A Study of Mylonitic Rocks From Major Fault Zones

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A. INTRODUCTION

The objectives of this study are to learn about the role of mylonitic rocks (and other cataclastic rocks) in the mechanics of faulting and to learn about the physical and chemical conditions of their formation. Knowledge of the conditions of formation of the fault rocks leads directly to knowledge of the former conditions within exposed fault zones. The type of evidence being sought is petrographic and petrochemical in nature; principal types of information being sought are textural and microchemical evidence of chemical reations that may accompany fault displacement, microchemical and mineralogical evidence of the history of physical conditions in the fault zones, and bulk chemical, microchemical and mineralogical evidence of the movement of volatiles and dissolved chemical species in the fault zones.

The first year of this study has involved:

1) sampling and field observation of fault zones in six areas of southern California;
2) preparation of petrographic thin sections of the collected samples;
3) electron microprobe analysis of mineral grains within selected samples;
4) whole rock chemical analysis of selected samples using rapid silicate analysis methods;
5) purchase and installation of automation instrumentation for our electron microprobe.

The sampled zones represent a broad range of depths of exposure, from near surface fault zones with gouge to broad, deep shear zones with high-grade cataclastic rocks. The results indicate that, for the studied zones at least, cataclasis at shallow to moderate depth (perhaps in a range of 0-15km) is accompanied by extensive hydration and/or carbonation of the fault rocks. Two deeper zones examined showed less extensive hydration and little carbonation, but such effects are significant at least locally within some parts of these deeper zones. For zones with extensive hydration and/or carbonation, the hydration/carbonation occurred over a broad range of physical conditions from amphibolite facies through greenschist facies to near-surface conditions. Textural evidence points to much of the hydration and carbonation occurring during active shearing. Microchemical data indicate that the geothermal gradients of the low- to medium-grade zones were intermediate. No evidence of significant transitory heating has been found.

B. AREAS SAMPLED

Initial field work was conducted in April, 1979 and further field work was accomplished during January, 1980. The six areas sampled are briefly described below. The first five areas were discussed in more detail in a previous technical report.

a) One area studied was along Upper Lytle Creek Ridge in the Telegraph Peak quadrangle. 80 samples were collected along a two mile traverse from the San Andreas Rift zone in Lone Pine Canyon, SW across several small shear zones and a 2000 ft. wide cataclastic zone of the Punchbowl fault zone and continuing to the bottom of the canyon occupied by the North Fork of Lytle Creek. A variety of rock types, cataclastic textural types, and grades of cataclasis were found here.

b) A mylonite zone in the Crafton Hills NW of Yucaipa in the Yucaipa quadrangle was investigated. Samples were collected along a 3500 ft. section across strike of the zone. Well-exposed within the mylonite zone is a discrete thrust fault with a thin zone of re-cataclasized mylonite. Overall the mylonite zone is characterized by abundant blastomylonites of various bulk compositional types, plus some uncataclasized, shallow-level intrusive igneous rocks.

c) Another area sampled is in the Mescal Creek quadrangle along the Angeles Creek Highway on Blue Ridge between the Punchbowl and Fenner faults. Several small shear zones are well-exposed in roadcuts.

d) Samples were collected from two thin thrust zones in the eastern Sierra Pelona in the Ritter Ridge quadrangle. The fault rocks associated with these thrusts are gouges and non-coherent breccias.

e) The classic area in Cucamonga Canyon (Alf, 1948; Hsu, 1955) was sampled in order to provide a look at a relatively deep-seated cataclastic zone and for comparison with other zones.

f) A week of field work was conducted in portions of the eastern Peninsula Ranges mylonite zone (described by Sharp, 1967, 1979) in the

Borrego and Palm Desert 15' quadrangles. Samples of cataclastic and, where present, noncataclastic rocks were collected from a number of locations, most of which are in the Borrego Valley-Clark Valley area. The eastern Peninsulan ranges zone is of interest because within it are cataclasized plutonic rocks of the southern California batholith. Since the parent rocks are relatively well-behaved with respect to chemistry, this zone provides a good opportunity to test the degree of chemical exchange with a pore fluid or with surrounding rock, with pore fluid as the diffusion media, during cataclasis. Also, the zone represents cataclasis at considerable depth, although the preliminary petrographic work indicates that a range of depths are represented in the zone; the high-grade conditions postulated by Theodore (1970) do not apply to all of the mylonites exposed in the zone.

C. PETROGRAPHIC AND MICROCHEMICAL OBSERVATIONS

Samples collected from the various areas have been petrographically examined for evidence of any chemical reactions that accompanied the faulting process. Within the shallower zones, such as the Punchbowl zone and Crafton Hills zone, there is evidence of a number of retrograde reactions; the results of several hydration reactions are pervasively present. Within the more deeply exposed zones, the Black Belt zone in the San Gabriel Mtns. and the eastern Peninsular Ranges zone, the extent of similar hydration reactions is more limited; little or no retrograde reaction effects have accompanied cataclasis in the Cucamanga Canyon rocks studied, but retrograde hydration reactions are locally important in parts of the eastern Peninsular Ranges zone. No evidence of prograde reactions which might have accompanied fault zone activity has been found.

Some types of possible reactions, either prograde or retrograde, are evidenced by changes of the composition of participating minerals over time. For instance, in an appropriate mineral assemblage, the composition of Ca-amphibole can vary with changing P-T conditions. The compositions of these amphiboles in the actinolite-hornblende series are in fact good indicators of relative grade and the ratio of P/T. The mineral compositions and compositional zoning relationship in individual mineral grains have been determined with the electron microprobe. Although a number of reactions have been investigated this way, the most useful information has come from looking at the results of the family of retrograde reactions that produces compositional variation in Ca-amphibole.

1. Amphibole data.

The reactions which can occur in a fault rock are obviously a function of the starting mineral assemblage, which is itself a function of bulk composition and the physical conditions of mineral growth. Many of the Pelona schist rocks from the Punchbowl fault zone and also some of the mylonites from the Crafton Hills zone contain Ca-amphiboles in the actinolite-hornblende series (Ca-amphiboles are present in samples from other areas studied as well, but we haven't analyzed any as yet). A typical observed reaction is the retrogradation of hornblende to form more actinolitic amphibole plus chlorite, epidote, and minor amounts of other minerals. In rocks with an assemblage including albite or oligoclase, epidote, quartz, chlorite, and amphibole, the amphibole composition is sensitive to changes in both P and T.

Figure 1a is a plot of electron microprobe data from amphibole grains in RA-11-L showing Al(IV) vs. Al(VI). These parameters are calculated by converting the weight percent data to cation percents and then normalizing the cation values to an ideal chemical formula for Ca-amphibole. This ideal formula is:

$$(Na,K)_{0-1}(Ca,Na)_2(Mg,Mn,Fe^{2+},Fe^{3+},Al^{VI},Ti)_5(Si,Al^{IV})_8O_{22}(OH,F)_4$$

The normalization used forces the sum of all cations, excluding Na, K, and Ca, to be 13. This makes some assumptions about site occupancy, but the use of another normalization method would only modify the plots slightly and would not alter the conclusions. The treatment of Ca-amphibole data is discussed at length by Laird (1977).

Figure 1b is a plot of Al(IV) vs. the sum of Al(VI) + Ti + Fe(3+), where Fe(3+) is calcualted by the assumption of a total plus-charge of 46 for the ideal formula. Both figures show essentially the same things. Within RA-11-L amphibole grains is a great compositional range and the entire range can be found within single, compositionally zoned grains. The more aluminum-rich points (analyses are from spots with diameters of 10 microns) are from darker cores within the grains; these represent hornblende formed under conditions of amphibolite or epidote-amphibolite facies metamorphism. Moving away from the dark cores out to the light-colored rims, the grains zone to more actinolitic compositions (pure actinolite has no Al(IV). The actinolitic compositions formed under greenschist facies conditions.

The interpretation of this zoning pattern is not without some ambiguity. However, the published and unpublished work of this author (Anderson, 1977a, 1977b, and in press) and Laird (1977) have shown that under medium- to low-grade metamorphic conditions that certain minerals are not very susceptible to solid-state diffusion and re-equilibration, but instead tend to preserve the history of changing composition with time by means of preserved compositional zoning. Ca-amphibole is one of these minerals that tends to preserve compositional zoning due to growth. The overprint of a distinct low-grade event upon older hornblende seems to result in rather sharp optical and compositional boundaries between newly formed actinolite and remnant hornblende. As metamorphic grade increases up into middle to high amphibolite facies, the effect of solid-state diffusion begins to be more significant, although of course any diffusion process is also dependent upon the time-scale involved.

If the amphibole zoning in RA-11-L is the product of mineral growth over time rather than some diffusion process, then the amphibole grains record a history of changing conditions within the fault zone. The grains grew as the rock was being brought upward in the fault zone or as the whole Punchbowl fault zone was brought up with the Upper Lytle Creek Ridge block between the San Andreas and San Jacinto faults. Obviously, this block must have undergone uplift and erosion in order to expose the low- to medium-grade cataclastic zone. The preferred alignment of actinolite grains with the fluxion structure in the mylonitic schist indicates that the Punchbowl fault zone was active as this uplift occurred. Actually, there is evidence of even relatively recent, but minor, activity in the fault zone in the form of an apparent bedrock-gravel fault contact.

The data shown in Figures 1a and 1b can be put to further use, as the composition of amphibole depends not only upon relative grade, but also upon the relative P/T ratio. The interpretation of the P/T ratio does not strongly depend on whether the interpretation of the zoning mechanism is completely correct. Comparing the RA-11-D data to the results of Leake (1965), Raase (1974), Graham (1974), and Laird (1977), these amphiboles were formed under intermediate P/T conditions, similar to the regional metamorphic conditions of the Dalradian rocks in southwestern Scotland and of intermediate pressure areas in the regionally metamorphosed Paleozoic rocks of western New England. The overall mineral assemblage in RA-11-L is appropriate for making the comparisons.

Another sample of Pelona schist, RA-23-A, from a shear zone on Blue Ridge to the NW of location RA-11 has Ca-amphibole with characteristics similar to those of the Ca-amphibole in RA-11-L. Figures 2a and 2b show the plots for RA-23-A amphibole. The compositional range for RA-23-A amphibole is not as great as for that of RA-11-L amphibole, but the overall trends are similar. The amphibole in RA-23-A also formed under intermediate P/T conditions.

Figures 3a and 3b are plots for amphibole in sample RA-7-E, a mylonite from the Crafton Hills zone. The analyzed points clustered at higher values of Al(IV) are hornblende cores which were probably pre-cataclastic in origin. The more actinolitic points, with lower Al(IV), are overgrowths on the horneblende cores and appear to have been formed during cataclasis. While the pre-cataclastic hornblende cores may have formed at a somewhat lower P/T ratio than any of the Upper Lytle Creek Ridge - Blue Ridge amphiboles, the actinolitic overgrowth is compositionally very similar to cataclastically formed, overgrown amphibole in the two preceding samples, RA-23-A and RA-11-L, and the two samples to follow, RA-16-B and RA-11-E.

Plots for Ca-amphibole in sample RA-16-B are shown in Figures 4a and 4b. RA-16-B is a sample of Pelona schist from a small shear zone adjacent and parallel to the main cataclastic zone of the Punchbowl fault zone on Upper Lytle Creek Ridge. As in the other cases above, the more hornblendic compositions with higher Al(IV) are from cores which are overgrown by more actinolitic rims produced during shearing.

Another analyzed sample with Ca-amphibole is RA-11-E, from the same location as RA-11-L. Plots for RA-11-E are shown in Figures 5a and 5b. These compositions are similar to those in the previous plots, except that the hornblende cores may have formed a somewhat higher grade conditions than were responsible for the hornblende cores in other analyzed fault rocks from the Upper Lytle Creek Ridge-Blue Ridge area. These and the above amphiboles formed under conditions of intermediate P/T.

2. Other reactions

One of several commonly observed reactions in the shallow- to moderate-depth (low- to medium-grade) cataclastic rocks is the alteration of plagioclase (typically with an original composition of Ab(70)An(30), but varying from case to case) to reaction products of nearly pure albite, plus epidote and/or calcite. In the studied rocks from the Crafton Hills zone and the Punchbowl zone, commonly both epidote and calcite were produced. In some samples, the plagioclase has been altered, at lower grade than the preceding reaction, to sericite (fine-grained white mica of varying composition), calcite, and perhaps epidote.

The association of epidote and albitic plagioclase is quite common in samples from the Crafton Hills zone and the Punchbowl zone. If any significant heating had accompanied faulting in these rocks, it might be expected that the dehydration reaction of epidote plus albite to form plagioclase would have occurred. This and similar reactions are observed in medium-grade regional metamorphic rocks. To date, we have not found any petrographic or microchemical evidence of this or any other dehydration reaction which accompanied cataclasis. This is an apparent indication that any frictional heating that accompanied displacement along the fault zones was not great enough to initiate such medium-grade metamorphic reactions (and certainly not nearly sufficient enough to initiate the formation of pseudotachylite by melting).

Garnet is observed to have been hydrated to chlorite and minor amounts of other minerals in a number of samples. Several samples from the eastern Peninsular Ranges zone have a less common reaction, the hydration of garnet (plus K-feldspar) to biotite and minor epidote. Figure 6 is a photomicrograph of garnet in sample RA-27-E in which this reaction has occurred. The reaction shown in Figure 6 and other hydration reactions such as the sericitization of K-feldspar shown in Figure 7 (sample RA-26-D) show that cataclasis within the exposed rocks of eastern Peninsular Ranges zone did not all occur at very high grade conditions, as may be the case for the rocks from Coyote Mtn. described by Theodore (1970).

D. WHOLE ROCK CHEMISTRY

To date we have analyzed about 40 whole rock samples of cataclastic and non-cataclastic rocks using standard rapid silicate analysis methods (primarily atomic absorption and colorimetric determinations, depending on the particular element). We have just begun to work on the samples from the eastern Peninsular Ranges mylonite zone and hopefully these will begin to answer some of the questions of interest that can be addressed by these methods. Until more data is available, it is not worthwhile to speculate on the interpretation of the data other than to say that no obvious trends of exchange, depletion, or enrichment with respect to major elements has been found for the suite of rocks collected within and near the Punchbowl fault zone. The chemicaldata is shown in Appendix A.

Figures 8a, 8b, and 8c show various plots of whole rock chemical data from a mylonite zone in Guatamala investigated by one of our students, Peter Muller (1980, Ph.D. Thesis, SUNY-Binghamton). The fault zone is within the Agua Fria granodiorite in the Los Amates quadrangle. Protomylonitic granodiorite has suffered exchange of Na_2O for K_2O while maintaining approximately constant total $Na_2O + K_2O$. The apparent uniformity of this process over a large volume of granodiorite suggests a circulating pore fluid system within the fault zone.

E. PRELIMINARY CONCLUSIONS BASED ON RESULTS TO DATE

The results from the studied zones lead to several conclusions about the nature of the fault zones at depth when the faults were active. The geothermal gradient was apparently moderate over a long period of time and there is no evidence of any significant transitory frictional heating (or any other sort of rapid temperature rise). The zones had relatively high fluid pressures compared to the load pressure, as evidenced by the abundance of hydration and carbonation reaction products and by the absence of evidence of significant frictional heating. In the case of the Punchbowl fault zone, fault activity continued over a period of time during which either rock slices or the entire zone was being brought upward.

On the surface, these conclusions would appear to contrast somewhat with those of Sibson (1977, 1979). However, Sibson has pointed out that there may be differences in relative fluid pressures from one fault zone to another, thereby producing differences in the amount of frictional heating. The fault zones observed in this study would seem incapable of producing silicate melts, which is the current interpretation of pseudotachylites (at least some of these) found in various fault zones. Fault zones with high relative fluid pressures would tend to have less heat generated by friction; these zones would therefore not have rapid transitory rises in temperature and would tend to have lower geothermal gradients than "dry" fault zones with lower relative fluid pressures.

The conclusions of this study not not support the conclusions of studies which suggest that significant frictional heating is a general phenomena applicable to major fault zones. Scholz and others (1979) have suggested that prograde metamorphic zones along the Alpine fault in New Zealand are the result of frictional heating and that the effects of the heating extend on the scale of kilometers beyond the fault zone proper. Such frictional heating would result in the growth of minerals under relatively low P/T conditions. Although the results of this study can't be extended to the Alpine fault zone, it does appear that a similar model cannot be applied to the Punchbowl fault zone and the immediately adjacent portion of the San Andreas fault zone. As this study proceeds, the problem of the relative importance of possible frictional heating needs to be addressed in other areas of the San Andreas system.

F. FUTURE DIRECTION OF RESEARCH

Future work will consist of further examination of collected samples plus the examination and sampling of other fault zones in the San Andreas system. Some of the questions to be addressed are: what were the relative P/T conditions in the fault zone; what were the fluid pressures relative to load pressures; what mineral reactions occurred and did they occur during shearing. Also, the nature of the fluid system in the fault zone will be addressed by looking at the extent and nature of chemical alteration of fault rocks. This will continue to be approached using bulk chemical analysis, but eventually the use of other techniques such as stable isotope analysis would be highly desirable.

As further field sampling proceeds on other fault zones, it should be possible to begin to make some generalizations about portions of the San Andreas system. At the present time, keeping the results of this study plus those of other studies in mind, it appears that there may be considerable variations in the physical and chemical conditions from one fault zone to another; this needs to be carefully tested.

One useful technique that will continue to be used is to look at the compositional details of Ca-amphiboles in fault rocks. Ca-amphiboles have been used successfully in interpreting regional metamorphic terrains ever since the electron microprobe came into common usage; they also hold the promise of telling about the relative P/T conditions and grade within and around fault zones. Used with care (the overall mineral assemblage must be considered, for instance), interpretations of significant frictional heating in a fault zone can be tested if amphibole-bearing rocks are present.

G. BIBLIOGRAPHY

Alf, R. M., 1948. A mylonite belt in the southeastern San Gabriel Mountains, Calif.: Geol. Soc. Amer. Bull., v. 59, no. 11, p. 1101-1120.

Anderson, J. R., 1977a. The polymetamorphic sequence in the Paleozoic rocks of northern Vermont: a new approach using metamorphic veins as petrologic and structural markers Ph.D. thesis : California Institute of Technology, 656p.

Anderson, J. R., 1977b. Compositional zoning in minerals from low- to medium-grade rocks of northern Vermont: testing the zoning mechanism: Geological Society of America Abstracts with Programs, v. 9, p. 235-236.

Anderson, J. R., in press. Metamorphic veins: markers of the polymetamorphic sequence in Vermont: submitted to Bull. Geol. Soc. Amer.

Graham, C. M., 1974. Metabasite amphiboles in the Scottish Dalradian: Contrib. Mineral. Petrol., v. 47, p. 165-185.

Higgins, M. W., 1971. Cataclastic rocks: U.S.G.S. Prof. Paper 687, 97p.

Hsu, K. J., 1955. Granulites and mylonites of the region about Cucamonga and San Antonio Canyons, San Gabriel Mountains, California: Calif. Univ. Pubs. Geol. Sci., v. 30, no. 4, p. 223-352.

Leake, B. E., 1965. The relationships between tetrahedral aluminum and the maximum possible octahedral aluminum in natural calciferous and sub-calciferous amphiboles: Amer. Mineral, v. 50, p. 843-851.

Laird, J., 1977. Phase equilibria in mafic schist and the polymetamorphic history of Vermont Ph.D. thesis : California Institute of Technology, 445p.

Raase, P., 1974. Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism: Contrib. Mineral. Petrol., v. 45, p. 231-236.

Scholz, C. H., J. Beavan, and T. C. Hanks, 1979. Metamorphism, argon depletion, heat flow and stress in the Alpine fault: Proc. Conf. VIII - Analysis of actual faults in Bedrock, U.S.G.S., p. 534-586.

Sharp, R. V., 1967. San Jacinto fault zone in the Peninsular Ranges of southern California: Geol. Soc. Amer. Bull., v. 78, p. 705-730.

Sharp, R. V., 1979. Some characteristicx of the eastern Peninsular Ranges mylonite zone: Proc. Conf. VIII - Analysis of Actual Faults in Bedrock, U.S.G.S., p. 258-267.

Sibson, R. H., 1977. Fault rocks and fault mechanics: Jour. Geol. Soc. London, v. 133, p. 191-213.

Sibson, R. H., 1979. Fault rocks and structure as indicators of shallow earthquake source processes: Proc. Conf. VIII - Analysis of Actual Fault Zones in Bedrock, U.S.G.S., p. 276-304.

Theodore, T. G., 1970. Petrogenesis of mylonites of high metamorphic grade in the Peninsular Ranges of southern California: Geol. Soc. Amer. Bull., v. 81, p. 435-450.

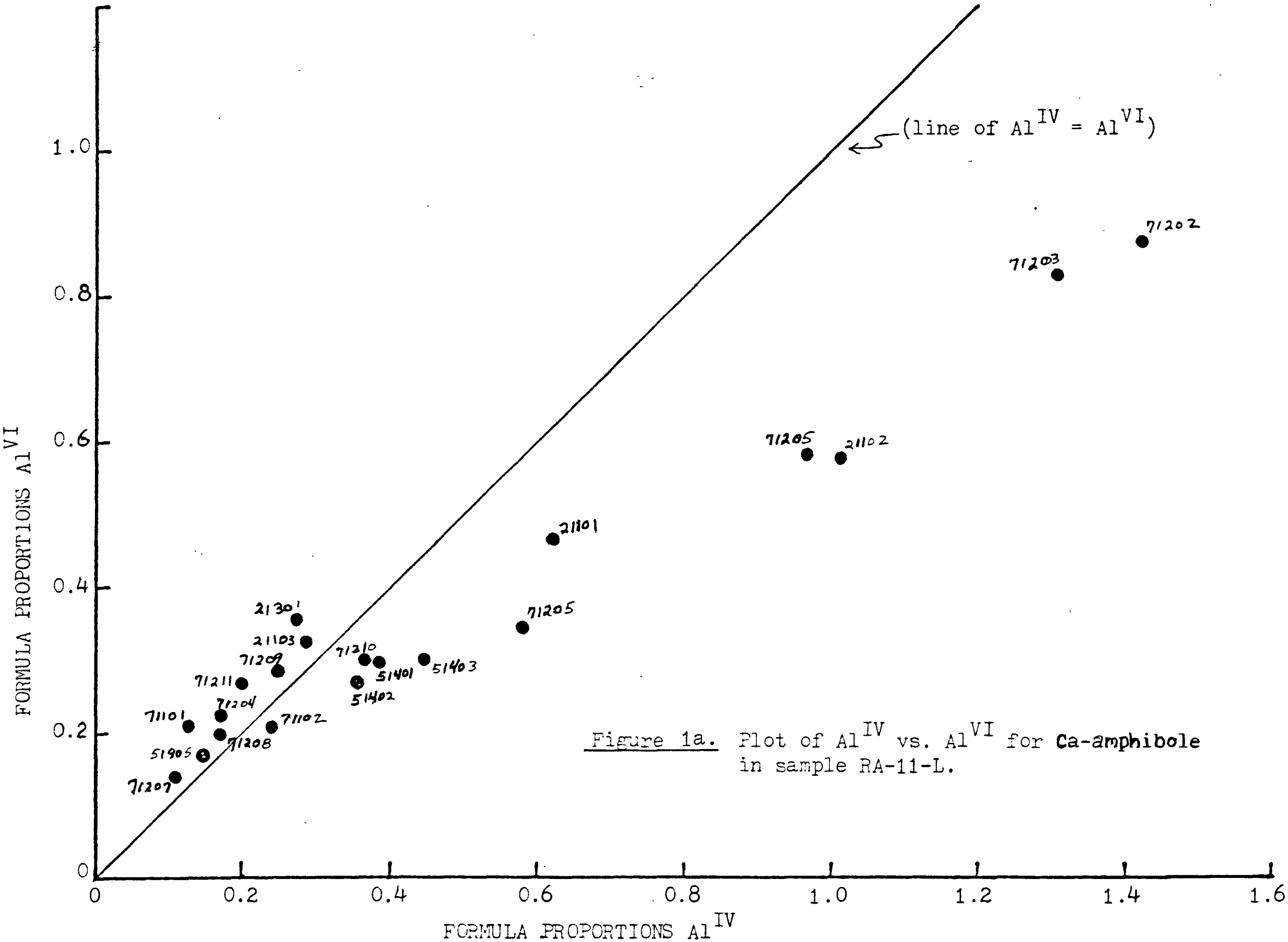


Figure 1a. Plot of Al^{IV} vs. Al^{VI} for **Ca-amphibole** in sample RA-11-L.

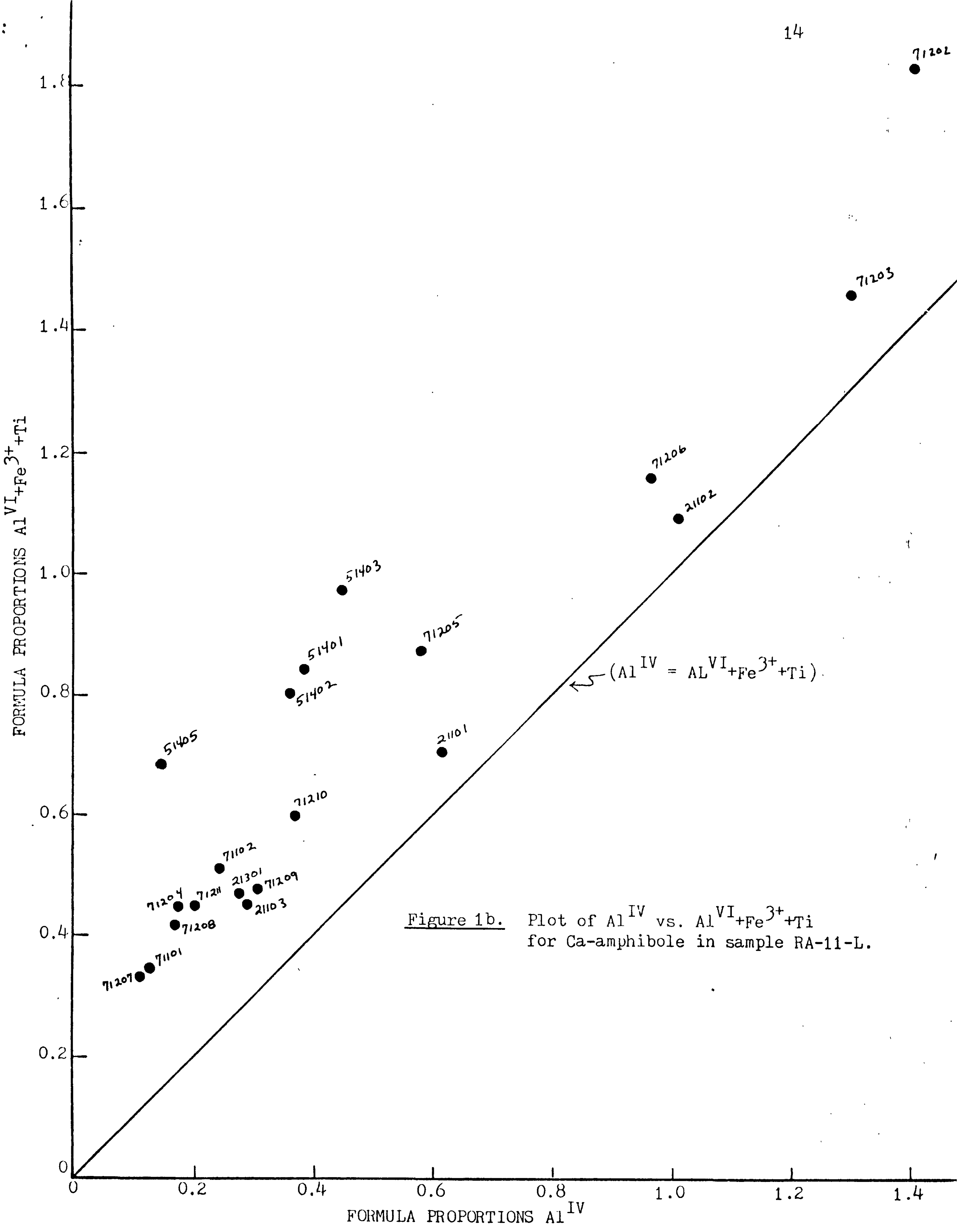


Figure 1b. Plot of Al^{IV} vs. $Al^{VI}+Fe^{3+}+Ti$ for Ca-amphibole in sample RA-11-L.

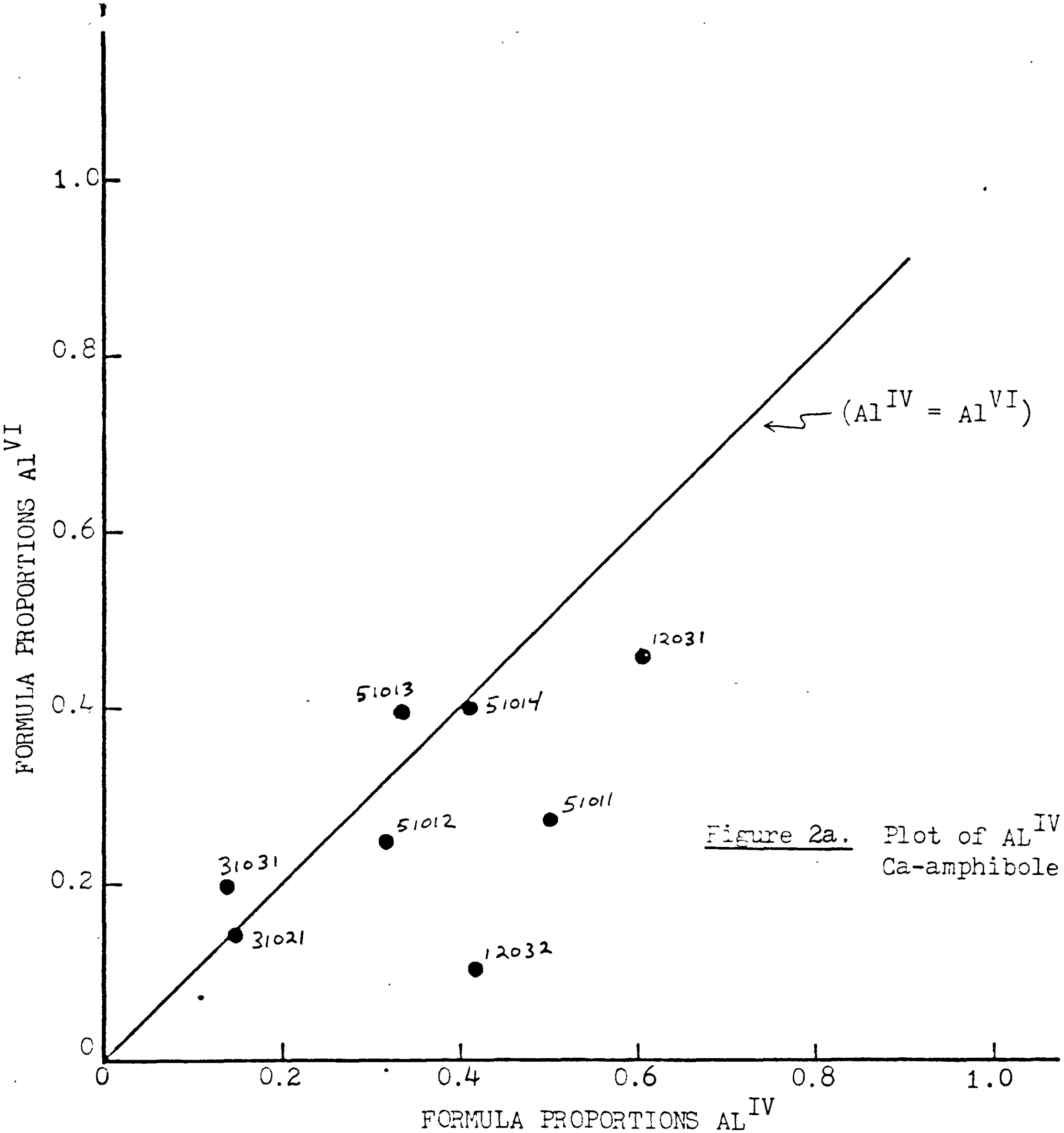


Figure 2a. Plot of AL^{IV} vs. Al^{VI} for Ca-amphibole in sample RA-23-A.

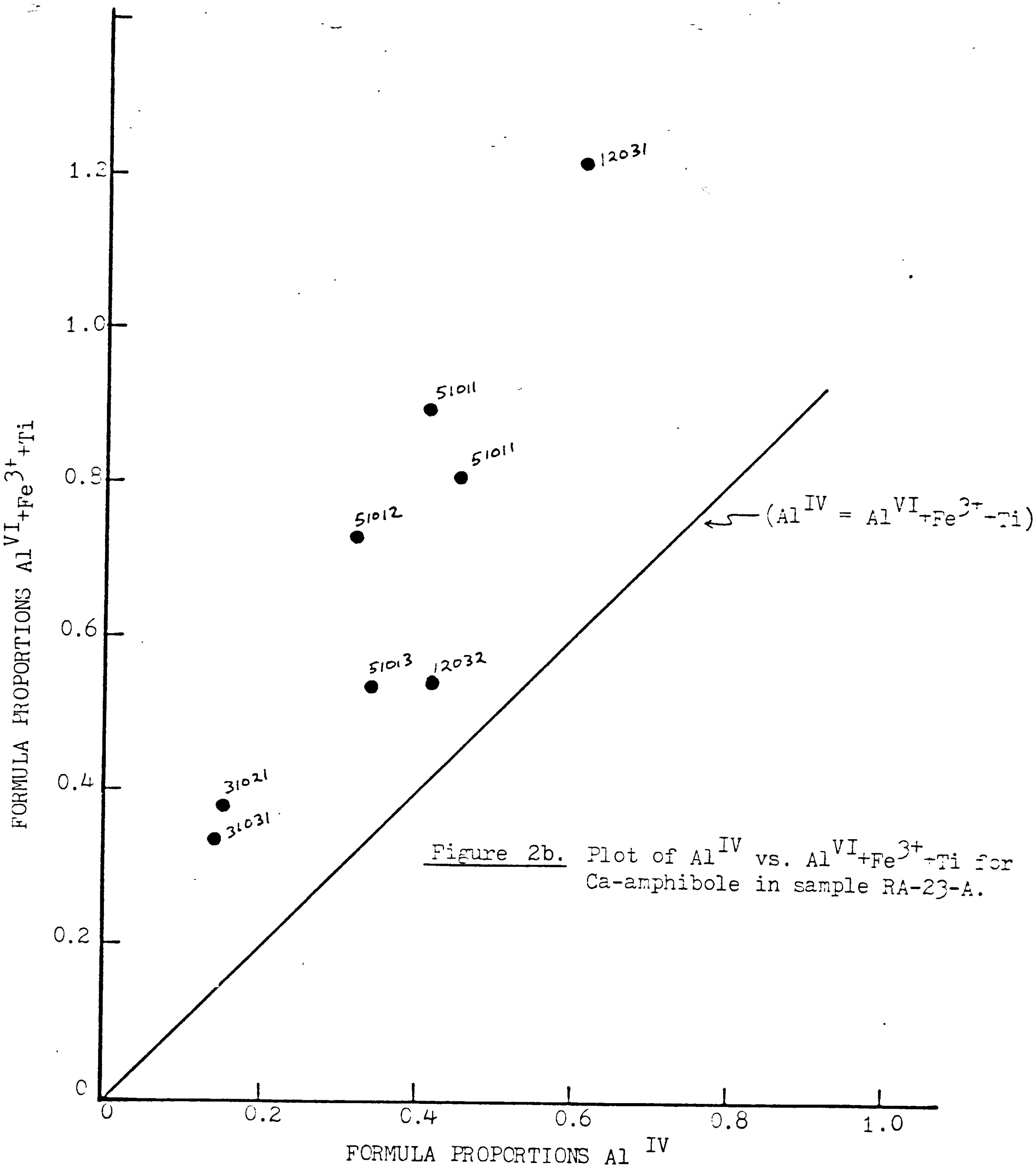


Figure 2b. Plot of Al^{IV} vs. $Al^{VI}+Fe^{3+}+Ti$ for Ca-amphibole in sample RA-23-A.

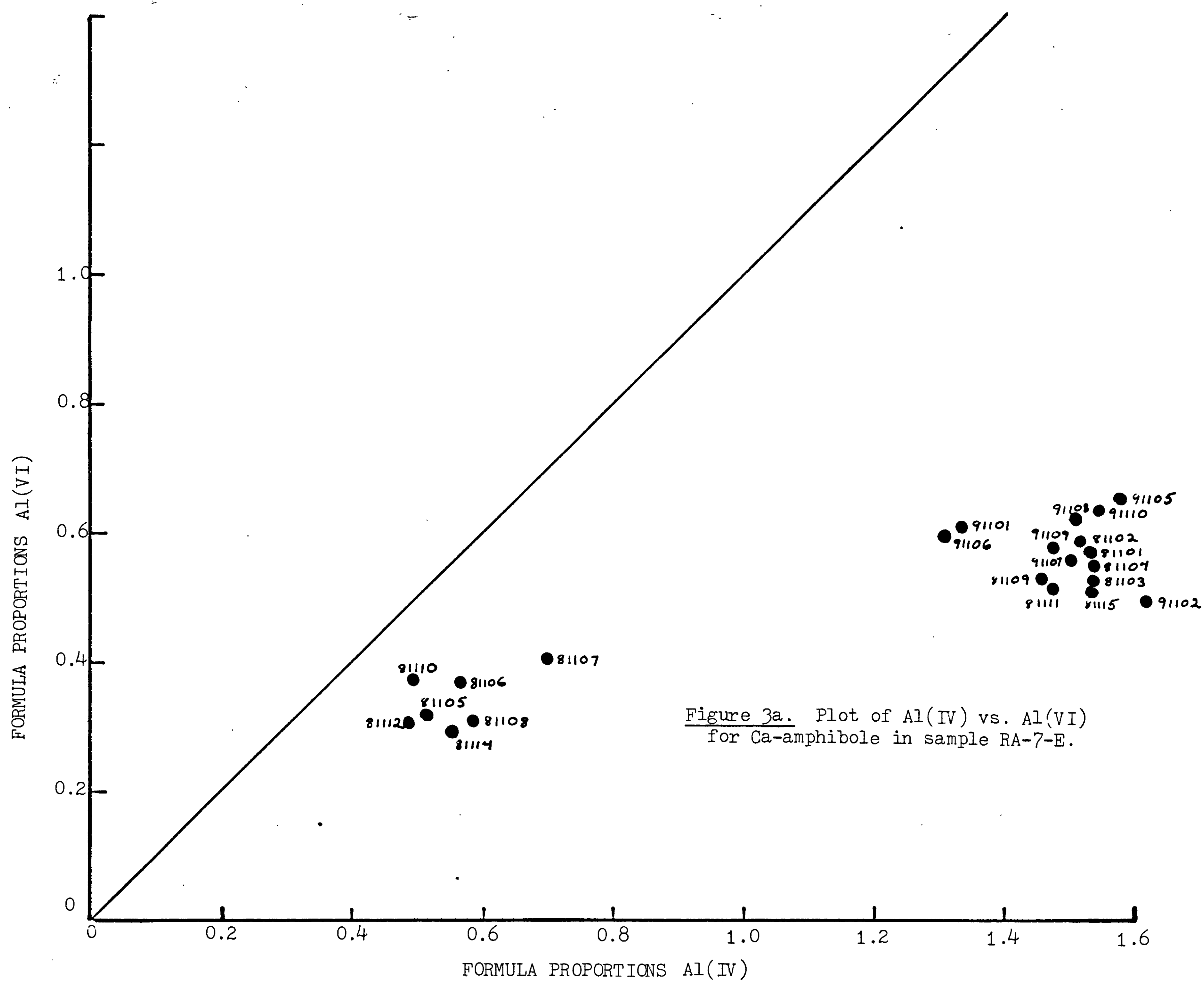


Figure 3a. Plot of Al(IV) vs. Al(VI) for Ca-amphibole in sample RA-7-E.

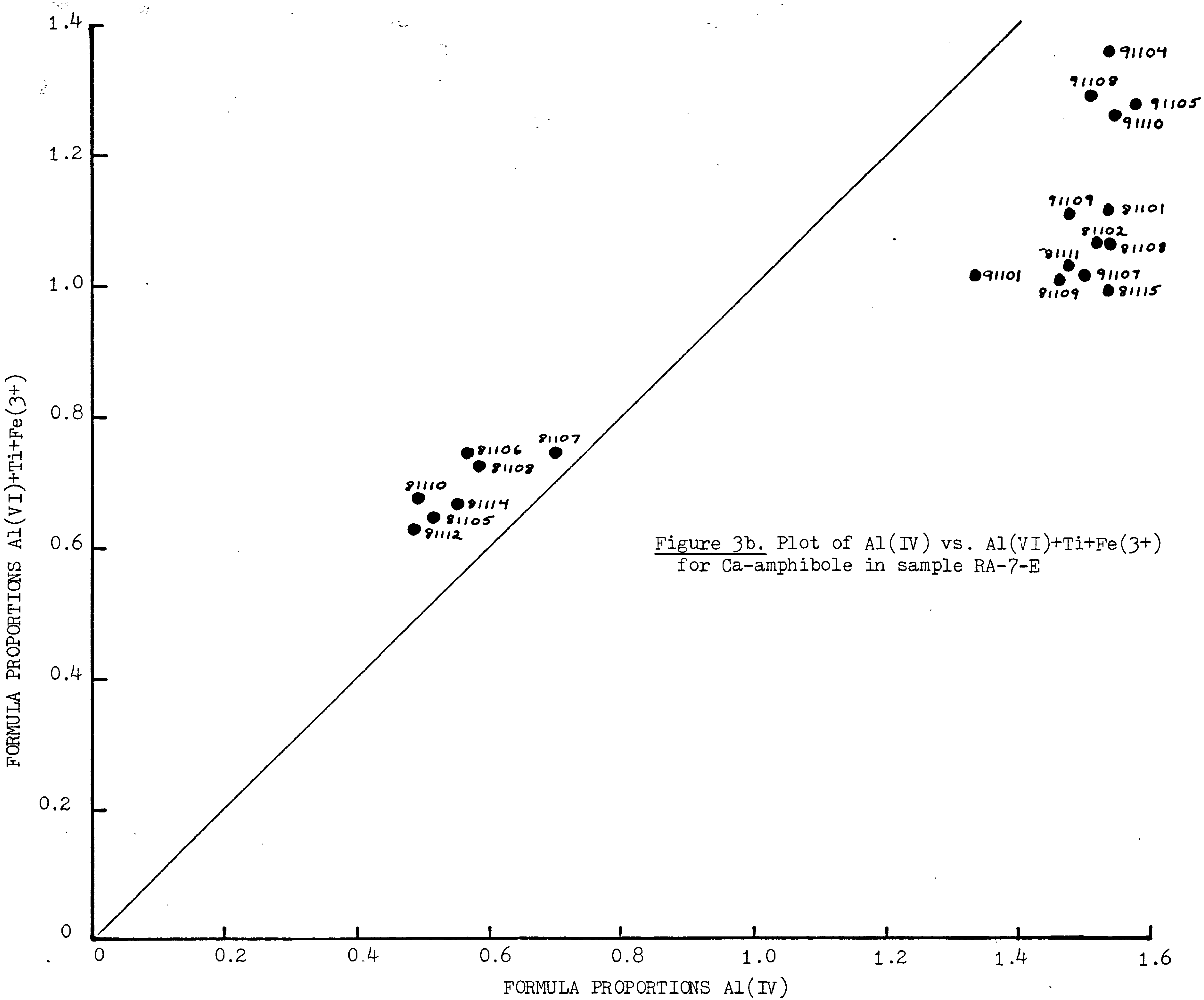


Figure 3b. Plot of Al(IV) vs. Al(VI)+Ti+Fe(3+) for Ca-amphibole in sample RA-7-E

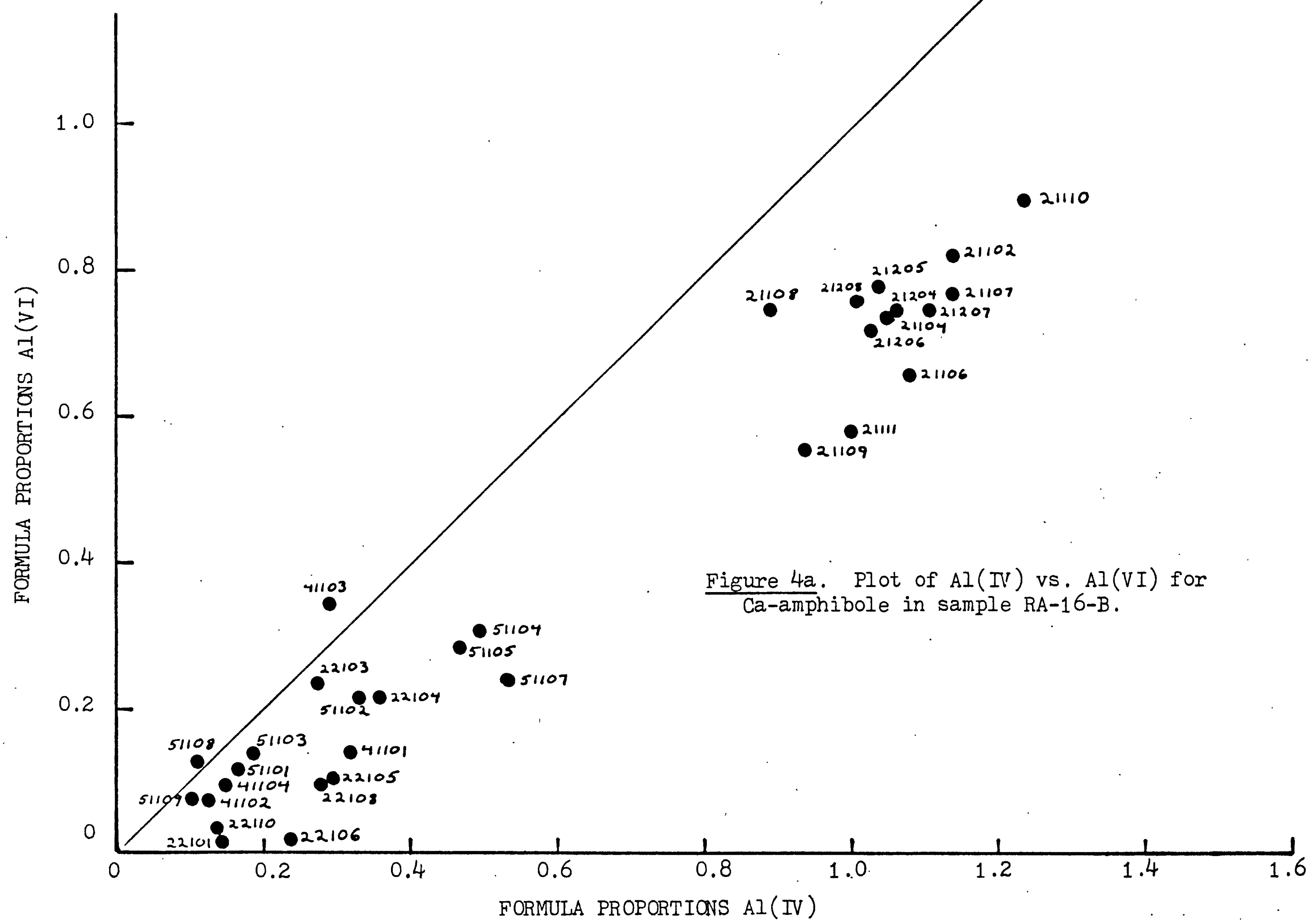


Figure 4a. Plot of Al(IV) vs. Al(VI) for Ca-amphibole in sample RA-16-B.

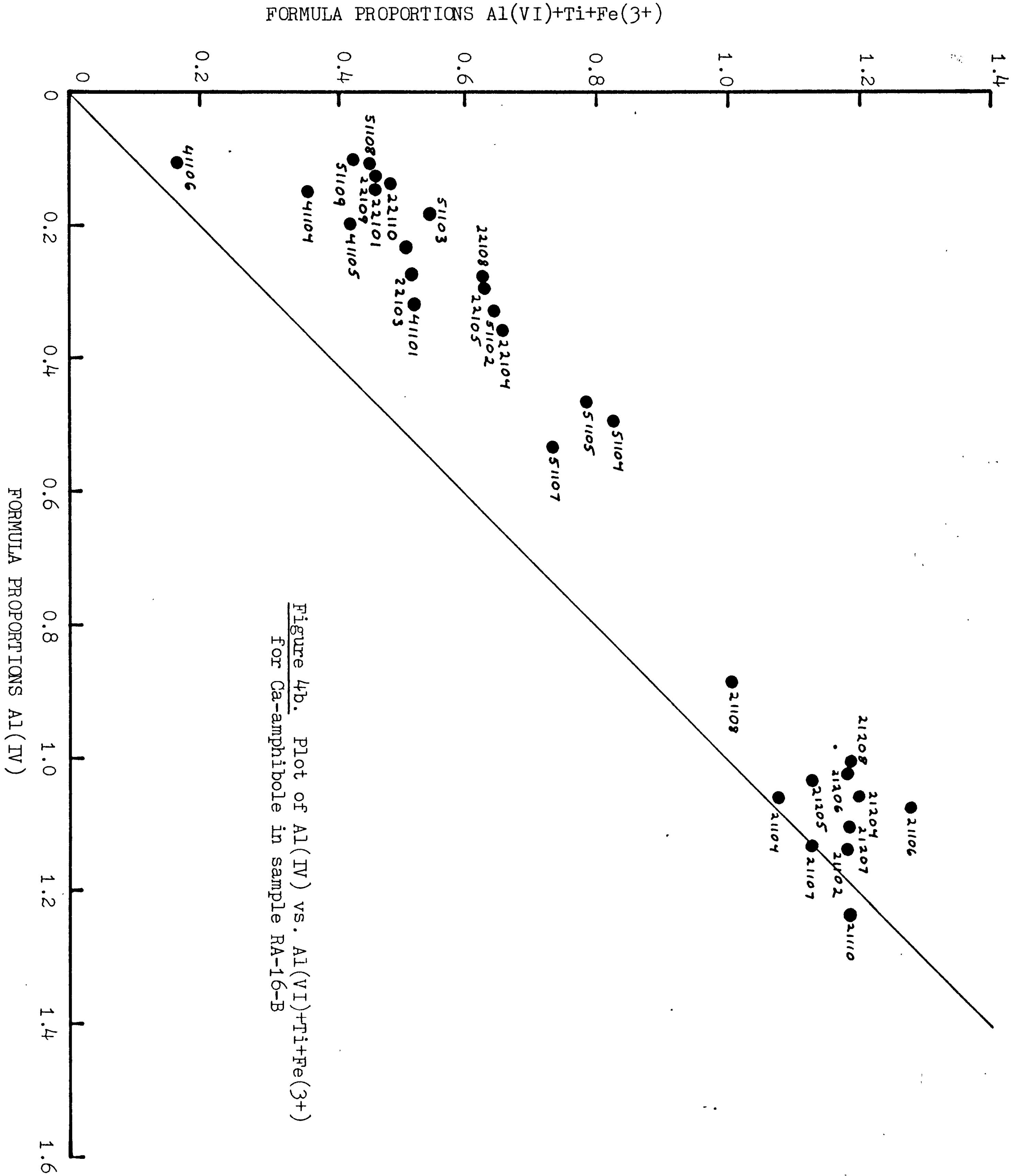


Figure 4b. Plot of Al(IV) vs. Al(VI)+Ti+Fe(3+) for Ca-amphibole in sample RA-16-B

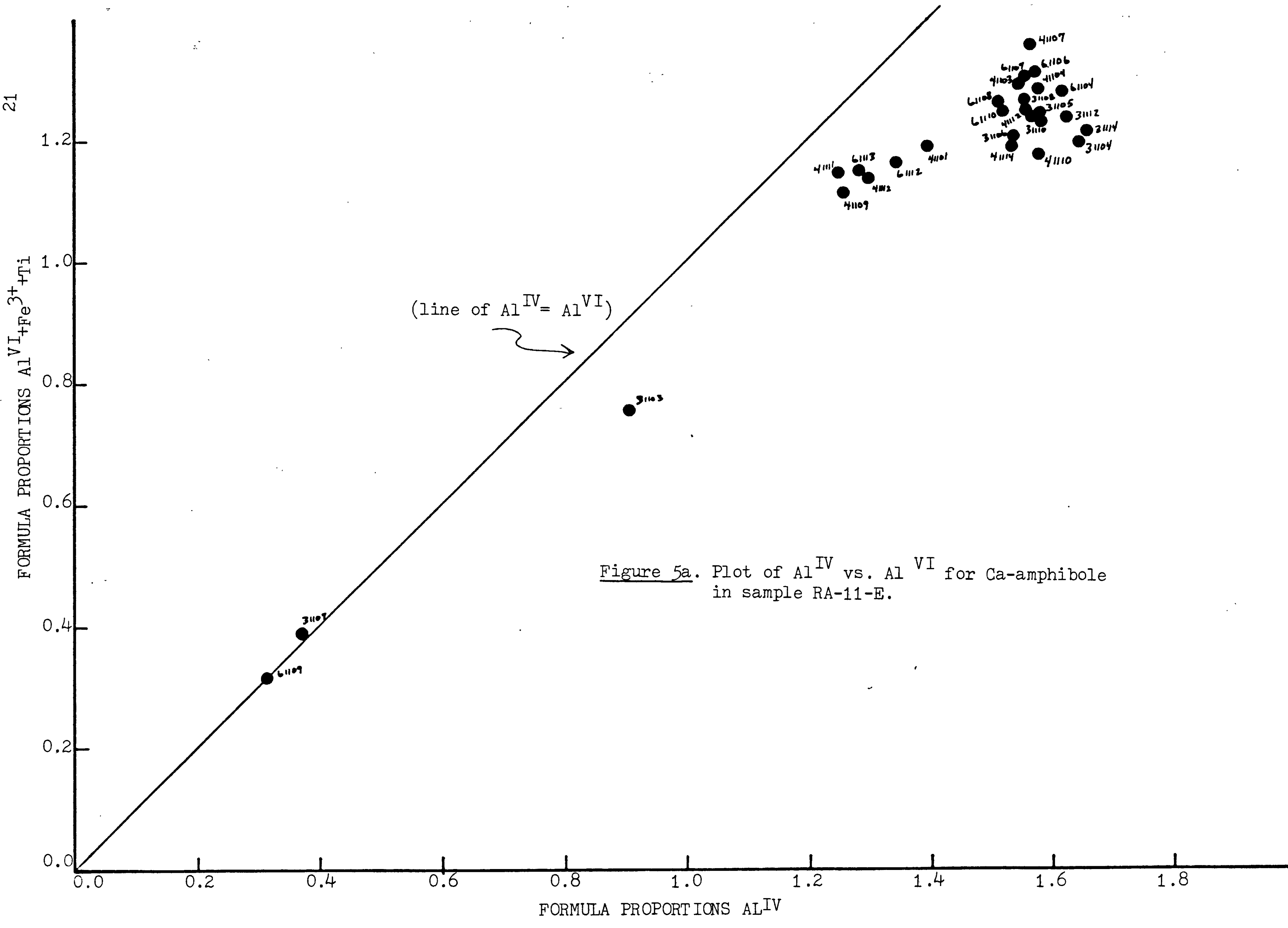


Figure 5a. Plot of Al^{IV} vs. Al ^{VI} for Ca-amphibole in sample RA-11-E.

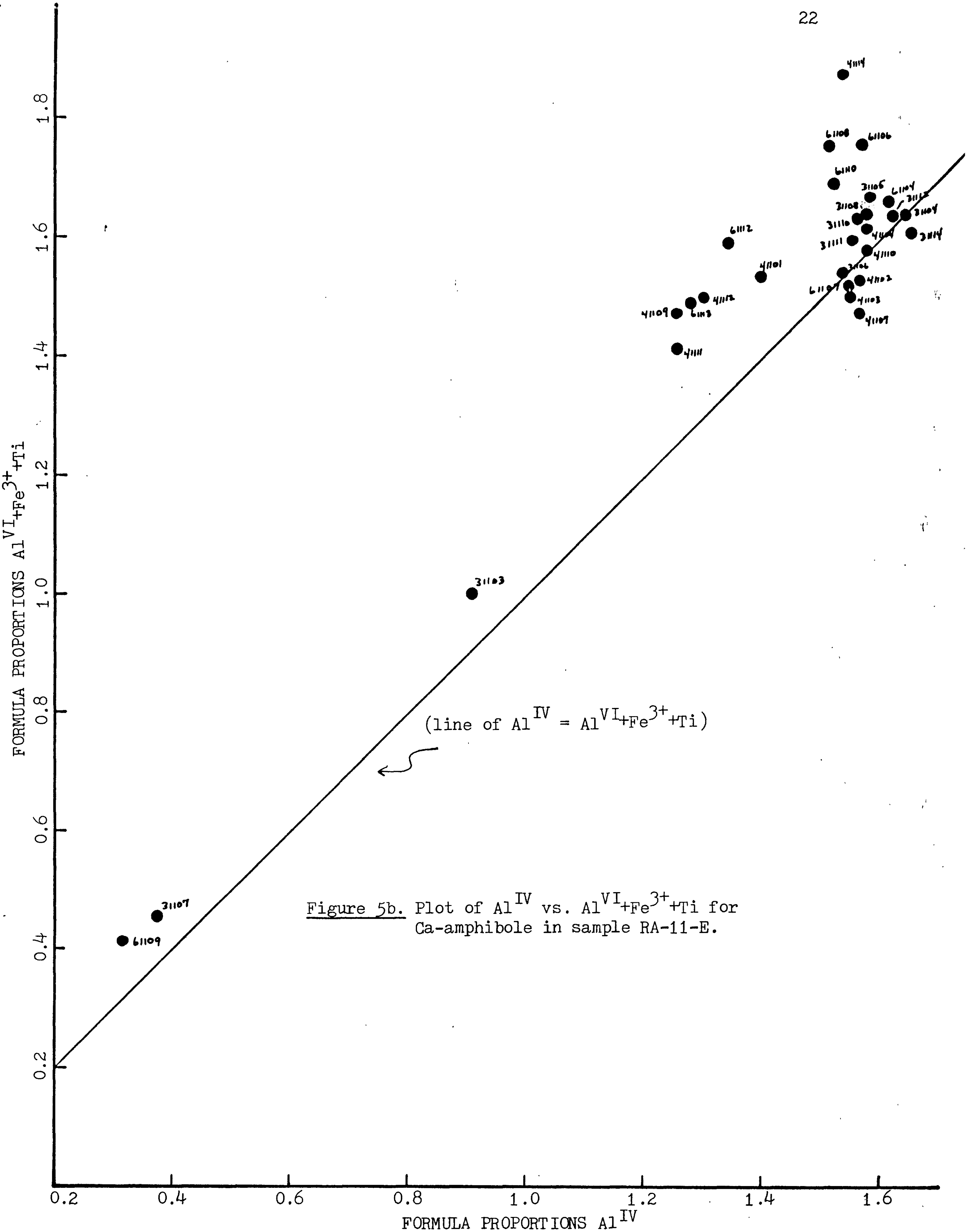


Figure 5b. Plot of Al^{IV} vs. $Al^{VI}+Fe^{3+}+Ti$ for Ca-amphibole in sample RA-11-E.

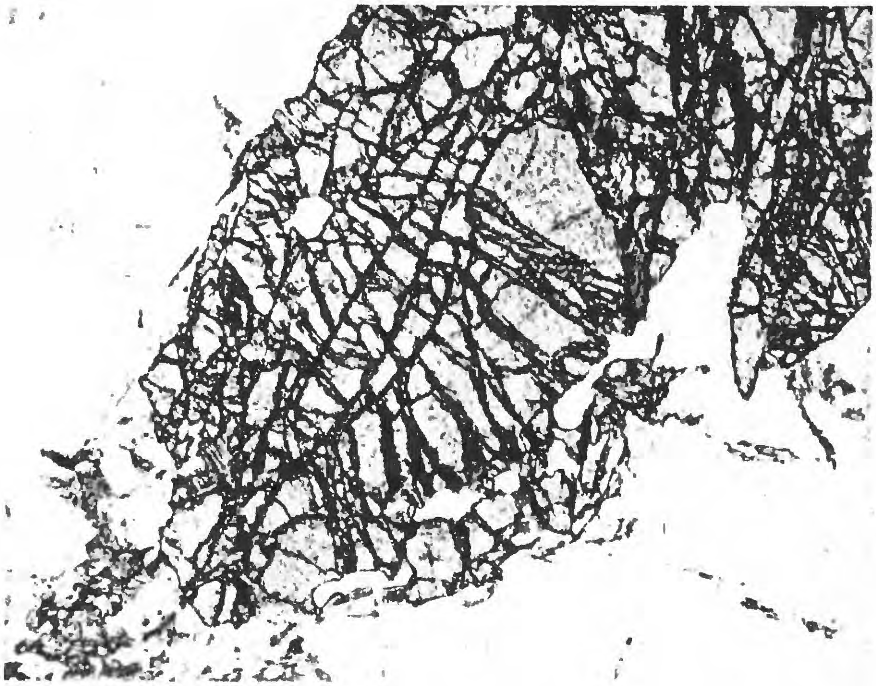


Figure 6. Photomicrograph of garnet grain partially altered to biotite (along fractures) and minor epidote in sample RA-27-E. Plane polarized light, 2.5 mm field of view.

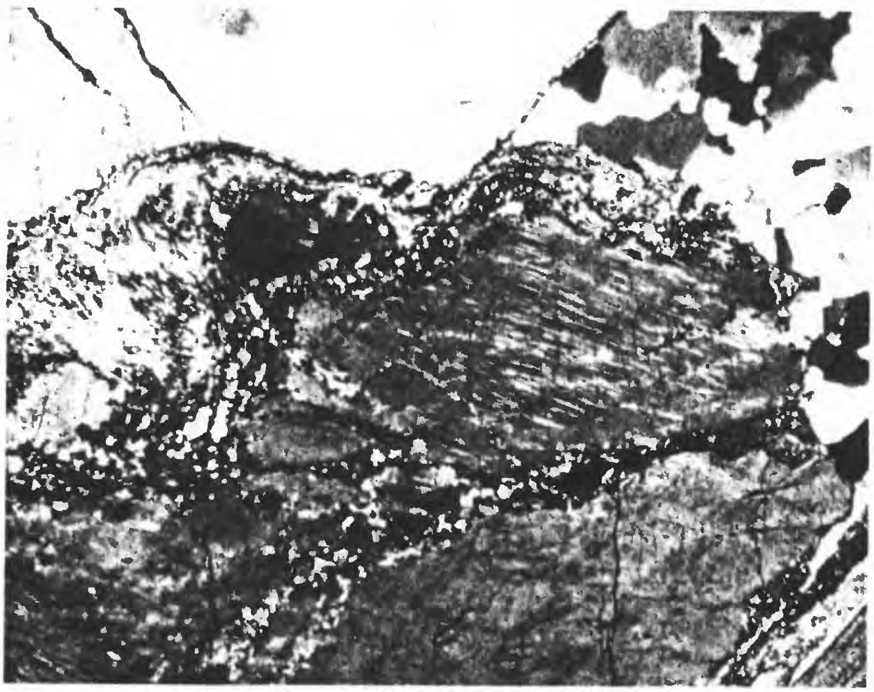
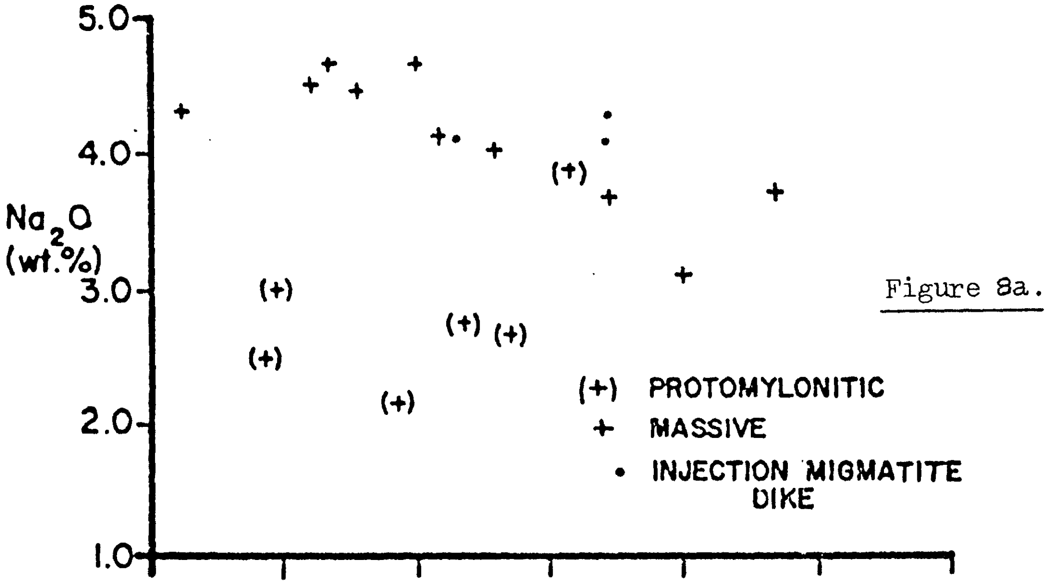
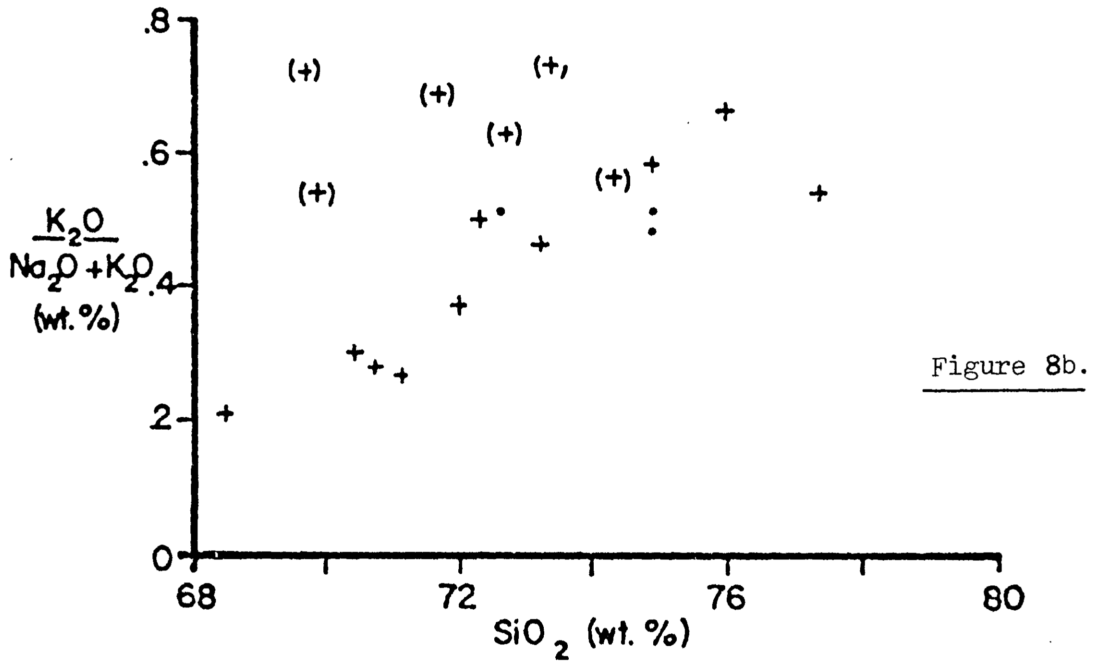


Figure 7. Photomicrograph of alkali feldspar grains partially altered to sericite along grain boundaries in sample RA-26-D. Crossed polarizers, 2.5 mm field of view.

Figure 8. Compositional plots for whole rock analyses of uncataclasized and cataclasized Agua Fria granodiorite, Los Amates quadrangle, Guatemala (Muller, 1980, Ph.D. thesis).





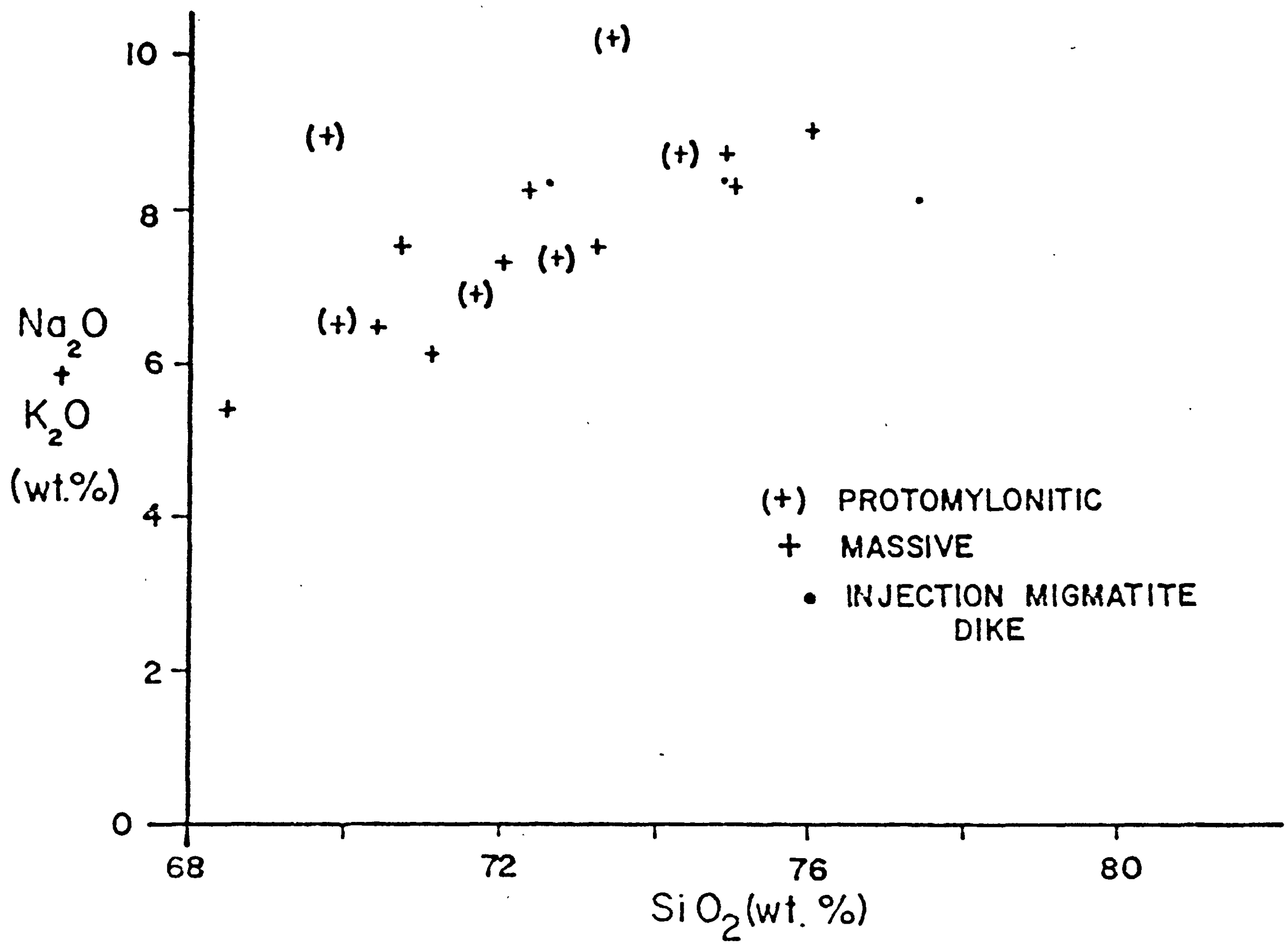

10
8
6
4
2
0
Na2O
+
K2O
(wt.%)
68
72
76
80
SiO2(wt.%)
(+) PROTOMYLONITIC
+ MASSIVE
• INJECTION MIGMATITE DIKE

Figure 8c.

Appendix A. Whole rock chemical analyses of cataclastic rock samples performed by rapid silicate analysis methods.

SAMPLE NO.	RA1-A	RA1-I	RA2-B	RA2-D	RA3-I	RA3-L	RA3-P
SiO_2	45.6	68.1	72.2	48.1	73.8	51.0	49.5
TiO_2	1.2	0.7	0.2	0.9	-	1.3	0.9
Al_2O_3	18.1	13.4	14.7	22.2	15.6	15.7	15.5
Fe_2O_3	2.3	2.5	1.0	2.9	0.1	2.7	1.9
FeO	7.1	2.2	0.7	8.4	0.2	4.2	8.8
MnO	0.3	-	-	0.4	-	0.1	0.2
MgO	8.8	2.3	0.1	4.0	-	4.1	6.4
CaO	10.3	3.8	2.1	7.8	0.6	6.8	10.8
Na_2O	1.8	2.3	3.9	3.3	5.4	2.9	2.9
K_2O	1.8	2.1	3.1	0.3	3.7	2.4	0.8
P_2O_5	0.1	0.1	0.1	0.1	-	0.3	0.1
H_2O^+	1.4	0.8	0.3	0.8	0.2	2.7	0.9
CO_2	NA	NA	NA	NA	NA	7.5	NA
TOTAL	98.8	98.2	98.5	99.2	99.6	101.7	98.7

SAMPLE NO.	RA3-Q	RA3-S	RA3-X	RA4-A	RA4-G	RA6-A	RA6-E
SiO_2	71.4	58.8	63.4	65.5	63.5	68.4	50.2
TiO_2	0.6	0.7	0.9	0.7	0.4	0.6	2.1
Al_2O_3	13.6	12.3	16.2	16.5	14.4	14.5	16.8
Fe_2O_3	1.2	1.4	1.9	1.8	0.7	3.7	1.4
FeO	2.8	4.1	3.8	3.0	1.5	3.0	6.7
MnO	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MgO	2.0	5.8	2.5	2.1	1.0	2.2	3.9
CaO	1.6	5.2	3.0	2.7	5.3	2.7	6.8
Na_2O	2.4	1.5	2.1	3.7	3.8	2.7	4.2
K_2O	2.3	1.3	2.9	2.9	2.7	2.6	0.8
P_2O_5	0.1	0.1	0.2	0.2	0.1	0.2	0.2
H_2O^+	0.7	2.8	1.5	0.9	1.5	1.2	2.1
CO_2	NA	6.8	2.4	NA	5.5	NA	5.3
TOTAL	99.0	100.9	100.9	100.1	100.6	101.9	100.6

(NA) = not analyzed

(–) = less than 0.05 wt. %

SAMPLE NO.	RA3-A=RA3-B	RA3-C	RA3-E	RA3-F	RA3-G	RA3-J	RA3-J	RA3-K	
SiO_2	67.0	54.3	96.8	70.2	53.7	34.3	79.2	72.8	72.7
TiO_2	0.5	0.3	-	0.5	0.1	1.9	0.1	0.3	0.4
Al_2O_3	9.1	4.2	0.4	13.7	19.9	13.7	10.9	12.9	13.7
Fe_2O_3	0.9	1.4	-	1.4	0.2	4.6	0.6	1.8	1.3
FeO	2.3	4.6	-	1.6	0.3	10.7	1.0	1.7	1.4
MnO	0.1	0.2	-	-	-	2.0	-	0.1	0.1
MgO	4.0	17.3	0.2	2.0	0.2	6.4	1.0	1.5	1.2
CaO	7.2	8.6	0.8	2.8	8.3	8.8	1.0	2.8	1.8
Na_2O	1.3	0.4	0.4	2.8	5.9	2.1	3.9	3.2	3.0
K_2O	1.4	0.1	0.1	2.5	3.6	0.2	1.7	2.1	2.4
P_2O_5	-	-	-	0.1	0.1	0.2	-	0.1	0.1
H_2O^+	1.2	4.2	0.3	1.4	1.3	4.9	0.6	1.9	1.8
CO_2	7.1	NA	0.7	2.0	4.6	10.0	NA	NA	NA
TOTAL	102.1	99.8	99.7	101.0	98.2	99.8	100.0	101.2	100.9

SAMPLE NO.	RA3-H	RA3-O	RA3-R	RA3-U	RA4-B	RA4-E	RA4-H	RA4-I	RA4-J
SiO_2	59.9	58.3	68.0	63.9	74.9	69.3	69.5	70.0	67.6
TiO_2	1.3	1.6	0.7	0.9	0.1	0.3	0.4	0.5	0.6
Al_2O_3	16.2	12.9	16.1	15.1	15.1	14.7	14.3	14.4	14.9
Fe_2O_3	2.5	2.6	1.1	1.6	0.2	0.7	0.7	1.3	1.2
FeO	4.2	4.5	3.2	3.7	0.3	1.3	1.3	2.0	2.6
MnO	0.1	0.1	0.1	0.1	-	-	-	0.1	-
MgO	6.7	3.5	5.0	4.8	-	1.7	1.9	1.4	2.2
CaO	5.9	5.2	2.1	1.2	1.5	1.9	2.0	1.4	1.5
Na_2O	3.0	1.2	1.0	2.6	4.8	3.4	5.9	4.2	3.5
K_2O	1.8	2.3	2.9	2.5	3.6	2.0	1.8	2.3	2.7
P_2O_5	0.2	0.1	0.2	-	0.1	-	-	0.1	-
H_2O^+	1.5	2.2	2.8	1.4	1.0	1.1	1.3	1.8	0.9
CO_2	NA	NA	NA	1.8	NA	4.6	2.6	1.1	2.2
TOTAL	103.2	97.8	100.0	100.6	100.9	101.4	102.1	100.5	99.4

SAMPLE NO.	RA5-A	RA5-B	RA6-G	RA6-I	RA6-J	RA11-A	RA11-O
SiO_2	70.0	74.9	50.8	69.0	67.5	47.8	46.7
TiO_2	0.4	-	0.8	0.4	0.6	2.9	-
Al_2O_3	14.9	15.1	17.4	14.0	15.6	12.4	13.6
Fe_2O_3	1.1	0.5	1.8	1.8	0.3	5.0	4.7
FeO	1.8	0.3	6.7	1.5	2.5	11.8	10.1
MnO	0.1	0.1	0.2	0.1	0.1	0.3	0.2
MgO	1.1	0.1	7.2	1.1	3.1	5.1	7.9
CaO	0.7	1.1	7.9	2.1	1.8	7.3	9.2
Na_2O	3.9	3.6	3.8	3.6	2.6	1.0	3.0
K_2O	2.2	3.2	0.5	2.2	3.1	0.3	0.3
P_2O_5	0.1	-	0.3	0.1	0.2	0.4	0.1
H_2O^+	1.2	0.3	1.4	1.8	1.3	3.8	3.0
CO_2	NA	NA	NA	NA	NA	2.8	1.4
TOTAL	97.5	99.2	98.8	97.7	98.7	98.1	100.2