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Evidence for a titaniferous diatreme or alkalic igneous rock in the subsurface, Harrison, Taylor, and Doddridge Counties, West Virginia

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ABSTRACT

A large titanium anomaly (anomaly A) was identified in Harrison, Taylor, and Doddridge Counties, West Virginia from a geochemical evaluation of statewide NURE stream sediment data. The anomaly is underlain by the Upper Pennsylvanian Monongahela Group, and encompasses the contact with overlying Dunkard Group coal measures. The anomaly is: (1) associated with cerium-group rare earth elements (REE), Ba, Sr, Au, Sn, Cu, Pb, Mn, Al, Th, Fe, and V; (2) elliptical in plan on the basis of a contour plot, and crosscuts the regional stratigraphic trends; (4) located on the edge of the Silurian evaporite basin; (5) associated with large-scale, northwesterly-trending LANDSAT lineaments; (6) localized on an intersection of a major northeasterly zone of right-lateral transcurrent faulting, and a northwesterly-trending zone of cross-faulting, fracturing, and jointing manifested by abrupt changes in strike of major structural elements; (7) between two large aeromagnetic highs, reflecting mafic basement rocks. (8) associated with gamma-ray anomalies in deep subsurface oil and gas well logs, and (8) associated with a linear zone of fluorine anomalies in water wells entering the area from the south parallel to the transcurrent faults and fold axes.

At the regional scale (1:1,000,000) anomaly A is defined by a cluster of discrete titanium highs that coincide with a regional anomaly zone of cerium, lanthanum, thorium, iron, and manganese. Northeasterly-trending regional anomalies of lanthanum and thorium make a sharp departure to the northwest in the area of anomaly A, coinciding with crossfaults of like trend and deflection of fold axes.

In detail, recontoured at a 1:500,000 scale, the circular clusters of regional titanium highs become a spectacularily high contrast, elliptical titanium pattern with a northwest-trending long axis of about 38 miles.

Mafic-ultramafic igneous occurrences in the region could have affinities to anomaly A. (1) To the northeast in Pennsylvania, on structural alignment with anomaly A, mica peridotite dikes intrude the coal measure sequence. One of these occurrences at Masontown, Fayette County is dated at about 185 Ma. The second dike occurrence in the coal measure sequence at Dixonville, Pennsylvania has not been dated to our knowledge. Both occurrences in Pennsylvania are on the flanks of the Chestnut Ridge anticline, which also crosses anomaly A. (2) Several occurrences of northwesterly-trending alkalic mafic and felsic dikes of Jurassic to Eocene age are intruded into joint sets southeast of anomaly A in Pendleton County, West Virginia. This same structural trend crosses anomaly A.

The many geological and geochemical similarities of anomaly A to the rift-related alkalic intrusions, carbonatites, and diatremes of the Illinois-Kentucky mining district, southeastern Missouri, and Magnet Cove, Arkansas leads us to conclude that the anomaly is due to a diatreme in the subsurface.

We discuss several recommendations for follow-up investigation. Anomaly A warrants further investigation for

possible diatreme-related mineralization (fluorite, sulfides, barite, REE, niobium, and tin, as well as Ti). The titanium distribution suggests that titanium minerals and associated REE minerals are being shed from bedrock near the upper reaches of tributary streams. Titanium and rare earth-bearing minerals are then distributed down-drainage to form placers at stream confluences, and in down-stream areas where gradient flattens.

INTRODUCTION

In a recent evaluation of NURE stream sediment data in West Virginia for a cooperative mineral resource assessment (Cannon and others, in press; Hinkle and others, in press; Watts and others, in press), it became apparent that a highly anomalous, discordant geochemical anomaly exists in the area of Harrison, Taylor, and Doddridge Counties, more or less centered on the town of Clarksburg (henceforth referred to as anomaly A). Anomaly A is in a regional tectonic setting that would permit the emplacement of alkalic igneous bodies and related diatremes (fig. 1).

Following is a discussion of the possible significance of anomaly A, but we wish to stress that we were unable to check the area in the field so the accompanying conclusions should be regarded as tentative.

METHODS

Samples used for this report were collected during the NURE program and analyzed by the Savannah River Laboratory (SRL) of the U.S. Department of Energy (DOE). We evaluated these data as part of the mineral resource assessment of West Virginia. The data initially examined were from computer tapes archived by the U.S.Geological Survey and include analyses of 2873 stream sediments from the Bluefield, Charlottesville, Cumberland, and Pittsburgh 1 x 2 degree quadrangles. The SRL anlyzed stream sediment samples by neutron activation methods for Hf, Al, Ce, Dy, Eu, Fe, La, Lu, Mn, Sc, Sm, Na, Ti, V, and Yb. (Cook, 1981a, 1981b; Fay, 1981; Fay and Cook, 1982; Cook, Fay, and Sargent, 1982).

In the initial evaluation, a subset of 354 NURE stream sediment samples with high element concentrations, in part related to anomaly A was selected from an area centered around Barbour and Harrison Counties. From the subset of 354 stream sediment samples, a further subset of 208 were used to evaluate the area of anomaly A.

The 208 samples were retrieved from storage and analyzed by emission spectrography for 35 elements and for gold by an atomic-absorption procedure (Grimes and Marranzino, 1968; Motooka and Grimes, 1976; modification of Thompson and others, 1968). Analytical data from these samples are available in Adrian and others (1992).

The titanium data generated by emission spectrographic methods is not as useful as the data from INAA in that the range of reporting is not as great, nor the reporting intervals as refined. Comparison of the data shows a range of 0.2-1 percent with a mean of .77 percent for the spectrographic data, and a range of .03-6.2 percent with a mean of .54 percent within the NURE data set. As a consequence of the greater range of reporting and the closer reporting intervals, we have relied on the INAA titanium data for the map delineation of anomaly A.

Part of the data evaluation involved statistical analyses using computer programs developed by the USGS. (Van Trump and Miesch, 1977). Basic statistics (mean, standard deviation, correlation coefficients) were calculated for the data sets. Product-moment correlation coefficients are used in this report to show some of the interelement relationships. A perfect correlation between two chemical elements is a positive 1.000; a perfect antipathy between elements is a -1.000, and a random or no relationship is 0.000. The positive association between element pairs ranges between 0.000 and 1.000, depending on degree of association.

The data were further examined by R-mode factor analysis, but very little use is made of it for this report, except in one instance as discussed in a later section.

The contour intervals for the map plots used here consist of the 50th, 75th, 85th, 90th, 95th, and 99th percentiles of the statistical distribution where the range of data allowed. Otherwise, the percentile parameter was used only as a general guideline (for example with some of the emission spectrographic data). The USGS contour program, CONPLOT, developed by J.B. Fife of the USGS was used to generate the maps. The method uses a standard cell average technique, based on gridded data, which in this case used fifty cells in the x-direction (that is, 2.5 mi. on a side at 1:500,000 scale and 5 mi. at 1:1,000,000).

GEOLOGY

The area of this report lies in the Appalachian Plateaus of central and western West Virginia. Streams in the Appalachian Plateaus, although influenced by structure and differing resistance to erosion of the various formations, have a pattern that approximates dendritic. Hence, the stream sediments collected there probably represent the most common local rock units.

Rocks ranging in age from Cambrian to Permian are exposed in West Virginia. Proterozoic rocks have been encountered in deep drill holes. Rocks of Pennsylvanian Monongahela age are at the surface in the area of anomaly A. They are covered by lower Permian (Dunkard) rocks on the western side. The Pennsylvanian rocks have been stripped near the eastern edge of the plateau to expose the older rocks of Mississippian age, but none crop out in anomaly A.

Likewise, rocks older than Mississippian are exposed only in the folded rocks of the Appalachian Mountains to the east of the area of this report. Cambrian and Ordovician rocks are most widespread in the easternmost panhandle as well, where they predominate. In general, most rocks of Mississippian and older age were deposited in or near marine environments and those of Pennsylvanian and Permian age were mostly deposited in non-marine environments. Marked lateral changes in character are found in both the Pennsylvanian formations and the older formations.

The Upper Silurian formations are of interest with respect to anomaly A. In the northwestern part of West Virginia, immediately to the north of anomaly A, the total thickness of Silurian rock salt exceeds 50 feet at depths of 6000-9000 ft. (King and Kirstein, 1987). The rock salt units are interlayered with sandstone, shale, and anhydrite. Although these evaporite deposits do not reach the surface, brines may ascend from them through fractures or other permeable zones and increase the salinity of surface and well water. More importantly for the present geochemical investigation, however, is the possibility that a highly corrosive hydrothermal brine driven by a subsurface heat source might have mobilized metals from these buried evaporites, bringing them to the present surface. We postulate that a hot magma might have existed beneath anomaly A and might also have contributed some of the anomalous metals.

The Dunkard basin in which anomaly A lies is Upper Pennsylvanian. It overlaps the Pocahontas basin in approximately the middle of the state, in the area of Calhoun, Gilmer, Kanawha, and Roane counties. The source area for the Dunkard sediments was located generally E-SE of the basin, in eastern West Virginia and Virginia. Although the environment of deposition was also deltaic, a much smaller volume of sediments were deposite d in comparison with the Pocahontas basin to the south (Arkle, 1974; Donaldson, 1974). Sediments in the Dunkard basin consist of Monongahela and Dunkard Groups, which are primarily nonmarine, with minor interbedded marine and coal beds present. Coals of the Dunkard basin contain more sulfur than those of the Pocahontas basin to the south (Arkle, 1974; Barlow, 1974). These sedimentary rocks crop out throughout the area of anomaly A, but anomaly A appears to transgress all sedimentary units in the sequence . In general the central part of anomaly A is located at the boundary of the Dunkard Group with the Monongahela Group, and at the southern margin of the Silurian evaporite basin as interpreted from drill holes (King and Kirstein, 1987).

Mafic igneous rocks of probable Triassic age have been known in Pendleton County, W. Va. and in neighboring Highland County, Va., since they were first publicized by Darton and Diller (1890). Igneous activity continued intermittently on the Virginia side with the intrusion in Jurassic time of felsic alkalic rocks and in Eocene time of more mafic rocks once again (Garnar, 1956; Dennison and Johnson, 1969; Rader and others, 1986). To the north in Pennsylvania, two localities are known in which mica peridotite dikes intrude the coal measure sequence (Honess and Graeber, 1926). The occurrence at Masontown, the closest mica peridotite dike occurrence to anomaly A, is dated at 185 Ma (Pimentel and others, 1975) and 188-175 Ma (Zartman, 1977). Both occurrences of mica peridotite in Pennsylvania structurally align with anomaly A (fig.1).

The rocks in the immediate region surrounding anomaly A are deformed into open folds trending northeasterly with frequent disruptions in strike, which are interpreted as crosscutting faults, geofractures, and joints that extend across the state from Virginia to Ohio (Woodward, 1968). Parallel to the strike of the beds, and extending into the area of anomaly A, is a zone of inferred transcurrent faulting in the basement which is considered an eastward extension of the "38th degree lineament" of the midcontinent region (Woodward, 1968; Snyder and Gerdemann, 1965).

REGIONAL GEOCHEMISTRY

Plate 1 shows the relationship of the regional patterns of lanthanum to anomaly A, and to some of the regional structural features. Isopleths of lanthanum were used to illustrate the close spatial relationship of the regional geochemical anomalies to the structure in the region. Although lanthanum demonstrates these relationships very well, similar patterns were obtained from plots of Th, Ce, Ti, Fe, and Mn (Hinkle and others, in press; Watts and others, in press). Anomaly A is at the intersection of the transcurrent faults with inferred crossfaults (Woodward, 1968). At the point of intersection, the northeasterly-trending regional lanthanum isopleths, which show close spatial correlation with the transcurrent faults, take a radical departure in trend to the northwest, coincidental with the northwest-trending crossfaults. This radical departure in isopleth trend demonstrates that the regional geochemical patterns are probably influenced by structure. We postulate that alkalic igneous rocks may have been intruded into some of these same structural zones, including those that intersect in anomaly A.

ELEMENT ABUNDANCES

Figures 2 and 3 summarize the NURE and USGS data in anomaly A. Even the detection of such elements as Mo, Sn, and Au is considered anomalous, and Fe, Ba, Co, Cu, La, Mn, Ni, Pb, Sr, V, Y, and Zn range above what we consider background.

The chief sedimentary unit exposed in the area is the coal-bearing Monongahela Group, which bears small amounts of titanium compared to the stream sediments from the same area. Coals from the Monongahela Group average about 500-700 ppm titanium, as calculated from percent TiO_2 measured in coal ash (Zubovic and others, 1979, 1980), whereas stream sediments in this area average about 5000-7000 ppm titanium on the basis of emission spectrographic analysis (Adrian and others, 1992) and range to 6.2 percent, according to the NURE neutron activation analysis. According to our data, these same sedimentary units are not shedding above median amounts of titanium farther south along strike, except in some discordant zones similar to anomaly A (Watts and others, in press).

Figure 4 shows that the maximum values for all of the selected elements except copper, molybdenum, nickel, and strontium are higher for stream sediments in anomaly A than the maximum values reported for coal ash. Although we concede that the higher nickel and molybdenum values in the stream sediments could be derived from coal beds in the drainage basins, the map distributions of copper and strontium (discussed below) spatially associate well enough with the titanium ellipse to suggest a cogenetic relationship.

The mean values show a much higher contrast between coal and stream sediments (fig. 5), and in all of the selected elements, mean values in stream sediments exceed those for coal ash.

ANOMALY A

The elliptical isopleths of anomalous titanium delineating anomaly A (fig. 6) have a northwest-trending long axis of approximately 38 miles that coincides with LANDSAT lineaments, and is consistent with the trends of joints, crossfaults, and geofractures in the region. Positive, multielement stream sediment anomalies and fluorine anomalies in well water accompany the anomalous titanium.

The Chestnut Ridge anticline, which is associated with the mica peridotite dikes in Pennsylvania (Honess and Graeber, 1926) transects anomaly A along a northerly to northeasterly orientation. The center of anomaly A is the western flank of the Chestnut Ridge anticline. Near the town of Bridgeport, a small town just west of Clarksburg, the Chestnut Ridge anticline is deflected sharply eastward from regional strike a distance of about 2 miles, apparently due to crossfaulting (Cardwell, 1982). Wolf Summit and the Arches Fork anticlines, on the western side of anomaly A show similar deflections (Cardwell, 1982; Plate 1).

Geophysical anomalies also characterize anomaly A. Two of the largest aeromagnetic highs in the state are associated with anomaly A (King and others, in press; Cannon and others, in press). The aeromagnetic anomalies have northwesterly long axes similar to the titanium ellipse, and overlap with, but are slightly displaced westerly from the titanium ellipse. Preliminary interpretation of these aeromagnetic highs indicates that they may reflect mafic basement rocks.

A second geophysical characteristic of anomaly A is the presence of gamma-ray anomalies in deep drill holes (Cannon and others, in press). Very high gamma-ray readings were recorded from a highly radioactive dark shale at the base of the Warren Sand beneath the area (Cardwell, 1982). Gamma-ray logs of the Devonian Hampshire Formation where intersected by oil wells penetrating zones beneath anomaly A indicate that the intensity of this formation is not much different from that of neighboring formations, but the intensities vary strongly and erratically in an area of about 900 sq. km that underlies eastern Doddridge and central Harrison counties. The northeastern boundary of this area is northwest-trending corresponding with manganese, lead, and titanium anomalies and the southwestern boundary of the erratic gamma-ray zone corresponds with the high contrast zone of the titanium ellipse. Total gamma-ray intensity includes radiation from uranium, thorium, and pottassium. The uranium and thorium could either or both be involved in the inferred mineralization in those counties. Minor growth faults at that depth were indicated by the well data. The erratic gamma-ray values are mainly unusually low. Perhaps this reflects the removal upward of U, Th, or both, to enhance the geochemical anomalies found at the surface.

Another observation, possibly reflecting on the character of anomaly A is the circular dome, about 13 mi. in diameter immediately northwest (area marked B on fig. 6). The dome is characterized by coincident cerium and lanthanum anomalies with titanium on the northern periphery. The dome consists of a central topographic high and a radial drainage pattern. The dome is linked to anomaly A structurally by the northwest-trending LANDSAT lineaments on the northern lobe of the titanium ellipse, and geochemically by similar geochemical signature. Therefore, this dome could be considered part of anomaly A.

One possible explanation for the discordant elliptical titanium distribution within anomaly A is that it is caused by leakage from a subsurface diatreme, or carbonatite related to a mafic intrusion in the basement. This conclusion is supported by :(1) the geochemical association, which is typical, but not totally diagnostic of alkalic igneous rocks and related mineral occurrences (Baldock, 1969; Erickson and Blade, 1963), and (2) regional geologic setting, which favors the occurrence of alkalic igneous bodies (fig.1).

GEOCHEMICAL SIGNATURE

The sample site distribution within anomaly A and surroundings is shown on figure 7. The element associations of anomaly A are discussed below.

The map distribution of associated elements both coincide and overlap with the titanium ellipse (figs. 8-16). Many of the anomalous elements are concentrated along the inner or outer periphery of the ellipse. Linear geochemical patterns of regional magnitude enter the area of the titanium ellipse from the south, as demonstrated on Plate 1. We interpret these regional patterns to be related to faults, and fold axes, that may have acted as structural control over the distribution of the geochemical anomalies. We postulate that within anomaly A itself the element distributions reflect zones of fenitized country rock, and/ or veinlets of titanium, REE, carbonate, and sulfide minerals introduced from below. The strong titanium high might reflect a mafic outer periphery of the structure, while the inner, low titanium zone might result from a less mafic inner core, perhaps consisting of carbonatite or a hydrothermally altered host rock. At this point we can only speculate.

Titanium

Elements that might be associated with titanium associations are suggested by correlation analyses; additional insight is afforded by R-mode factor analysis. For example, R-mode factor analysis using a 4-factor model for the state-wide NURE data set shows that titanium is part of the factor 2 element association of Ti-Al-Fe-Mn-Na-Sc, possibly related to sheet silicates derived from drainage basin shale. Comparison of the product-moment correlations on the other hand indicates that the association of titanium with the REE elements and thorium is stronger in anomaly A than the state as a whole. The titanium associations in anomaly A suggest a heavy detrital mineral suite that we consider unrelated to shale sources:

Statewide Data Base	Al	Ce	Sm
Ti	.23	.21	.21

Anomaly A	Ce	Th	Sm	Al
Ti	.26	.24	.22	.21

On the other hand, titanium is not as closely associated with REE as aluminum is on a statewide basis (significant at the 99th percentile):

Statewide Data Base	La	Ce	Sm
Al	.44	.46	.41

The better correlations of aluminum with REE on a statewide basis compared with titanium could have many explanations beyond the scope of this report. We consider primary associations in shale only one of many possibilities.

The spectrographic data subset within anomaly A shows the following correlation coefficients:

	Ag	Zr	Sn	Nb	Y	Mo
Ti	.57	.28	.27	.20	.20	.19

The Ti-Ag and Ti-Sn pairs are statistically nonsignificant because of the small number of samples with detectable silver and tin. The other correlation coefficients are significant at the 95th percent level of confidence and above. However, the two nonsignificant correlations probably indicate a trend of associations that would emerge with more data. Al was not obtained in the emission spectrographic analysis.

The association of titanium with Sn, Zr, Nb, Y, and Mo typifies alkalic igneous rocks (for example Magnet Cove, Arkansas). These elements can be accommodated in various titanium minerals and associated minerals typical of alkalic complexes. At Magnet Cove late stage veins contain rutile, brookite, and molybdenite, and the rocks contain accessory minerals such as sphene, magnetite, perovskite, apatite, and garnet. Elsewhere ilmenite, titanite ($CaTiSiO_5$) and perovskite ($CaTiO_3$) are reported as accessory minerals in diatremes (Snyder and Gerdemann, 1965; Baldock, 1969). Hence alkalic rocks or a

Although a detailed mineralogic study of these very fine-grained sediment samples has not been made, a cursory Scanning Electron Microscope (SEM) observation of one sample from the high titanium zone revealed some ilmenite. For now however the mineralogic makeup of anomaly A is mostly speculative, based on the chemical associations.

Cerium

The regional isopleth map of cerium shows spatial correlation with titanium in anomaly A. The detailed plot (fig. 8) on the other hand, which provides more resolution of the anomaly configuration shows that cerium is chiefly concentrated on the periphery of the titanium ellipse. For example, cerium shows one linear isopleth pattern that enters anomaly A from the southwest on alignment with the northeasterly bulge on the titanium pattern. We regard the linear north-northeasterly trending geochemical anomalies as possible paths of mineralizers related to transcurrent faults or anticlinal axes.

Cerium anomalies also correlate spatially with the structural dome immediately to the northwest of the titanium ellipse (area B). The close relationship of anomaly A and the structural dome to the northwest-trending LANDSAT lineaments suggests that the two anomalous areas may be related structurally and genetically.

A northerly trend of cerium anomalies overlaps with a general northerly-trending titanium high west of the main titanium ellipse, and links with the structural dome (area B). The geochemical pattern is clearly transgressive. We suggest that it is related to a post- Pennslyvanian fault or structural weakness intruded by alkalic dikes. A nearly identical regional trend of anomalous REE is duplicated where it coincides with a northerly-trending transcurrent fault in the basement shown by Woodward (1968). Details of that anomaly are discussed elsewere (Watts and others, in press; Hinkle and others, in press).

Correlation coefficients for cerium at the 99th percent level of confidence are as follows (568 Nure samples):

	Sm	Th	Al	U	Sc	V	Yb	Ti
Ce	.73	.65	.52	.44	.40	.37	.31	.26

Most of these correlations could have been predicted. The rather low (but significant) correlation of cerium with titanium probably reflects the map distribution patterns, which show that the distribution of some of the high cerium is outside the periphery of the titanium ellipse, and in the low titanium area within the titanium ellipse.

Lanthanum

Lanthanum highs fall are chiefly on the outer periphery of the titanium ellipse (fig. 9). The linear titanium pattern east of the ellipse coincides with the linear isopleth pattern of La. A north-northeasterly pattern of lanthanum enters the area of the titanium ellipse and then forms a strong peripheral pattern on the southwestern portion of the ellipse in a similar pattern to cerium. The north-northeasterly lanthanum isopleth pattern may be the southwestern portion of the ellipse in a similar pattern to cerium. The north-northeasterly lanthanum isopleth pattern may be a reflection of lanthanum mineral deposition within a transcurrent fault or on an anticlinal axes. A closure on the Chestnut Ridge anticlinal axis is shown on a subsurface structure contour map (Cardwell, 1976) beneath the area of the lanthanum anomaly, and just to the south of the titanium ellipse.

Correlation analysis of the spectrographic data (208 samples) and the NURE data (568 samples) shows the following associations:

	Spec					NURE					
	Ag	Y	Mo	Ti		Ce	Sm	Th	V	Ti	Fe
La	.94	.18	.14	.10	La	.75	.61	.51	.22	.18	.18

The La-Mo and La-Ag associations of the spectrographic data set are not statistically significant because of the low number of detectable molybdenum and silver. The associations however seem worth showing because they indicate with more detailed sampling of the area the associations could emerge as valid. The La-Y and La-Ti associations in the spectrographic data set are statistically valid at the 98th percent level or above. All of the NURE associations are statistically valid at the 99th percent level.

Strontium, gold and tin

The distribution of anomalous strontium is elliptical with a low in the center, and shifted slightly to the northeast of the titanium ellipse (fig. 10). Thus, the highest strontium areas coincide with portions of the central low of the titanium ellipse. Probably because of these map distribution overlaps with high strontium areas coinciding with titanium lows, in high-low distributions of titanium and strontium, an inverse relationship, the correlation coefficient for the two elements is -.07. Therefore, inferences based on the correlation coefficient alone can be misleading. The similar symmetry in map distribution of the strontium and titanium anomalies suggest that they are related, but zonal. In addition, we observe that the strontium content is usually high in alkalic igneous rocks (for example Baldock, 1969; Erickson and Blade, 1963; Olson and others, 1954); therefore, these stream sediment anomalies lend support to the diatreme/alkalic igneous model postulated for anomaly A.

Gold and tin values are plotted with strontium. There were 10 gold values reported from the outer perimeter of anomaly A, ranging from detected at .002 ppm to .18 ppm. The eighteen reported tin values from anomaly A and its perimeter range from detectable at 10 ppm (slightly less than) to 100 ppm.

Below are the highest correlation coefficients for strontium, gold, and tin, which we interpret as possible mineralization associations:

	Ag	Sn	Cu	Ba	Ga	Ca	Ni	Fe	Mg
Sr	.94	.57	.52	.49	.45	.39	.37	.36	.31

	B	Zr			
Au	.71	.64			
	Ba	Sr	Fe	To	Zr
Sn	.64	.57	.44	.27	.24

Strontium, barium, copper, and tin are shown by the correlation analyses to be closely associated, which is consistent with the map distribution of these elements. All of the strontium correlations, except silver, are significant at the 99th percent level. The Ag-Sr correlation is nonsignificant statistically, but may be geologically significant. The geologic significance at this time is not readily apparent. Coal could be a source, but would not account for the elliptical pattern of strontium, and its close similarity to that of titanium.

The gold-boron correlation is statistically significant at the 99th percentile level, whereas the Au-Zr is statistically nonsignificant, but no doubt geologically significant (only 6 pairs). A gold-tourmaline association is suggested by the Au-B correlation. The geologic significance of the association is not certain, but the map distribution of gold suggests that it may be related to the outer periphery of the titanium anomaly.

The tin in anomaly A may occur as a minor constituent in rutile, perovskite, anatase (brookite?) or leucoxene because tin readily substitutes for titanium in the lattices of titanium minerals. Tin occurs as a minor constituent in the rare zirconium-bearing eudialyte [$Na_4(Ca,Ce,Fe)_2 Zr Si_6O_{17} (OH,Cl)_2$] and kimzeyite [garnet family, $Ca_3 (Zr,Ti,Mg,Fe,Nb)_2 (Al,Fe,Si)_3 O_{12}$] at the Magnet Cove igneous alkalic complex (Erickson and Blade, 1963). However, as seen from the correlation coefficient of Sr-Ti, the association is not strong, and the number of correlation pairs are not enough for it to be statistically significant. An explanation for this paradox may be that there are numerous repository minerals for titanium, but only a select few from a special environment would contain titanium and tin both.

The strong association of tin with strontium and barium, both statistically significant correlation at the 99th percent level of confidence, suggests that tin might be held in the lattice of a mafic igneous mineral or a feldspar, along with barium and strontium. All of these elements were found to be anomalous in several minerals at Magnet Cove (Erickson and Blade, 1963). It is no doubt significant that the highest tin value (100 ppm) coincides with a zone of highest strontium on the southern lobe of the strontium ellipse.

Barium

Barium analyses show values up to 2000 ppm. Barite was seen by scanning electron microscope (SEM) in one high titanium sample from anomaly A. The same sample contains high REE and thorium in a mineral aggregate associated with the barite. Hence, we assume that the barite and the REE were formed in the same environment. The dominant anomaly is northwesterly in trend coinciding with the long axis of the titanium ellipse (fig. 11). This transgressive pattern (crosscutting the stratigraphy) may reflect leakage along a zone of fractures or faults.

Product-moment correlation analyses of the 208 sample data set show the following high correlations at the 99th percent confidence level:

	Sn	Mg	Cu	Ga	Ni	Sr	Mn	V	Fe	Co	Ca	Be
Ba	.64	.57	.54	.51	.50	.49	.49	.45	.41	.40	.40	.39

	Sc	Na	Pb
Ba	.34	.29	.27

As with strontium, the correlation coefficient of Ba-Ti is -.07, indicating no relationship. The zonal distribution pattern of barium in which the highest barium values occupy the titanium low within anomaly A is the probable explanation. As with strontium also, the distribution of high barium within the titanium low may reflect zones of differing rock composition, related directly to the genesis of anomaly A. The element associations of barium indicated by the correlation analysis typify the alkalic igneous/carbonatite environment (Erickson and Blade, 1963; Baldock, 1969), although they are not by themselves diagnostic.

Copper

Copper values in anomalous area A range up to 100 ppm. The isopleth map (fig.12) shows a very close correlation of the copper patterns with the low area within the titanium ellipse, and an excellent coincidence with strontium and barium highs. The correlation coefficient of Cu-Ti is -.18, reflecting as with strontium and barium, the map distribution of high copper in the central low area of the titanium ellipse.

Except for Cu-Zn, which is statistically nonsignificant, but probably geologically significant, and Cu-Mo, which is statistically significant at the 95 percent level, the following are statistically significant at the 99th percent confidence level:

	Ni	Fe	Ba	Be	V	Sr	Mg	Co	Pb	Sc	Mo	Zn
Cu	.60	.54	.54	.53	.53	.52	.51	.45	.43	.38	.36	.33

	Mn
Cu	.32

The Cu-Ni, Cu-Fe, Cu-Co, Cu-Mo, Cu-Zn, and Cu-Mn associations suggest that sulfide minerals are a likely source of anomalous copper. A second major source of anomalous copper might be limonite derived from sulfides. Other possible sources of the copper anomalies are mafic mineral grains, and secondary copper minerals. Chalcopyrite and other copper minerals are known to occur in diatremes and alkalic igneous complexes, and occasionally copper is economic (Baldock, 1968; Erickson and Blade, 1963; Olson and others, 1954; Grogan and Bradbury, 1968). There is evidence that copper mineralization related to ultrabasic type carbonatites may be an intrinsic late-stage phase of development, and is not a fortuitous occurrence (Baldock, 1968).

The Cu-Ba, and Cu-Sr associations reflect coextensive anomaly distributions of these elements in anomaly A. In brief, all of the element associations suggested by the correlation analyses are known to occur in alkalic igneous/diatreme environments.

Lead

The map pattern of above median lead in anomaly A likewise is in the shape of a half ellipse (fig.13). High values of lead occur in a zone centered on Bridgeport, which immediately to the south is the point where the Chestnut Ridge anticline is deflected eastward about 2 miles (Cardwell, 1982, p.30). The most persistant anomaly trend is northeasterly flanking the northeasterly bulge of the titanium anomaly. The lead anomaly pattern might be related either to the flanks of a fold or to a fracture or fault system of like trend.

Product-moment correlation analyses of the spectrographic results within anomaly A are as follows:

	Zn	Cu	Mg	Be	Mn	Ba	V	Ga	Mo	Sc	Sr
Pb	.99	.43	.35	.30	.28	.27	.26	.26	.25	.22	.22

The element associations of lead are similar to those of copper and are interpreted similarily. These are partly sulfide mineral associations with suggestions of oxide and carbonate minerals. One possibly significant indicator here is the relatively high correlation of Pb-Mg, suggestive of a carbonate (carbonatite?), or mafic igneous association for the lead.

Manganese

The manganese anomalies on the basis of the NURE data set seem to form a halo within the southeastern portion of the titanium ellipse, and outside its periphery (fig.14). An apparently manganese depleted area crosses the center of the titanium ellipse on an east-northeasterly trend, parallel to a similar trend of high manganese values and the northeasterly bulge in the titanium pattern. These adjacent zones of high and low manganese suggest an underlying structural cause of the distribution patterns, probably intensified by weathering. Both zones nearly coincide with the trends of LANDSAT lineaments and the northern flank of the Chestnut Ridge anticline (see Cardwell, 1982 for the configuration of the anticline). Also, areas of apparent element depletion (geochemical lows) adjacent to extreme highs are commonly seen in regional geochemical data in hydrothermally altered areas associated with igneous bodies.

Two other zones of high contrast manganese trend northwesterly and northerly, entering anomaly A from the south. We infer that these anomalies reflect epigenetic disperson in fractures. Hence, the anomalies may be due to manganiferous minerals now weathered to secondary Mn-oxides, subsequently dispersed to the drainage basin alluvium. Strontium, barium, copper, and aluminum show similar trends to those of manganese within these areas. The high amounts of aluminum suggests acid conditions may occur in the respective drainage basins of these anomalies.

Product-moment correlation analyses of NURE data from anomaly A indicate that manganese is most closely associated with vanadium, followed by aluminum, as seen on the maps plots. Residual concentration from weathering of drainage basin bedrock and coprecipitation of Mn-oxides and clays in the stream beds probably account for the Mn-Al association:

	V	Al	Sc	Sm	Ce	Ti
Mn	.41	.27	.21	.16	.15	.15

The relatively low correlation coefficient for the Ti-Mn pair probably reflects the zonal map distribution of the two elements in which manganese lows are within the titanium ellipse and the highest manganese is on the southeastern outer periphery of the high titanium zone.

Product-moment correlation analyses of the emission spectrographic data set show these associations:

	Co	Ni	Ba	Mg	Be	Sc	V	Na	Ga	Cu	Pb
Mn	.59	.51	.49	.49	.39	.37	.36	.34	.34	.32	.28

From the high correlations of manganese with cobalt, nickel, and barium, we infer that secondary oxides and oxyhydroxides of manganese are the chief mineralogic host to anomalies of those metals as well as perhaps some of the anomalies of vanadium, copper, and lead within anomaly A. This inference is based on the common association of these elements in amorphous and crystalline Mn-oxides and oxyhydroxides. Secondary Mn-oxides can be products of deep weathering in place, and later mechanical dispersion into stream beds, or they can result from hydromorphic dispersion and precipitation in the streambed. Acid water conditions and reducing conditions promote the chemical migration of the manganese. The associated metals are then scavenged by coprecipitation and adsorption. The presence of pyrite in the bedrock promotes these surficial processes.

Aluminum

The similarity in areal distribution of aluminum and titanium (fig. 15) is predictable on the basis of the known geochemistry of the two metals. Titanium is usually associated with aluminous host rocks in both metamorphosed and unmetamorphosed terranes (Force, 1976) and with alkalic rocks in igneous terranes (Herz, 1976). The geochemical association of titanium and aluminum in the weathering environment moreover is demonstrated by the high titanium content of bauxite (Patterson and Dyni, 1973, p.37).

Drainage basin shale might be the first source that may come to mind for the high aluminum zones in anomaly A, but the distribution patterns of the aluminous zones show that they crosscut the regional trend of the stratigraphic units in a similar manner to other elements comprising anomaly A. The map plot shows that above median aluminum follows two subparallel, linear northerly to northwesterly-trending trends within, in relation to the titanium ellipse. One possible cause of these high aluminum concentrations could be flocculation of Al-hydroxide at the water-stream bed interface from highly acid groundwater entering the stream environment. These conditions could be brought about by intense leaching within fractures of the same trend as the aluminum anomalies. The acid ground water could result from oxidizing sulfides within the proposed fracture system. Alternatively, as discussed above with respect to manganese however, intense weathering could also have resulted in the residual concentration of aluminum in the drainage basin bedrock, which subsequently was swept into the drainage basin alluvium. Detailed studies are necessary to determine which is the dominant cause for the selective concentration of aluminum along certain zones within anomaly A.

Simple correlation analyses of the NURE data set within anomaly A show the following significant, positive correlations:

	V	Sc	Na	Ce	Sm	Fe	La	Mn
Al	.72	.70	.53	.52	.50	.43	.40	.27

Zirconium

Samples from the central zone and portions of the periphery of anomaly A are depleted in zirconium (fig. 16). Zirconium depletion is inferred on the basis of the ubiquitous occurrence of high zirconium in stream sediments in the region surrounding anomaly A.

One northwesterly-trending zone within the general area of zirconium depletion may be significant. The zone coincides with a similar trend of high tin (fig 10), and with the hashured (titanium depleted ?) area within the titanium ellipse. It may be that the Zr-Sn relationship reflects the presence of zirconium minerals with tin as reported at Magnet Cove, Arkansas (see above discussion of the Sr-Sn-Au anomalies). The implications of this apparent zirconium depletion, which generally blankets anomaly A are not known at this time, but may be worth investigating. Usually alkalic igneous systems contain high amounts of zirconium.

Positive correlations with zircon are as follows. More realistic correlation results could be obtained if the upper 15 percent of the samples, (that is, those which exeed the upper reporting levels of the spectrographic method) were included in the correlation analysis:

	Au	Ti	Sn	Y	B	Nb
Zr	.64	.28	.24	.24	.17	.14

The correlation of Zr-Au, Zr-Sn, and Zr-Nb are statistically nonsignificant, but might be geologically significant. With some exceptions such as the one coincident map pattern of Zr-Sn discussed above, anomalies involving zirconium and the other closely correlated elements occur chiefly on the outer margin of the titanium ellipse. Nevertheless, the associations might reflect a suite of heavy minerals that closely relate to the underlying source rocks of anomaly A.

CONCLUSIONS

We prefer to invoke a cause other than normal basin sedimentation to account for geochemical anomaly A. It can be argued that if these geochemical signatures typify lithologic compositions within the Pennsylvanian sedimentary sequence, the same geochemical characteristics should prevail elsewhere in the succession along regional strike; our data suggest this is not the case. There are, however, other transgressive titanium anomalies farther south, following similar trends to the lanthanum on Plate 1, that might likewise relate to northwesterly-trending alkalic dike systems and related structures similar to those proposed for anomaly A (Watts and others, in press; Hinkle and others, in press).

Basalt, breccia, and albitite dikes found in Pendleton County are the only igneous rocks known in West Virginia (Garnar, 1956; Fullagar and Bottino, 1969; Dennison and Johnson, 1971), as far as we are aware. Comparable rocks in a neighboring areas of Virginia have yielded radiometric ages as young as Eocene, but most are probably of Triassic and Jurassic age. A few miles to the northeast in Pennsylvania, dikes of mica peridotite of about 185 Ma are reported in the Pennsylvanian coal measures near Masontown, in Fayette County (Pimentel and others,1975) and a second set is reported at Dixonville, Pennsylvania in Indiana County (Honess and Graeber, 1926). Both of the Pennsylvania occurrences of mica peridotite dikes are located in the trough of a syncline adjacent to the Chestnut Ridge anticline. This same anticline passes through the area of anomaly A and deflects sharply near the town of Bridgeport (Cardwell, 1982) on the eastern margin of anomaly A.

Two mineralized alkalic complexes may be appropriate models for anomaly A. The first might be Hicks Dome in southern Illinois. There fragments of Precambrian material were carried upward 8000 feet (Snyder and Gerdemann, 1965, p.466). The formation of diatremes in southern Illinois and southeastern Missouri began with the intrusion of alkalic magma in the Precambrian basement--in the case of Hicks dome during the late Paleozoic. The intrusion was then followed by gas buildup and violent explosion during the Permian, raising the stratigraphic section thousands of feet vertically and bringing rock fragments upward. Afterwards there was intrusion of mafic and ultramafic dikes followed by fluorite-sulfide mineralization (Grogan and Bradbury, 1968; Snyder and Gerdemann, 1965). Hicks dome has been dated by K-Ar at 281-258 Ma (Zartman, 1977).

Hicks dome is only one of many diatremes and mafic-ultramafic rocks that cut Pennsylvanian sediments and coal measures in the midcontinental region (Snyder and Gerdemann, 1965; Zartman, 1977). There are many similarities between these occurrences and anomaly A.

The second possible analogy to anomaly A is Magnet Cove in the Ouachita basin of Arkansas. The geochemical characteristics of Magnet Cove (Erickson and Blade, 1963) provide a worthwhile model for comparing anomaly A. The Magnet Cove titaniferous deposit is an alkalic igneous-carbonatite complex intruded into folded and faulted Paleozoic rocks. Localization of igneous emplacement was at abrupt change in strike of major structural elements, as we propose for anomaly A. There is evidence of explosive activity (Erickson and Blade, 1963). The titanium minerals at Magnet Cove include rutile, brookite, perovskite, anatase, and sphene, all within veins mostly hosted by carbonatite. Anomalous barium, strontium, and cerium-group REE minerals, manganese, vanadium, base metals, and tin as traces in oxide and sulfide minerals are associated with the deposit. The tin at Magnet Cove is found in Zr-rich minerals and in rutile and brookite. The slightly elevated tin content of some samples from anomaly A therefore could be significant.

Two of the largest aeromagnetic highs in the state are associated with anomaly A (King and others, in press). The aeromagnetic anomalies have northwesterly long axes similar to the titanium ellipse, and overlap with, but are slightly displaced westerly from the ellipse. Preliminary interpretation of these aeromagnetic highs indicates that they may reflect mafic basement rocks (King and others, in press). In that mafic alkalic basement rocks typify the diatremes such as Hicks dome in the midcontinent (Snyder and Gerdmann, 1965), we consider this a favorable characteristic. The Hicks dome model allows for the mechanism of bringing materials to the surface in an explosive manner thousands of feet, but does not preclude ascending hydrothermal solutions as well. The presence of evaporites in the subsurface would be useful in the generation of metalliferous, heated fluids.

Finally, we know that evaporite deposits at depth could provide a source of metals as well as a brine solution to transport them. The heat and fracture permeability that explosive activity related to an alkalic intrusion could provide is a very efficient mechanism for producing a zone of mineralized leakage. We consider vertical leakage into surface country rock, and deposition of titanium, REE, oxide, carbonate, and sulfide minerals to be the ultimate cause of the stream sediment geochemical anomalies.

RECOMMENDATIONS

We recommend further study of anomaly A that would include:

(1) Follow-up field study to identify the immmediate bedrock sources of Ti and associated elements in the anomalous drainage basins. This might involve follow-up sampling employing heavy mineral concentrates to ascertain Ti-rich bedrock sources. Location of specific areas should be followed by a search of bedrock for igneous dikes, extensive brecciation, for veins and stringers of sphene, perovskite, rutile, ilmenite, leucoxene,

rare earth minerals, unusual Zr-minerals, fluorite, barite, hematite, carbonate minerals, and base-precious metals, and any other evidence that would suggest hydrothermal alteration or fenitization of the country rocks. The detailed follow-up in bedrock areas might be accompanied by sampling of soils and saprolite where appropriate.

(2) Search drill hole records for reports of unusual mineral occurrences, igneous rock types, brecciated host rock and faulting, fracturing, and brecciation with carbonate or hematite stringers that would suggest explosive structural disturbances and/or fenitization of the country rock.

(3) Ground magnetic surveys should be done in anomaly A. Carbonatites and mafic-ultramafic rocks should have considerable magnetite that would give strong peaks locally.

(4) Because economic placer deposits could result from slightly, but subeconomically mineralized drainage basin bedrock, investigate for placer accumulations of titanium, REE, and possibly other valuable minerals in downstream areas of the titanium ellipse (fig. 17). Below are some suggested areas to search for mineralized bedrock sources and downstream placers:

(a) Comparison of the tributary patterns with anomalies in the northern lobe of the titanium ellipse suggests possible placer accumulations of titanium and REE minerals near the towns of Haywood, Gypsy, and Shinston. These placers appear to accumulate downstream from bedrock source areas near the towns of Flemington, Rhinehart, and Oakdale; outcrops or soil anomalies of high titanium, REE and associated elements might be found near these towns. The geochemical pattern suggests cumulative contributions of titanium from mineralized bedrock in the upper to middle drainage basin bedrock of the tributary streams, which has resulted in the elongated northwesterly trend of the titanium isopleth.

(b) The southern lobe of the titanium pattern also follows a northwesterly trend, although the association with LANDSAT lineaments is not as clearcut. The bedrock source areas are indicated by the titanium isopleths to be in the upper portions of tributaries draining northward from the towns of Jane, McWharter, Rockford, and Jarvisville.

(c) The linear north to northwest-trending titanium anomaly west of the main elliptical high of anomaly A begins near the town of Coldwater, and follows northward downstream on Tom's Fork. Heavy titanium and REE minerals might be accumulated in placers near West Union, at the confluence of Tom's Fork with the main river. The chief source of the titanium appears to be bedrock near the town of Coldwater at the headwaters of Tom's Fork. The source of titanium and REE in this zone may be a northerly-trending mineralized structure.

(5) The dome immediately northwest of anomaly A (marked B on fig. 6) should be field examined in the same manner as described for anomaly A.

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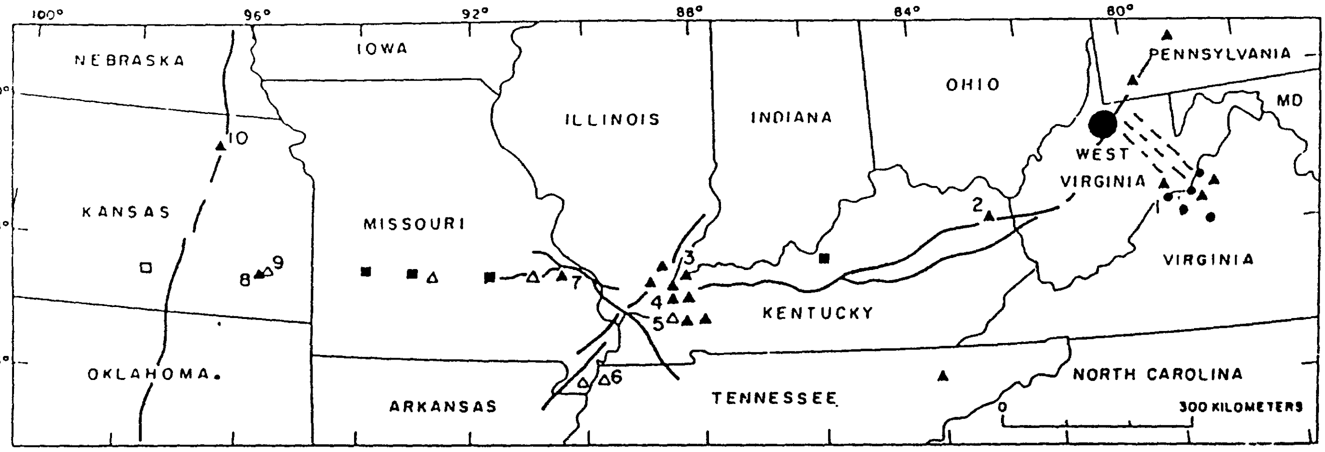


Figure. 1 Occurrences of alkalic rocks and related cryptovolcanic features within the 38th parallel lineament. Known ages range from 46.9-47.2 Ma at Highland Co., Virginia to 377-388 Ma at Avon, Missouri. Symbols represent individual bodies or localized clusters (open where found in subsurface only): circle, felsic rocks, mostly nepheline syenite and phonolite; triangle, mafic rocks, mostly nepheline basalt, mica peridotite, land lamprophyre; square, intensely disturbed localized uplift of probably cryptovolcanic origin. Heavy lines represent prominent basement faults, modified on the basis of present data; dashed where inferred. Large circle is anomaly A. Figure modified from Zartman (1977).

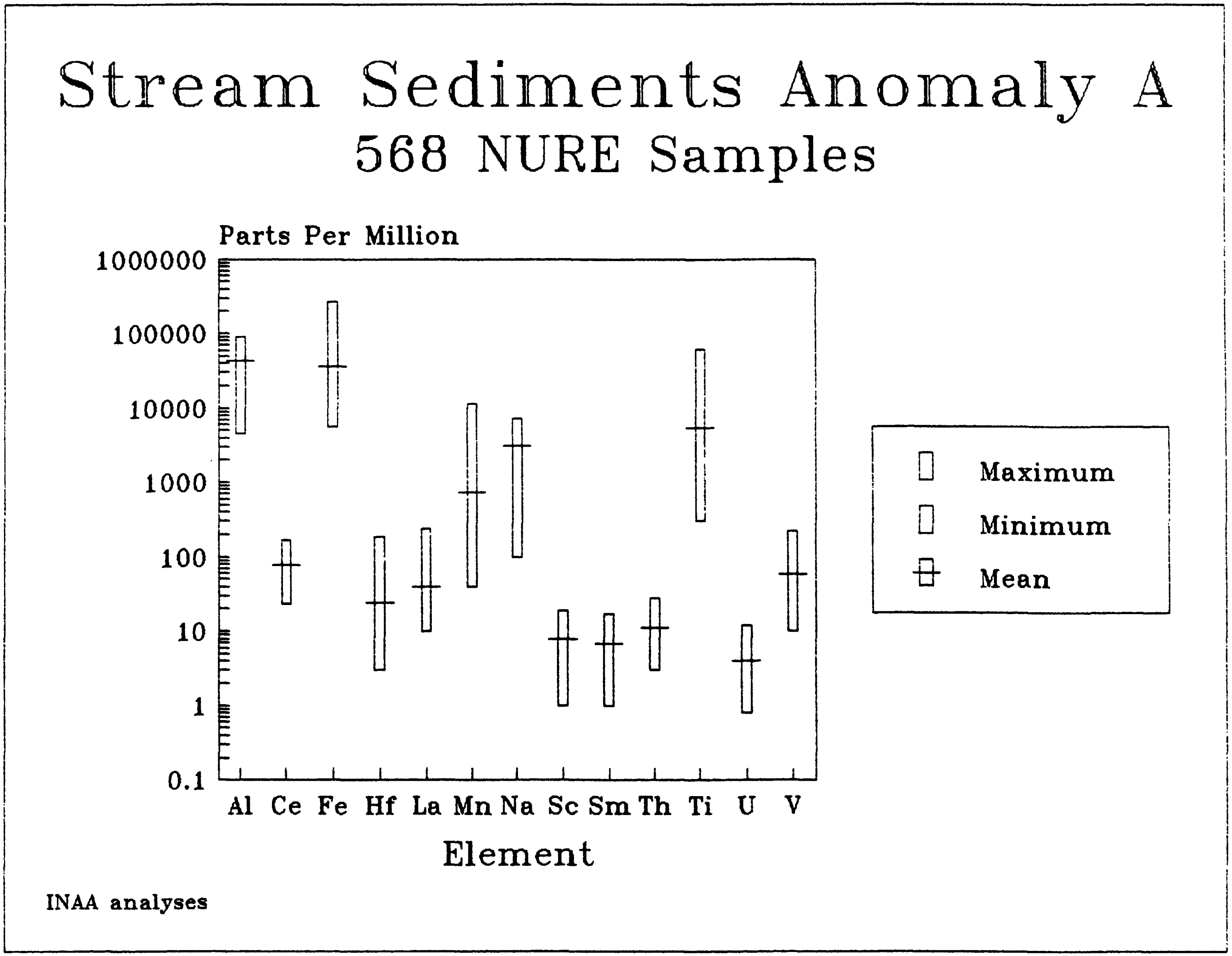


Figure 2. Element abundances in anomaly A from NURE data

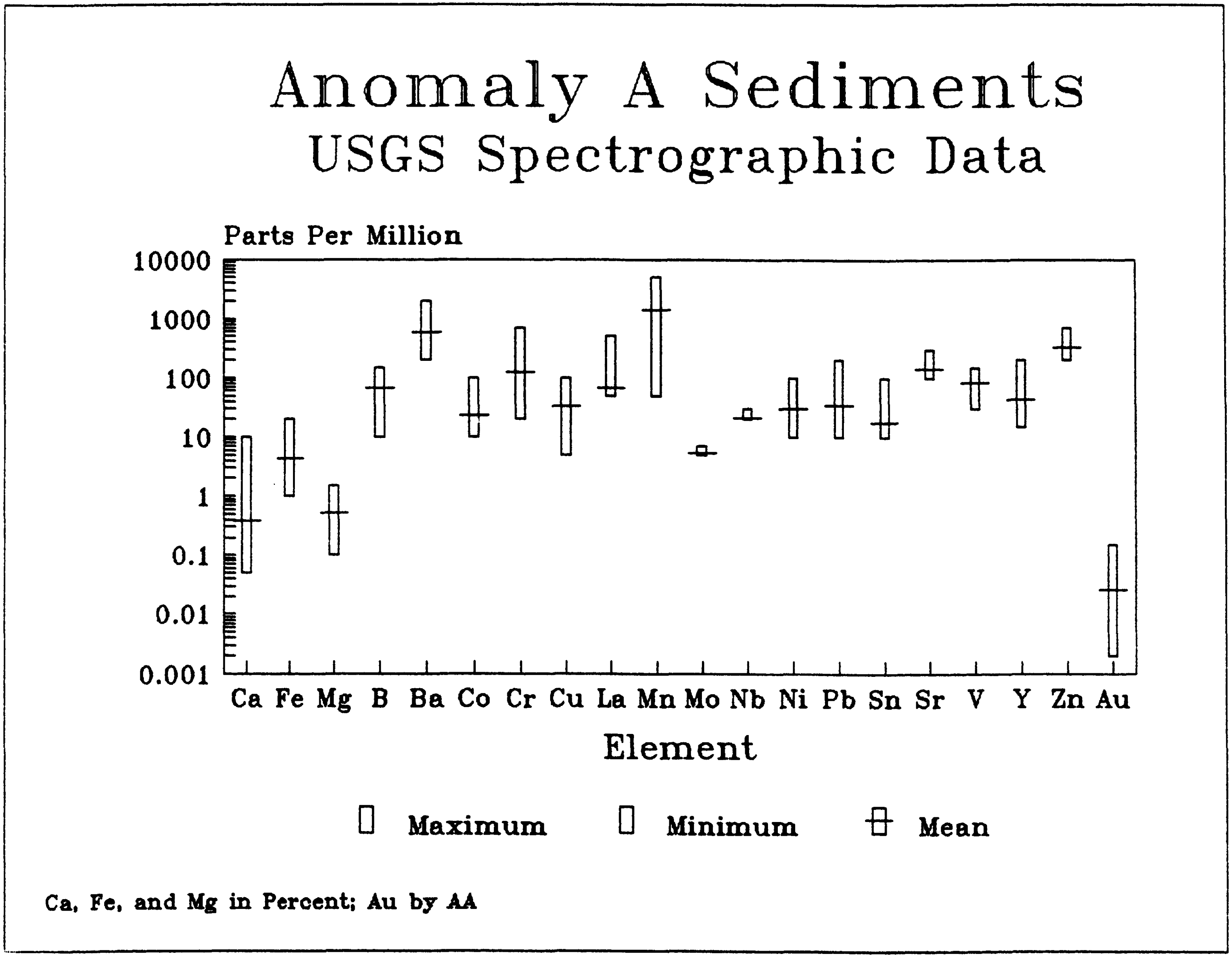


Figure 3. Element abundances in anomaly A from USGS data

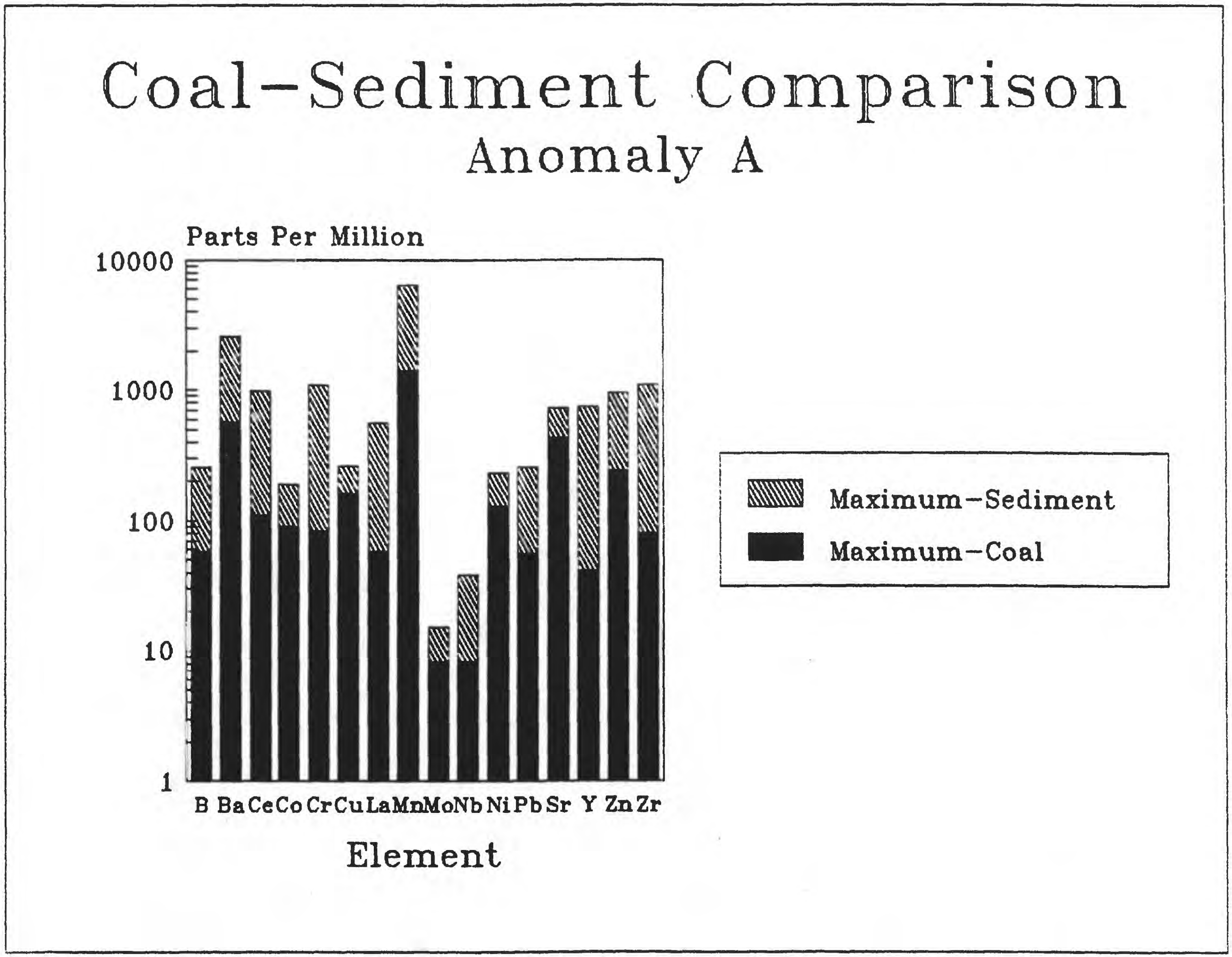


Figure 4. Comparison of maxima of stream sediment and coal ash

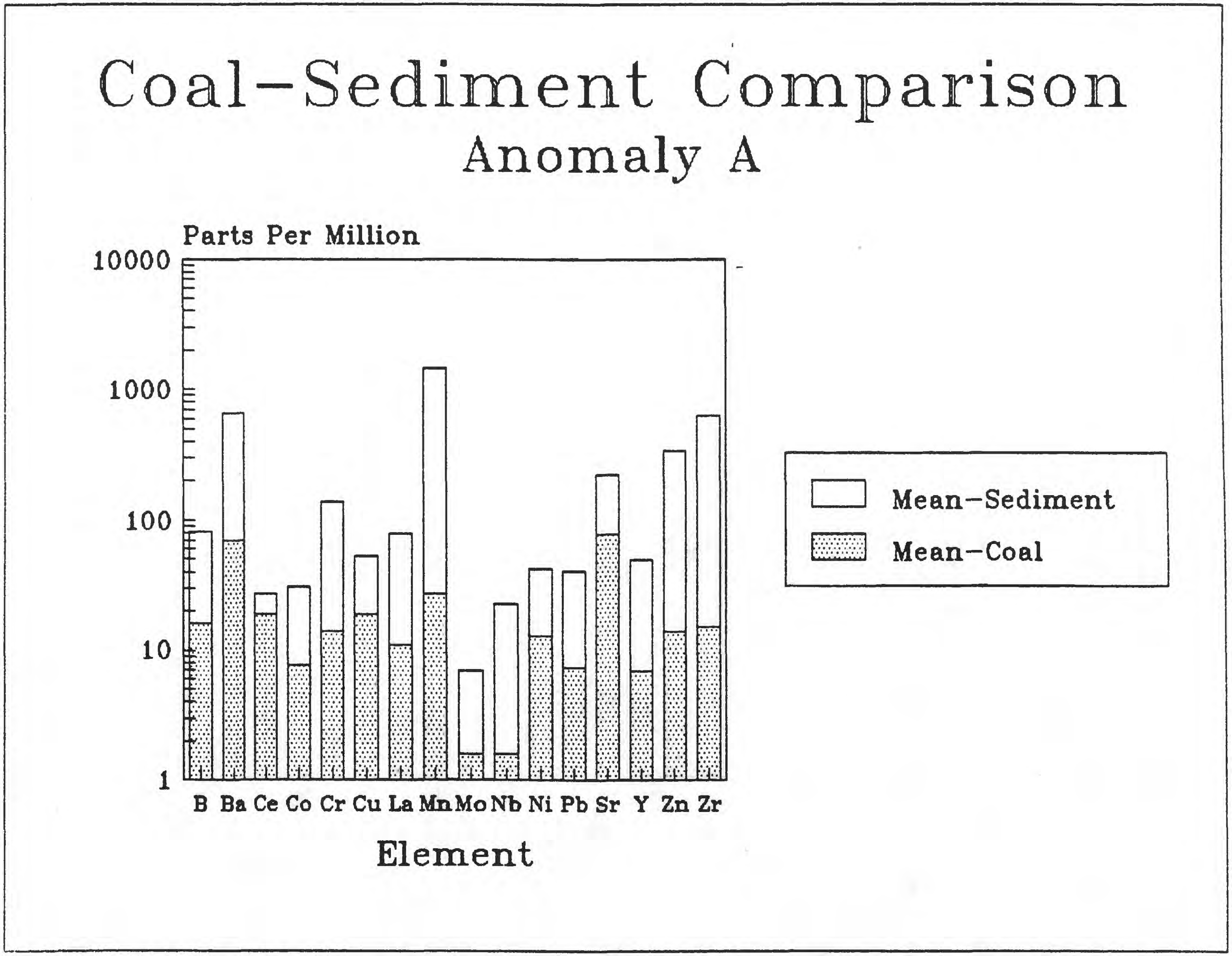


Figure 5. Comparison of means of stream sediment and coal ash

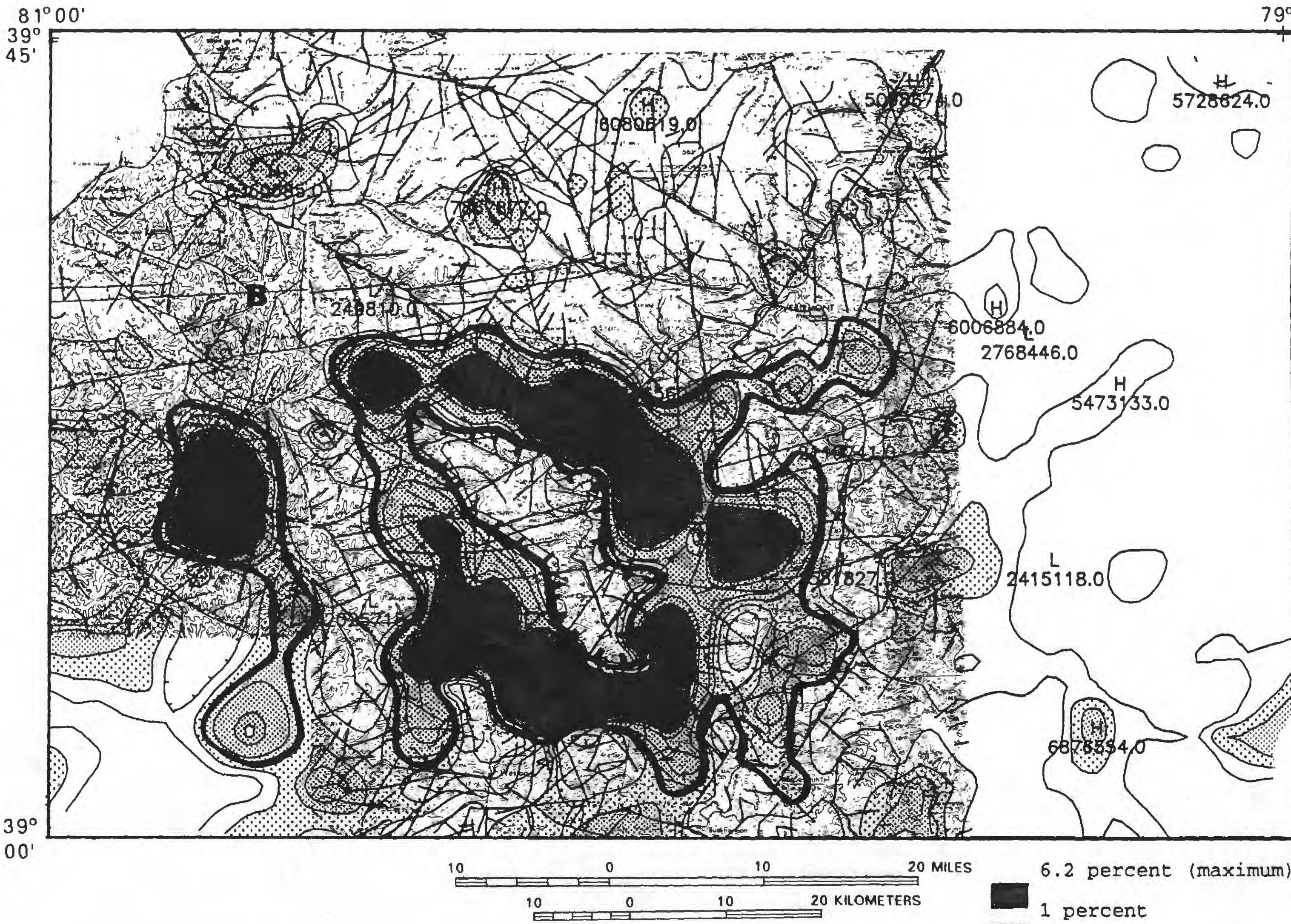


Figure 6. Ti distribution in relation to LANDSAT lineaments

Outline of anomaly A-hashure is a Ti low
Landsat lineament (Reynolds, 1979)
Isopleths of Ti concentrations(ppm except as indicated)-hashures are a Ti low-as percentiles of the NURE data distribution within anomaly A

Fig 3,4

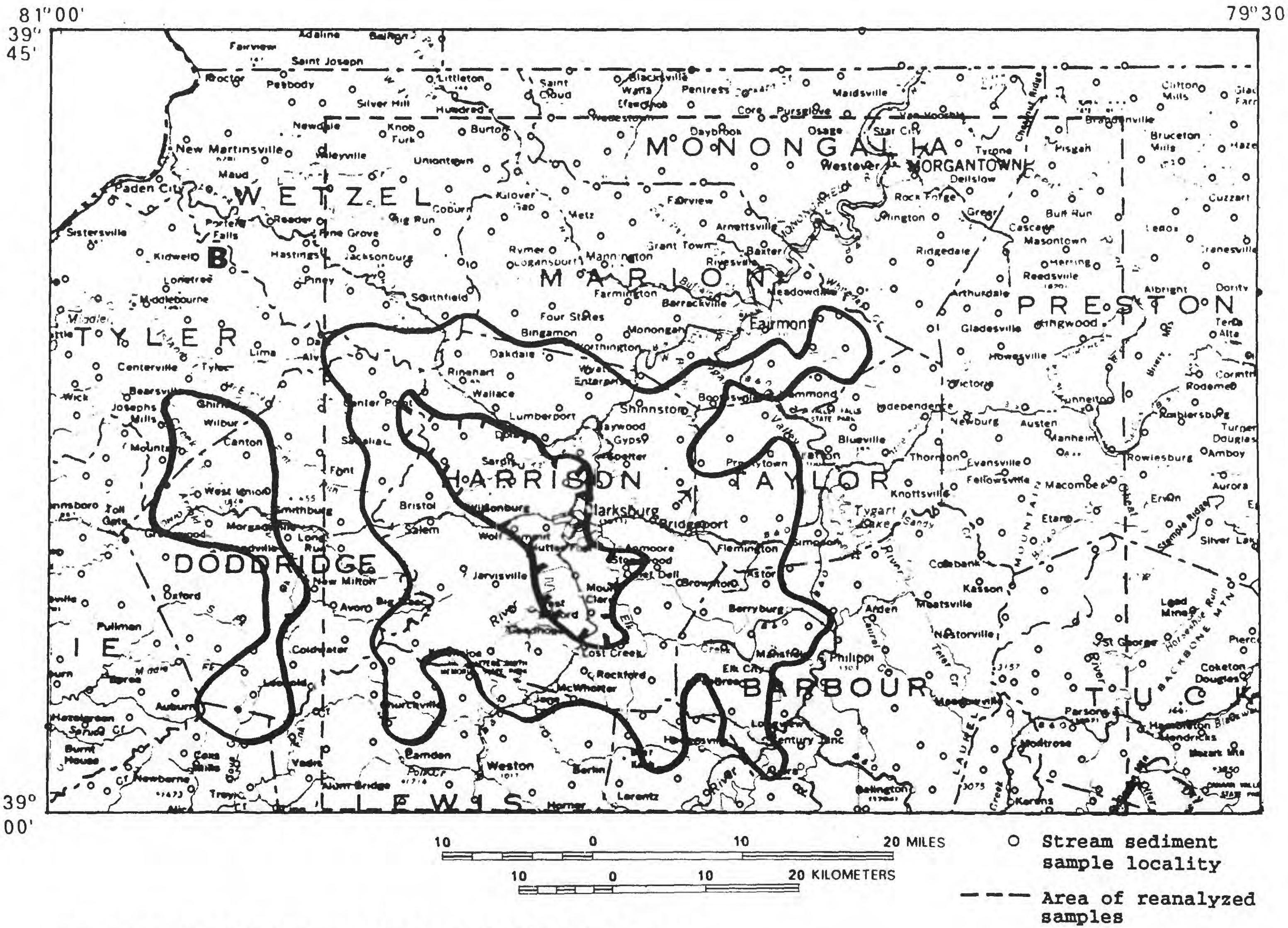
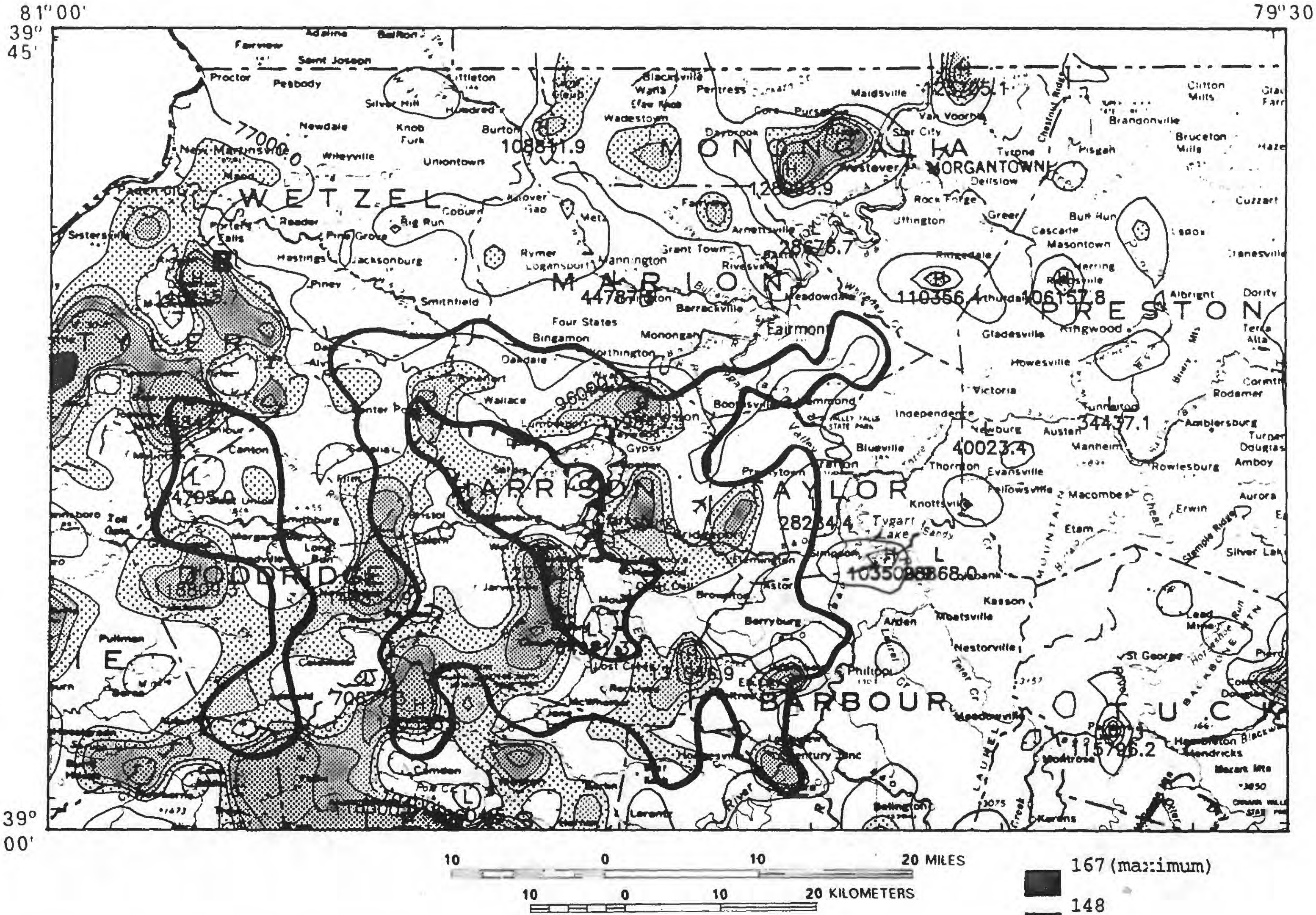


Figure 7. Distribution of stream sediment sample sites
Outline of anomaly A-hashure is a Ti low



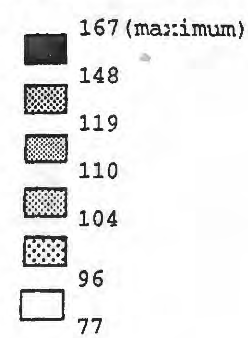


Figure 8. Cerium distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of Ce concentrations(ppm)-hashures are a
Ce low-as percentiles of the NURE data
distribution within anomaly A

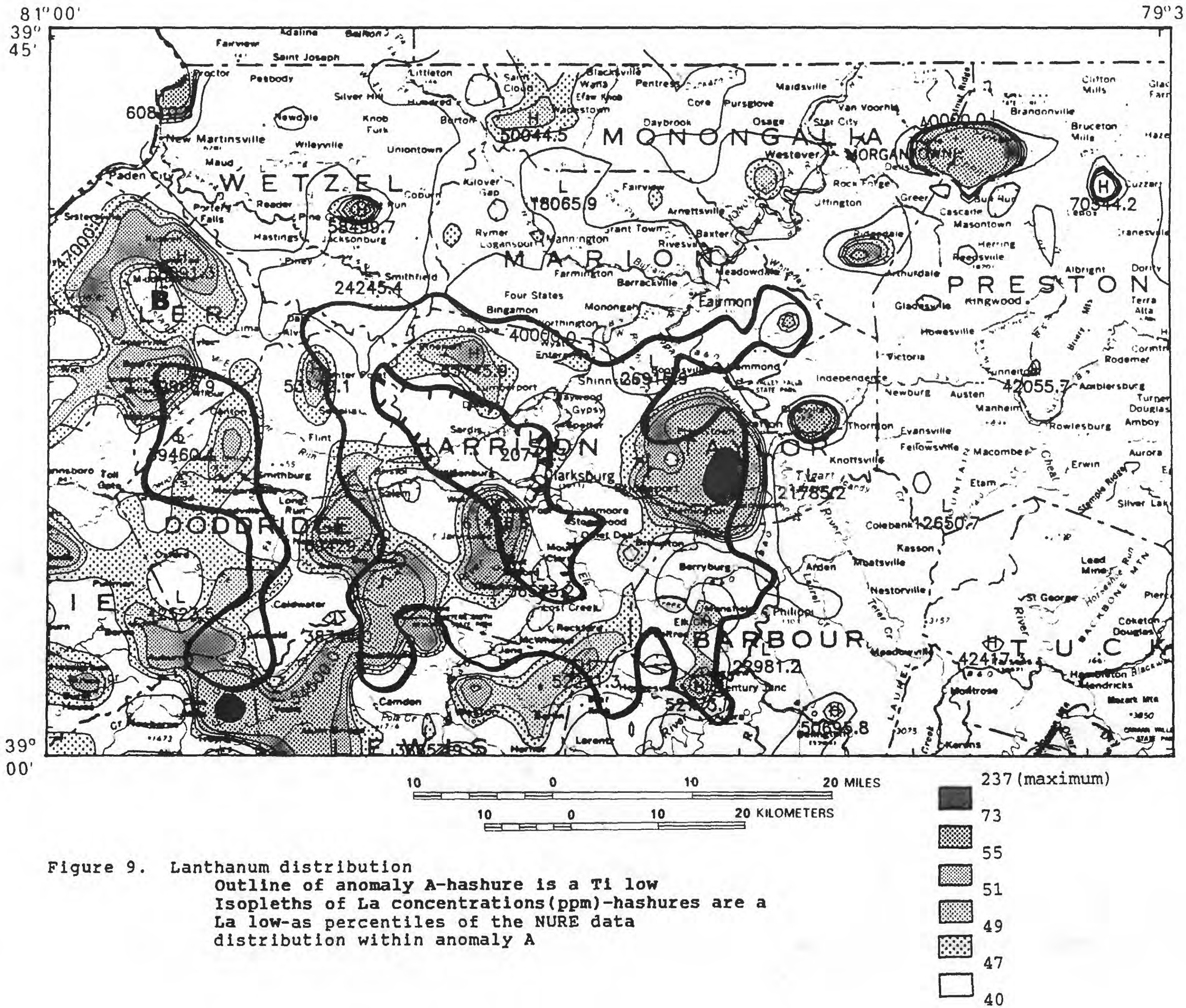


Figure 9. Lanthanum distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of La concentrations(ppm)-hashures are a
La low-as percentiles of the NURE data
distribution within anomaly A

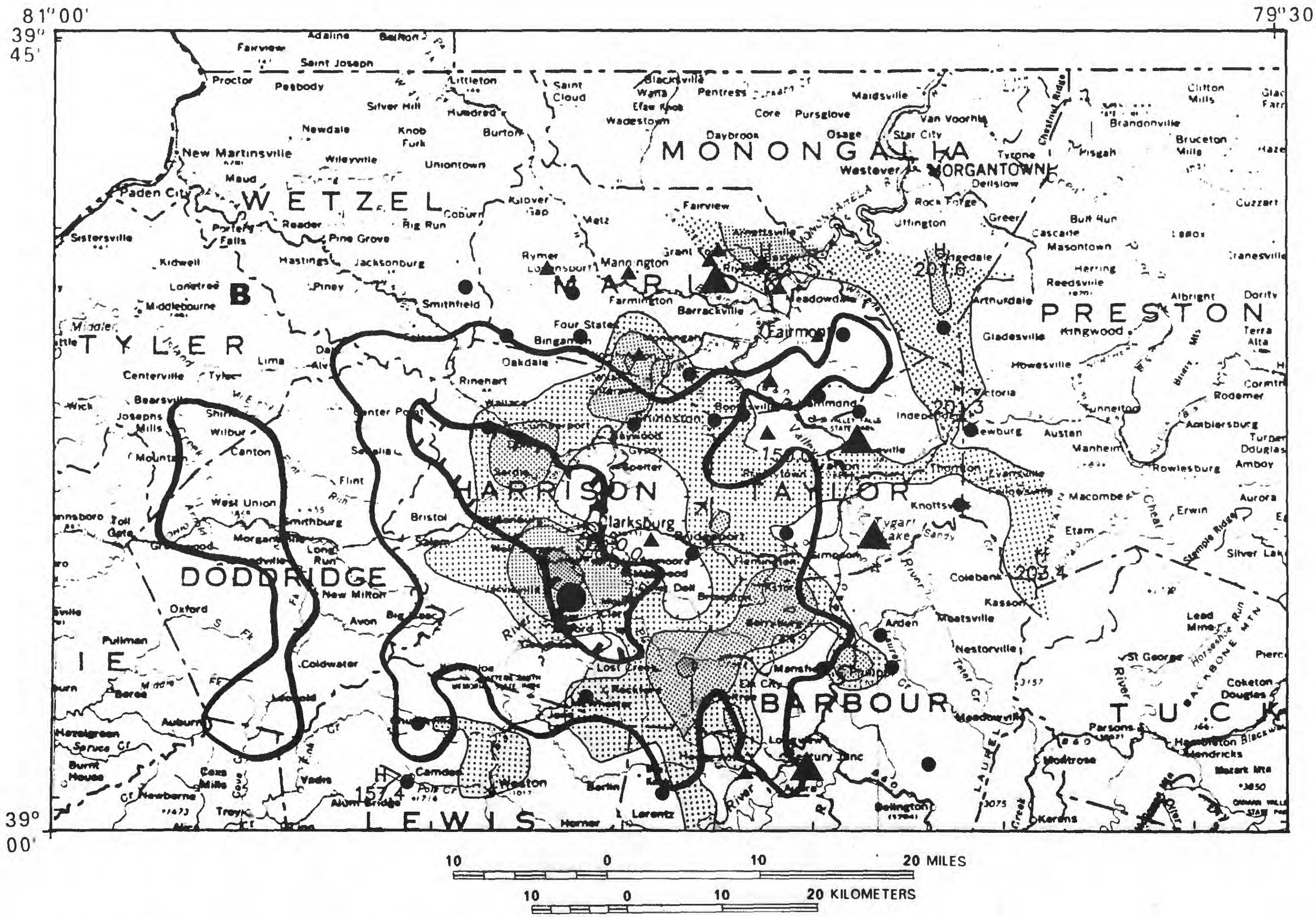


Figure 10. Strontium, gold, and tin distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of Sr concentrations(ppm)-hashures are a
Ba low-median value and above of the USGS data
distribution within anomaly A

- 300 (maximum value)
- 200
- 150

Gold symbols

- ▲ Detectable (at slightly less than .002ppm)-.010 ppm
- ▲ .011-.15 ppm

Tin symbols

- ● Detectable (at slightly less than 10 ppm)-15 ppm
- ● Reported value of 100 ppm

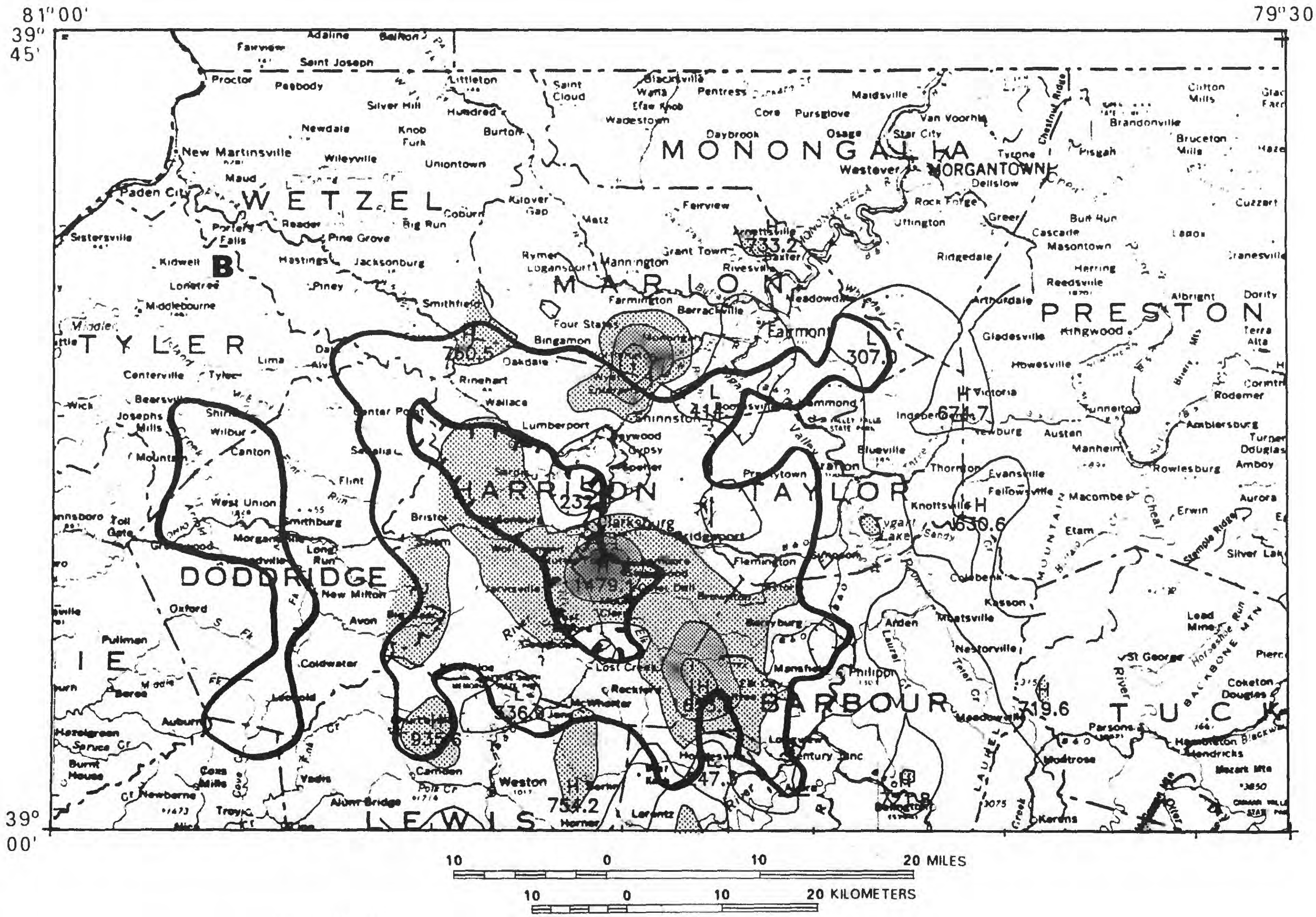


Figure 11. Barium distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of Ba concentrations(ppm)-hashures are a
Ba low-median value and above of the USGS data
distribution within anomaly A

2000 (maximum)
1500
1000
700
500

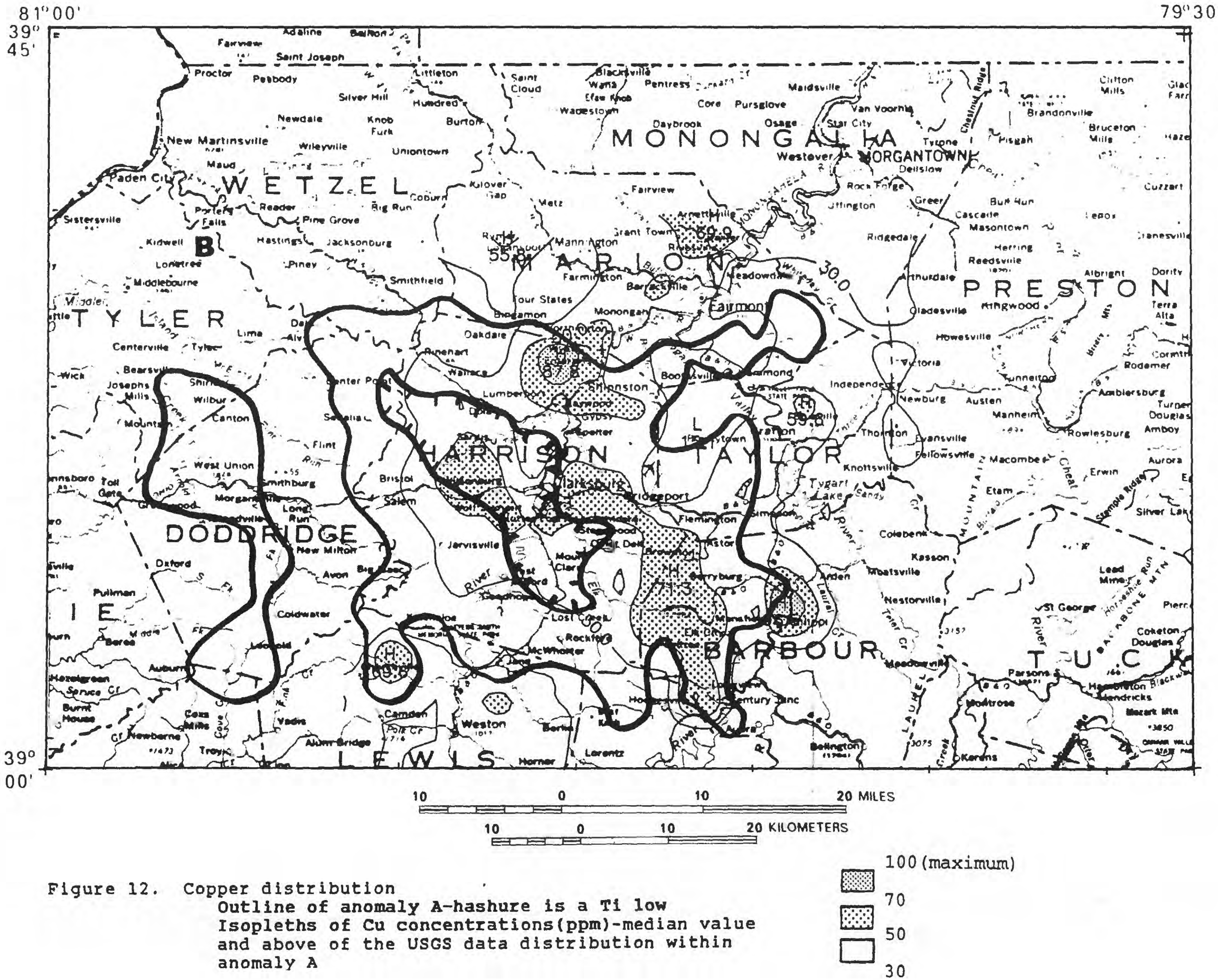


Figure 12. Copper distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of Cu concentrations(ppm)-median value and above of the USGS data distribution within anomaly A

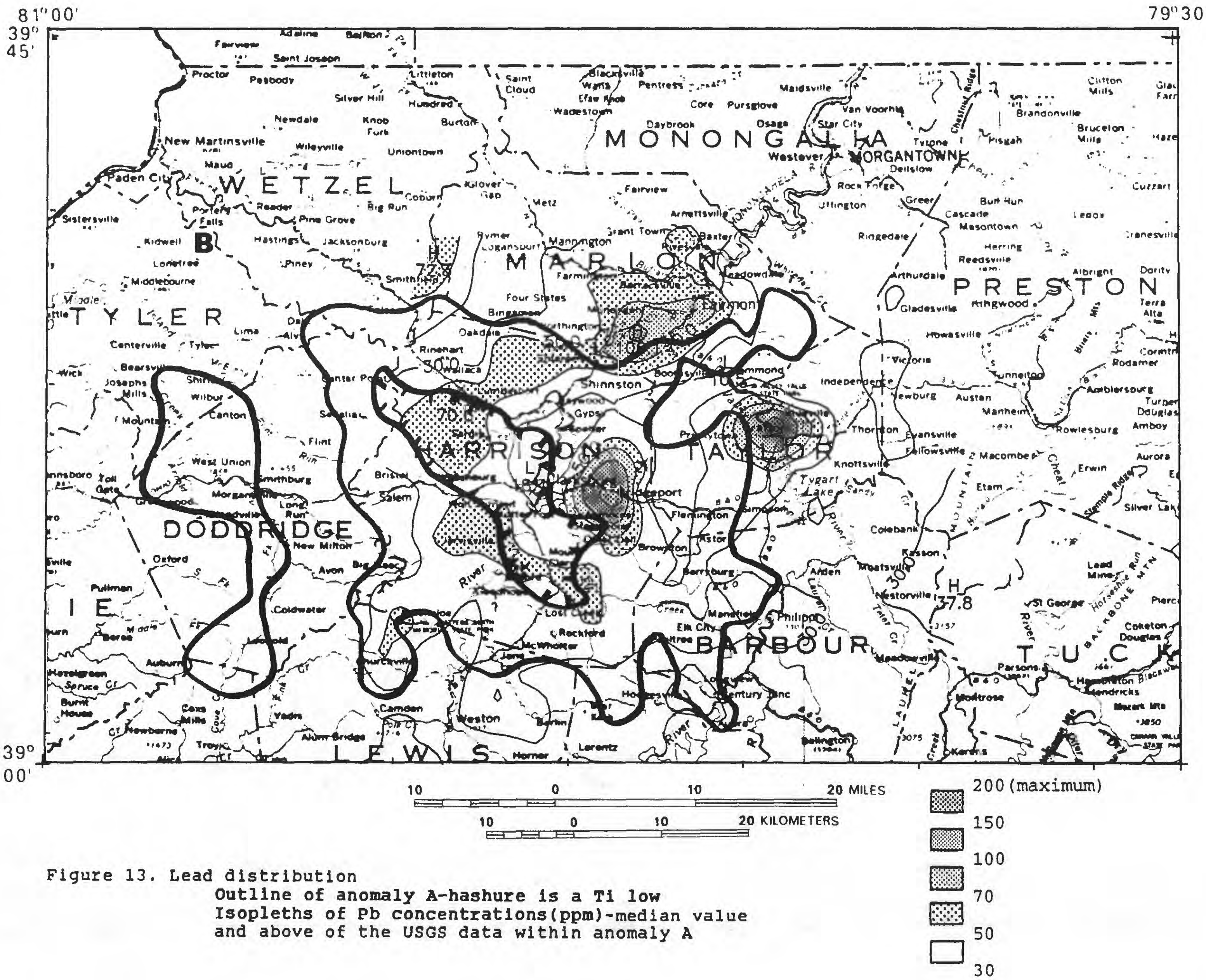


Figure 13. Lead distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of Pb concentrations(ppm)-median value
and above of the USGS data within anomaly A

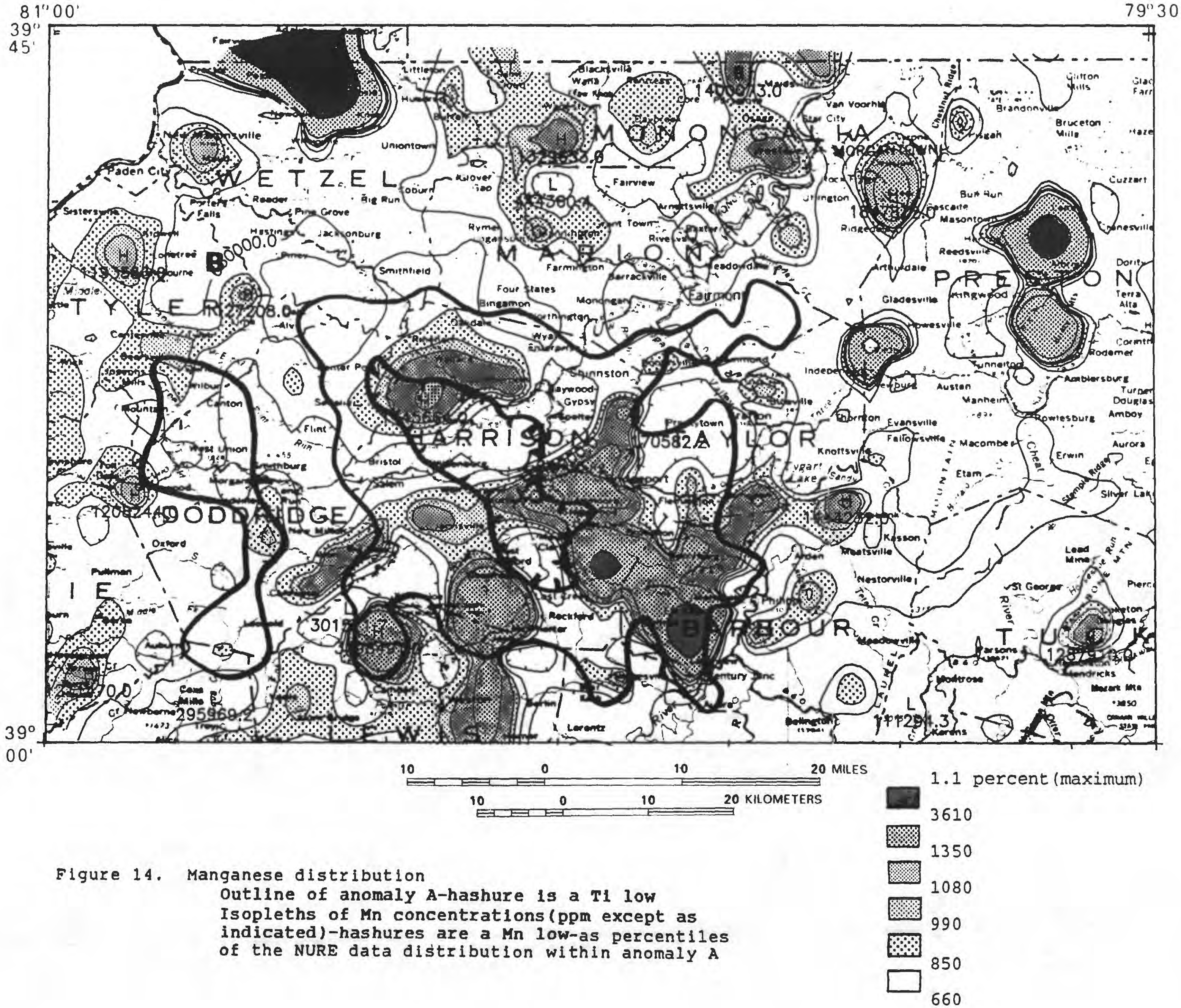


Figure 14. Manganese distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of Mn concentrations(ppm except as indicated)-hashures are a Mn low-as percentiles of the NURE data distribution within anomaly A

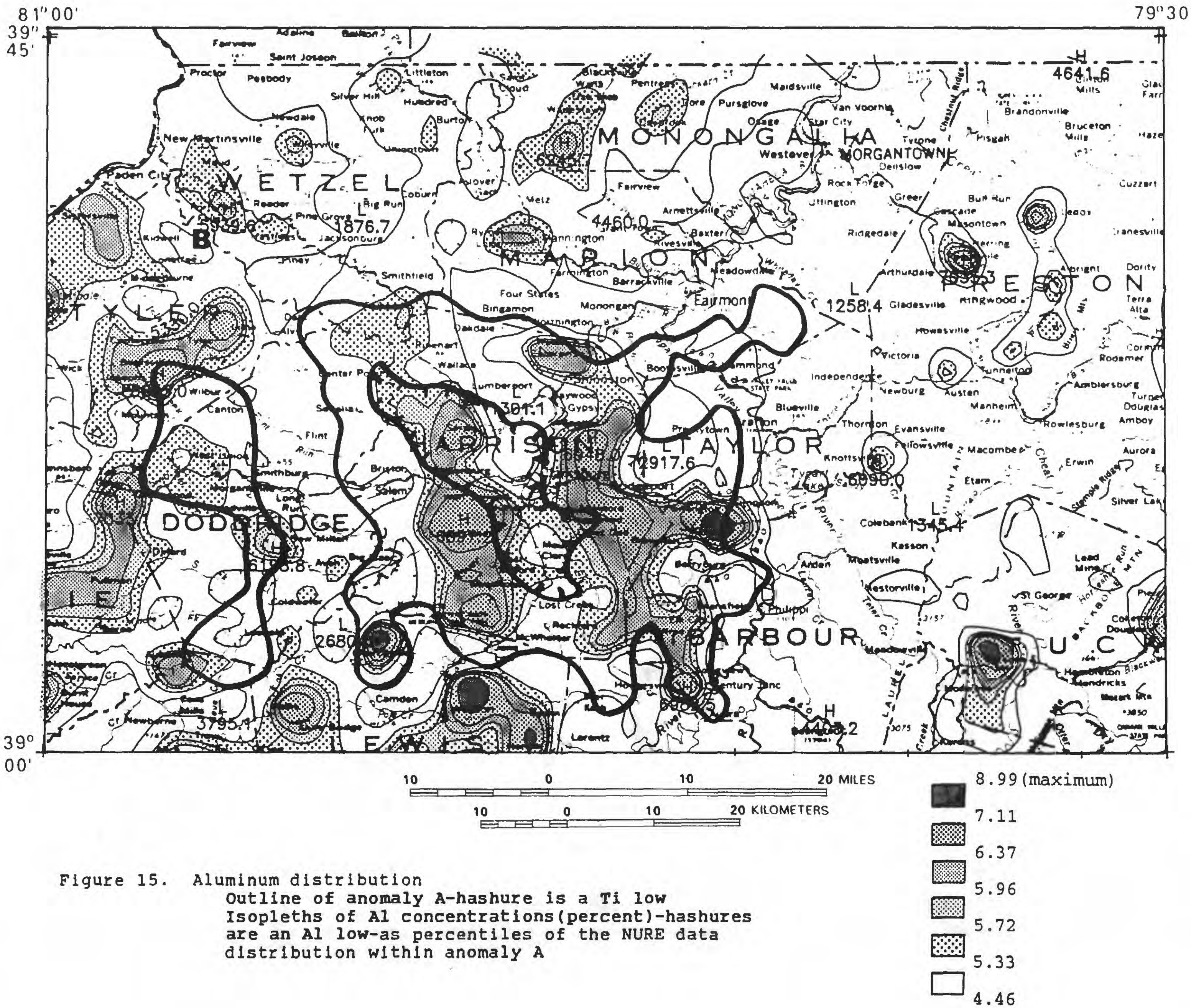


Figure 15. Aluminum distribution
Outline of anomaly A-hashure is a Ti low
Isopleths of Al concentrations(percent)-hashures are an Al low-as percentiles of the NURE data distribution within anomaly A

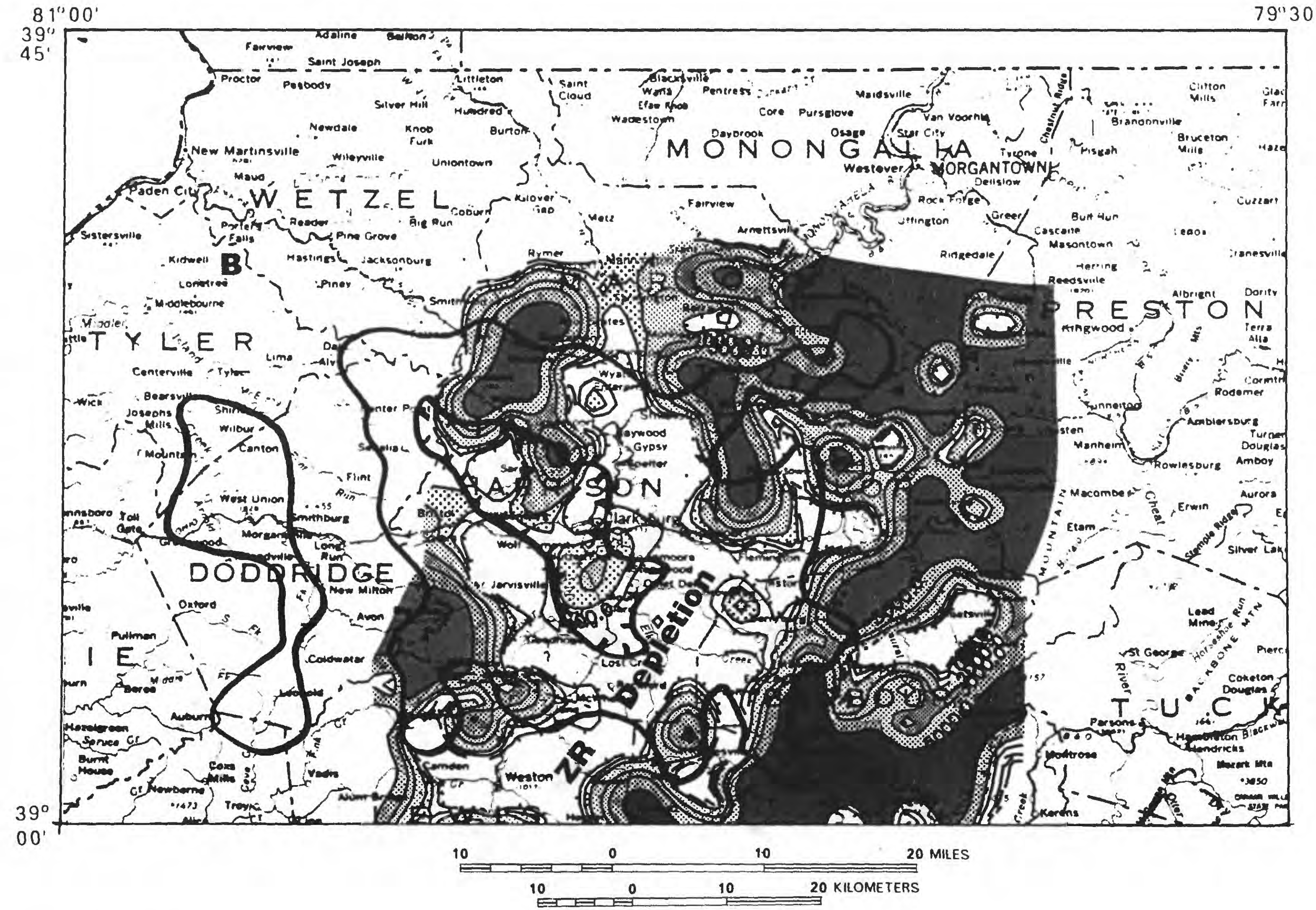


Figure 16. Zirconium distribution
Outline of anomaly A-hashure is a Ti low
Zr concentrations(ppm)-shows zones of
values above and below 500 ppm (75 percent of
values are above 500 ppm) The zones of values
below 500 ppm are considered areas of Zr depletion

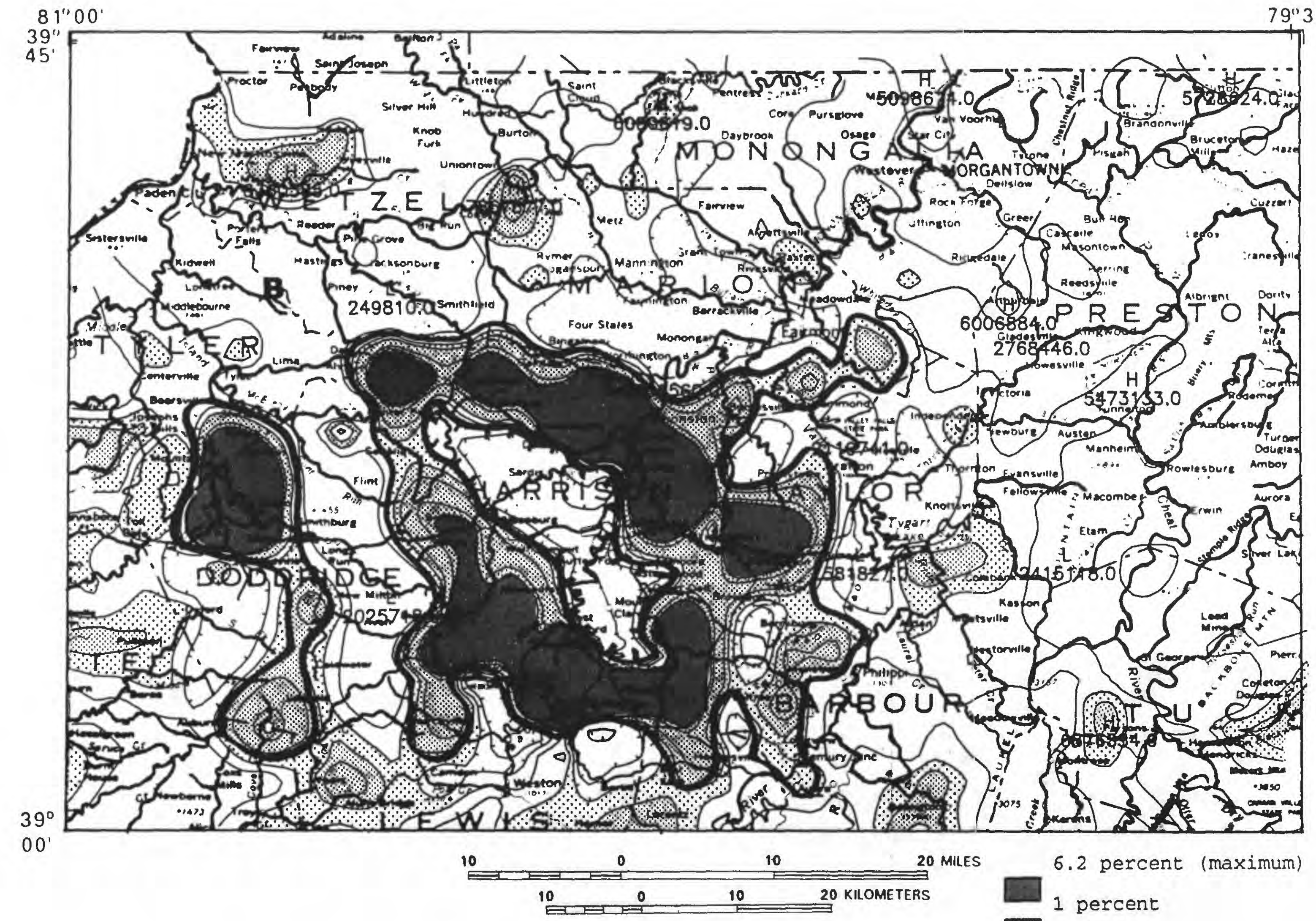


Figure 17. Titanium distribution in relation to drainage basins
Outline of anomaly A-hashure is a Ti low
Isopleths of Ti concentrations(ppm except as indicated)-hashures are a Ti low-as percentiles of the NURE data distribution within anomaly A