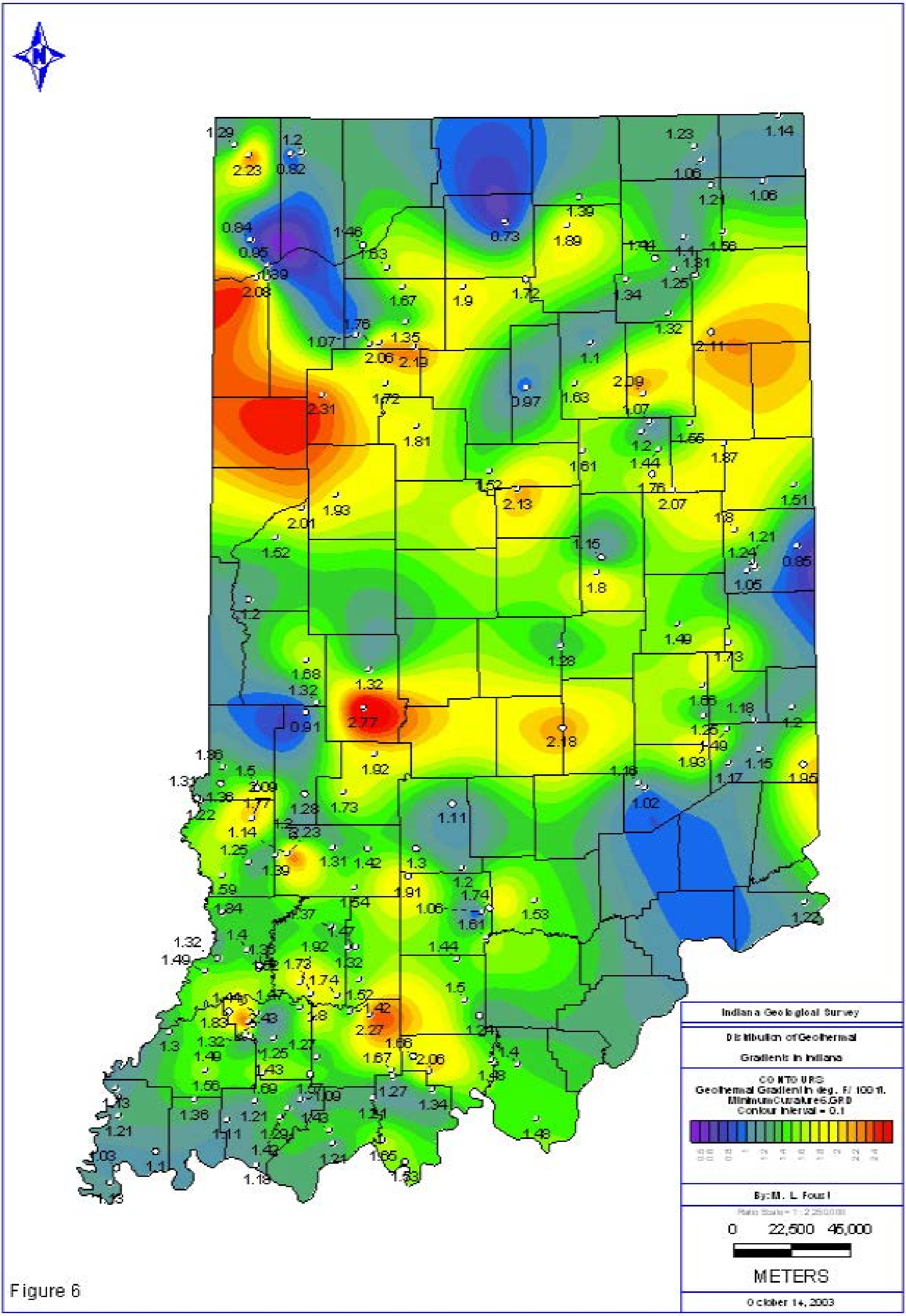
Figure 5



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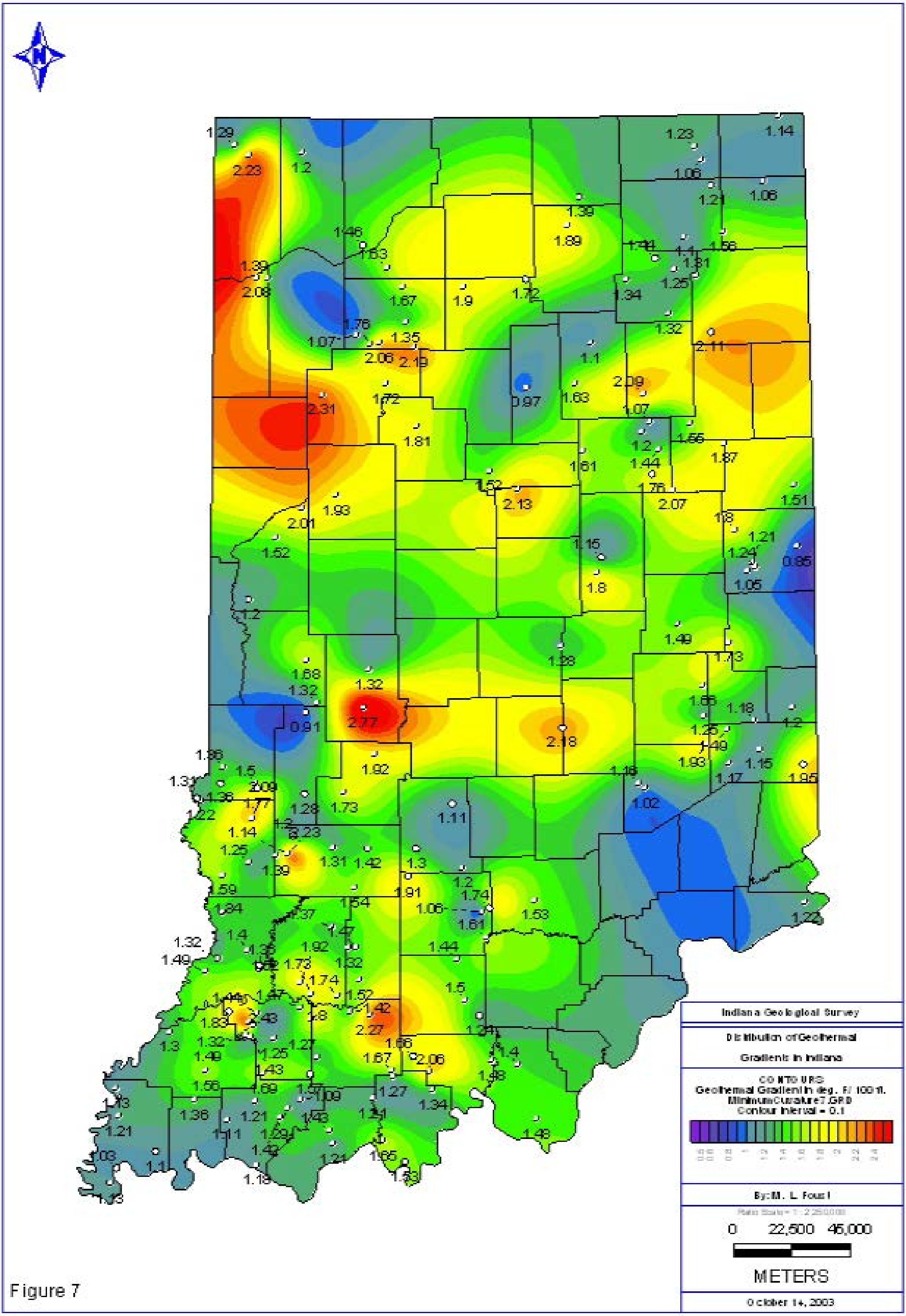
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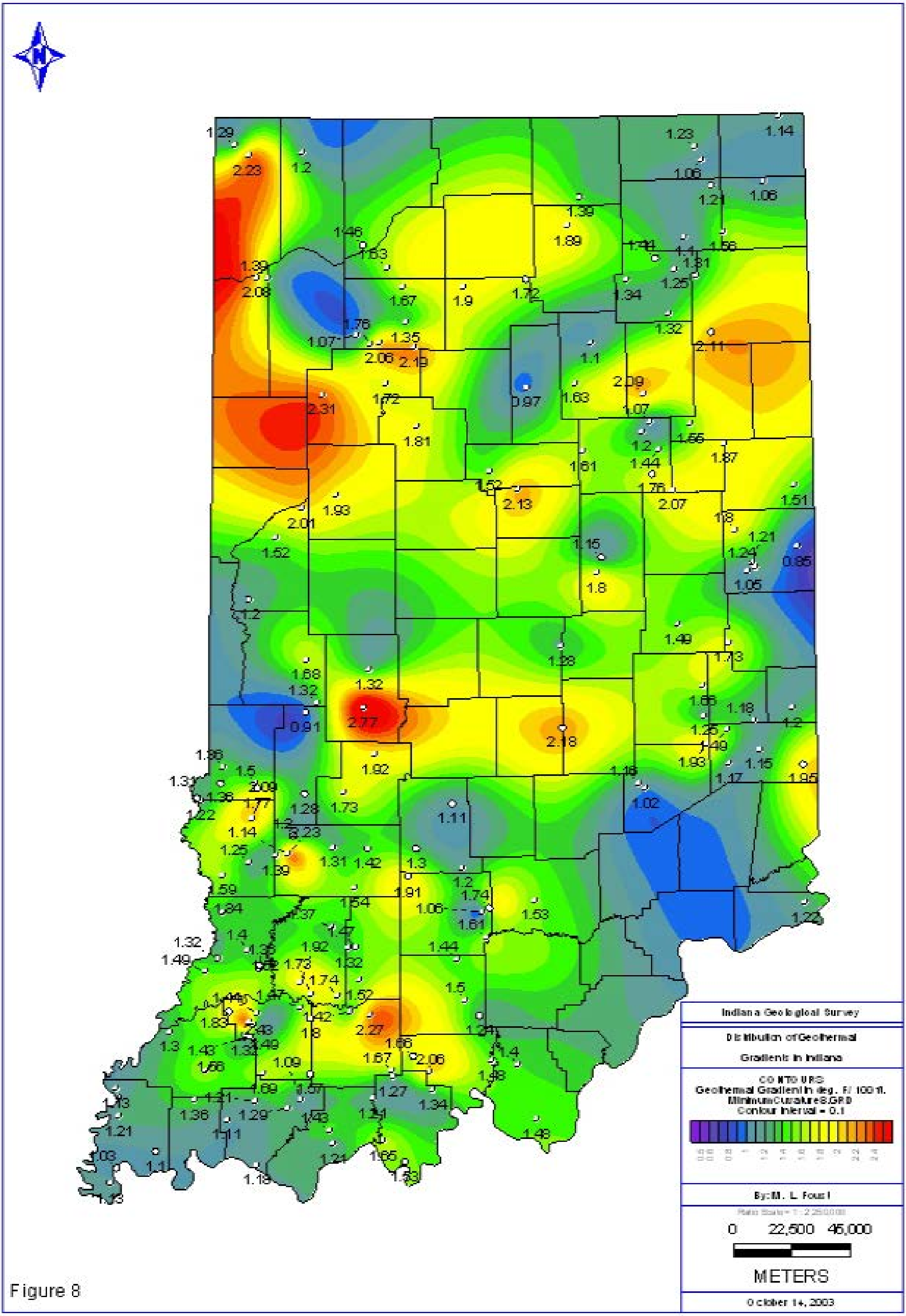
Figure 7



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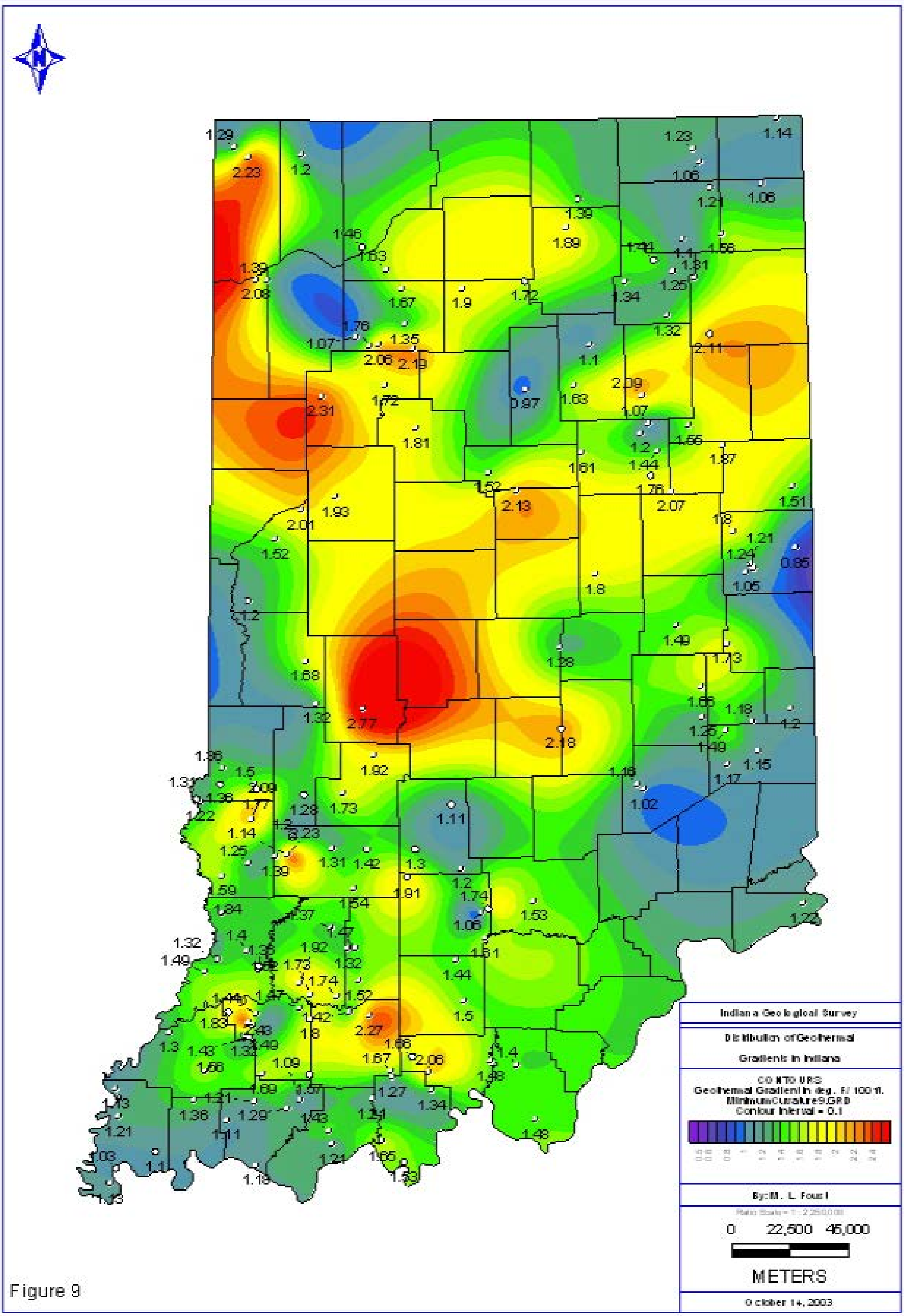

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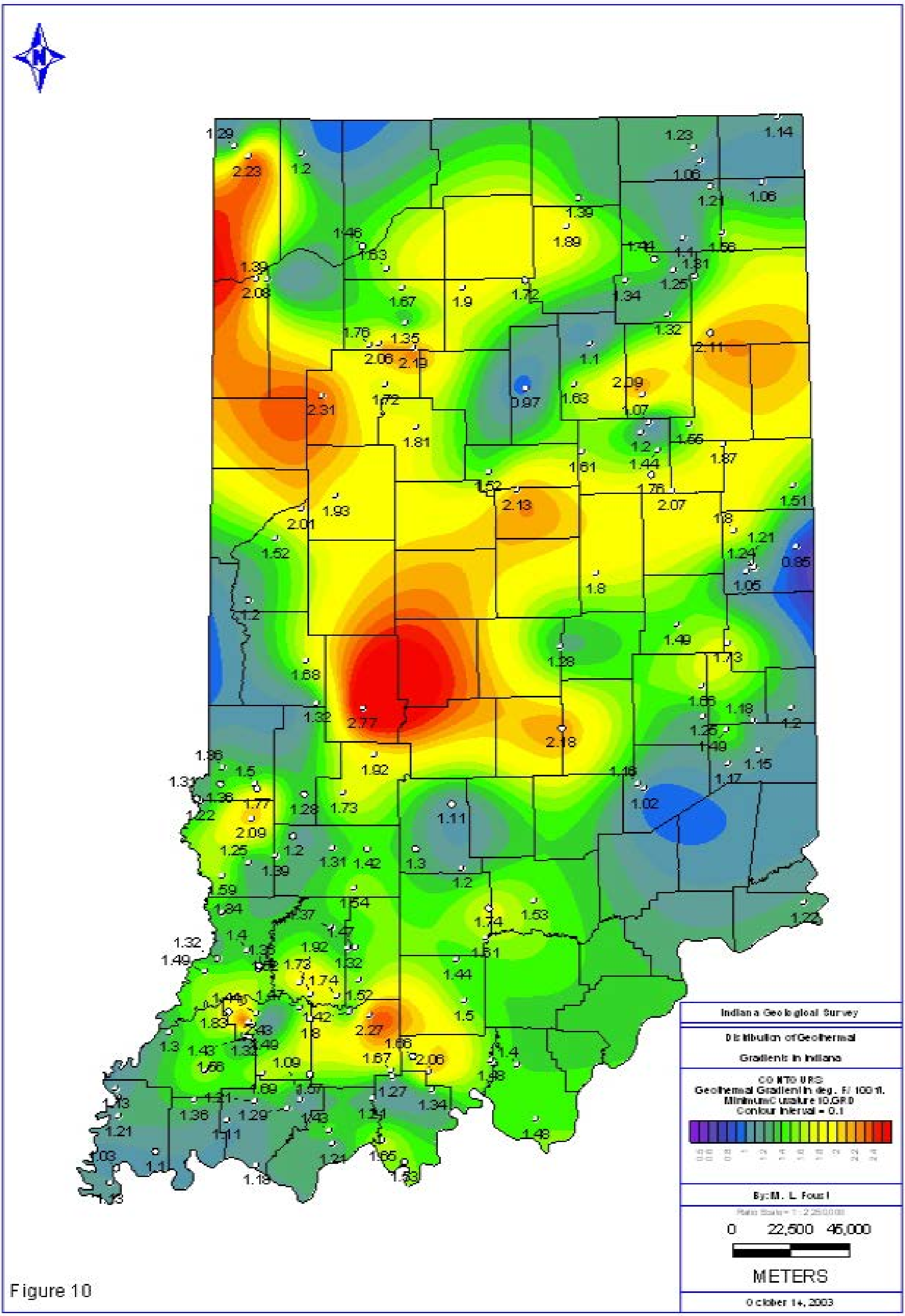
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Ratio Scale = 1 : 2,250,000
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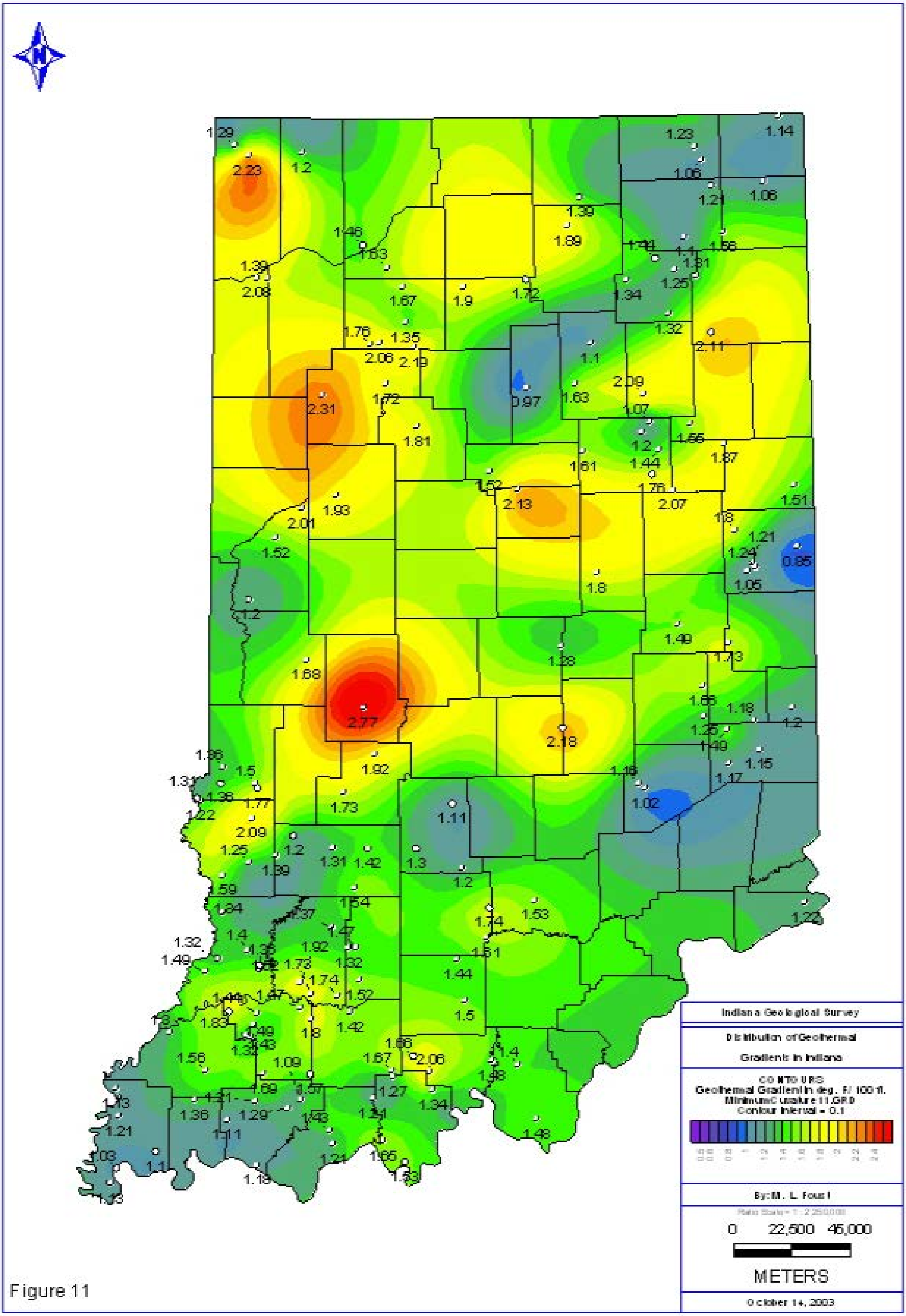
22,500
45,000
METERS
October 14, 2003

Figure 10



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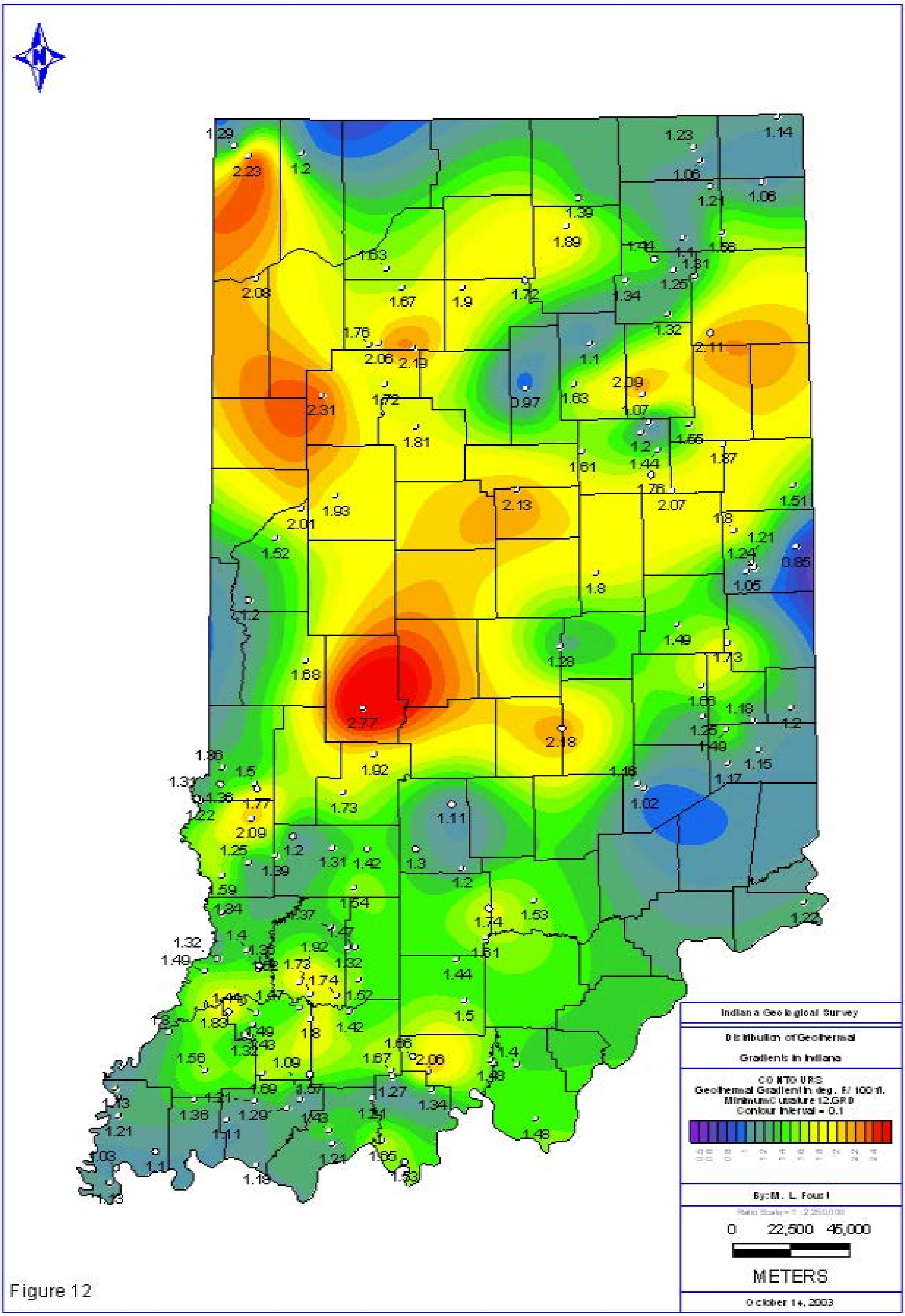
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By: M. L. Foust
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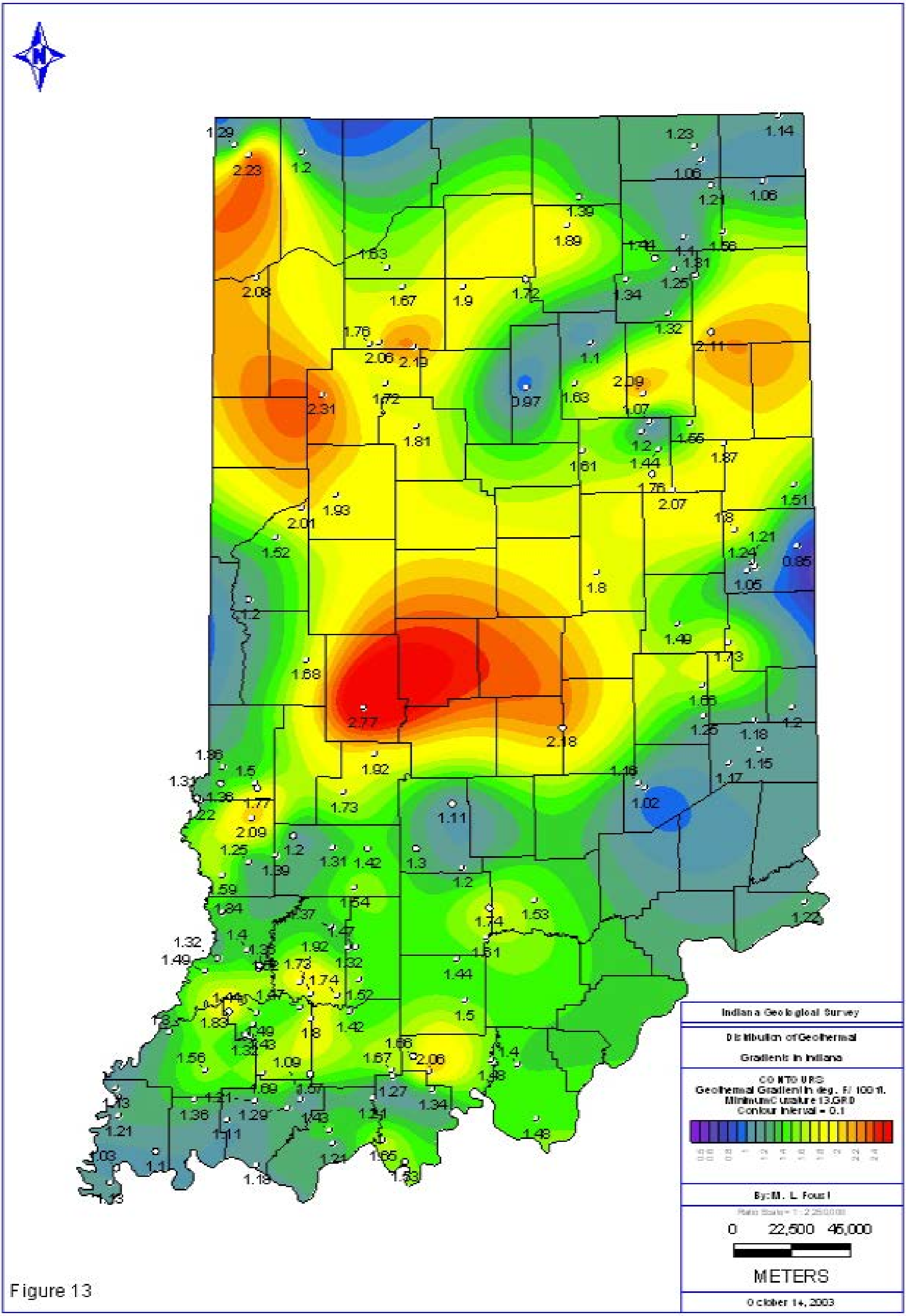
October 14, 2003

Figure 12



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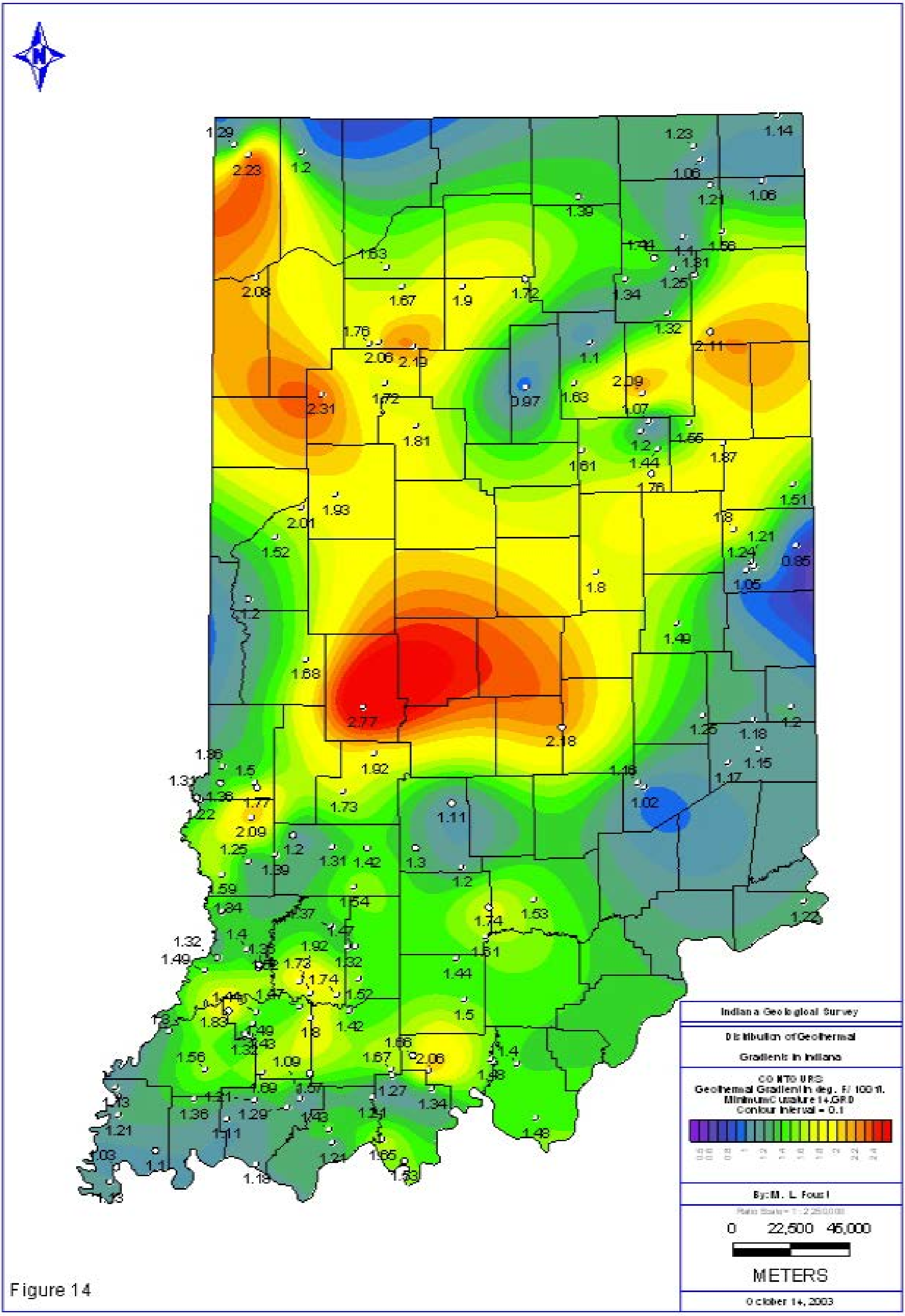

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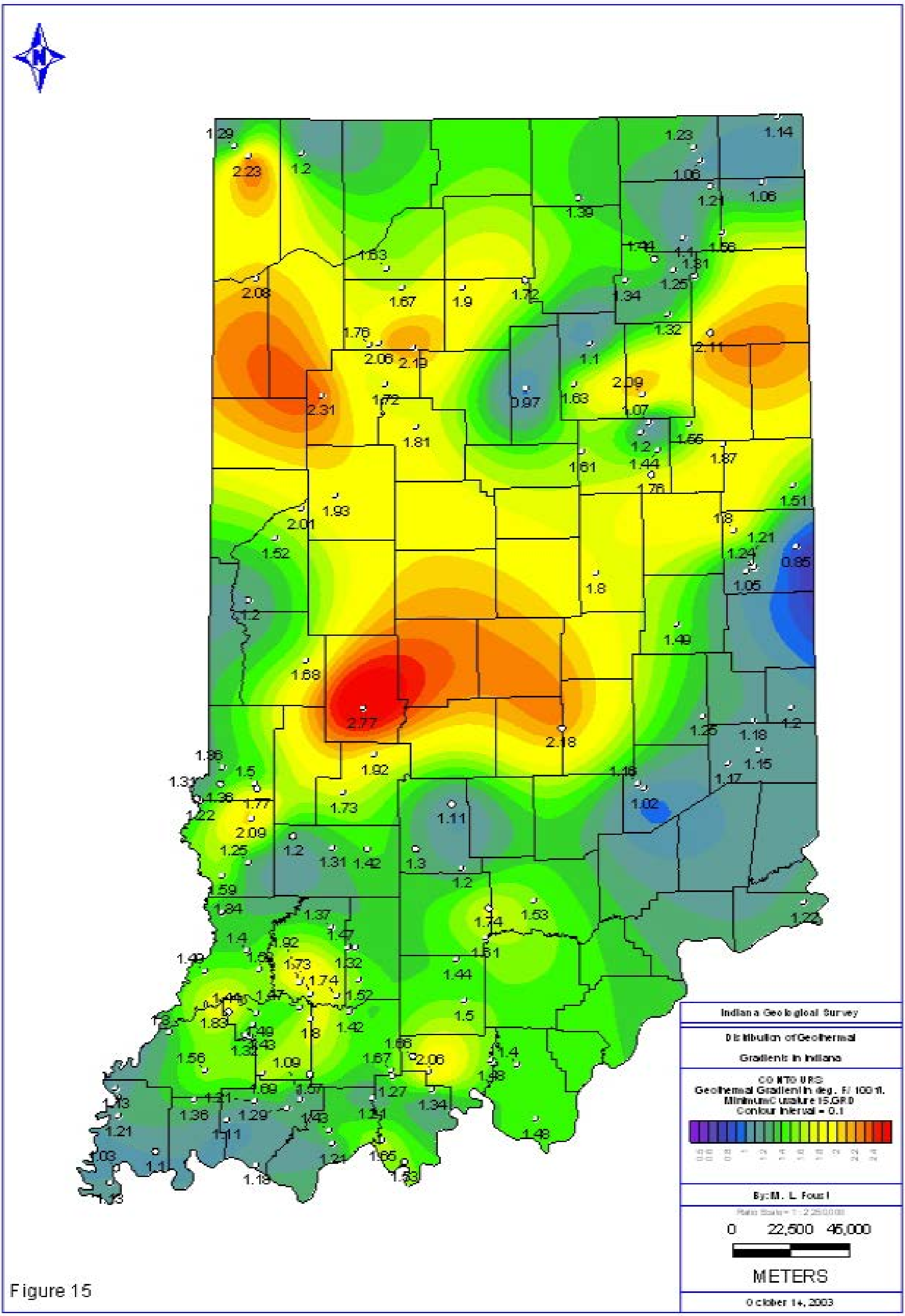

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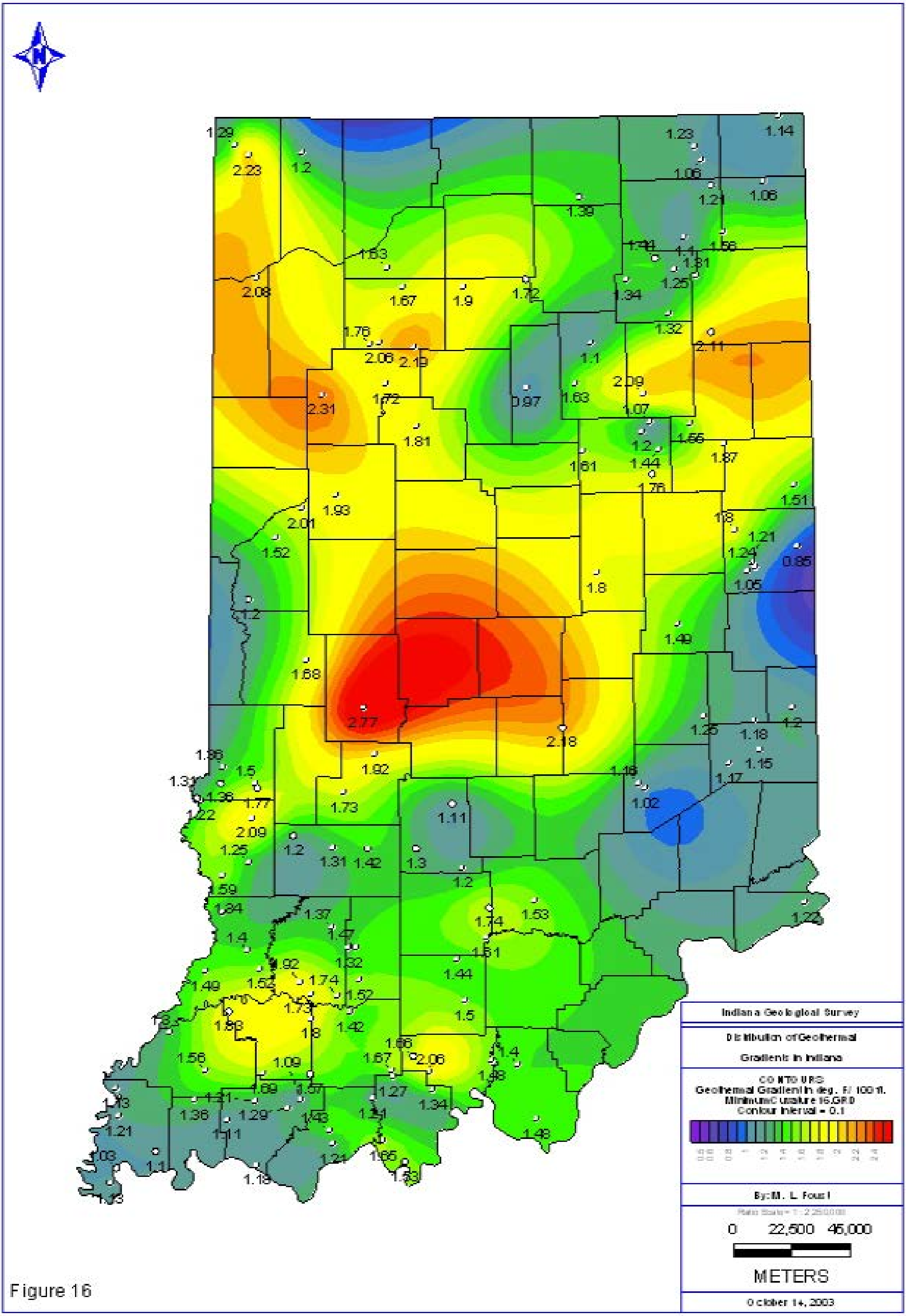

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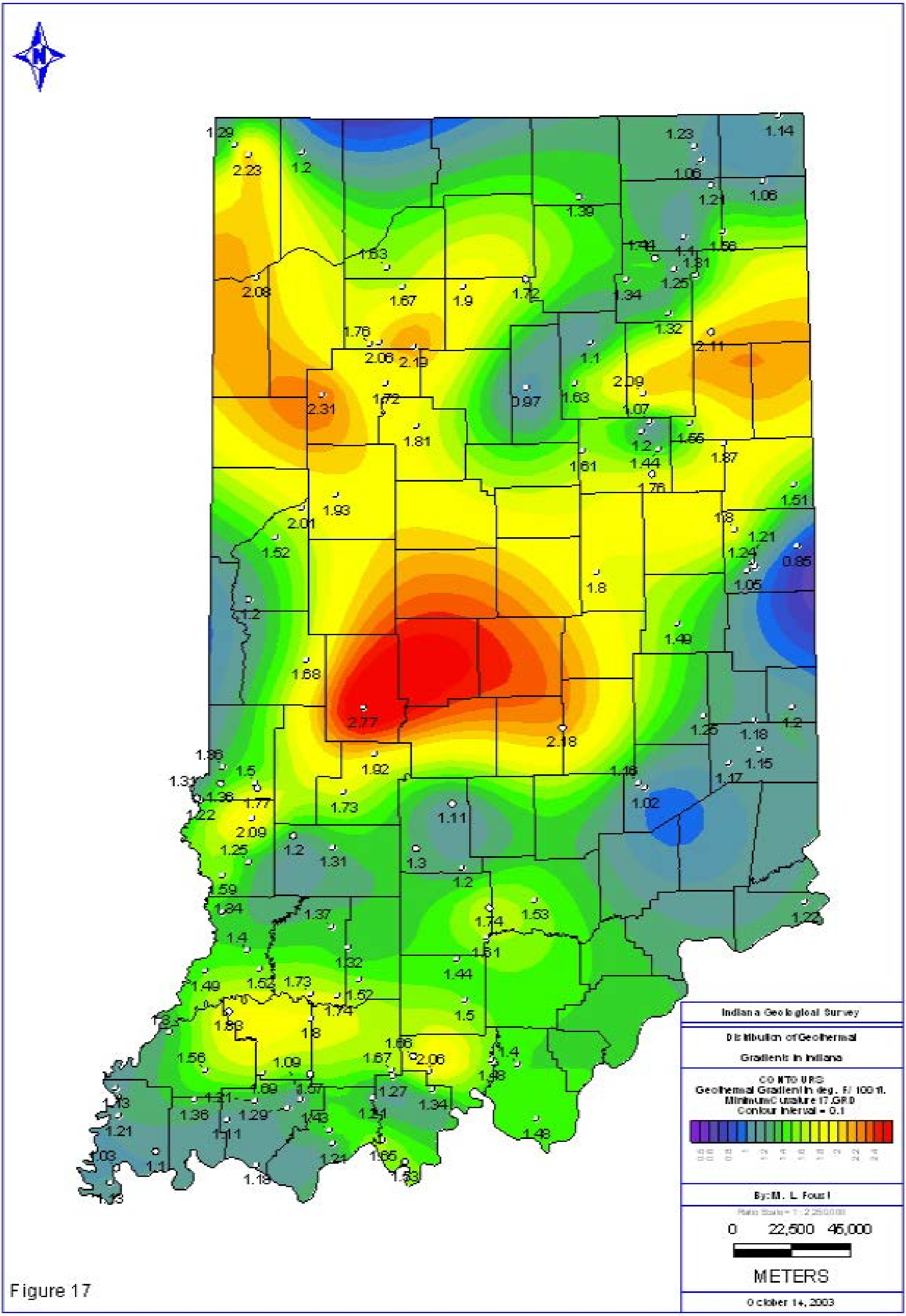

Figure 17

PETRA 10/24/2003 10:25:47 AM

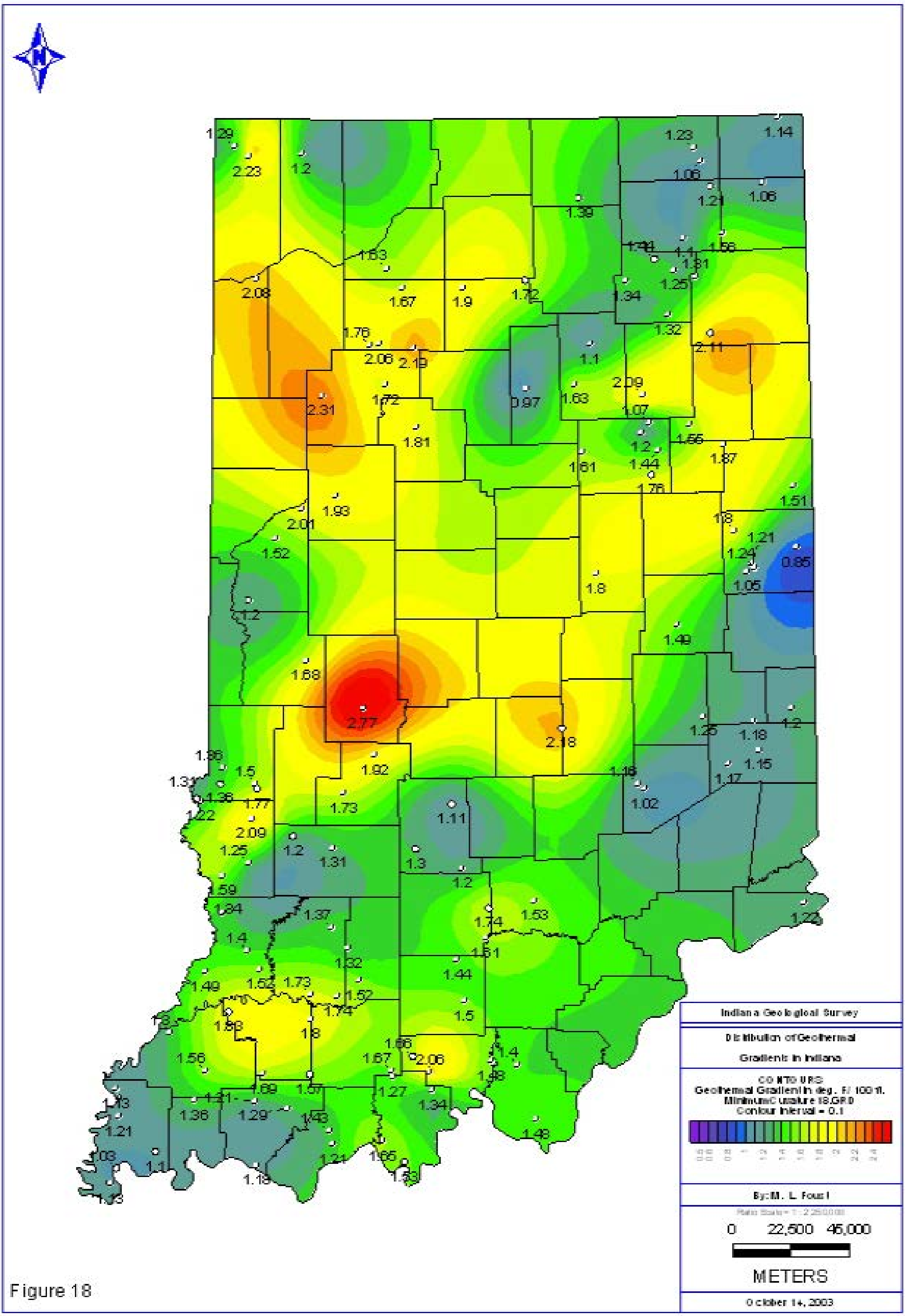

Figure 18

PETRA 10/24/2003 10:17:04 AM