AN INTEGRATED GEOPHYSICAL STUDY OF THE ZUNI LINEAMENT IN NEW MEXICO

by

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ABSTRACT

A zone of crustal weakness associated with the Zuni Lineament in the southern half of New Mexico has been delineated by lead isotope measurements, a microearthquake study and magnetic depth soundings. The lead results of Slawson and Austin (1962) revealed the possible existence of a northwest trending zone of isotopically similar lead, bounded on either side by isotopically variable leads. This feature passes through Socorro and Alamogordo, New Mexico, and is coincident in this area with the Zuni Lineament. The microearthquake results (Sanford and Long, 1965) show that a shallow crustal zone of weakness is associated with the isotopically similar zone. The magnetic results (Schmucker, 1964; Livingstone, 1966) confirm that the structure is shallow, and also indicate that it may be a region of high electrical conductivity.

It is suggested that this zone of weakness centred on the Zuni Lineament has served as a conduit system for hydrothermal mineralizing solutions which carried the lead to its final sites of deposition. The lead was originally introduced into the Precambrian rocks about 1550 m.y. ago, mixed with radiogenic rock lead of that age about 30 m.y. ago, and then finally emplaced.

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CHAPTER I

1.1 Outline of Problem.

The present report is an attempt to correlate the results of some geophysical surveys in south and central New Mexico with geochemical and geological information. Lead isotope data (Slawson and Austin, 1962; this report), magnetic depth soundings (Schmucker, 1964; Livingstone, 1966), a microearthquake investigation (Sanford and Long, 1965), all have a bearing on the geologists' discussion of lineaments in New Mexico (Mayo, 1958). Constraints imposed by the different models employed seriously limit the possible interpretation of the nature of the lineaments, especially the nature of the Zuni Lineament.

A lineament is probably best described as a large-scale, approximately linear arrangement of structural features, although geologists themselves disagree over precisely what the term means. A lineament is marked by some or all of the following: faults, folding, uplifts, volcanics and intrusives. Its linear nature is believed to be due to shearing at depth.

The Zuni Lineament is thought to consist of the Guadalupe Mts. in western Texas; the Sacramento Uplift, Mt. Taylor volcanics, and Zuni Uplift in New Mexico; the Defiance Uplift in northeastern Arizona; and the Circle Cliffs Uplift, High Plateau volcanics, and the Gold Hills district of Utah. Superimposed features such as the Sevier fault and the Rio Grande graben suggest no recent movement has taken place along the lineament. It is crossed by other lineaments at numerous points (Mayo, 1958; Kelley, 1955).

1.2 Isotopic Correlation with Zuni Lineament.

In a lead isotope study of what appeared to be a geologically simple area, Slawson and Austin (1962) discovered a remarkable correlation between the geographic distribution of the lead samples and their isotopic composition. Leads of an essentially similar isotopic composition (x ranging from about 18.4 to 19.0 - see Table 1-1 for explanation of symbols) were found to occur within a northwest trending belt, bounded on either side by leads of a variable isotopic composition (x ranging from about 19.2 to 25.4). The belt, lying along a line joining Alamogordo and Socorro, New Mexico, coincides in this area with the Zuni Lineament.

1.3 Geomagnetic Measurements in South-central New Mexico.

In geomagnetic mid-latitudes, the external field of geomagnetic variations is found to be fairly uniform over large areas. If the variations measured by a chain of 3-component magnetometers (measuring the horizontal (H) and vertical (Z) components of the earth's field as well as the angle (D) between $\underline{H}$ and true north) are found to be consistently different from station to station, the differences can be attributed to the effect of inhomogeneities in the electrical conductivity distribution within the earth. Simple models of the earth's conductivity structure can then be set up and the surface fields that would be produced by them calculated. The parameters of the models are adjusted to

	$t = 0$ (present)	at any time t	$t = t_o = 4.55$ (age of Earth)
$\frac{206}{204}$	a	x	$a_o = 9.56$
$\frac{207}{204}$	b	y	$b_o = 10.42$
$\frac{208}{204}$	c	z	$c_o = 30.00$
$\frac{235}{204}$	V	$Ve^{\lambda' t}$	$Ve^{\lambda' t_o}$
$\frac{238}{204}$	$\propto V$	$\propto Ve^{\lambda t}$	$\propto Ve^{\lambda t_o}$
$\frac{232}{204}$	W	$We^{\lambda'' t}$	$We^{\lambda'' t_o}$

decay scheme	constant ($\times 10^{-9} yrs^{-1}$)
$U^{238} \rightarrow Pb^{206}$	$\lambda = .1537$
$U^{235} \rightarrow Pb^{207}$	$\lambda' = .9722$
$Th^{232} \rightarrow Pb^{208}$	$\lambda'' = .0499$

$$\propto = U^{238} / U^{235}$$

Table 1.1 Explanation of symbols used in isotopic work.

obtain agreement between the calculated and observed results. If agreement is obtained, then the model is considered perhaps to be an approximate representation of the earth's conductivity structure.

There are two major limitations to this method. The first is that only simple models can be used, otherwise calculations of the surface fields are far too complicated. The second limitation is that, by using simple models, the possibility exists that two or more models may fit the observed data. Nonetheless, it is possible to make some deductions about the earth's conductivity structure.

A magnetic depth sounding study by Schmucker (1964) along the southern New Mexico - Texas boundary revealed the existence of a conductivity anomaly to the southeast of the isotopic anomaly and approximately aligned with it. The region between Las Cruces, New Mexico, and Cornudas, Texas was found to be a transition zone between $\frac{Z}{D}$ ratios of about 0.05 to the west and of 0.15-0.20 to the east. The character of the long-period magnetic variations (>1 hr) recorded across the transition zone requires a large-scale change in the earth's conductivity at a depth of a few hundred kilometers. Schmucker has interpreted the results as a step discontinuity in the deep mantle structure. The step model by itself, however, does not provide complete agreement between observed and calculated surface fields, so it is necessary to assume the existence of a highly conductive region (Figure 1.1) between Las Cruces and Cornudas. The

STATIONS

TU	Tucson
LAC	Las Cruces
ORO	Orogrande
COR	Cornudas
SWE	Sweetwater

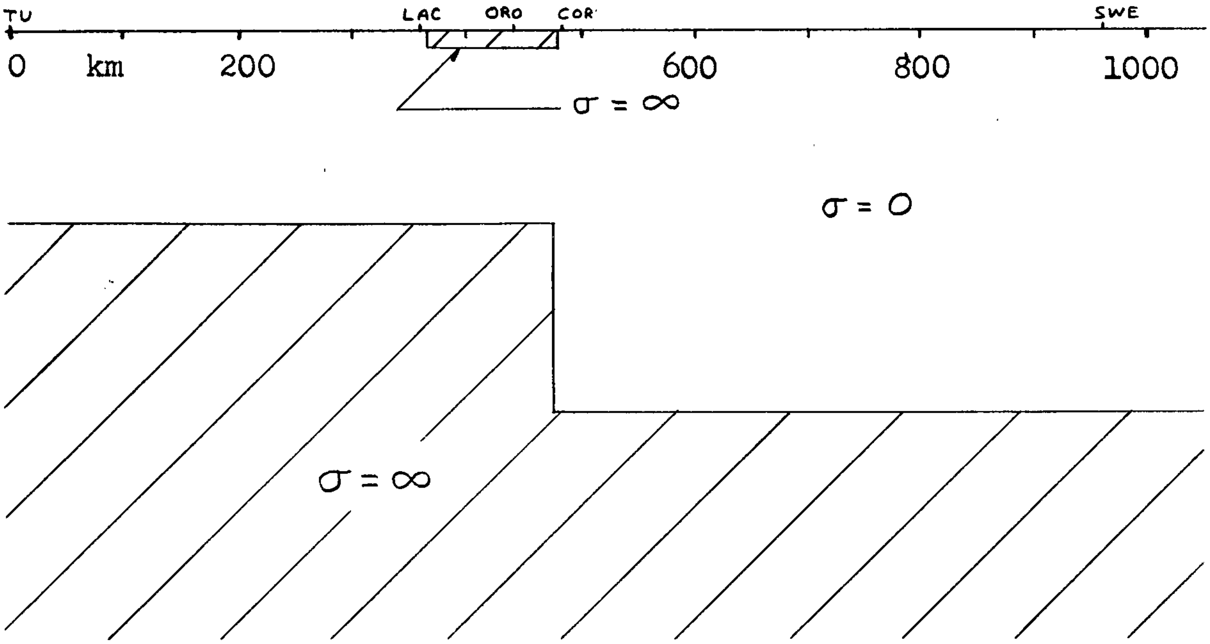

FIG. 1.1 Model of conductivity structure of crust and upper mantle between Arizona and Texas (after Schmucker, 1964)

region is at a very shallow depth, trends north-south and is about 100 km. wide.

1.4 Seismic Results from Socorro Area.

Some seismic evidence for the zone of weakness believed associated with the lineament is presented by Sanford and Long (1965). They have used an array of from three to five high-magnification seismographs, located 5 km. west of Socorro, to record nearby microearthquakes (S-P $\leq$ 2.5 sec.) at the rate of about 600 a year. From surface explosions, corrections for the geologic setting and elevation of the individual stations have been determined and applied to the records. For an individual earthquake, the direction of the epicentre is obtained by comparing the corrected P arrival times at each station of the array. The wave is assumed to have travelled in a straight line from the focus to the station with a velocity of 6 km./sec, and the distance to the focus is found from the S-P interval, assuming Poisson's ratio is 0.25. Errors in the relative locations of the foci are believed to range from <1 km. to <4 km., depending on the quality of the records and the number of stations recording the shock. Errors in the absolute locations are unknown.

About 25% of the microearthquakes observed have S_xP* and S_xS* arrivals associated with them. The arrivals are

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* The two types of seismic waves that travel through the earth are P waves (longitudinal waves) and S waves (transverse waves). When either type of wave encounters a velocity discontinuity, both P and S waves are reflected from it. An S_xS wave is an incident S wave reflected as an S wave from a crustal discontinuity, while an S_xP wave is an incident S wave reflected as a P wave from the same discontinuity.

believed to be reflections from a crustal discontinuity at a depth of 18 km. Probable S_xS phases have been found on seismograms of weak shocks associated with three earthquakes located in the Sierra Ladrones, 35 km. north of Socorro (Sanford and Holmes, 1962). They could come from a discontinuity 18 km. deep if the mean depth of the foci were 4.8 km. The latter figure is indeed possible, so the feature is not confined to the Socorro region. A plot of travel times against the S-P interval for such shocks is shown in Figure 1.2, together with theoretical curves for S_xP and S_xS reflections from a horizontal velocity discontinuity at a depth Z of 18 km. One curve is drawn for a focal depth h of 9 km., the other for a focal depth of 4 km. The curves bracket the data equally well, so little adjustment in h and Z is possible. Examination of the distribution of the focal depths of the microearthquakes confirms most (68%) of them occur between 4 and 9 km.

In order to obtain useful information from the observed data, a model has been used. This particular model has assumed no refraction of seismic waves, a relatively homogeneous crust, and a symmetrical release of energy from the foci. All three assumptions will contribute to differences between the model and the actual crustal structure.

The foregoing material has been a review of a series of somewhat disconnected recent studies having a bearing on the delineation of the Zuni Lineament and an explanation of it.

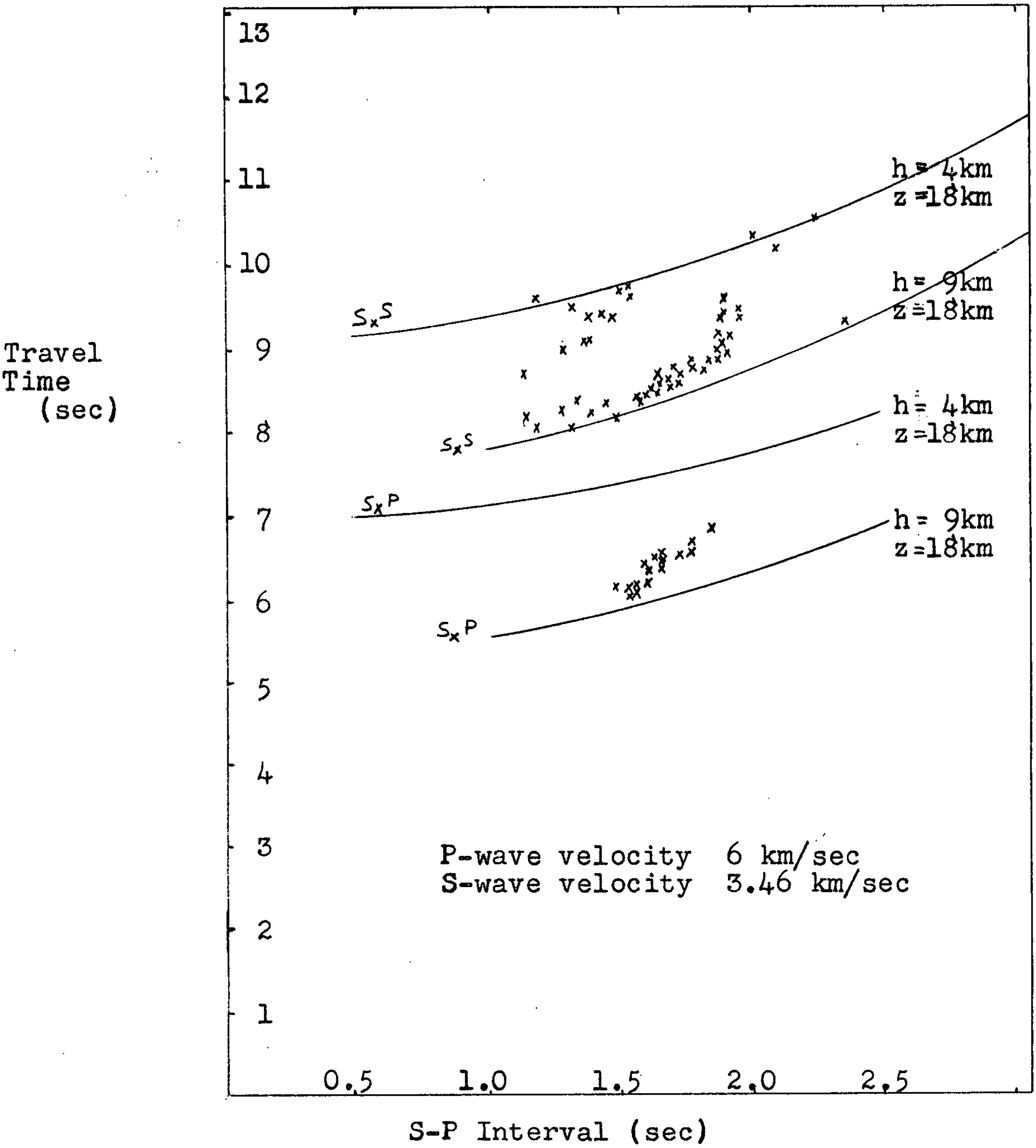

FIG. 1.2 Observed and theoretical travel times for S_xS and S_xP waves for Socorro microearthquakes (after Sanford & Long, 1965)

CHAPTER II

2.1 Interpretation of Lead Isotope Data.

The two models most frequently used in the interpretation of lead isotope measurements are outlined in the appendix. The single-stage model furnishes a simple interpretation for the small number of leads that appear to satisfy the model. The interpretation is almost certainly too simple, yet provides, in some cases, an approximation to the actual history of the lead. The two-stage model is also a crude representation of the development of a lead; given the complex geological history of most areas, it is unlikely that only two events have affected the lead there. However, the equations for the two-stage leads (eq. A.3) can be solved completely, while the equations for the three-stage, four-stage, etc. leads cannot be solved for unique values of the variables.

2.2 Explanations of Isotopic Distribution.

Slawson and Austin (1962) have offered a simple explanation for the observed pattern of isotopic distribution. They postulate that the lineament represents a zone of vertical crustal weakness which has acted as a conduit for hydrothermal mineralizing solutions. Their interpretation is that single-stage lead from a period of mineralization 1600 m.y. ago was mixed in Tertiary time with radiogenic lead, formed by the decay of uranium and thorium over the period 1600 m.y. ago to the time of the mixing, to produce anomalous leads of similar isotopic compositions. The leads were then transported upward by mineralizing solutions, evidence for which has been presented by Smith (1963). The solutions travelling along the conduit provided by the lineament acquired relatively little radiogenic lead from wallrock and the leads were therefore deposited with only minor changes in their isotopic compositions. Those solutions that travelled outward from the conduit system acquired variable amounts of radiogenic lead as they percolated through the wallrock and those leads were therefore deposited with variable isotopic compositions.

Mauger, Damon and Livingston (1965) have criticized the foregoing hypothesis on the grounds that no structural evidence of the conduit system centred on the lineament is presented, and that the assumption of ascending hydrothermal mineralizing solutions to explain the isotopic data is unnecessary, hydrothermal solutions implying a different genesis for rocks and ores. They point out that ten of twelve of the isotopically similar leads are either contained in volcanic rocks or adjacent to intrusive rocks, whereas of the isotopically variable leads, only seven of the fourteen have intrusives in their vicinity. They agree that the Zuni Lineament may represent a vertical zone of weakness but feel that it may have served as the locus for the ascent of igneous rocks rather than mineralizing solutions. The observed isotopic ratios are then explained as being due to the conditions of extraction of the lead from the surrounding rocks. The authors state that lead extracted from heated igneous rocks is more likely to be "normal" (containing a smaller amount of radiogenic lead) isotopically than lead extracted from old rocks in the absence of a heat source. The observed isotopic distribution is therefore explained as a result of the lineament being a zone of weakness along which igneous activity has occurred rather than a conduit system for hydrothermal mineralizing solutions.

2.3 Seismic Definition of Isotopic Zone.

A map of the epicentres of some microearthquakes recorded by Sanford and Long (1965) and a projection of the foci on to an east-west vertical cross-section comprise Figure 2.1. It is apparent that no microearthquakes occur northeast of a line striking northwest and dipping 55° towards the Rio Grande valley. The line is found to coincide approximately with the boundary of the isotopic anomaly, which is quite well defined at this point. The agreement between the lines lends support to the contention that the lineament represents a zone of weakness, a zone in which the rocks cannot readily withstand strains and stresses building up within them.

2.4 Geomagnetic Measurements.

Preliminary total magnetic field measurements carried out across the isotopic anomaly by C.E. Livingstone and kindly interpreted by Dr. T.J. Ulrych revealed that the top of the Precambrian basement is at a depth of about 4 km. just north of Socorro. From Figure 2.1b it appears that the number of microearthquakes decreases significantly above about 4 km. Most microearthquakes, then, occur in the upper Precambrian basement.

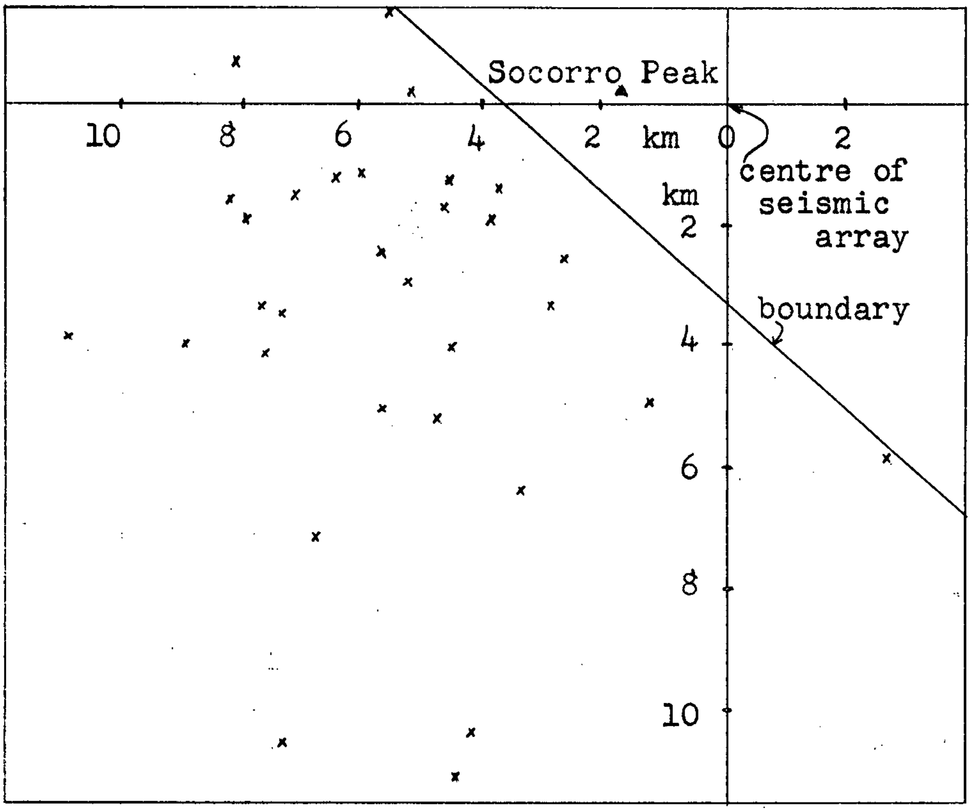

FIG. 2.1a Epicentres of Socorro microearthquakes

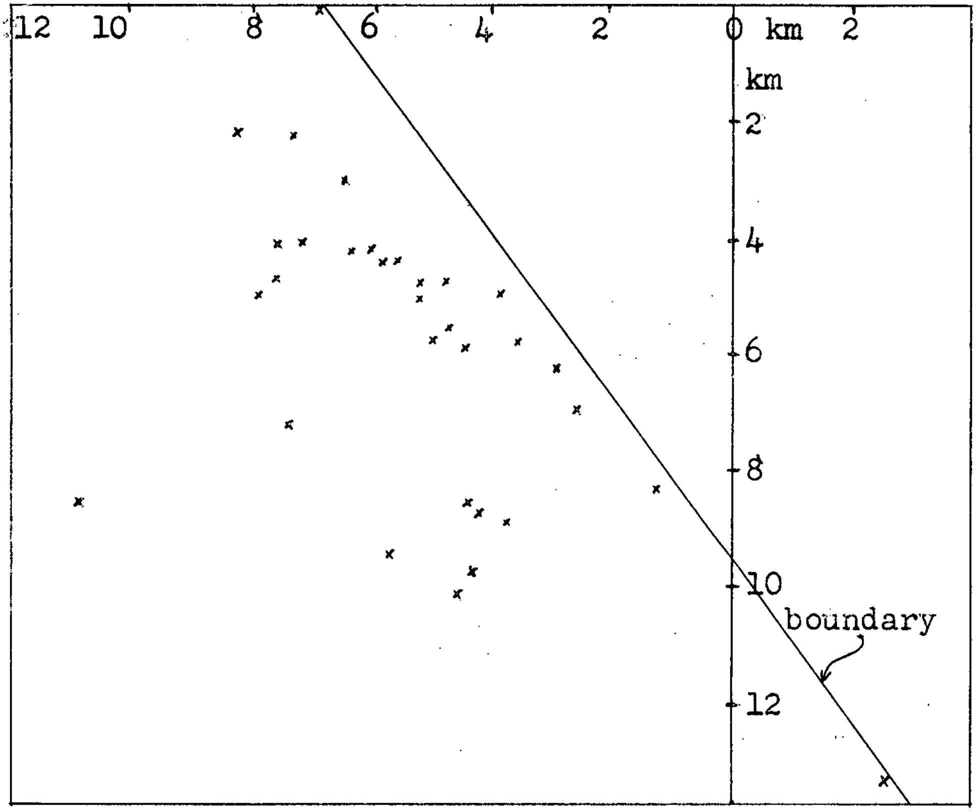

FIG. 2.1b Projection of microearthquakes on to an E-W cross-section

The magnetic depth sounding study by C.E. Livingstone revealed no obvious deep conductivity structural changes within the earth. Because of the low speed of the recording chart of the Askania magnetometers, the high frequency variations needed for shallow crustal studies were not recorded. It is not impossible that a shallow, highly conductive belt is associated with the isotopic anomaly and is an extension of the shallow conductivity feature postulated by Schmucker. The crustal discontinuity found by Sanford and Long (1965) at a depth of 18 km. could then mark the lower boundary of the isotopic zone.

2.5 Th/U Contouring.

Sinclair and Walcott (1966) have calculated the Th/U ratios for the samples as reported by Slawson and Austin and plotted contours of the values to show their geographic variations. The contouring supports evidence indicating that some structural feature connected with the Zuni Lineament controls the isotopic distribution of the samples in that the contours are not continuous across the suggested boundaries but are symmetric about the lineament. The authors feel that their contouring demonstrates that there are two centres of mineralization along the lineament, one near Socorro and the other about 20 miles to the southeast. They have also plotted a histogram of the Th/U ratios and find from it evidence of two distinct Th/U populations. Consequently they modify the mineralizing history proposed by Slawson and Austin by postulating that the leads were originally deposited into two different Th/U environments, then mineralized as previously described (Section 2.2).

The preceding constitutes an attempt to correlate the results of different types of geophysical studies in order to restrict the possible interpretations of the Zuni Lineament.

CHAPTER III

3.1 Geology of Area.

Isotopic analyses were carried out on nine leads from New Mexico, including three collected from the same general area that Schmucker's work covered.

The following description of the sample area, encompassing Socorro, Lincoln, Sierra, Otera and Dona Ana counties, is abstracted from Slawson and Austin (1962): the northwest portion of the area is located in the basin and range type mountains on the border of the Colorado Plateau, while the southeastern portion crosses the north-south trending block-faulted mountains of the New Mexico Rockies. The Rio Grande graben passes through the sampled area. Tertiary gravels and lava flows cover most of the area, although Paleozoic sediments and some Mesozoic and Precambrian rocks are exposed along the mountains. There is some limited exposure of Laramide intrusives.

3.2 Sample Preparation and Analysis.

The samples were prepared in essentially the manner described by Ulrych (1960). Galena was leached with dilute HCl to form lead chloride, which was precipitated by cooling, then filtered out and washed with cold distilled water. The lead chloride was re-dissolved in hot distilled water, potassium iodide added to the solution, and the resulting lead iodide precipitate filtered and dried. Tetramethyllead was prepared by reacting the lead iodide with methyl iodide and a Grignard reagent, methyl magnesium bromide in ethyl ether. (The purpose of the MeI is to increase the yield of tetramethyllead.) The resulting mixture of tetramethyllead and ethyl ether was separated into its constituents by vapour phase gas chromatography as developed by Ulrych (1960). The tetramethyllead was analyzed on the 90°, 12 inch single focusing mass spectrometer designed and built by Drs. F. Kollar and R.D. Russell. All the samples were intercompared as described by Kollar et al (1960) with the U.B.C. No. 1 standard* and the data reductions for four of the five loops were carried out automatically, using the system described in the appendix.

3.3 Discussion of Results.

The values obtained are given in Table 3.1, and also plotted on Pb^{207}/Pb^{204} - Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} - Pb^{206}/Pb^{204} graphs in Figure 3.1. Straight lines have been fitted through the points using a weighted least-squares fit suggested by York (1966). The weights used were the reciprocals of the percentage uncertainties. The slope of the line drawn through the nine samples is 0.0952 ± .0067, in agreement with the value of 0.0931 ± .0033 obtained for 63 samples by Slawson and Austin (1962), a value subsequently modified to 0.0938 ± .0029 by later work.

The samples can be interpreted in terms of a two-stage history (Appendix A.1). If the Bosque del Apache sample is a single-stage lead, then its age can be taken as t_1, and the corresponding t_2 found from equation A.4.

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* A split of the widely circulated Toronto #1003 sample.

Sample no.	Name	x	y	z
501	La Bonita	25.32	16.34	42.67
502	Box Canyon	20.68	15.91	39.94
504	Hansonburg	22.30	16.06	40.64
505	Bosque del Apache	16.19	15.46	36.03
507	Linchburg	18.55	15.74	38.72
508	Kelly	18.74	15.73	38.82
530	Modoc	18.20	15.66	38.99
532	Orogrande	18.96	15.78	39.31
533	Courtney	18.72	15.86	39.27

Table 3.1 Lead isotope ratios for some New Mexico samples

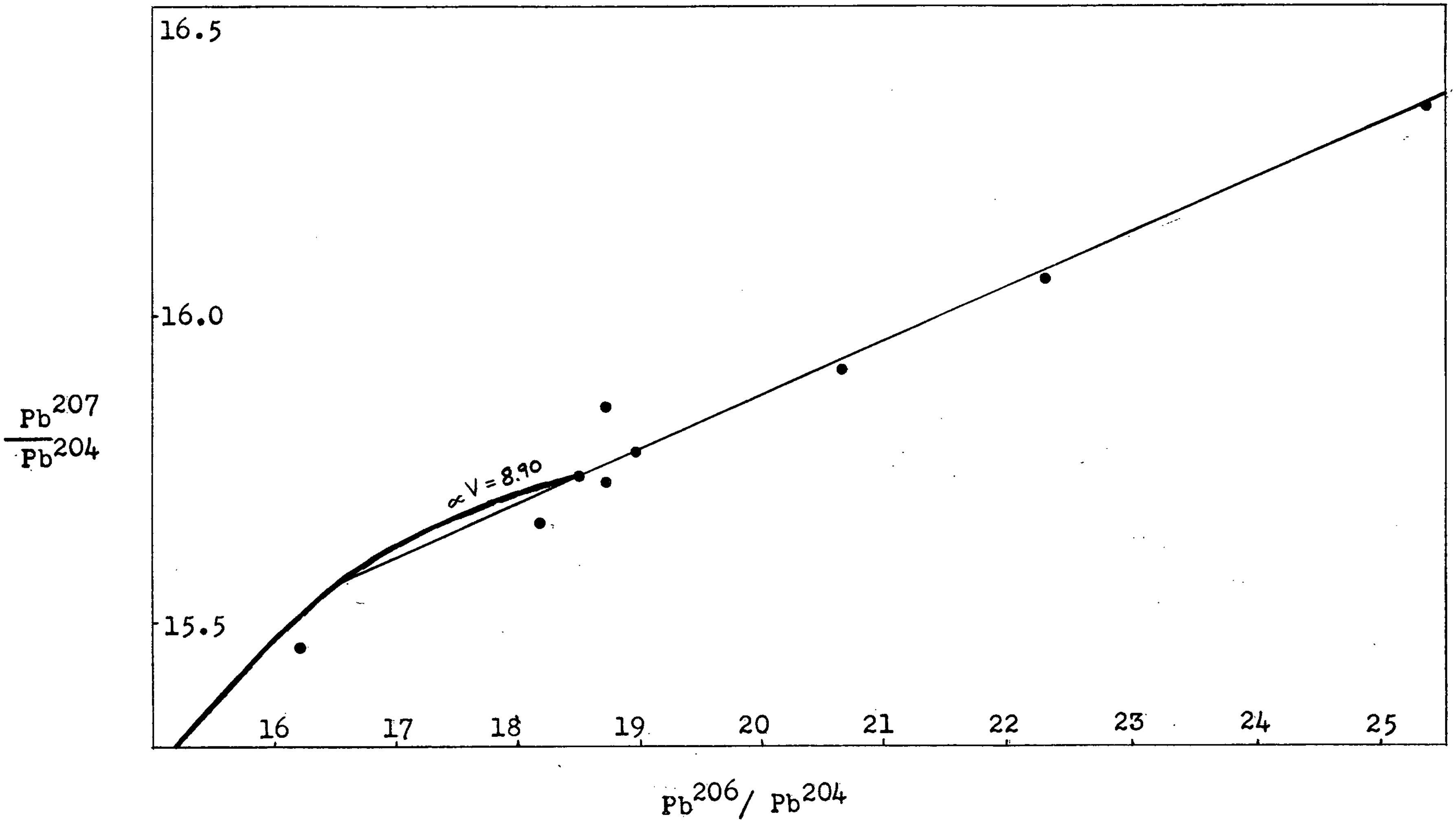


FIG. 3.1a Isotopic plot of New Mexico leads

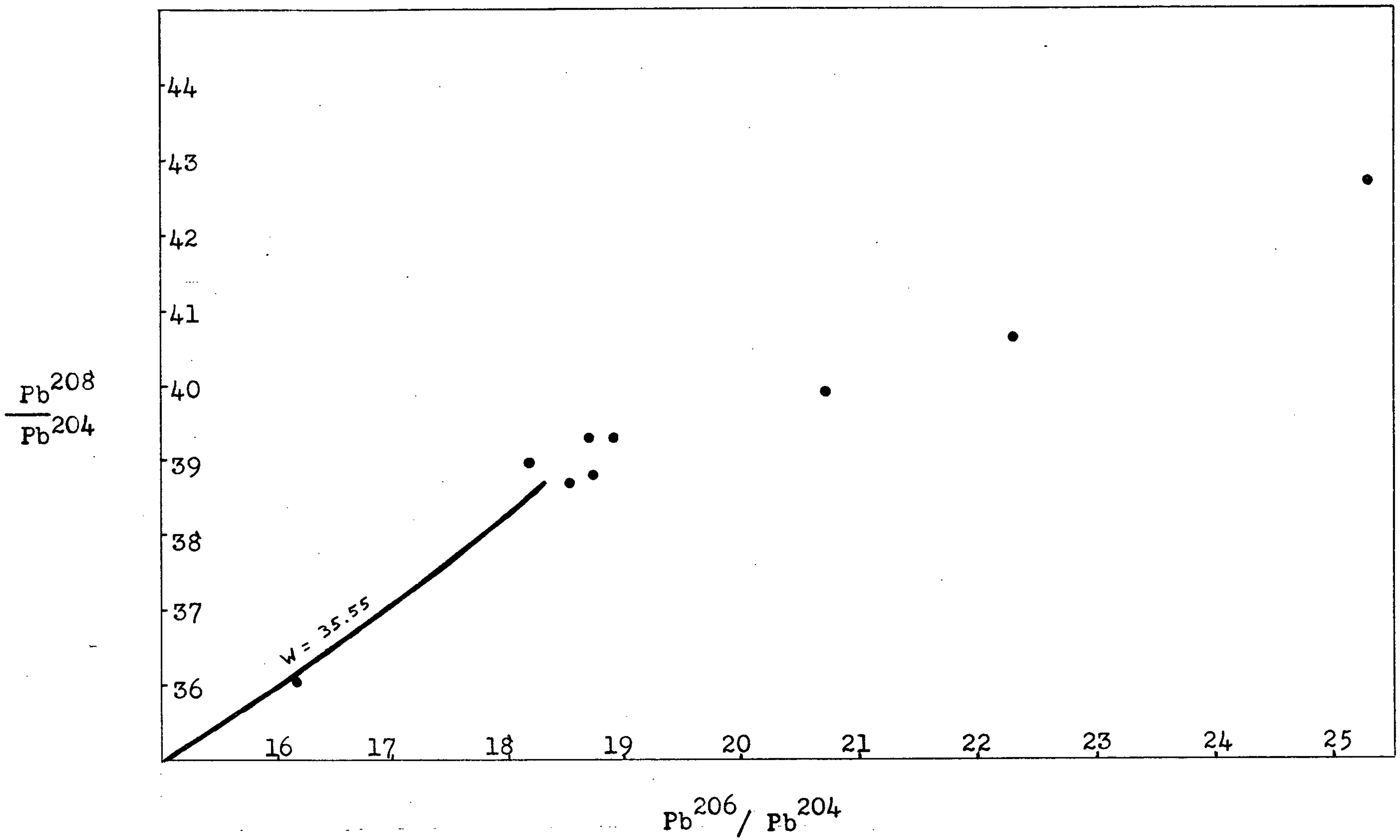


FIG. 3.1b Isotopic plot of New Mexico leads

Using equation A.2 an age of 1500 m.y. is calculated for the Bosque del Apache sample. For this value, αV for the sample is found to be 8.80, and its Th/U ratio is 3.83. Taking into account the uncertainties in the constants in equation A.2, as well as the suspected variations in the αV and W ratios for the postulated deep crustal or upper mantle source, it appears the Bosque del Apache lead may be described as primary-like. It is quite possibly not a single-stage lead, but cannot readily be distinguished from one.

Consequently, the value of t_1 is taken to be 1500 m.y. The corresponding value of t_2 is 90 m.y. which is perhaps too high. It is possible to choose a more reasonable value for t_2 of 30 m.y. (Weber and Bassett, 1963), being the approximate age of widespread volcanic activity (Smith, 1963). The corresponding value of t_1 is then 1550 m.y. In view of the deviation in the two-stage lead line, these ages are not significantly different from those previously given, but should be preferred to them because of the doubtful primary nature of the Bosque del Apache lead.

The interpretation then is that lead, uranium, and thorium were incorporated into a crustal environment about 1550 m.y. ago. The Bosque del Apache deposit was formed at this same time. Tectonic activity 30 m.y. ago mixed in varying proportions older lead and the radiogenic lead generated between 1550 m.y. and 30 m.y., and the leads were then emplaced.

Muehlberger and Denison (1964) have reported a few Rb-Sr and K-Ar ages for the Precambrian rocks of south-central New Mexico. They are given in Table 3.2.

Location	Mineral	Method	Age
Sierra Oscura Lincoln Cty.	whole rock	Rb-Sr	1300 m.y.
Rhodes Canyon* Sierra Cty.	whole rock	Rb-Sr	1430 m.y.
Hansonburg district* Sierra Cty.	microcline	Rb-Sr	1570 m.y.
	biotite	K-Ar	1360 m.y.

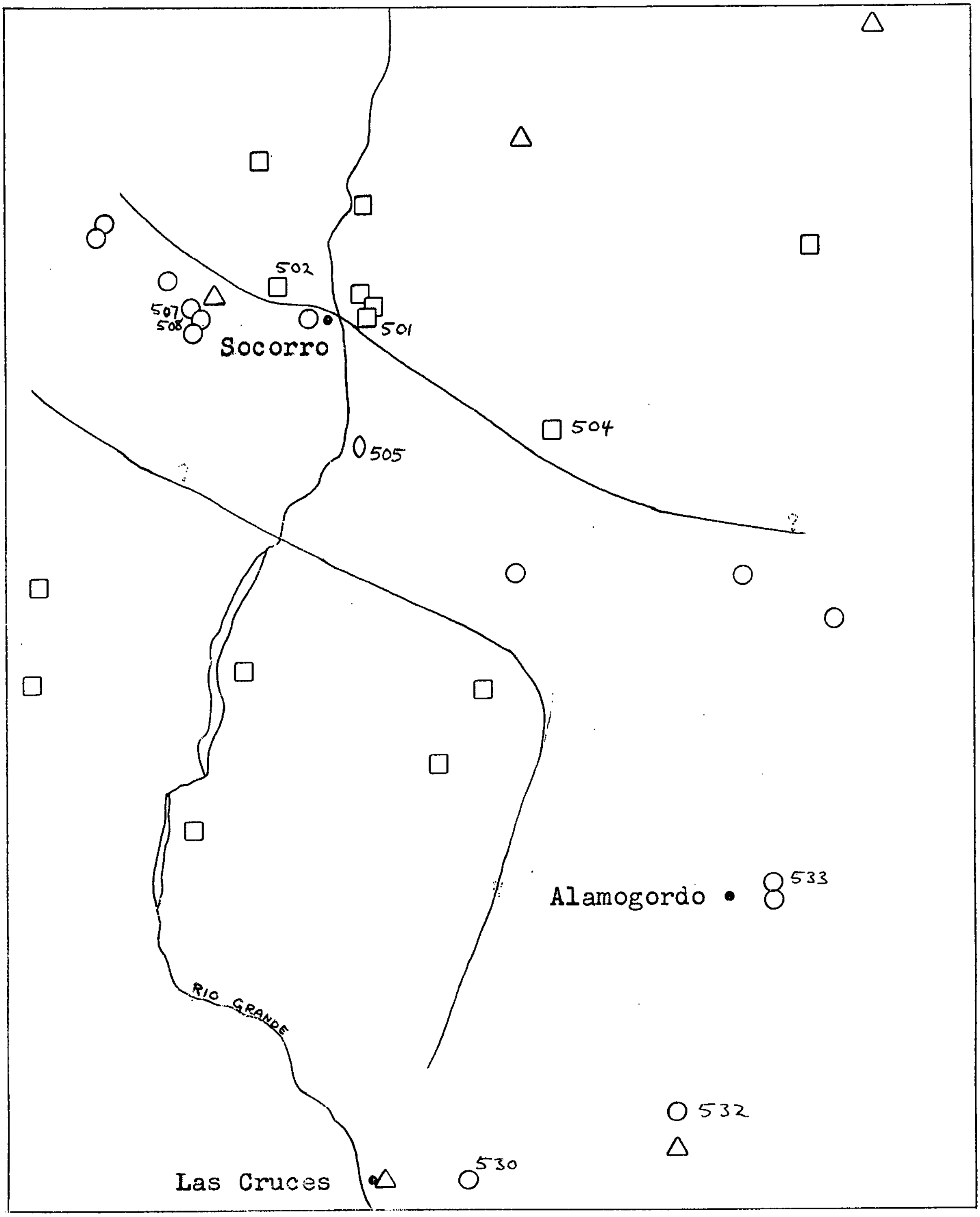
* Lead samples collected from same region.

Table 3.2 Some Precambrian ages from south-central New Mexico (Muehlberger and Denison, 1964).

The authors have interpreted these ages as representing a metamorphism and granitic intrusion about 1570 m.y. ago, followed by further igneous activity about 1350 m.y. ago. Taking into account the 6% uncertainty in the Rb-Sr half-life, the agreement between the 1570 m.y. age and the 1550 m.y. lead age is quite impressive. The igneous activity of about 1350 m.y. ago does not appear to have been accompanied by any lead mineralization.

3.4 Geographical Distribution of Samples.

Figure 3.2 is a map of the relevant area, showing the locations of the samples analyzed by Slawson and Austin and the present author, as well as the locations of the geomagnetic stations used by Schmucker (1964) and Livingstone (1966). The boundaries between the isotopically similar and isotopically variable leads are also drawn. The isotopic anomaly appears to extend into the region in which Schmucker



SYMBOLS USED

△ geomagnetic station ○ "similar" lead

☐ "variable" lead

FIG. 3.2 Locations of lead samples and geomagnetic stations postulated his surface conductivity anomaly, so it is certainly possible that the two are related.

The present author has contoured U/Pb and Th/Pb ratios in a manner similar to that of Sinclair and Walcott (1966). While results are by no means conclusive, they appear to indicate only one centre of mineralization, located in the Socorro-Magdalena area. Mayo (1958) has suggested that the Magdalena area could indeed be a focus for mineralization processes because the Zuni Lineament, Morenci belt and Cordilleran Front belt all meet near Magdalena, producing a region of crustal weakness.

CHAPTER IV

Approximately 1550 m.y. ago, lead, uranium, and thorium were introduced into the Precambrian rocks of west and south-central New Mexico. About 30 m.y. ago, tectonic activity in the area resulted in quite thorough mixing in the Precambrian basement of the 1550 m.y. old lead and radiogenic lead, generated by the decay of the uranium and thorium, to produce lead of a fairly uniform isotopic composition. The lead was then carried upward by hydrothermal mineralizing solutions to sites of deposition. Some of the lead-bearing solutions ascended along a conduit system provided by a shallow zone of crustal weakness centred on the Zuni Lineament, and therefore acquired relatively little radiogenic lead from the wallrock. These leads were deposited with essentially similar isotopic compositions. Other lead-bearing solutions percolated through the wallrock rather than the zone of weakness and consequently acquired variable amounts of radiogenic lead. These leads were deposited with variable isotopic compositions.

The z - x diagram (Figure 3.1b or Figure 3-B p.24, Slawson and Austin, 1962) supports this explanation. The virtually constant ratio of Pb^{208} to Pb^{206} for the isotopically similar leads confirms that only small amounts of radiogenic rock-lead have been added to the lead formed by the homogenization process. Otherwise, given the inhomogeneous Th/U ratios (Heier and Rogers, 1965) in crustal rocks, the points on the graph would show much more scatter, as the data for the isotopically variable leads do. The scatter of the latter verifies that they have passed through the wallrock.

Hydrothermal mineralizing solutions flowing along the conduit system rather than lead extraction by magmatic heating appear to be responsible for the observed pattern of isotopic distribution. Smith (1963) has found geologic evidence of hydrothermal mineralizing solutions in the mines of Socorro Peak, located within the zone. The zone of weakness is a shallow crustal feature and therefore could not have served as a locus for the ascent of igneous bodies, since such bodies tend to come from greater depths. If the thermal gradient near the surface of the earth is 10-50 C°/km., then granite could not become molten at depths $<$ 20 km., a depth which increases when pressure effects are also considered. It should also be pointed out that the hydrothermal solutions are only considered as the agent carrying the lead from a shallow crustal environment to its site of final mineralization, so that a difference in the genesis of rocks and ores is not necessarily postulated.

Seismic results and magnetic depth soundings have provided additional information about the zone of weakness. The seismic work has shown that it can be correlated with the isotopic anomaly, and that it extends to a depth of about 18 km. Geomagnetic work (Livingstone, 1966) has confirmed that the zone of weakness is a shallow crustal feature, and has indicated that it may extend at least to the New Mexico - Texas border (Schmucker, 1964). The lead isotope data show that the zone of weakness is a northwest trending belt, coincident with the Zuni Lineament. It is, then, another structural feature of the lineament. That the feature is a region of weakness can be related to the idea that lineaments are associated with ancient deep trans-current faults.

Experiments to test the validity of some of the preceding conclusions can be performed. Conductivity measurements on the surface and near-surface layers of the crust would reveal whether or not the postulated highly conductive layers really exist. An extension of Sanford and Long's microearthquake work could confirm the observed correlation between seismicity and the isotopic boundary, in addition to confirming the position of the latter. Further lead isotope analyses could define the extent of the isotopic features. Samples from the New Mexico-Texas border area and southwestern New Mexico (Silver City area) would be especially interesting. Techniques currently being used in this lab for the extraction of small amounts of lead from other sulphide ores could be applied in areas where galena is not readily available. Only by further experiments such as these can the problem of the observed isotopic distribution of leads in New Mexico and its correlation with the Zuni Lineament ever be fully understood.

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APPENDIX A.1

Lead Models.

The single-stage model: At a time t_o, the earth is considered to have been in a molten state so that homogenization of the U/Pb, Th/Pb and lead isotope ratios occurred. After cooling of the earth, the state of homogenization persisted in a source region in the lower crust or upper mantle, with the lead isotope ratios changing due to the decay of uranium and thorium. At a subsequent time t_1, lead was removed from the source, separated from the U and Th, and emplaced in a lead deposit. From the time t_1 up to the present, the isotopic ratios are considered to have remained unchanged. The ratios are given by:

$$\begin{aligned} x &= a_o + \alpha V(e^{\lambda t_o} - e^{\lambda t_1}) \\ y &= b_o + V(e^{\lambda' t_o} - e^{\lambda' t_1}) \qquad (A.1) \\ z &= c_o + W(e^{\lambda'' t_o} - e^{\lambda'' t_1}) \end{aligned}$$

with the symbols as defined in Table 1.1. The first two equations can be combined to yield an equation (Equation A.2) which may be solved

$$\frac{y - b_o}{x - a_o} = \frac{1}{\alpha} \frac{e^{\lambda' t_o} - e^{\lambda' t_1}}{e^{\lambda t_o} - e^{\lambda t_1}} \qquad (A.2)$$

The two-stage model: Once again, a deep crustal or upper mantle region is postulated as the source of a single-stage lead emplaced in a crustal environment at a time t_1. Also at time t_1, uranium and thorium were incorporated into the same environment. At a subsequent time t_2, tectonic activity recurred in the area and caused the mixing in varying proportions of radiogenic lead generated between t_1 and t_2 with some of the single-stage lead to produce the two-stage leads. Mineralization then occurred. If x_1, y_1, z_1 are the ratios of the single stage leads emplaced at t_1, and x, y, z are the ratios of a two-stage lead, then

$$\begin{aligned} x &= x_1 + \alpha V_1(e^{\lambda t_1} - e^{\lambda t_2}) \\ y &= y_1 + V_1(e^{\lambda' t_1} - e^{\lambda' t_2}) \qquad (A.3) \\ z &= z_1 + W_1(e^{\lambda'' t_1} - e^{\lambda'' t_2}) \end{aligned}$$

from which the slope of the straight line defined by the leads is:

$$R = \frac{y - y_1}{x - x_1} = \frac{1}{\alpha} \frac{e^{\lambda' t_1} - e^{\lambda' t_2}}{e^{\lambda t_1} - e^{\lambda t_2}} \qquad (A.4)$$

The slope of this line is then independent of V_1 and depends only on the interval t_1 to t_2. The time t_1 can often be determined from the age of single-stage leads from which the two-stage leads developed. Using equation A.4, t_2 can then be found.

APPENDIX A.2

Automatic Reduction of Data.

The measuring system of the mass spectrometer is designed to measure accurately the intensities of the different ion beams. The ions are collected on a Faraday cup and leaked to ground across a 10^{11} ohm resistor. The resulting voltage across the resistor is balanced by a servo-voltmeter consisting of a potentiometer and a driving motor. The voltage across the potentiometer is then proportional to the ion beam intensity. The position of the potentiometer shaft is also proportional to the voltage across the potentiometer, so the shaft position is proportional to the ion beam intensities. The practice is to record the position of the potentiometer shaft, rather than to measure peak heights displayed on a chart recorder. The shaft position can be read automatically by means of an encoder, and the information put onto paper or magnetic tape.

At the moment, the information from the mass spectrometer is punched onto paper tape in units known as "words", with each word consisting of 6 characters. The first four characters of each word contain the shaft position (proportional to peak height) of the potentiometer in the measuring system. The fifth character contains information such as attenuation used, scan direction, and, when necessary, the "scan separate" and "scan reject" signals. The final character is always an "end of line" punch which denotes the end of a word. Words are recorded at a rate of 2 per second, and there are usually about 900 words for a pair of spectra consisting of eight peaks in each scan direction.

In recording the data for a pair, the procedure used is first to generate the "scan separate" signal by pressing the button on the mass spectrometer console, to record 10-20 words on the baseline of each attenuation used, and then to scan down-mass over the $Pb(CH_3)_3^+$ spectrum. Baselines are again recorded at the low-mass end of the spectrum, the spectrum scanned up-mass, the baselines recorded for a third time, and the pair is then terminated by another "scan separate" signal. Up to 25 pairs may be recorded in this manner.

Identification for each sample is punched at the start of the paper tape and the information on it is transferred to magnetic tape, with 21 words occupying 1 record of magnetic tape. The data can then be processed by the reduction program "PILOT", which is currently stored on the IBM 1301 disc file at the U.B.C. Computing Centre. The cards required for the program are:

```
$JOB  (Job No. and name of user)
$CLOSE                        S.SU04,REMOVE
                              ↑
$TIME  (as needed)            col.16
                              ↓
$EXECUTE                      PILOT
TAPE
* (List of options if desired - see Table A.1)
```

The options PTAPE, GO, DECK, and CALC are currently preset, so that the program will automatically process information

Option	Description	"Negative" option	Preset value (V5/66A)
PTAPE	mass spectrometer output on paper tape	NOPAP	TRUE
MTAPE	mass spectrometer output on mag. tape	NOMAG	FALSE
GO	process sample	NOGO	TRUE
DUMP	output filtered data	NODMP	FALSE
SELECT	process sample whose identification starts in col. 71 of "option" card	DOALL	FALSE
DECK	outputs data cards	NODECK	TRUE
REPEAT	processes all samples on the mag. tape	-	FALSE
CALC	calculates lead ratios	NOCALC	TRUE
MAX	outputs raw peak heights, peak tails, etc.	NOMAX	FALSE
SKIP,XX	skips XX records on mag. tape	-	FALSE

Table A.1 Options available for program "PILOT" originally on paper tape, producing lead ratios and a deck of data cards. Any other options may be used simply by listing them on the final card.

The total time required by the program can easily be estimated. About 20 sec are used by the computer to set up the program, and the time required to process a pair and calculate lead ratios from it is about 18 sec.

Lead isotope ratios can be obtained from data cards by using the following cards:

```
$JOB (Job no. and name of user)
$EXECUTE                PILOT
                        ↑
CARDS                   col. 16
data cards
```

The time required by the computer is about 20 sec to set up the program and 1 sec a pair to calculate the lead ratios.