THE GEOCHRONOLOGY OF ACADIAN PLUTONISM IN SOUTHEASTERN QUEBEC

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ABSTRACT

Concordant U/Pb zircon and/or titanite or monazite ages have been obtained for five major, undeformed, calc-alkaline plutons of the Appalachians of southeastern Québec. These are interpreted as ages of crystallization for the Scotstown (407+/- 3 Ma), Lac Aux Araignées (383 +/- 3), Winslow (377 +/- 7 Ma), Aylmer (375 +/- 3 Ma) and Ste. Cécile (374 +/- 1 Ma) plutons. Many other titanite samples gave $^{208}Pb/^{238}U$ dates that are 6 to 30 Ma younger than the concordant zircon dates from the same samples. This is probably the result of a combination of Pb loss and incorrect common Pb correction.

Rb/Sr isochrons for four of these plutons, and for the Beebe and Stanhope plutons, show considerable isotopic heterogeneity and correspondingly high errors in ages. The isotopic heterogeneity is likely caused by post-solidification metasomatic alteration by host rock fluids. Where the scatter is least (Ste. Cécile) the Rb/Sr age (364 +/- 14 Ma) is similar to the U/Pb mineral age (374 +/- 1 Ma). The $^{87}Sr/^{86}Sr$ initial ratios range from 0.7065 to 0.710 and are probably related to the source of the magmas. The relatively high initial ratios and the peraluminous nature of the plutons preclude a significant mantle contribution to the magmas. These ratios are typical of melts generated in Rb-depleted lower crust. These undeformed plutons are probably the result of melting of the lower continental crust near the end of crustal thickening caused by compression during the Acadian Orogeny.

SOMMAIRE

Cinq intrusions calc-alkalines, non deformees, situees dans les Appalaches au sud-est du Québec ont été datées à l'aide du zircon (U/Pb) et/ou de la titanite ou de la monazite. Les résultats obtenus pour ces cinq intrusions (Scotstown, 407 +/- 3 Ma; Lac Aux Araignées, 383 +/- 3 Ma; Winslow, 377 +/- 7 Ma; Aylmer, 375 +/- 3 Ma; Ste. Cécile, 374 +/- 1 Ma) sont interprétés comme des âges de cristallisation. Les échantillons de titanite ont donné des âges ($^{206}Pb/^{238}U$) de 6 à 30 Ma inférieurs à ceux donnés par les zircons se trouvant dans les memes échantillons. Cette différence est causée d'une part par une perte de plomb et d'autre part par les erreurs associées à la correction du plomb commun dans le calcul des âges.

Les intrusions de Beebe, de Stanhope et quatre des intrusions mentionnées ci-dessus montrent des isochrons Rb/Sr qui sont affectés d'une hétérogénéité isotopique produisant ainsi des incertitudes dans le calcul des âges. L'intrusion de Ste. Cécile donne un âge Rb/Sr (364 +/- 14 Ma) compatible avec l'âge U/Pb (374 +/- 1 Ma). Les rapports initiaux $^{87}Sr/^{86}Sr$ variant de 0.7065 à 0.7100 ainsi que la nature péralumineuse des intrusions suggèrent des magmas produits dans la croûte inférieure, où il y a une diminution dans les teneurs du Rb. Les intrusions non déformées des Appalaches, produites durant l'orogénie Acadienne, sont probablement formées par un magma provenant de la croute continental inférieure suite à un épaississement crustal.

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CHAPTER 1

INTRODUCTION

Intrusive igneous rocks in the Québec Appalachians occur only in north-central Gaspé and an area of southeastern Québec. The latter are probably westernmost members of an extensive zone of Acadian magmatism in New England and the Maritime Provinces of Canada. The peraluminous, undeformed Acadian intrusives studied in this project are the Scotstown, Lac Aux Araignées, Aylmer, Ste. Cécile, and Winslow complexes of southeastern Québec. Two other Acadian intrusives of southeastern Quebec, Beebe and Stanhope-Averill plutons, and the deformed, Taconian Moulton Hill granitic rocks of the Ascot-Weedon Formation have also been included in this study, but less extensively analyzed in terms of age and petrological nature.

Appalachian Orogen : An Overview

The recent literature on the Appalachian orogen illustrates the diversity of models used to explain the formation of this eastern North American mountain belt. The first model based on plate tectonic theory, proposed by Wilson (1966) and later supported by Bird and Dewey (1970), involved the simple single-cycle opening and closing of a proto-Atlantic ocean referred to as Iapetus. There is general agreement on the time of expansion ("rift" and then "drift"), the timing of the initial rifting being about 600 Ma (Stukas and Reynolds 1974) based on the radiometric dating of the Long Range Swarm of mafic dykes. The transition from rift to drift occurred at about 550-570 Ma (Williams and Hiscott 1987) on the basis of stratigraphic arguments. This later event is also supported by radiometric ages (565 Ma) obtained on carbonatites belonging to a single rift system extending at least from central Canada to eastern Sweden (Doig 1970). The time of closure of the Iapetus ocean is, however, much disputed. Williams (1979) assigns a Caradocian age (465 Ma) for the complete destruction of Iapetus, which is in agreement with the study of Williams and St.Julien (1978) who propose a pre-Silurian closure. Other researchers prefer a Devonian time of closure (Dewey 1969; Boucot et al. 1964). Poole (1976) suggests a Late Silurian closure, whereas Wilson (1966) and Dewey and Kidd (1974) argue that the closure of Iapetus occurred in several stages. Finally, Dickinson (1974) is altogether opposed to just one cycle of opening and closing, advocating that 200 million years is sufficient time to have had several cycles, based on present rates of ocean floor spreading and plate subduction.

Another model, which is based on paleomagnetic data, involves major strike-slip movements (sinistral transcurrent faulting) on faults bounding terranes of different lithological character (Morris 1976). The paleomagnetic data are interpreted to indicate about 2,000 Km of sinistral strike-slip movement.

For example, the Precambrian (i.e. Avalonian) rocks of Eastern Massachusetts began their journey in the Carboniferous at about the latitude of Florida (with respect to North America), and came to rest opposite western Massachusetts some 25 Ma later (Kent and Opdyke 1978, Van der Voo et al. 1979). However, recent paleomagnetic studies by Séguin (1982b) cast doubt on the Kent and Opdyke (1978) model. The geological evidence suggests that a much smaller amount of dextral slip occurred, mainly on faults parallel to pre-Acadian paleogeographic realms (Bradley 1983).

A recent model proposed by Williams and Hatcher (1982, 1983) involves the accretion of suspect terranes against the North American cratonic margin. Suspect terranes are recognized by contrasts in stratigraphy, structure, metamorphic and plutonic histories, faunas, mineral deposits, and paleomagnetic signatures (Williams and Hatcher 1982). Williams and Hatcher (1982, 1983) note the fact that times of deformation in the orogen coincided with the main phases of accretion. They also state that plutonism and metamorphism were related spatially as well as temporally, and both were associated with all major orogenic events. This model is supported by studies based on seismic results (Ando et al. 1983, 1984; Stewart 1985) and the chemistry of the plutonic rocks (Ayuso 1980, 1986; Andrew 1983; Wones 1980) across the orogen. The different tectono-stratigraphic zones are underlain by their own characteristic lower crust. In Osberg's (1978) model, he too demonstrates that the orogen consists of a collage of geologically distinct basement units.

The major problem with synthesizing the different plate tectonic models for the Appalachian Orogen is the lack of agreement on the polarity and number of subduction zones required to produce the orogen (if subduction zones are a part of the model). There is agreement for the Taconic Orogeny, that is interpreted as polyphase deformation and metamorphism in the continental-rise prism, probably accompanied by ophiolite obduction, as the leading edge of the North American continent moved under the oceanic crust along an eastward-dipping subduction zone (Williams 1979). This view is also supported by the following researchers : Robinson and Hall (1980); Osberg (1978); Haworth et al. (1978); Strong et al. (1974); Rodgers (1981); Rowly and Kidd (1981); Church and Stevens (1971); Malpas and Strong (1975); Strong (1977). Researchers who have advocated west-dipping subduction zones are Ruitenberg et al. (1977), Bird and Dewey (1970), and Hon and Roy (1981).

McKerrow and Ziegler's (1971, 1972) model consisted of simultaneous eastward and westward dipping subduction zones. This model was preferred and later enhanced by Bradley (1983).

Williams (1979) divided the Appalachian Orogen into five broad zones based on stratigraphic and structural contrasts between Cambro-Ordovician and older rocks (Fig. 1). From west to east, these are the Humber, Dunnage, Gander, Avalon, and Meguma zones. In this geological context, the study area lies within the

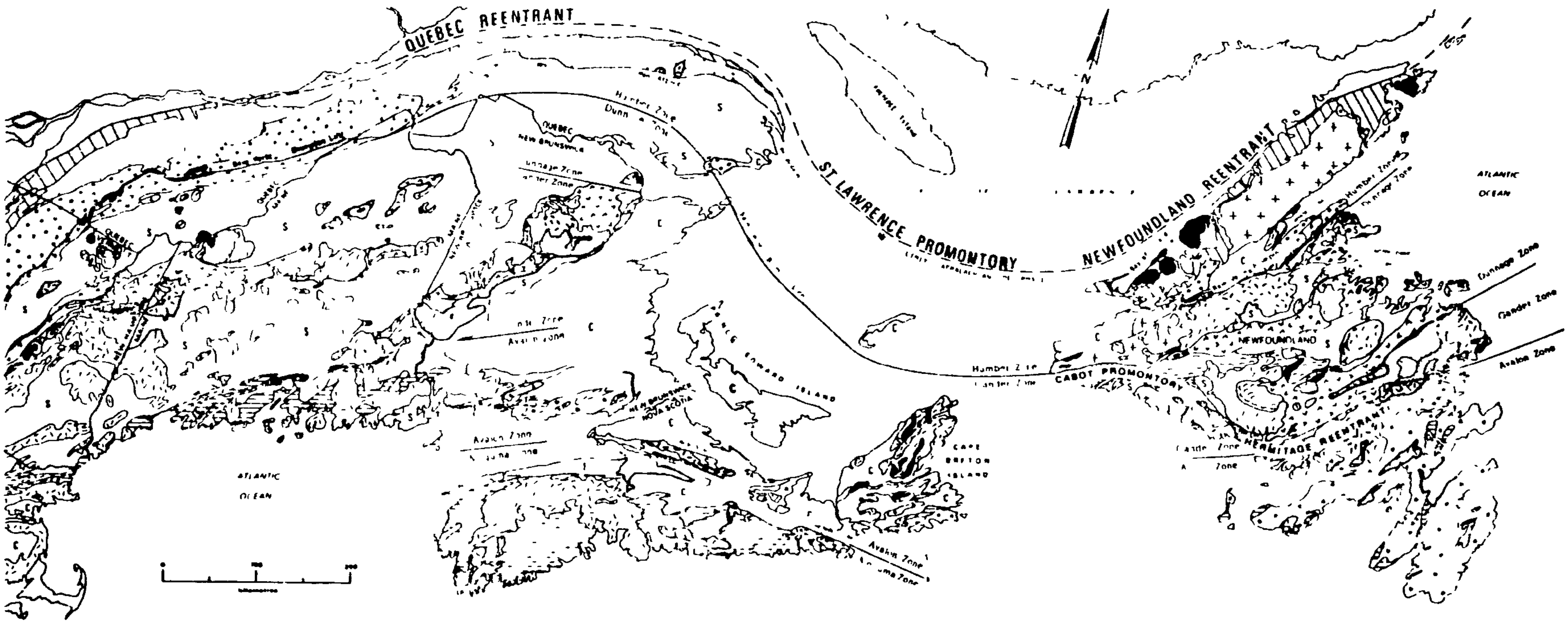


Fig. 1. Lithostratigraphic tectonic zones of the Appalachian Orogen from Williams (1979).

Dunnage zone. This zone is interpreted to be the vestige of an oceanic domain (Iapetus) and is composed principally of island arc sequences (Kean and Strong 1975) and melanges (Horne 1969; St.Julien and Hubert 1975; Kay 1976; Hibbard and Williams 1979), all deposited on oceanic crust (Upadhyay et al. 1971; Kay 1975; Smitheringale 1972; Laurent 1975, 1977). Important rock types include tholeiitic basalt, calc-alkaline andesite and rhyolite, pelagic and hemipelagic sediments and turbidites (Norman and Strong 1975; Kidd 1977; Williams 1979).

Orogenic events such as deformation and plutonism accompanying closure of Iapetus have traditionally been divided into two phases. The first, Taconic Orogeny, is represented by recumbent folds as the dominant structure in the Ordovician thrust sequences. A later period of mild deformation but extensive plutonism of Devonian age is referred to as the Acadian Orogeny.

Taconic Orogeny

Taconic deformation is most reasonably interpreted to mark a closing of the Iapetus Ocean and the destruction of its continental margin (Williams, 1979). The main area of influence of the Taconic Orogeny is the northwestern side of the northern Appalachians, with local effects elsewhere (Rodgers 1970). The Taconic Orogeny is responsible for almost all the deformation that we now observe in the Cambrian rocks of the Québec Appalachians (St.Julien and Hubert 1975). These rocks are found in St.Julien and Hubert's (1975) autochthonous, external, and internal domains, and are analagous to the Humber and northwestern part of the Dunnage (north of the Silurian-Devonian Gaspé Connecticut-Valley Synclinorium) zones of Williams (1979). The boundary between the Humber and Dunnage zones is the Baie Verte-Brompton Line (St.Julien et al. 1976; Williams and St.Julien 1978), a steep structural zone characterized by ophiolite occurrences (Williams 1979). The Humber zone consists of a crystalline basement which was formed during the Grenville Orogeny, overlain by mainly sedimentary rocks (Williams 1979). These sedimentary rocks include: shelf, flysch, and regressive sequences (autochthonous domain), a Lower Cambrian clastic-carbonate assemblage (Sutton and Nôtre Dame Anticlinoria), a Cambrian shale-feldspathic sandstone assemblage, and an Upper Cambrian-Lower Ordovician shale-limestone conglomerate (External Domain). The next youngest lithostratigraphic assemblages are: ophiolites, a shale-melange (St. Daniel Formation), a slate-sandstone "tuff" (Magog Formation) and a calc-alkaline volcanic assemblage (Ascot and Weedon Formations) all of which belong to the internal domain (St.Julien and Hubert 1975).

Metamorphism and Deformation

The degree of deformation in the Cambro-Ordovician rocks is mild. The main structures are Ordovician recumbent folds that are usually a product of thrusting, directed westward and northwestward across the North American miogeocline (Williams and

Hatcher 1982, 1983 ; Rodgers 1970). The degree of metamorphism is low, typically greenschist facies (Rodgers 1970).

The Age of the Taconic Orogeny

The deformation and metamorphism associated with the Taconic Orogeny is believed to have taken place during Middle Ordovician time (440-465 Ma) (Rodgers 1970; Williams 1979; St.Julien and Hubert 1975; Williams and Hatcher 1982). The age assigned to the destruction of Iapetus is constrained by radiometric ages obtained from the ophiolites located along the Baie Verte-Brompton Line. For example, Laurent and Vallerand (1974) constructed a 40K/40Ar isochron plot from six localities along about 70 Km of the ultramafic belt. The amphibolites are directly associated with the peridotites of Thetford Mines and Asbestos (Laurent and Vallerand 1974). The plot yielded an age of 561 Ma, from which the authors speculated that a significant part of the ophiolite complex formed in Middle Cambrian time. Clague et al. (1981) obtained a K/Ar date of 491 Ma for the amphibolite-grade metamorphic aureole formed at the base of the ophiolite during its emplacement Lowdon et al. (1963) obtained two ages of 495 Ma (K/Ar, muscovite and biotite) for the contact metamorphic aureole around the ultramafic intrusions at Mont Albert. Leech et al. (1963) obtained two K/Ar ages of 490 and 486 Ma for two muscovite samples from "granitic" intrusions in the Thetford lower unit. Poole et al. (1963) resampled these granitic intrusions and obtained ages of 477 and 481 Ma (K/Ar, muscovite). Poole (1980) resampled the Thetford granites and obtained a Rb-Sr whole-rock isochron age of 466 +/- 13 Ma (initial $^{87}Sr/^{86}Sr$ ratio = 0.7172 +/- 0.0011). He concluded that these granites were either generated in a volcanic regime and subsequently homogeneously metasomatized during the Mid-Ordovician polyphase deformation of the ophiolite, or originated by melting of granitic crust (or continental sediments) as the ophiolite was thrust over the continental edge, and later metasomatized during continued deformation. These lenses of massive rodingite and small bodies of deformed hornblende-biotite and biotite-plagioclase diorite were the object of a later study by Clague et al. (1985), in which a nine-sample, combined Rb/Sr whole-rock and mineral isochron for the Black Lake Granite, gave a date of 456+/-4 Ma. The initial $^{87}Sr/^{86}Sr$ ratio is 0.7171 and clearly indicates a crustal origin for the granite. The ages from the isochrons for the other "granites" in the Thetford Mines ophiolite (Colline de Granite, King Mountain, and Vimy Ridge) are imprecise, but their well constrained initial Sr ratios range from 0.716 to 0.720. These ratios suggest that the Thetford felsic intrusions were derived by partial fusion of sedimentary rocks. Clague et al. (1985) suggested that these felsic intrusions penetrated the base of the ophiolite during nappe emplacement (same as Poole's (1980) conclusion). In summary, the ages obtained from the Québec ophiolites indicate that ocean floor was present by 561 Ma and that ophiolite obduction occurred at approximately 480 to 490 Ma. Nappe emplacement of Taconic structural slices continued until at least 456 Ma. This history is supported by the absence of felsic intrusive rocks in the subadjacent Caldwell and Rosaire group rocks. Therefore, as late as 456 Ma ago there was movement on thrusts separating the ophiolite from the Caldwell and Rosaire Group rocks (Clague et al. 1985).

Plutonism

Magmatic activity associated with the Taconic orogeny occurs only locally. For example, Poole (1980) and Keppie (1985) suggested that Ordovician plutonism was mainly confined to the Miramichi Anticlinorium (an Ordovician volcanic arc terrane in New Brunswick). Poole (1980) obtained a Rb/Sr isochron date of 498 +/- 19 Ma for the Sugar granite, a subvolcanic pluton located in the anticlinorium. This age is the same as that of the volcanic rocks of the Tetagouche group, New Brunswick. Fyffe et al. (1977) obtained a 489 +/- 14 Ma Rb-Sr isochron age for a deformed granite 85 Km northeast of the Sugar granite. There is also a record of Ordovician igneous activity from 470 to 480 Ma (Rb-Sr whole-rock and U-Pb zircon) in southern New Brunswick (Olszewski and Gaudette 1980), and in southeastern New Hampshire (Aleinikoff 1978) as well as evidence of Ordovician magmatism and migmatization in the coastal area of Maine (Wones 1974).

Rodgers (1970) states that granodiorites and ultramafic plutons are the main types of plutonic rocks associated with this first orogenic phase and that true granite of pre-Devonian age is rare in the Appalachians. Within the study area of southeastern Québec, the deformed Moulton-Hill granite may be related to Ordovician arc volcanism.

Acadian Orogeny

The Acadian Orogeny affected the whole of the Northern Appalachians, except its northwestern margin (Rodgers 1970). It is generally believed that the Acadian Orogeny resulted from the closing of an ocean basin (Dewey 1969; McKerrow and Ziegler 1971, 1972; Schenk 1971; Dewey and Kidd 1974; McKerrow and Cocks 1977, 1978; Keppie 1977a, 1977b; Williams 1979). This orogeny closed the remaining marine troughs, initiating the period of continental deposition, and produced most of the observable structural features in the pre-Carboniferous rocks (Rodgers 1970). Most of the granitic and other intrusive rocks of the region were then emplaced (Rodgers 1970). One popular model is that the orogeny is the result of collision between the North American margin (with its already accreted terranes) and the Avalonian terrane (Dewey and Kidd 1974; Schenk 1978; Hatcher and Williams 1982, 1983), or with a microplate (basement D of Osberg 1978) or the accretion of the Meguma Terrane in the Northern Appalachians (Williams and Hatcher 1983).

Alternatively, Schenk (1976) proposed that the diachronous orogenies (Taconic and Acadian) were produced by oblique collision. That is, collision occurred in the Silurian in the

Northern Appalachians (Caledonian-Taconic Orogeny), in the Devonian in Atlantic Canada (Acadian Orogeny), and finally in the Late Paleozoic in the U.S. (Alleghanian Orogeny).

Metamorphism and Deformation

Although the Devonian (Acadian) orogeny affected the entire orogen, it seems to have been most intense in its interior parts. It is characterized by upright folds, that reflect a shortening across the system, rather than the recumbent structures resulting in horizontal transport during the Taconic Orogeny. Unlike the effects of the Taconic Orogeny, the patterns of Acadian Orogeny provide little evidence for the location of Silurian-Devonian continental margins or suture zones of Devonian age (Williams 1979).

Although the main Acadian structures are upright folds, regional variations in structure and metamorphism do occur. These variations could have been produced by collision along an irregular continental margin, offset by a transform fault (Burke and Dewey 1973; Thomas 1977; Williams 1979; Stockmal et al. 1987). During continental collision, protuberances collide first and become the loci of intense strain, thrusting, and the development of cryptic sutures welding the continental masses. Embayments would be less intensely deformed because they may never completely close, and therefore may preserve oceanic basement beneath thick sedimentary sequences (Dewey and Kidd 1974).

Some thrusting has also taken place in the Acadian Orogeny, because Silurian rocks located in the Gaspé-Synclinorium of southeastern Québec overlie the Taconic deformed zone of the Québec Appalachians, and the axis of the synclinorium cuts obliquely across the Baie Verte-Brompton Line (Béland 1974; St.Julien and Hubert 1975; Williams and St.Julien 1978). Ando et al. (1984) and Chamberlain and England (1985) also recognized major thrust-fault zones that may be related to Devonian continental collision.

The Silurian-Devonian sedimentary series in the Connecticut Valley-Gaspé Synclinorium are characterized by sub-greenschist to low-greenschist facies regional metamorphism (Harron 1976). The low degree of metamorphism and the preservation of the Thetford Mines ophiolites (obducted oceanic crust) are probably the result of incomplete suturing (Dewey and Kidd 1974; Dewey 1975), indicating that the ancient continental margin in the Québec Eastern Townships region was an embayment.

The Age of the Acadian Orogeny

Rodgers (1970) suggested that the orogeny occurred at approximately 360 to 400 Ma. Williams (1979) postulated a 400 to 420 Ma age for this period of deformation. Donohoe and Pajari (1973) compiled stratigraphic, structural, and/or radiometric data from eastern Maine, New Brunswick and adjoining areas of Québec, that suggested that the intense deformation phase of the Acadian Orogeny occurred in Early Devonian time in southwestern

New Brunswick and adjacent Maine, and occurred later northward to the St. Lawrence River.

If the Acadian Orogeny is the result of collision between the Avalonian basement and the accreted North American basement regimes, then Osberg (1978) concluded that the paucity of geologic features related to subduction at this junction suggests that this Acadian suture is cryptic. Gaudette (1981) determined an age of 410 +/- 7 Ma (U/Pb analysis of zircons from quartz diorite of the Middle Road unit) for the Union ultramafic complex, Maine, that he interpreted to be a remnant of Iapetus oceanic crust. These ultramafic rocks were emplaced along a cryptic Acadian suture during North America-Avalonian collision (Gaudette 1981). This primary (crystallization) age of 410 Ma would be a maximum age for collision and disappearance of Iapetus ocean floor (Gaudette 1981). Studies by a number of investigators in the Northern Appalachians have defined a minimum time of peak Acadian metamorphism of 385 to 400 Ma (Dallmeyer 1979; Gaudette et al. 1975; Pajari et al. 1974; Cormier and Smith 1973; Naylor 1971; Lyons and Livingston 1977; Spooner and Fairbairn 1970). These data and the age of the Union ultramafic complex strongly suggest that the Acadian event, from final closure of Iapetus and collision of the Avalonian microcontinent, through the peak of Acadian deformation, occurred in a period of less than 20 Ma in the Maine-New Brunswick area of the Northern Appalachian system (Gaudette 1981). Other authors who have also advocated a brief climactic event for the Acadian Orogeny are Larocque (1986) in the north-central Gaspé region, Naylor (1971) in eastern Vermont, and Hubacher and Lux (1987) in northeastern Maine.

In Newfoundland, the Visean and Ackley granites that straddle the boundary between the Avalon and Meguma terranes gave an Ar/Ar (biotite and hornblende) minimum age of 345 Ma (Dallmeyer et al. 1983), and a Rb/Sr whole-rock minimum age of 355 +/- 10 Ma (Bell et al. 1977), respectively, for the juxtapositioning of the two terranes.

Combining the Newfoundland, Maine and Canadian Maritime Provinces data, the Acadian Orogeny occurred from 355 to 410 Ma, and this longer (than 20 Ma) span of time could be the result of diachronous collision (oblique subduction).

Connecticut Valley-Gaspé Synclinorium

The Southeastern Québec Acadian plutons, which are the focus of this isotopic study, are hosted by the rocks of the Connecticut Valley-Gaspé synclinorium (Fig. 2). The rocks of the synclinorium seem to represent deep-water deposition (Rodgers 1970). Bradley (1983) described the synclinorium as an elongate, post-Taconian basin in which rapid subsidence was localized during the Silurian but affected the entire belt during the Early Devonian. The oldest post-Ordovician rocks are a widely distributed, generally thin (< 1 Km is typical), diachronous sequence of Silurian quartz conglomerates, sandstones, limestones, and calcareous mudstones (Bradley 1983).

The simultaneous onset of volcanism in the Piscataquis Belt (Miramichi Anticlinorium) and rapid subsidence in the southwestern Gaspé suggests a genetic ralationship that would place the Connecticut Valley-Gaspé Trough in a back-arc setting, as suggested by Rodgers (1981) and Hon and Roy (1981).

Plutonism

Areal Distribution

Granitic and granodioritic intrusions, mainly related to Acadian Orogenesis, are abundant in the southern Canadian Appalachians, and are most common in the Dunnage and more easterly zones (Williams 1979). The development of granitic and granodioritic magmas was synchronous with the main phase of regional metamorphism (Osberg 1978) and deformation (Williams and Hatcher 1982, 1983), and was a consequence of collision between the different crustal blocks of Osberg (1978), or of the terranes of Williams and Hatcher (1982, 1983). Compositional differences between the plutons may be due to the type of crustal material melted during collision (Osberg 1978; Strong and Dickson 1978). Williams (1979) described those plutons intruding the mafic volcanic and sedimentary rocks of the Dunnage zone as composite batholiths dominated by calc-alkaline hornblende-biotite granodiorite, quartz diorite and granite. Those intruding metasedimentary rocks and gneissic terranes of the Gander zone are mainly two-mica garnetiferous leucogranites and megacrystic biotite granites, respectively. Megacrystic biotite granites are also common in parts of the Avalon and Meguma zones (Williams

1979).

Ages of Acadian Plutons

There is no obvious pattern of ages for the Acadian plutons in the North American segment of the Appalachian Orogen. Although the Appalachian Orogen was the product of continental or microplate collision due to ongoing subduction off a continental margin (analogous to the Cordilleran Orogen), there are neither age nor $^{87}Sr/^{86}Sr$ initial ratio distributions like those of the Sierra Nevada Batholith of California (e.g. DePaolo 1981; Wones 1980). The lack of systematic changes in bulk composition and Sr initial ratios does not favor an origin by subduction at an island arc or Andean continental margin (Williams and Hatcher 1983). This view has been expressed independently for plutons in Newfoundland (Strong 1980), New Brunswick (Fyffe et al. 1981), and Maine (Wones 1980).

Faul et al. (1963) plotted the ages of post-Taconian granites as histograms and these yielded a bimodal distribution in time, with one peak at 360 Ma and the other at about 400 Ma. Later studies also supported two distinct periods of intrusive activity during the Acadian Orogeny (Spooner and Fairbairn 1970; Fairbairn 1971; Cormier and Smith 1973). Recent U/Pb and Rb/Sr investigations in northeastern Massachusetts (Zartman and Naylor 1984) suggest that plutonism may have been continuous throughout Taconian to Acadian time. Lyons and Livingston (1977) dated plutons of the New Hampshire Plutonic series (Rb/Sr whole rock isochrons) and concluded that plutonism was continuous from 360 Ma to 410 Ma.

Petrogenetic Models

A popular model proposed for the generation of the large number of Acadian plutons is that they are partial melts from different compressed and thickened crustal blocks resulting from an episode of collision (Osberg 1978; Strong and Dickson 1978; Fyffe et al. 1981; Dewey and Kidd 1974; Williams and Hatcher 1982). Mckenzie and Clarke (1975) state that the Devonian magmatic activity was either the result of partial fusion of an underlying crystalline basement or a mixture of mantle material and crustal contaminant.

Larocque (1986) suggested a continental post-collision tectonic setting for the north-central Gaspé rocks, and that the magmatic activity may have been related to a tensional environment in a strike-slip zone in the foreland of a collided plate. Along similar lines, Strong (1980) and Hanmer (1981) suggested that the Acadian plutons were generated along major shear zones.

Geological and Tectonic Setting of the Study Area

The study area lies within the Dunnage tectonostratigraphic zone, interpreted to be the vestige of an oceanic domain (Iapetus). It is composed principally of island arc sequences and melanges, all deposited on oceanic crust. The Dunnage zone in southeastern Québec can be divided into subzones; rocks of Cambrian to Upper Ordovician age, and turbiditic rocks of Silurian-Devonian age (Connecticut Valley-Gaspé Synclinorium).

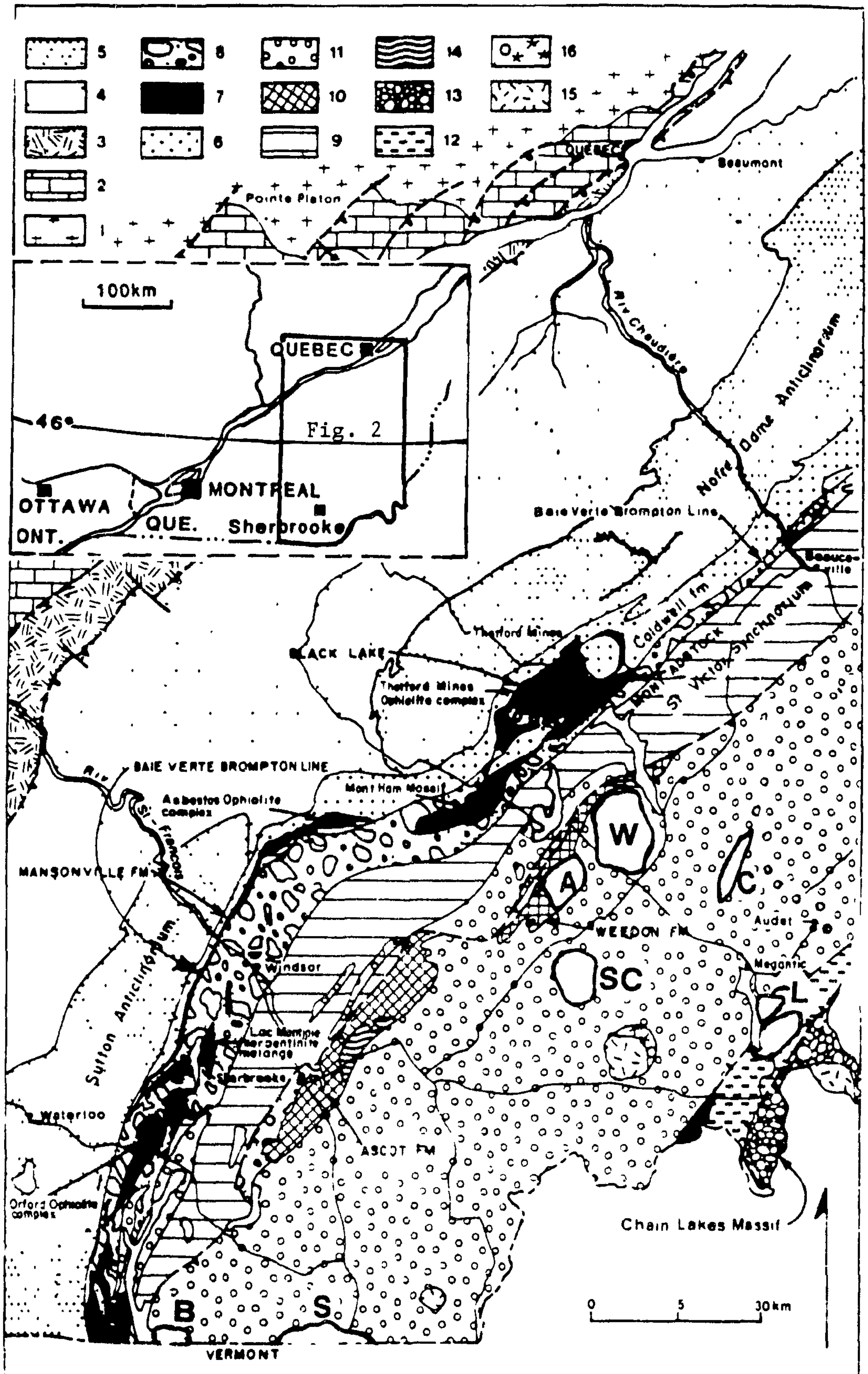
The oldest unit of Cambrian to Upper Ordovician age is the St. Daniel Formation, which consists of block phyllites (melange) containing fragments of reworked Cambrian rocks and locally of ophiolitic rocks (Laurent 1975), and therefore represents the accumulation of sediments on oceanic crust (St.Julien and Hubert 1975). This formation is overlain by the Middle Ordovician Beauceville Formation and St. Victor Synclinorium both of which are part of the Magog Group. The St. Victor Synclinorium and its southeastern extension, the Ascot-Weedon Formation, are the remains of a synchronous island arc (St.Julien et al. 1983). The Moulton-Hill Granite, a deformed subvolcanic pluton spatially and genetically related to Ascot volcanism (Poole 1980), is the only Taconian pluton isotopically analyzed in this study.

The rocks of the Connecticut Valley-Gaspé Synclinorium that lie to the southeast of the Cambrian to Upper Ordovician Formations, are the hosts of the Acadian granitoid rocks sampled for this age determination project. They are the Scotstown, Winslow, Aylmer and Ste. Cécile plutons of Québec, and the Lac Aux Araignées, Beebe and Stanhope-Averill complexes that straddle the border with the United States (Fig. 2). In southeastern Québec, the Connecticut Valley-Gaspé Synclinorium is largely composed of rocks of the Silurian-Devonian St.Francis Group (Clark 1937; Duquette 1961). The St.Francis Group is a thick

Fig. 2. Study Area in the Eastern Townships of southern Québec. A = Aylmer pluton, B = Beebe pluton, C= Ste. Cécile pluton, L = Lac Aux Araignées, S = Stanhope-Averill pluton, Sc = Scotstown pluton, W = Winslow pluton. The map is from St.Julien et al. (1983).

Explanation

1 Grenville basement ((pC)
2 St Lawrence platform (CO)
3 Foreland thrust belt (O)
4. Allochthons of the external domain (CO)
5. Allochthons of the internal domain (mainly Bennett Schist) (CO)
6. Caldwell Group and Mansonville Formation (C)
7 Ophiolites (C)
8. St. Daniel and Brompton Formations (me-'lange) (LO)
9. St Victor synclinorium (Magog Group (MO)
10 Ascot-Weedon Formation (L-MO)
11 Connecticut Valley-Gaspé synclinorium (SD)
12. Frontenac Formation (O?)
13 Chain Lakes Massif (Helikian)
14 Ordovician granites
15 Devonian granites
16 Mesozoic alkaline intrusive rocks Heavy line, trace of seismic line.


5
4
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Pointe Platon
QUEBEC
Beaumont
100km
QUEBEC
46°
Fig. 2
OTTAWA
ONT.
MONTREAL
QUE.
Sherbrooke
Riv Chaudière
Notre Dame Anticlinorium
Baie Verte Brompton Line
Beauce-ville
Thetford Mines
BLACK LAKE
Thetford Mines Ophiolite complex
Caldwell fm
St Victor Synclinorium
BAIE VERTE BROMPTON LINE
Mont Ham Massif
Asbestos Ophiolite complex
MANSONVILLE FM
W
A
C
Audet
WEEDON FM
Windsor
SC
Megantic
L
Sutton Anticlinorium
Lac Montjoie Serpentinite melange
Sherbrooke
Waterloo
ASCOT FM
Orford Ophiolite complex
Chain Lakes Massif
B
S
0
5
30km
VERMONT

sequence of sandstones, slates and limestones resting unconformably on the Cambro-Ordovician Ascot Formation volcanics (Harron 1976). The St.Francis Group comprises in ascending order, the Lambton, Ayers Cliff (Kelly 1975), and Compton Formations (St. Julien 1970). The Compton Formation, which is the host of the Scotstown, Beebe, Stanhope, and Winslow plutons, is a monotonous turbiditic sequence of alternating grey and black shale and fine-grained laminated sandstones (St.Julien et al. 1983). The Aylmer pluton was intruded at the contact between the rocks of the Weedon (Ascot) Schists and Compton Formation. The Lac Aux Araignées complex is hosted by rocks of the Compton Formation on its northeastern side, and the Precambrian quartzo-feldspathic gneisses of the Chain Lakes Massif on its southeastern side. The Chain Lakes Massif is interpreted to be allochthonous Precambrian gneissic basement that was thrust westward along seismically-identified east-dipping thrust faults during the closure of the Iapetus ocean (Ando et al. 1984).

Previous Work

Geological Mapping and Related Studies

Early maps and reports covering the study area and the surrounding region (Lac Memphremagog-Orford-Sherbrooke) are the works of Clarke and Fairbairn (1931), Ambrose (1942, 1943), Fortier (1945, 1946), Cooke (1937, 1950), Doll (1951, 1961), and Baer (1961). Duquette (1960, 1961) mapped the Lac Aylmer-Weedon region and its surroundings. Duquette recognized the continuity between the rocks of the Weedon schists and Ascot formation. Lamarche (1965) explored in detail the map-area south of Sherbrooke. He demonstrated that the Ascot formation, which was the principal subject of his study, was composed primarily of volcanic rocks that experienced the effects of three distinct deformational events.

More recent work conducted on a regional scale includes a compilation map at a scale of 1 :50,000 of the Orford-Sherbrooke region (St.Julien 1970a) and mapping of the region east of Lac Memphremagog by de Romer (1975, 1976, and 1980). Still on a regional scale, Lamarche (1972) and St.Julien et al. (1972) outlined the tectonic units of the southeastern part of the province. Williams' (1978) regional study focussed on illustrating the distribution of the lithofacies of the Appalachian Orogen.

Petrological Studies

The granites studied in this project were not the focus of much attention until the detailed studies of Bourne (1984, 1985, 1986) and Danis (1984, 1985) Burton (1931) studied the granite bodies of the region to determine their composition and assess their commercial possibilities During a regional mapping project, Cooke (1950) redefined the contacts of the Scotstown batholith and described the complex as a homogeneous biotite-hornblende-granite. Duquette (1960, 1961) briefly described the Aylmer granite as a light grey, medium-grained granite of

"Stanstead" type (referring to the fact that the granitic complexes look very similar to one another) that intrudes rocks of both the Ascot-Weedon formation and the St. Francis group. He goes on to say that the rock is made up of quartz, feldspar, biotite, and muscovite and contains abundant inclusions of pre-existing rocks. Kelly (1975) gave a brief description of the geology of the Ste. Cécile complex. He divided the complex into four units based mainly on grain size. The four units are . medium-grained biotite-granite; fine-grained biotite granite; aplitic granite; and felsic dykes and sills. His study of the complex did not include chemical nor modal analyses. Kelly (1975) focussed his attention on the molybdenum mineralization associated with the felsic dykes near the pluton.

The Lac Aux Araignées pluton was studied by Marleau (1968), Cheve (1978), Westerman (1980), and Ayuso (1986). Marleau (1968) and Cheve (1978) described the complex as granitic in composition. Westerman (1980) studied the American half of the Lac Aux Araignées granitoid. He considered that the complex was composed of three individual plutons (instead of three different phases belonging to one pluton), and refuted the idea that the three plutons (phases) were comagmatic and genetically related. Ayuso (1986) determined the lead-isotopic compositions of feldspars in plutons across all of Maine including the Lac Aux Araignées pluton. He concluded that all have relatively radiogenic lead for their ages that suggests continental crustal sources. However, he suggested that the plutons he sampled from the Connecticut Valley-Gaspé Synclinorium may have had a more significant component from the subcontinental mantle.

None of the above petrological studies of the Québec Acadian granites were as detailed as the work conducted by J. Bourne (1984, 1985, and 1986) and D. Danis (1984, 1985). Bourne's and Danis' investigations had the following goals : To study the petrographic variations and relations between the different phases within each pluton; to study the major element, trace element, and rare-earth-element chemistry of the complexes in order to assess their economic potential; and to compare the plutons to other similar rocks in Québec and elsewhere. The basis of Bourne's and Danis' petrographic studies was the use of the feldspar staining technique. The many samples collected from the plutons were cut, stained, and point-counted. This resulted in quite precise (+/- 2%) determination of the quartz, plagioclase, and potash feldspar contents. Each sample was then assigned a name according to the classification of plutonic rocks developed by Streckeisen (1973).

Geochronology

The Acadian granitic plutons of southeastern Québec have not been extensively dated. All previous geochronological work has been by the K/Ar mineral method (Table 1). Three of the ages for the Ste. Cécile pluton (353 Ma, 367 Ma, and 373 Ma) were obtained by Bourne (1986) as a personal communication from Lapointe, but he does not describe the methodology nor what

Table 1. **Previous Ages for the southeastern Québec Plutons.**

PLUTON	ROCK TYPE	K/Ar AGE (K) Rb/Sr AGE (Rb) (+/- 1SD)Ma	REFERENCE
Aylmer	Granite	379 (K) (biotite)	Lowdon (1960)
Ascot	Moulton-Hill Granite	322 +/- 14 (K) (sericite)	Wanless (1968)
	Moulton Hill Granite	397 +/- 38 (Rb) (whole-rock)	Poole (1980)
		418 +/- ? (Rb) (whole-rock)	Poole (1980)
Ste. Cécile	Granite	362 (K) (biotite)	Lowdon (1960)
	Quartz Vein*	360 (K) (muscovite)	Lowdon (1960) Lowdon (1960)
	?	353, 367, 373 (K)	Bourne (1986)**
Stanhope-Averill	Granite	346 +/- 4 (K) (biotite)	Erdmer (1981)

* sample is from a quartz-feldspar-muscovite vein containing molybdenite, pyrrhotite, galena and rare stannite.

** personal communication from Lapointe in 1984 in Bourne (1986).

phases of the pluton were sampled. The molybdenum mineralization in the Ste. Cécile pluton (360 Ma, Table 1) seems to be synchronous with the time of intrusion and crystallization of the magma (362 Ma) as indicated by the K/Ar dates.

For the few Taconic intrusions, there is a low age of 322 +/- 14 Ma (K/Ar, sericite) for the Moulton-Hill pluton of the Ascot Formation (Wanless 1968). This date probably reflects the time of post-emplacement greenschist metamorphism. Poole (1980) also sampled the Moulton Hill granite and produced an 11 point Rb/Sr whole-rock isochron that gave an age of 505 +/- 88 Ma, and an initial $^{87}Sr/^{86}Sr$ initial ratio of 0.7100. Poole (1980) divided the samples into two domains that were aligned parallel to the northeast southwest regional structural trend of the area, on the basis of their rubidium and strontium contents. However, there was no petrological evidence to support this grouping. The samples in the northwestern domain yielded a date of 397 +/- 38 Ma and the samples in the south easternern domain gave a date of 418 Ma. The Ascot-Weedon formation has been stratigraphically dated as Middle-Ordovician in age (St.Julien and Hubert, 1975). Therefore, these young ages (322 +/- 14 Ma, 397 +/- 38 Ma, and 418 Ma) for the Moulton-Hill granite are almost certainly the result of Ar-loss and loss or re-equilibration of radiogenic Sr in these altered rocks.

In summary, the few ages determined for the southeastern Québec Acadian plutons suggest that magmatic activity in the study area occurred in Late Devonian-Early Carboniferous time.

CHAPTER 2

PETROGRAPHY OF THE SOUTHERN QUEBEC ACADIAN PLUTONS

Unless otherwise noted, all petrographic and geochemical data and interpretations in this chapter are summarized from Bourne (1984, 1985, 1986) and Danis (1984, 1985). The Harker variation diagrams and conclusions drawn from them are those of the author, but the data are those of Bourne and Danis. The purpose of this chapter is to aid interpretation of the Sr isotopic data, account for inheritance in zircons, and to identify the tectonic setting so as to make the age determinations useful.

Scotstown Pluton

Geological Setting

The Scotstown pluton has a surface area of approximately 50 km^2 (Fig. 2). Its average composition is granodiorite. The emplacement of the magma produced a contact metamorphic aureole in the Silurian-Devonian Compton formation that in some places is 1.5 Km wide. The pressure at the time of emplacement, deduced from the contact metamorphic assemblage, is 0.8 to 3.0 Kb. No foliation has been noted anywhere in the pluton.

Before describing the petrography of the pluton, I wish to emphasize that both Bourne and Danis strongly advocated that the Scotstown, Winslow, and Lac Aux Araignées plutons have undergone a postsolidification, metasomatic process they called "tonalitization". This process converts a rock type such as a granodiorite into a tonalite by removing potassium and introducing silica. The complexes include phases of both igneous ("i") tonalite and a tonalite produced by metasomatism ("m"). The reasons that such a process was proposed are the following: The amount of quartz in the more basic rocks is equal to or greater than that in the more acidic rocks. Secondly, a more hydrated ferromagnesian mineral (biotite) is present in the basic rocks, whereas amphibole is present in the more acidic phases. This is contrary to what is expected during progressive fractional crystallization. That is, the amount of water should increase. The balanced reaction given to justify the process is:

1 Plag.(An40) + 3.4 K-Feld. + 1.2 Hornblende + 0.8 H_2O =

1 Biotite + 4 Plag.(An30) + 2.4 K_2O

This reaction requires water in order to take place, and may be magmatic, metamorphic, or meteoric in origin. The reaction also liberates potassium that will eventually be incorporated into secondary minerals such as muscovite and sericite or leave the system through fractures and be absorbed by the surrounding country rocks (Danis 1984).

Petrography

The most basic phases in the complex are a gabbro-quartz diorite unit, quartz diorite, and two diabase dikes. The southern diabase dike lacks visible contacts with the main granitoid body, so that its relationship to the main plutonic body is uncertain. The gabbro-quartz diorite unit usually occurs as dikes or inclusions, but some is present as monolithic outcrops. The quartz diorite is a medium-grained, equigranular rock that only outcrops in the northeastern part of the complex.

As was mentioned earlier, two types of tonalites have been distinguished. The igneous (i) tonalite, which is abundant in the northern part of the complex, is equigranular and composed of euhedral to subhedral plagioclase with interstitial potassium feldspar. The plagioclase also occurs as inclusions in the potassium feldspar (poikiolitic texture). The metasomatic (m) tonalites are located at the contacts with the country rocks and are not very abundant. Myrmekitic plagioclase is a very common texture in this rock unit.

Granodiorite is the most voluminous phase in the complex. It has an equigranular, medium-grained (1-5mm) texture with biotite and sphene being the principal mafic and accessory minerals, respectively.

A granitic phase occurs as a lobe oriented in a north-northwesterly direction in the western part of the complex. Pegmatites and felsic dykes are very rare and occur only in the northern part of the pluton.

Geochemistry

The rocks of the pluton are corundum normative, i.e. peraluminous (Chappell and White 1974). Plotted on an AFM diagram the samples define a calc-alkaline trend. The rare-earth-element spectra have strong negative slopes and no negative Eu anomaly. Hyndman (1972) ascribes the absence of a Eu anomaly to high water pressure during crystallization, which is a characteristic of calc-alkaline magmas. The Harker variation diagrams (Appendix A) demonstrate that although the pluton is composed of different phases, these are comagmatic and related by fractional crystallization, not of plagioclase feldspar because of the lack of a Eu anomaly, but of hornblende and biotite.

Lac Aux Araignées Pluton

Geological Setting

The Lac Aux Araignées pluton straddles the Québec-Maine border (Fig. 2) and has a surface area of 300 Km^2. The pluton was found to be normally zoned by Bourne (1984) (feldspar staining method) but Westerman (1980) claimed that it is reversely zoned (a more evolved felsic rim and a basic core). Bourne (1984) studied the metamorphic assemblage in the contact aureole of the complex, and determined the maximum pressure to be approximately 4 Kb.

Only the western lobe of the Lac Aux Araignées complex will be described in detail because it is the part that was sampled for the Rb/Sr whole-rock and U/Pb age determinations.

Petrography

Tonalite is found immediately adjacent to the country rocks. It does not outcrop abundantly but it is possible that it forms an outer belt circling the intrusion. The origin of this tonalite is again attributed to a postsolidification metasomatic process. The same mineralogical relationships are observed here as at Scotstown, where biotite is abundant in the outer parts of the pluton, whereas hornblende becomes dominant in the core. As well, these metasomatic tonalites are only present at the contact with metasedimentary rocks : This phase is absent in the eastern lobe because the surrounding rocks are the anhydrous, high-grade metamorphic rocks of the Chain Lakes Massif.

Granodiorite is the dominant rock of the western lobe, and is a sub-solvus two feldspar rock in which plagioclase is commonly zoned and the potassium feldspar is interstitial. Biotite is the dominant mafic mineral with traces of hornblende. Accessory minerals include titanite, apatite, epidote, zircon and allanite.

The granitic phase of the western lobe is a light-grey, equigranular rock, but also contains pegmatite dikes, country rock xenoliths and granodioritic inclusions that are lenticular and strongly stretched. Hornblende and titanite are more abundant here than in the granodiorite phase.

The western lobe is in general more porphyritic than the eastern lobe, and the porphyritic texture is more common at the contacts of the pluton. Plagioclase phenocrysts 10-15 mm in diameter are common and are often aligned parallel to the contact. This foliation decreases towards the centre of the pluton. The plagioclase has the unusual feature of being inversely zoned (rim is more calcic than the core).

Geochemistry

The C.I.P.W. normative calculation yields a corundum normative composition for the rocks of the pluton, and samples describe a calc-alkaline trend on an AFM diagram. The rare-earth-element spectra have negative slopes and no negative Eu anomaly. The Harker variation diagrams (Appendix A) indicate an origin by fractional crystallization for the different phases of the pluton.

Winslow Pluton

Geological Setting

The Winslow pluton (Fig. 2) has a surface area of 135 Km^2, and it has a contact metamorphic aureole up to 1 Km wide with contact metamorphic mineral assemblage that yields pressure estimates of 2.2 to 4 Kb.

The granitoid can be divided into three major phases. These are a hornblende-diorite (northern border), a contact phase of tonalite or leucodiorite (southern border), and a granodiorite of variable composition in the central part of the complex.

Petrography

The hornblende-diorite is a medium to coarse-grained rock that is composed of pyroxene, hornblende, actinolite, plagioclase and interstitial quartz. Two sub-units of this rock type are a quartz diorite and magmatic tonalite.

The tonalite found at the edge of the complex is again postulated to be the result of the same post-solidification, metasomatic process that took place in the Scotstown and Lac Aux

Araignées plutons.

The less basic rock types are granodiorite, quartz monzodiorite, and granite. The mafic mineral in the granodiorite and granite is biotite, whereas equal amounts of hornblende and biotite occur in the quartz monzodiorite. Acessory minerals in all three phases include titanite, epidote, apatite, allanite, and zircon. Alteration minerals are muscovite and chlorite.

Aylmer Pluton

Geological Setting

The Aylmer pluton (Fig. 2) has a surface area of 57 Km^2. It is reversely zoned, varying from tonalite in the centre to granite at the contact. The mineral assemblages in the contact metamorphic aureole of the intruded Weedon schists and Compton formation give emplacement pressures of 1.5 to 3.8 Kb.

Petrography

The Aylmer pluton has granitic phases along its southern, western, and northern borders. The granites with a low plagioclase/total feldspar ratio have large crystals of muscovite, no biotite, and contain garnet. They also contain large numbers of host rock inclusions. The granites with more plagioclase contain only biotite as the mica phase and are generally less altered, equigranular, homogeneous, and free of inclusions.

The tonalites occupy the central part of the pluton and are surrounded by a granodioritic ring. The granodiorites have textures and a mineralogy similar to that of the tonalites. Both are medium-grained and contain 5 to 10 % biotite, the tonalites containing more biotite than the granodiorites.

There are many large, up to 1,000 m2, country rock xenoliths in the interior of the complex. The foliation in the xenoliths parallels the structural trends in the country rocks.

Geochemistry

Bourne (1986) analyzed whole-rock samples for major and trace elements. The samples define a calc-alkaline trend in an AFM diagram. All but one of seven rare-earth-element spectra have strong negative slopes and no Eu anomaly. All samples of the most evolved phases of the pluton (i.e. normative Qz + Alb + Or >= 0.95) plot in one place on a normative quartz-albite-orthoclase ternary diagram. This is interpreted to be the result of a lack of a post-solidification or late crystallization fluid phase. The samples do not plot at the granite minimum but a pressure of emplacement of about 3 Kb is likely, because Ca in the haplogranitic system shifts the granite minimum to the right (Winkler 1979). The rocks are corundum-normative, so that the pluton is peraluminous. Finally, the Harker variation diagrams (Appendix A) show that the different phases of the pluton are comagmatic, and formed mainly by fractional crystallization, but not by fractionation of plagioclase feldspar because of the lack of a Eu anomaly.

Ste. Cécile Pluton

Geological Setting

The Ste. Cécile pluton (Fig. 2) has a surface area of 36 Km^2. Its average composition is granodioritic and it consists of both granite and granodiorite phases. The intrusion produced a metamorphic contact aureole 1.5 Km wide. The metamorphic assemblage in the contact aureole yields a pressure of about 2 Kb. The complex is reversely zoned.

Petrography

The granitic unit consists of zoned plagioclase and potassium feldspar with lobate margins. Biotite (2 to 5 %) is the only mafic mineral. Accessory minerals include titanite, epidote and muscovite. There are very few inclusions of host rocks.

The granodioritic phase is similar to the granitic phase, except that both plagioclase and biotite are more abundant. Titanite is the dominant accessory mineral.

The pluton is cut by two generations of narrow (<10 cm), fine-grained aplite dikes. The first generation was emplaced in a plastic host rock because the contacts are curvilinear. The second generation dikes have sharp, planar contacts indicating emplacement when the rock had solidified. There are few pegmatites and these occur mainly in the northern part of the pluton. Their margins consist of potassium feldspar, enclosing a core of euhedral quartz, epidote and calcite.

Geochemistry

Analyses plotted on an AFM ternary diagram define a calc-alkaline trend. The rare-earth-element spectra have strong negative slopes and no negative Eu anomaly. The normative quartz-albite-alkali feldspar ternary plot indicates that very little post-solidification metasomatism took place because of the lack of scatter with respect to the location of the granite minimum. The position of the granite minimum corresponds to a pressure of formation (H_2O) of 3 Kb, which is a slightly higher pressure than was estimated from the metamorphic assemblage (2 Kb). The Harker variation diagrams (Appendix A) show that the different phases of the pluton are likely related by fractional crystallization of hornblende and biotite, and not of plagioclase feldspar because of the lack of a Eu anomaly.

Stanhope-Averill Pluton

Geological Setting

The Stanhope-Averill pluton straddles the Québec-Vermont border in the vicinity of Stanhope, Québec, and Averill Lake, Vermont (Fig. 2). The pluton has a surface area of 120 km^2 , most of which is in Vermont. It is a massive, homogeneous granite that intrudes the metasediments of the Connecticut Valley-Gaspé Synclinorium. The granite has been described as medium- to-coarse-grained, and grayish-white to pink (Myers 1964).

The complete lack of foliation, and the apparent deformation of the metasediments prior to the intrusion of the pluton indicate that it is a post-tectonic granite (Myers 1964). Myers (1964) therefore concluded that the Stanhope-Averill granite is part of the White Mountain Magma series (Mississippian age) because of its similarity to the Conway granite (as described by Billings (1956)). However, the pluton is more likely Acadian because of a K-Ar (biotite) age of 346 +/- 4 Ma determined by Erdmer (1981).

Petrography

The rocks consist of quartz, potassium feldspar (partly sericitized), plagioclase (oligoclase), biotite (3-12%), and muscovite (1%) (Goodwin 1963; Myers 1964). The texture is hypidiomorphic granular and, in places subporphyritic, because of the large potash feldspar grains (Myers 1964).

Pegmatite dykes are common and generally strike N20E and are parallel to one of the joint-sets that transect the granite. The mineralogical composition of the pegmatites is the same as that of the granite except that the pegmatites contain more muscovite (Myers 1964). The contacts between the granite and the country rock are sharp and inclusions of metasediments are not common (Myers 1964). The inclusions have sharp contacts with the granite, and are identical to the metasediments outside the pluton. No preferred orientation of the inclusions was observed (Myers 1964). There are no chemical analyses available.

Beebe Pluton

Geological Setting

The main body of the Beebe granite is between Lake Memphremagog and the town of Beebe Plain. It also straddles the Québec-Vermont border (Fig. 2). Its surface area is approximately 40 Km^2. The granite is extensively quarried because of its homogeneity and lack of visible alteration.

Petrography

The Beebe rocks are homogeneous, medium-to-coarsed grained, equigranular biotite granite and granodiorite. Biotite is the principal mafic mineral and there is less than 1 % muscovite.

Moulton Hill Granite - Ascot Formation

Geological Setting

The Moulton Hill granite is an elongated body of deformed metatrondjemite and metagranodiorite, northeast of Sherbrooke, Eastern Townships, Québec (unit 14, Fig. 2). It is about 15 km long and up to 2 km wide, and has intruded felsic and mafic volcanic rocks and associated, mainly pelitic, sedimentary rocks of the Ascot Formation (St.Julien 1970; St.Julien and Lamarche 1965; Lamarche 1967).

The Ascot Formation lacks fossils but is believed to be of similar age as the lithologically correlative Tetagouche Group of northern New Brunswick, which is of Early to Middle Ordovician age (480 to 500 Ma), and the Middle Ordovician Beauceville and St. Victor Formations of the Magog Group lying along the northwestern contact of the Ascot Formation (St.Julien and Hubert 1975).

Petrography

Poole (1980) describes a sample of metagranodiorite from the northeastern part of the pluton, as containing intensely saussuritized plagioclase, commonly rimmed with clear albite. The quartz is strained and the potash feldspar is interstitial. The mafic mineral is completely altered to chlorite, muscovite and epidote.

Poole (1980) also describes a metatrondhjemite sample, from the southern half of the pluton, as having deformed saussuritized plagioclase. The quartz is intensely deformed and some is polygonized. The mafic mineral is completely altered to chlorite and muscovite-rich surfaces define a schistosity. Other samples in the southern half of the intrusion are also intensely sheared, contain brown-weathering carbonate aggregates, and muscovite has grown along shear surfaces.

Geochemistry

Hynes (1980) analyzed thirty-nine samples from the host volcanic rocks, for major elements as well as for Rb, Sr, Zr, Y and Nb. Most of the analyses are from the non-porphyritic mafic rocks with only four analyses of the mafic to intermediate porphyritic rocks and three samples of the porphyritic felsites. He concludes that the normally immobile elements (eg. Ti, Y, and

Zr) have been affected by secondary processes and that primary inter-element ratios are compatible with an island-arc origin although TiO_2 concentrations are a little high (1.5 wt.%).

CHAPTER 3

GEOCHRONOLOGY

Analytical Methods

$^{87}Rb/^{86}Sr$ ratios were determined by X-ray fluorescence (XRF) spectrometry using a Rh-target tube and a power level of 90 KV/30 mA. Peak and background positions were measured for 80 and 20 s, respectively, and repeated three times. One hundred and thirty-two analyses of the United States Geological Survey standard GSP-1 monitor (i.e. without correction to another standard) give a standard deviation for one analysis of only 0.3 %. In a recent study by Doig (1987), 42 samples were analyzed by this method as well as by isotope dilution. The average bias was -0.6 %, well within the pooled estimates of error of the methods. $^{87}Sr/^{86}Sr$ ratios were measured on the 15 cm mass spectrometer. The precision is about ten times poorer than that we can achieve on the new VG sector instrument, but in this study, residuals from isochrons are much larger than the precision of the older instrument. Isochrons were regressed by a method based on York (1966), and 1.42 X 10-11 a-1 was used for the decay constant of ^{87}Rb. The errors in isochron parameters are at the 95% confidence level for consistency with the Pb data, and include appropriate student's-t factors based on the number of samples regressed.

Zircons were processed by a method similar to that of Krogh (1973), and using a mixed ^{205}Pb-^{235}U spike. U and Pb were separated from sphene and monazite using a hydrobromic acid elution technique, repeated twice. Monazite presents special problems in terms of dissolution: We use 11 N HCL at 220 degrees Celcius in the usual steel-jacketed teflon capsules. The blank for the entire analytical procedure ranged from 7 to 30 pg Pb.

The samples were measured on a VG Sector mass spectrometer. U is run as the dioxide on a single Re filament with silica gel. All significant sources of error are propagated into the coordinate values of the concordia diagram at a confidence level of 95 %. These include measurement error, confidence in the fractionation factors, error in the U/Pb ratio of the spike, and the effect of the common Pb correction.

Rb/Sr Geochronology

Introduction

The precision of the Rb/Sr whole-rock age determination method depends on the spread in Rb/Sr ratios and on the homogeneity of the $^{87}Sr/^{86}Sr$ initial ratio. Heterogeneity of the initial ratio in igneous rocks that may result in poor isochrons can be caused by host rock assimilation, or by subsolidus alteration in an open system by fluids with different isotopic composition (Dicken et al. 1980; Taylor 1980; Juteau et al. 1984). Other mechanisms that may result in isotopic heterogeneity include magma mixing when there are significant contributions from isotopically contrasting mixing members, or tapping of magmas from isotopically heterogeneous sources (eg.

Halliday et al. 1980; Myers et al. 1984).

Magma may be generated from partial melting of continental crust. This will generally result in initial ratios higher than 0.705 because the Rb/Sr ratio of the continental crust is higher than the bulk earth average. The actual initial ratio of crustal melts depends on a number of factors such as whether the source rocks have been depleted in Rb at an early stage (postulated to occur in granulite rocks (Rollinson and Windley 1980)), or what rock-types were involved in the melting event. The age of the rocks that are partly melted is also important.

The nature of the lower crust beneath the Dunnage and Gander terranes in southeastern Québec, and elsewhere in the Appalachians, has been variously postulated to be Grenvillian continental crust or oceanic crust. Haworth (1978) suggested that there is Paleozoic oceanic crust beneath the Dunnage and Gander terranes, but that this oceanic crust may occur as an allochthonous unit within the upper crust rather than below the Dunnage terrane.

Keen et al. (1986) obtained marine seismic reflection profiles across the northeastern extremity of the Canadian Appalachians, North of Newfoundland. They interpreted the lower crustal unit identified beneath the eastern Dunnage and Gander terranes to be continental, but distinct from the Grenville crust to the west. They also state that the ancient passive margin of North America extends eastward underneath the Dunnage terrane for about 70 Km.

Séguin (1982b) suggested that the continent-ocean transition is located east of the Nôtre Dame Mountains (western boundary of Dunnage terrane). St.Julien et al. (1983) concluded, on the basis of seismic data from southeastern Québec, that Grenville basement is present under the autochtonous rocks of the external zone and under the allochton, probably at least to the internal nappe zone. Green et al. (1986), in an interpretation of seismic reflection data of the Québec-Maine region postulated that Grenville basement extends a considerable distance eastward beneath the Dunnage terrane.

Finally, Spencer et al. (1987) obtained high-quality seismic reflection data across the northern Appalachians in Québec and Maine. The interpretation of these data from the southeastern Québec-western Maine region provides strong evidence that the rocks of the predominantly oceanic Dunnage zone are allochtonous, having been thrust westwards over Precambrian Grenville basement after the closing of the Iapetus Ocean. Exotic terranes such as the Cambro-Ordovician island-arcs south of the Baie Verte-Brompton Line and the Precambrian Chain Lakes Massif have been thrust over Grenville basement in a "thin-skinned" fashion (Spencer et al. 1987). It is therefore highly probable that Grenville crust did exist below the study area at the time of intrusion.

Another possible source of magma is the mantle. The present day $^{87}Sr/^{86}Sr$ ratio for the depleted mantle as observed in mid-ocean ridge basalts is about 0.7030 (Allegre et al. 1981). However, there is abundant evidence for isotopic heterogeneity of the subcontinental and oceanic mantle, with initial ratios up to about 0.708 (Menzies et al. 1984; Hoffman and Hart 1978).

Bell et al. (1982) defined the nature of the deep subcontinental mantle in Ontario by measuring the Sr isotopic ratios of carbonatites. Their deep-seated nature (> 100 Km), rapid movement to the surface, and high Sr contents precluding significant contamination, make them an ideal rock type for this type of investigation. On this basis, Bell et al. (1982) concluded that the primitive mantle, similar in chemical composition to bulk earth, underwent significant differentiation 2800 Ma ago leaving a depleted mantle with an average $^{87}Sr/^{86}Sr$ ratio today of only 0.7032. The data also suggest that from at least 1000 to 2800 Ma this depleted mantle (0.702 overall), retained its isotopic identity.

Rb-Sr Data

Scotstown Pluton

Fig. 3 is the isochron diagram for the Scotstown pluton. Samples Sc-12, Sc-13 and Sc-14 were collected from the granitic phase of the pluton. Sc-1, Sc-5 and Sc-9 are from the granodioritic part of the pluton, and sample Sc-3 is a metasedimentary xenolith.

The seven samples give a date of 410 +/- 38 Ma and an

Table 2. Rb-Sr Isotopic Data.

Sample	Rb (ppm)	Sr (ppm)	87Rb/86Sr	87 Sr/86 Sr
			Scotstown	
Sc-1	120.4	245.3	1.4173	0.71510 (22)
Sc-3	277.7	224.5	3.5839	0.72750 (12)
Sc-5	93.4	261.2	1.0345	0.71310 (20)
Sc-9	78.1	358.5	0.6344	0.70990 (15)
Sc-12	109.3	213.9	1.4840	0.71520 (20)
Sc-13	104.8	254.6	1.1911	0.71430 (12)
Sc-14	91.7	303.1	0.8721	0.71160 (13)
			Lac Aux Araignées	
L-1	135.1	393.6	0.9942	0.71270 (14)
L-2	216.5	383.4	1.6348	0.71572 (12)
L-3	118.0	393.5	0.8703	0.71114 (12)
L-4	107.5	499.3	0.6203	0.71048 (15)
L-5	102.3	504.2	0.5852	0.70957 (18)
L-6	86.1	658.7	0.3768	0.70850 (20)
L-7	109.6	476.4	0.6663	0.70978 (20)
L-8	87.3	509.6	0.4962	0.70930 (15)
L-9	108.2	516.6	0 6087	0.71059 (14)
L-10	117.8	474.2	0.7170	0.71069 (25)
L-11	99.9	526.4	0 5490	0.71026 (20)
L-12	103.1	539.7	0 5550	0.70926 (12)
			Winslow	
W-1	102.9	282.2	1.0484	0.71880 (16)
W-5	104.6	249.5	1.2089	0.71494 (15)
W-6	147.4	205.3	2 0783	0.71850 (20)
W-7	102.1	261.7	1.1338	0.71488 (12)
W-9	68.7	189.6	1.0387	0.71145 (20)
			Aylmer	
A-1	96.6	129.3	2.1467	0.71867 (14)
A-2	135.3	168.7	2.3279	0.71866 (20)
A-3	97.8	153.7	1.8387	0.71828 (12)
A-4	84.2	191.5	1.2703	0.71457 (15)
A-5	132.6	164.3	2.3268	0.71992 (13)
A-6	97.7	136.4	2.0766	0.72179 (15)
A-9	123.4	122.3	2.9291	0.72116 (8)
A-10	142.1	52.1	7.9415	0.74833 (20)
A-13	103.5	51.6	5.8407	0.74114 (12)
A-14	98.7	33.6	8.6856	0.75825 (10)

Table 2. continued.

			Ste. Cécile		
C-4	488.2	111.6	12.8161	0.77574	(17)
C-7	128.7	183.6	3.3465	0.72377	(18)
C-9	410.8	114.2	10.4813	0.76090	(15)
C-14	120.1	366.3	0.9488	0.71390	(21)
C-15	184.4	286.9	1.8668	0.71618	(20)
C-18	184.3	195.3	2.7350	0.72292	(18)
C-21	89.4	397.8	0.6504	0.71096	(20)
C-22	369.5	122.1	8.7907	0.75180	(15)
C-26	113.7	450.4	0.7258	0.71180	(20)
C-30	115.8	327.6	1.0200	0.71274	(21)
			Stanhope-Averill		
S-1	232.9	270.6	2.4910	0.72018	(12)
S-2	226.6	256.1	2.5549	0.72070	(15)
S-3	237.2	255.4	2.6910	0.72113	(10)
S-4	249.3	253.1	2 8570	0.72135	(10)
S-5	247.5	270.0	2.6561	0.72060	(30)
S-6	249.8	205 2	3.5320	0.72595	(18)
S-7	247.7	203.6	3.5240	0.72477	(15)
S-8	269.0	199.2	3.9281	0.72751	(15)
			Beebe		
B-12	245.4	101.6	7 0543	0.74340	(15)
B-14	80.9	430.7	0 5424	0.71124	(14)
B-16	59.5	542.8	0.3146	0.70948	(8)
			Moulton-Hill		
As-1	85.5	71.8	3 4553	0.73330	(14)
As-2	12.8	168.8	0 2201	0.70870	(30)
As-3	86.7	40.6	6 2202	0.75350	(15)
As-4	106.9	80.6	3.8546	0.73741	(15)
As-5	108.6	89.8	3 5370	0.73363	(4)
As-6	33.2	21.4	4.4904	0.73853	(9)
As-9	128.0	48.0	7.7692	0.76039	(7)
As-10	114.2	38.1	8.7279	0.76349	(5)
As-11	125.3	41.5	8.7924	0.76465	(7)
As-12	9.2	42.8	0 6209	0.71109	(7)
As-13	4.3	31.2	0 3987	0.71133	(9)

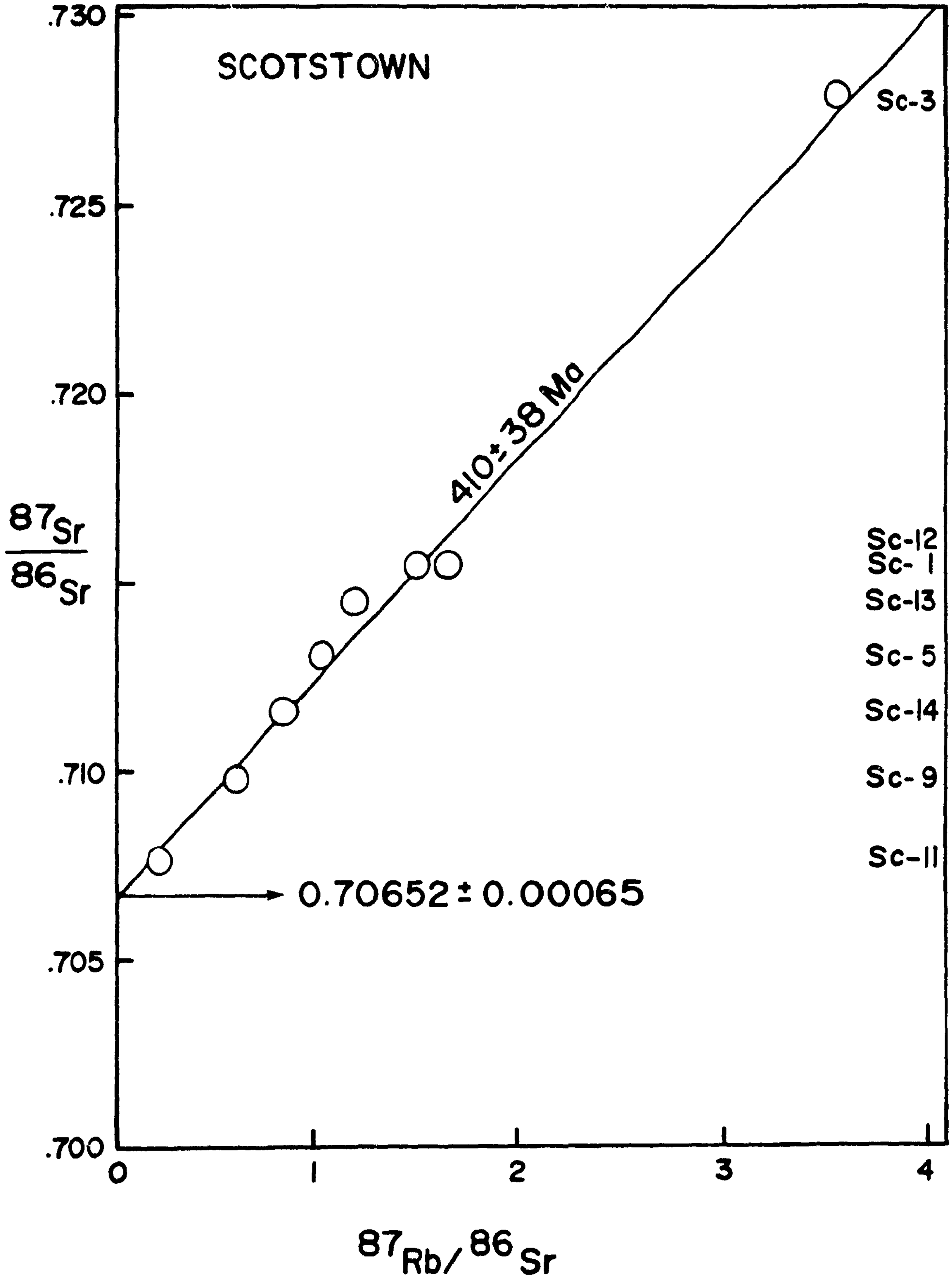

Fig. 3. Scotstown Rb/Sr whole-rock isochron.

initial $^{87}Sr/^{86}Sr$ ratio of 0.70652 +/- 0.00065 (Fig. 3). Because of the large number of sedimentary xenoliths, isotopic mixing of magma and host rock was anticipated, and this is why the xenolith was sampled. Unfortunately the granitic samples alone scatter widely and do not yield a meaningful age. The date of 410 +/- 38 Ma is largely controlled by sample Sc-3(xenolith), and is similar to the U/Pb ages to follow. This implies that the xenolith equilibrated isotopically and can not be used to represent a mixing component. How well it equilibrated is impossible to determine, so that we have no age information from the Rb/Sr data.

The initial ratio is better constrained, individual granite and granodiorite samples giving moderately high and variable values (0.7059 to 0.7072). The scatter is most probably caused by one or more of assimilation of host rocks, post-magmatic introduction of radiogenic Sr by fluids, or an isotopically heterogeneous source region. The last could mean either contamination at depth of a mantle derived magma, or an origin by partial melting of crustal rocks. Contamination of a mantle derived magma is not supported because of the lack of abundant basic phases in the pluton. Numerous sedimentary xenoliths suggest assimilation. Bourne's (1984) "tonalitization" or postsolidification metasomatic process explained some petrographical and geochemical inconsistencies mentioned earlier. It is therefore likely that the Rb-Sr system was disturbed at the time of this metasomatic process. In summary, the magmatic history of the Scotstown complex may be a scenario that would consist of partial melting of Grenville lower crust, followed by assimilation or alteration at the present level of exposure.

Lac Aux Araignées Pluton

Outcrops are not abundant and are restricted to roadsides and lakeshores due to extensive vegetation cover and the large water reservoirs (Lac Mégantic and Lac Aux Araignées). Nevertheless, twelve samples were obtained from the northern part of the western lobe. Ten of the samples are granodiorites (L-3 to L-12), and the remaining two samples are granites (L-1, and L-2).

The granodiorites are fairly homogeneous with some variation in grain size and mafic mineral content. The plagioclase/total feldspar ratio for this suite of samples varies from 0.66 (L-11) to 0.82 (L-8). The granite samples (L-1, and L-2) resemble the porphyrytic granodiorite samples except for their slightly greater potassium feldspar content.

The isochron (Fig. 4) gives an age of 402 +/- 62 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70653 +/- 0.00066. The granodiorite samples do not provide much variation in the Rb/Sr ratio (Table 2). Their chemical homogeneity mirrors their petrographic homogeneity. This lack of variation and the scatter of the data points contributes to the large error in the age determination. The granite samples (L-1 and L-2) have greater Rb/Sr ratios and to some degree control the slope of the isochron. However,

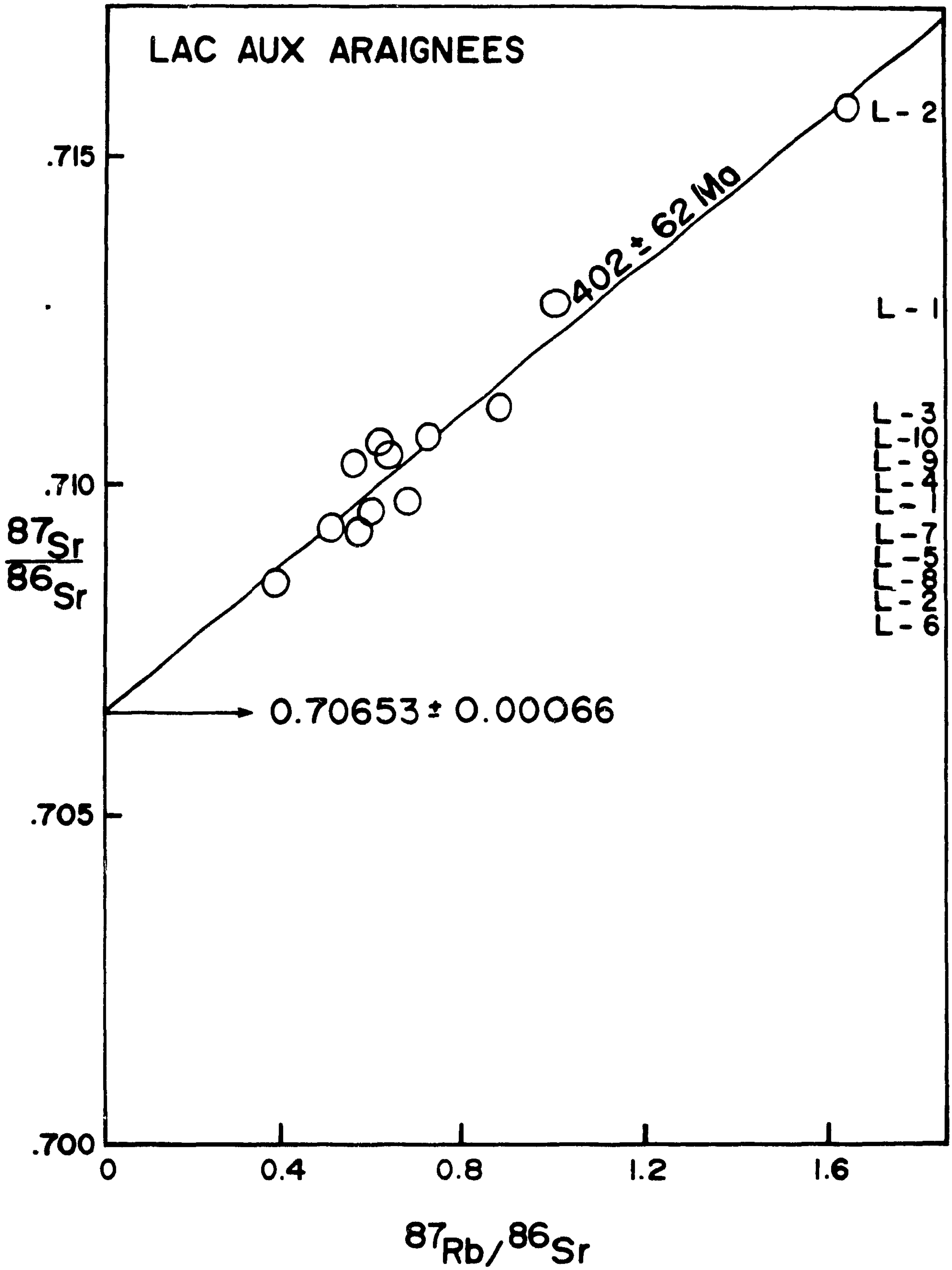

Fig. 4. Lac Aux Araigées Rb/Sr whole-rock isochron.

unlike the Scotstown high-Rb sample, there is no reason to exclude these granite samples from the isochron.

Bourne (1984) stated, as for the Scotstown pluton, that the Lac Aux Araignées pluton had undergone postsolidification metasomatic alteration. This metasomatic process may again be the cause for the disturbance of the Rb/Sr isotopic system.

The initial ratios of the Scotstown complex (0.7065) and Lac Aux Araignées complex (0.7065) are identical and could represent very similar source regions or processes. To comment on their relative ages would not be useful because of the large errors in both their ages.

Winslow Pluton

Eleven samples were collected and failed to produce a usable range of the $^{87}Rb/^{86}Sr$ ratio (Table 2). Therefore, only five samples were analyzed isotopically. Four of the samples (W-1, W-5, W-6 and W-7) were collected from roadside outcrops along route 161 at the southern extremety of the pluton. The fifth sample (W-9) was collected from the northern extremity of the pluton, 200 m from the contact.

Samples W-5 and W-7 are dark-gray leucodiorites, composed mainly of plagioclase (An30 to An40) and mafic minerals (35 to 45 %) such as hornblende and pyroxene. Sample W-1 is grey, medium-grained tonalite and sample W-6 is coarse-grained tonalite. W-9 is a sample of the northern hornblende diorite phase.

The five points produce an errorchron of 298 +/- 670 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.710200 +/- 0.0130 (Fig. 5). These very large errors are caused by the lack of variation in the $^{87}Rb/^{86}Sr$ ratio (Table 2) and very large scatter in the position of the data points. Using any reasonable age estimate for these samples, or better still, the U/Pb age (titanite) of 377 +/- 7 Ma to follow, the samples span a very wide and high initial ratio range of 0.7064 to 0.7129.

Like the Scotstown and Lac Aux Araignées plutons, intrusive contacts have not been observed between sampled sites that yield these different initial ratios. There is continuous exposure in the case of the Scotstown granodiorite samples. For Winslow, the lack of intrusive contacts between some samples, lack of xenoliths, and the very variable initial ratios strongly support the hypothesis of postsolidification metasomatism, and by analogy this process could explain the lesser scatter of the Scotstown and Lac Aux Araignées data.

Aylmer Complex

Samples A-1 to A-6 were obtained from a quarry located on Mount Aylmer. All of these samples are granodiorites, and are homogeneous, equigranular and medium-grained (2-3 mm) rocks, containing feldspar (65 %), quartz (25-30 %) and interstitial biotite (7%). The plagioclase/total feldspar ratio is about 0.8.

The remaining samples are equigranular, medium-grained, homogeneous and inclusion-free granites. Samples A-9 and A-10 are from the Lac Elgin quarry and samples A-13 and A-14, which

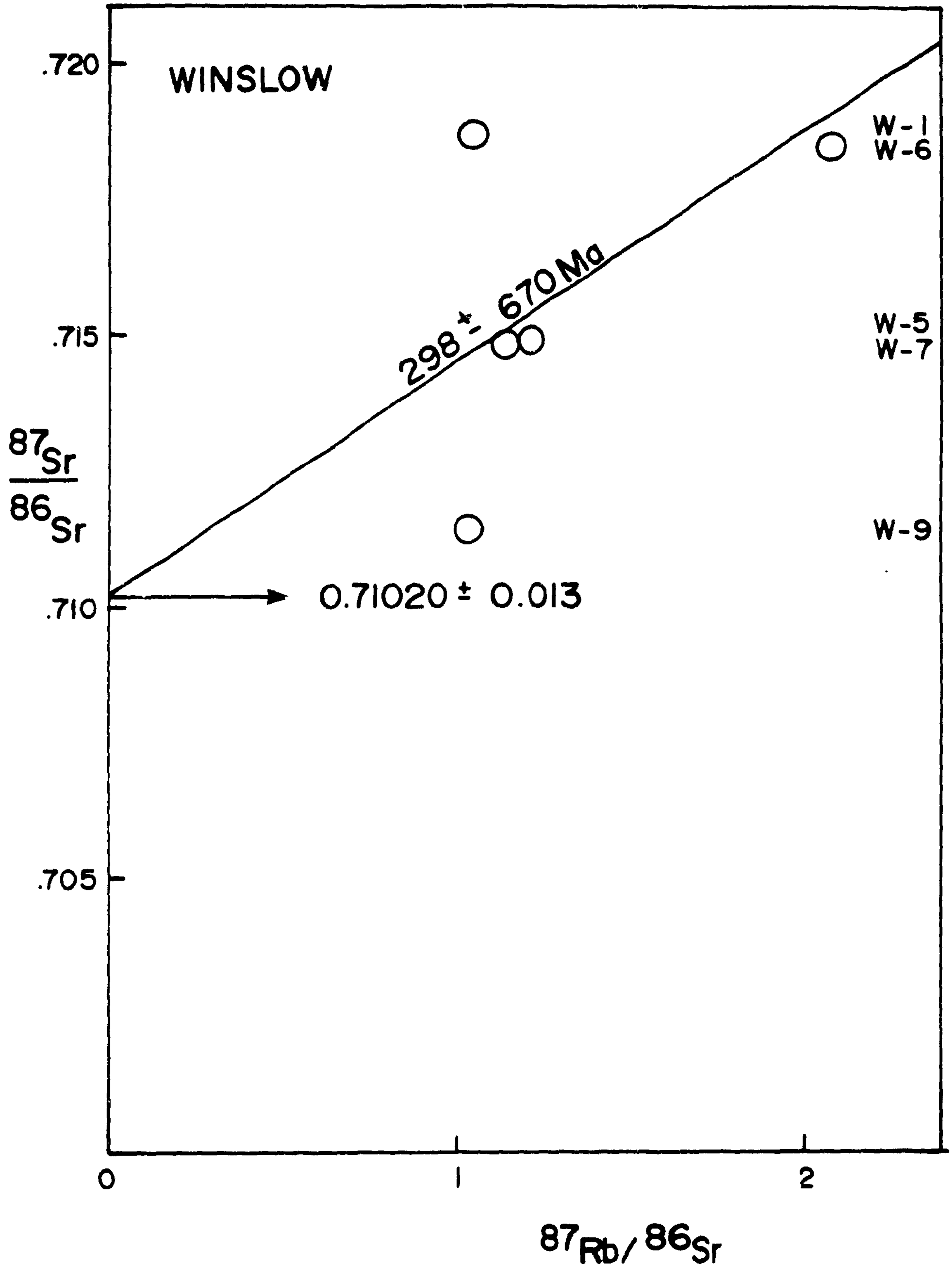

Fig. 5. Winslow Rb/Sr whole-rock isochron.

are relatively weathered, are from surface outcrops along a transmission line. The granites typically contain very little biotite (0-2 %) but do contain minor amounts of garnet and primary muscovite. The average plagioclase/total feldspar ratio is approximately 0.5.

The isochron (Fig. 6) yields an age of 393 +/- 42 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7072 +/- 0.0028. The granodiorite samples do not span a wide range of $^{87}Rb/^{86}Sr$ ratios (Table 2). The moderate scatter in the isochron may have been caused by the assimilation and/or partial melting of chemically heterogeneous country rock or by a post-solidification metasomatic process introducing radiogenic strontium. The initial ratio of 0.70706 is slightly greater than the initial ratios of the Scotstown and Lac Aux Araignées complexes. This can be the result of increased crustal assimilation at the present level of intrusion, supported by the presence of primary muscovite and garnet in some of the samples.

White and Chappell (1977) describe the petrographic characteristics of s-type granites as containing at least biotite, no hornblende, and more commonly containing muscovite, garnet and cordierite (White et al. 1986). S-type granites are also characterized by xenoliths but it is important that these xenoliths represent the residuum from the source area and not high-level inclusions (White et al. 1986). The chemical characteristics of s-type granites include an aluminous

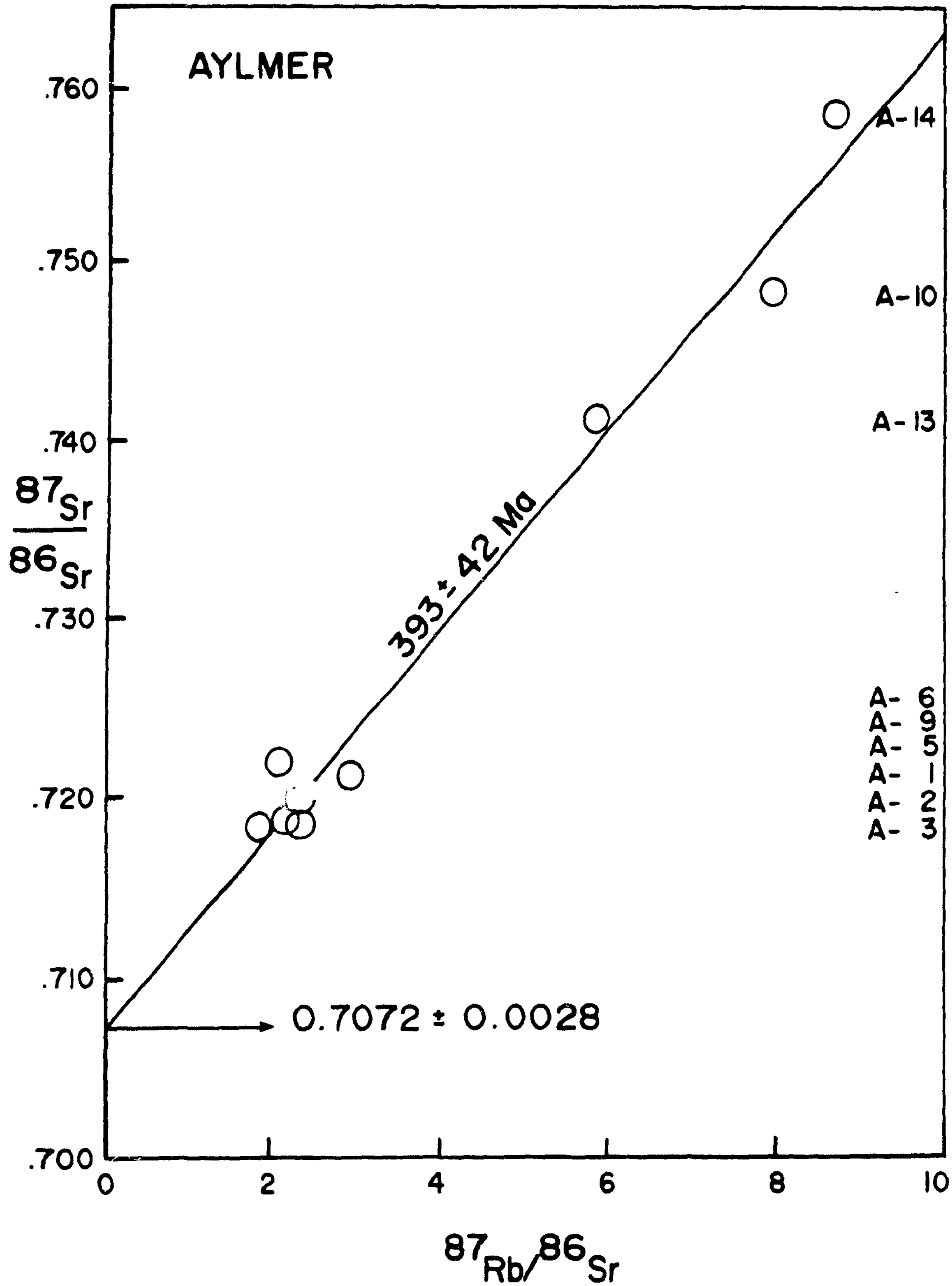

Fig. 6. Aylmer Rb/Sr whole-rock isochron.

composition (Al_2O_3 wt. % / $Na_2O + K_2O + CaO > 1$, and also corundum normative) and that the initial $^{87}Sr/^{86}Sr$ ratio exceed 0.708. The Aylmer pluton does not satisfy all these conditions because its initial ratio is less than 0.708, it did not crystallize cordierite, and finally, the xenoliths are high-level inclusions. The reason that the inclusions are interpreted to be high-level xenoliths is because the larger ones have the same structural orientation as the enclosing country rocks.

In summary, the Aylmer pluton may have originated through the partial melting of the lower continental crust combined with an unknown amount of upper crustal contamination (i.e. metasediments) resulting in a magma with a partial s-type signature.

Ste. Cécile Pluton

Samples C-17, C-14, C-15 and C-26 are medium-to-coarse grained, equigranular biotite granites with various degrees of subsolidus alteration (C-14 is highly altered and C-15 is relatively fresh).

Samples C-21 and C-30 are medium-to-coarse-grained, equigranular biotite granodiorites with trace amounts of titanite and magnetite.

Samples C-4, C-18 and C-22 are cross-cutting, aphanitic, potassium feldspar-rich aplites. The dykes are 2.5 to 5.0 cm thick, have sharp contacts with the host granite/granodiorite, and have silica-rich borders that grade into a feldspathic core.

Sample C-9 is a fine-grained, gray, quartzo-feldspathic dike containing small amounts of biotite and muscovite.

Together, the ten samples produce a Rb/Sr whole-rock isochron yielding an age of 364 +/- 14 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7076 +/- 0.0012 (Fig 7). As was the case for the other plutons, the granite and granodiorite samples have a small spread in the $^{87}Rb/^{86}Sr$ ratio (Table 2). The age obtained is therefore highly dependent on the position of the aplite sample points. An isochron composed uniquely of aplite samples and the quartzofeldspathic dike (C-9) yields an age of 368 +/- 27 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70708 +/- 0.0035. This age is essentially identical to that from all the samples combined. It is therefore reasonable to conclude that the aplite phase is comagmatic with the main intrusive phase.

The initial $^{87}Sr/^{86}Sr$ ratio of 0.7076 is sufficiently high to exclude the mantle as a primary source region (the amount of crustal material needed to contaminate an already Sr-rich melt would be large). The magma was probably formed in the lower crust.

Stanhope-Averill Pluton

Samples S-1, S-2 and S-3 were obtained from a roadside outcrop approximately 6 Km northwest of Stanhope, 400 m from the pluton's northern margin. They are medium-grained, equigranular granodiorite with 5 - 7% biotite as the principal mafic mineral.

Samples S-4 and S-5 were obtained along the same road but

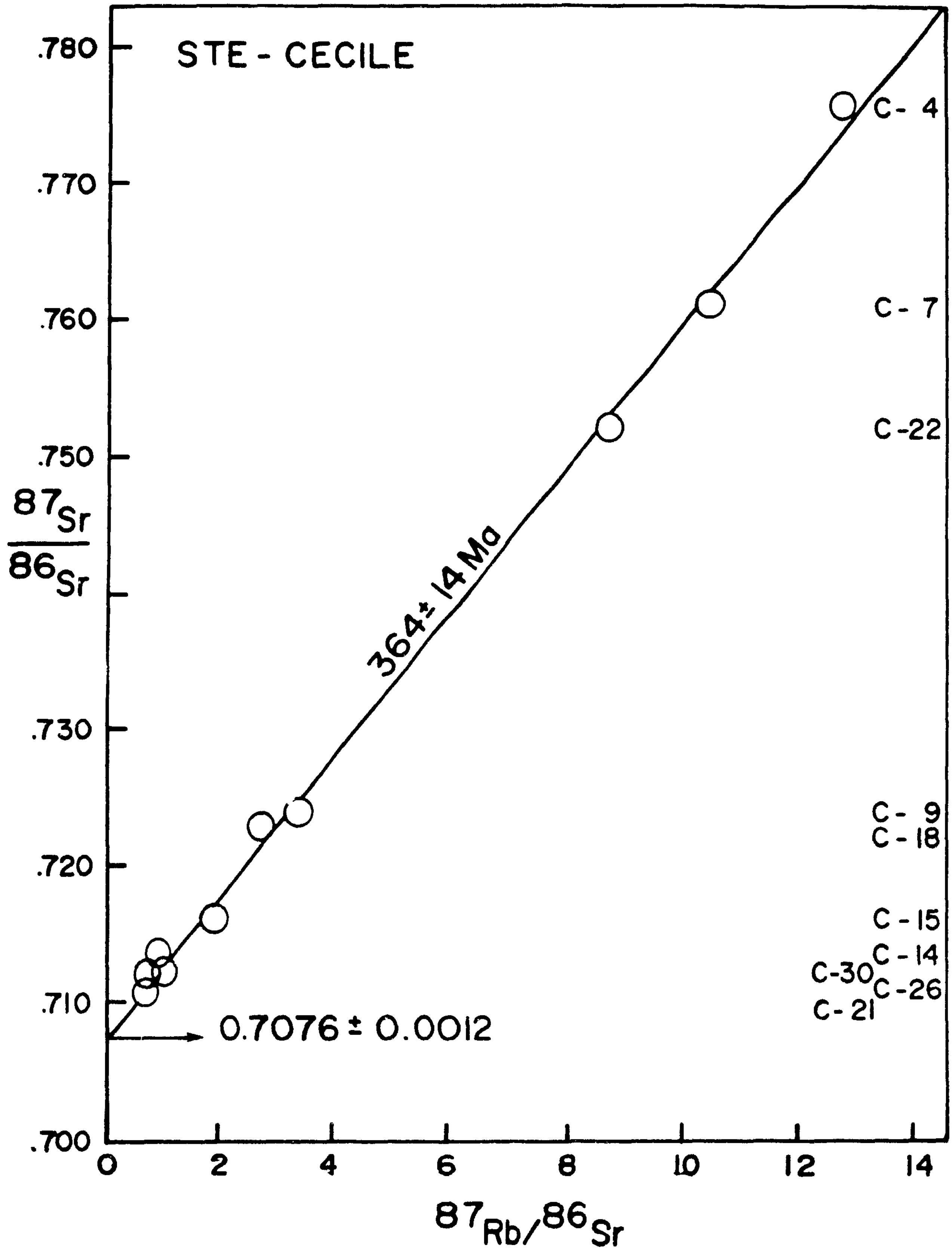

Fig. 7. Ste. Cécile Rb/Sr whole-rock isochron.

more toward the pluton's interior. They closely resemble samples S-1 to S-3.

Samples S-6 to S-8 are coarse-grained (3-5 mm), equigranular, biotite (2%) granites from an abandoned quarry 2 Km north of Stanhope, close to the pluton's northeastern margin.

The eight points give a whole-rock isochron age of 363 +/- 53 Ma with a $^{87}Sr/^{86}Sr$ initial ratio of 0.70713 +/- 0.00094 (Fig. 8). The scatter of the data points is probably caused by a metasomatic process involving fluids from the host rocks, because of the uniformity of the rocks and lack of xenoliths (Chapter 2). This is all the more likely given the fact that sampleable outcrops are limited to the margins of the pluton. Isotopic heterogeneity occurs on a scale of metres so that this is unlikely to be a function of the source region of the magma.

Beebe Pluton

The presence of abundant granite quarries provided easy access and greater opportunity for obtaining fresh samples than was the case for some of the other plutons. Although a large number of samples were collected (17) there was very little variation in the Rb/Sr ratio. The granodiorite samples (B-14, B-16) have similar,low Rb/Sr ratios (0.15 and 0.25). Sample B-14 is from the Bussière quarry, 1 Km northeast of Graniteville. Sample B-16 is from a quarry 0.5 Km east of Graniteville. Sample B-12 is from a 5 cm-wide felsic dyke composed of porphyritic K-feldspar and quartz crystals with minor amounts of muscovite and

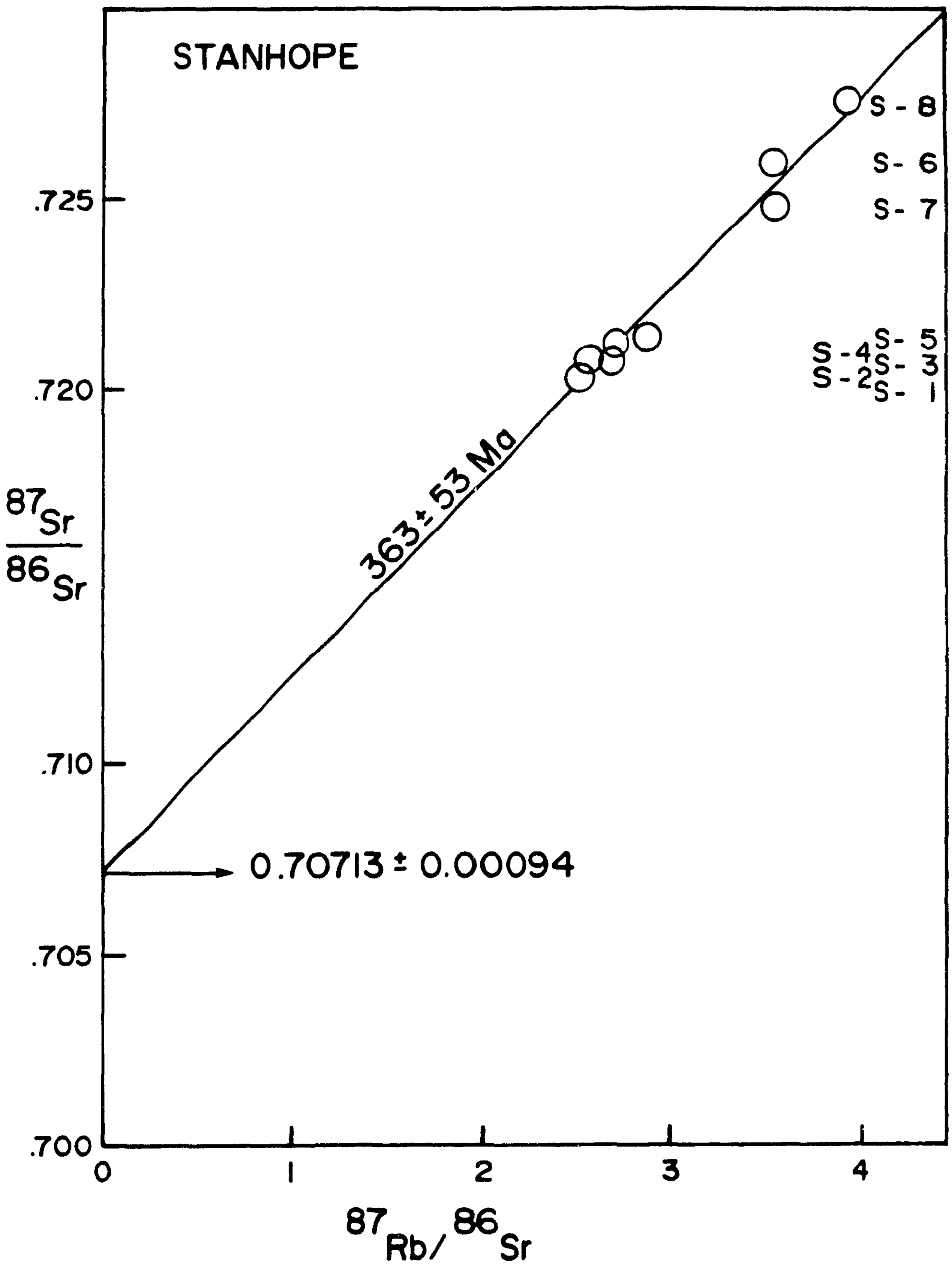

Fig. 8. Stanhope Rb/Sr whole-rock isochron.

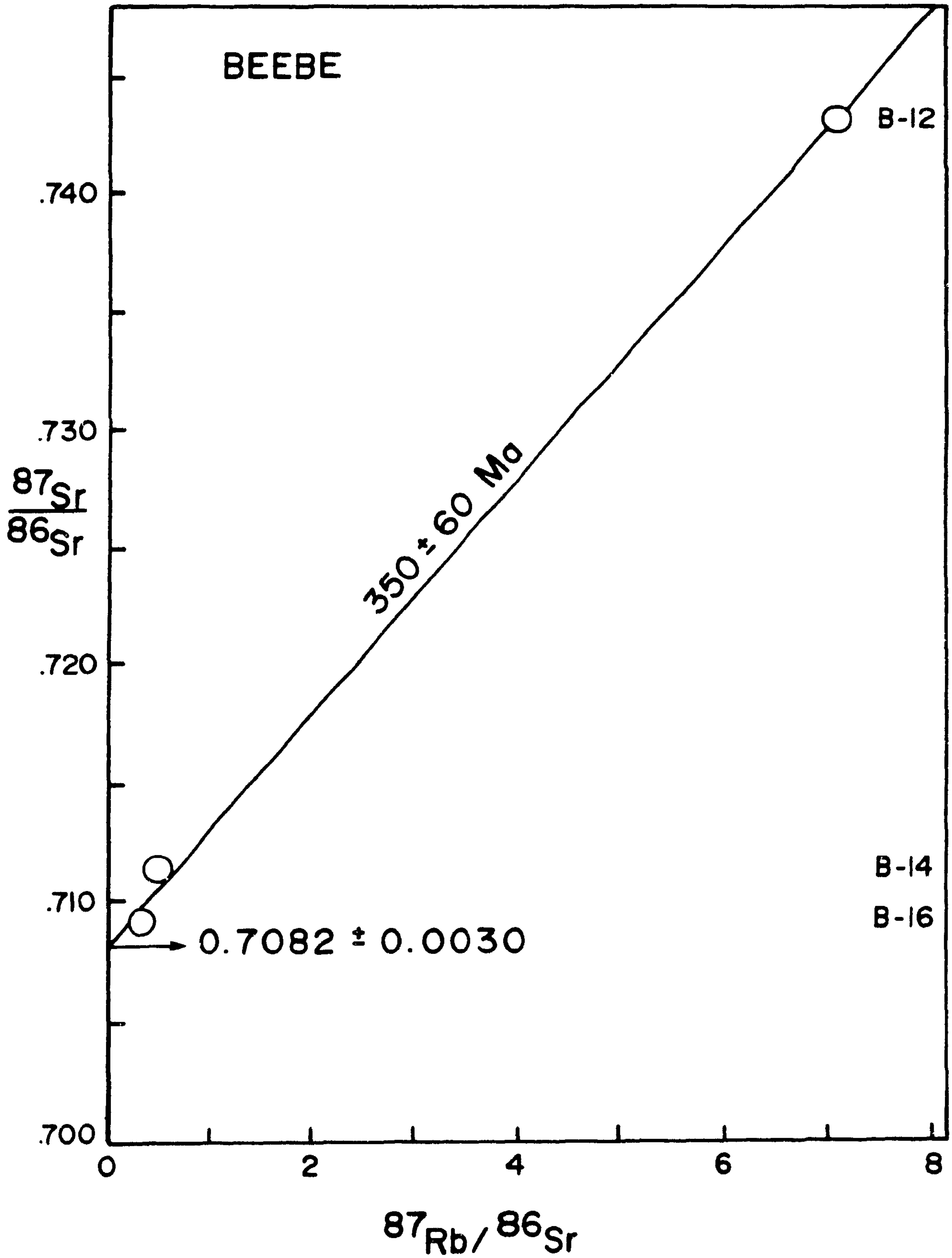

Fig. 9. Beebe Rb/Sr whole-rock isochron.

pyrite, from a small quarry 2 Km northwest of Beebe Plain.

Together the three samples produce an isochron with an age of 350 +/- 60 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7082 +/- 0.0030 (Fig. 9). The better constrained initial ratio is the highest of the plutons and could be the result of increased crustal contamination. However, because of the small number of points all these conclusions are rather suspect.

Moulton-Hill Granite

Fig. 10 is the Rb/Sr whole-rock isochron obtained from samples of the Moulton-Hill granite. Five are medium to coarse grained metatrondjemites (As-1, As-2, As-10, As-12, As-13) that are slightly foliated and intensely saussuritized. Samples As-4, As-5, As-6, As-9 and As-11 are metagranodiorite from the southern half of the intrusion. They are medium to coarse grained, and contain many fractures filled with sericite. Sample As-3 is a porphyritic meta-rhyolite consisting of porphyritic albite crystals surrounded by an intensely sassuritized quartzofeldspathic matrix. This sample also contains mafic inclusions with a slight foliation.

The eleven samples yield an isochron with an age of 461 +/- 35 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70914 +/- 0.0026 (Fig. 10). The scatter in the data points may be the result of a pervasive carbonitization event that occurred in the Ascot and St. Francis Formations surrounding the granite (St. Julien and Lamarche 1965; Lamarche 1967). A ferruginous carbonate of apparently hydrothermal origin has been introduced into the

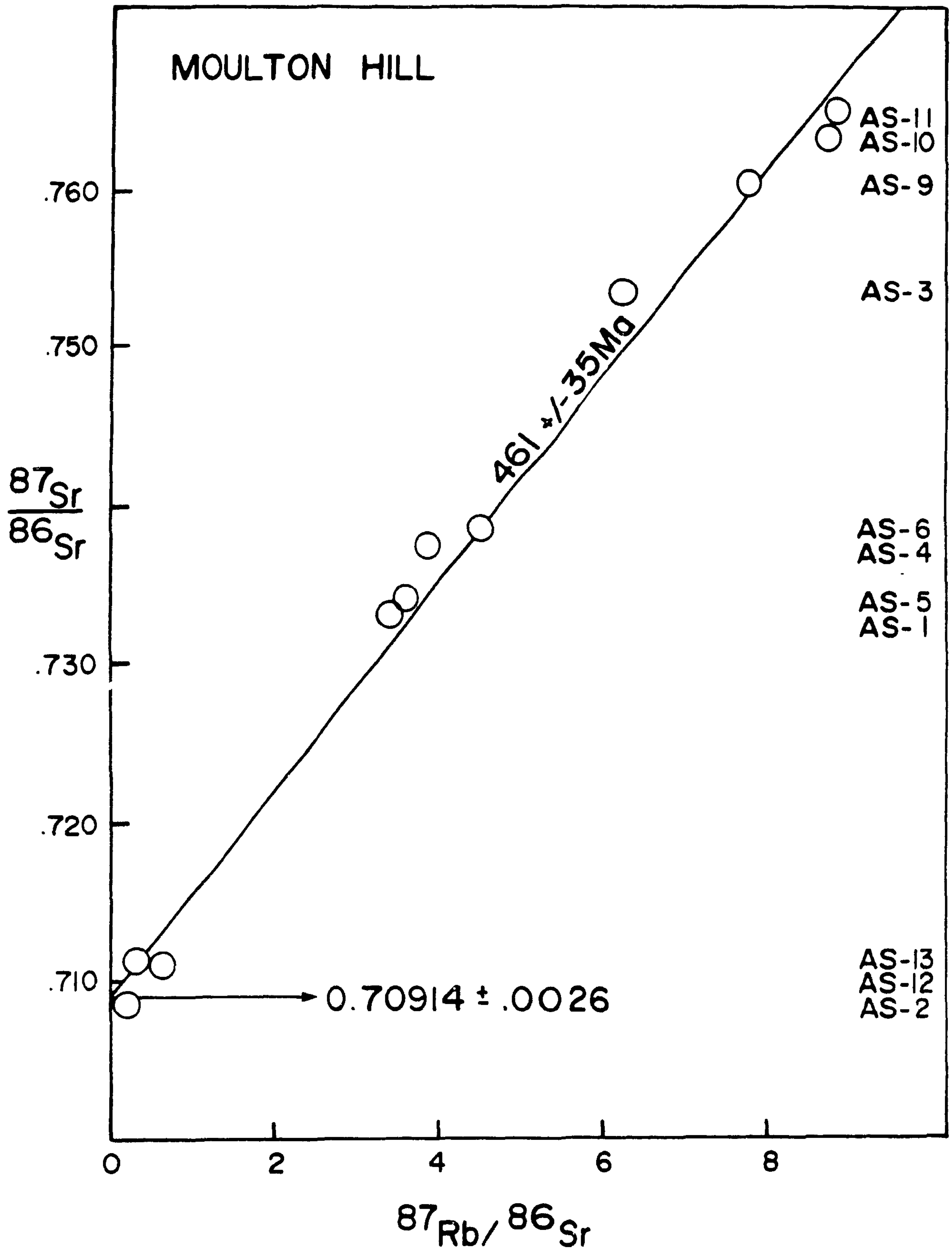

Fig. 10. Moulton Hill Rb/Sr whole-rock isochron.

stratified rocks, and some Devonian diorite and gabbro dikes and sills. Some carbonatized areas are irregularly shaped and more than 2 Km long. This process has perhaps altered the strontium isotopic ratios by the addition or removal of radiogenic strontium and/or rubidium (Poole 1980). The mobilization of trace elements in the Ascot volcanic rocks was also described by Hynes (1980) (see Chapter 2). He noted that there was a strong correlation between trace element concentrations and degree of carbonitization of the metabasalts. He attributed the overall mobility of the immobile elements to high CO_2 levels in the fluid phase during metamorphism. The date of 461 +/- 35 Ma could therefore be the result of such a hydrothermal process, so that this date would be a minimum age for the Ascot Formation. However, St.Julien and Hubert (1975) assigned a Middle Ordovician (460-480Ma) stratigraphic age to the Ascot-Weedon Formation. Therefore, the intrusion of the Moulton-Hill granite may have been synchronous with the formation of the Ascot-Weedon volcanic rocks. The high $^{87}Sr/^{86}Sr$ initial ratio of 0.7091 and the preservation of xenocrystic zircons of Grenville age in the pluton (Genereux, personal communication 1988) indicate that the Ascot Formation may have been a continental arc.

Summary of Rb-Sr Data

Excluding the Taconic Moulton-Hill granite, the Rb-Sr whole-rock isochron ages for the southeastern Quebec plutons indicate that magmatism in the study area occurred from mid-

Devonian (410 Ma) to Late Devonian (364 Ma) times. However, the Rb-Sr isochron method does not permit precise age distinctions between the Scotstown, Lac Aux Araignées, and Aylmer plutons because of the large errors in the age determinations. The ages support field evidence that the plutons are Acadian. The intrusive activity is probably the result of melting of lower crust caused by crustal thickening as the result of compression during the Acadian Orogeny. Partial melting in the lower crust may have been aided by the pooling of a juvenile magma at the lower crust-depleted mantle boundary, but no low initial ratios were determined for individual samples, as was observed in the analogous study by Larocque (1986) for the Gaspé region.

The initial $^{87}Sr/^{86}Sr$ ratios range from 0.7065 to 0.710, ratios typical of melt generated in Rb-depleted lower crust. The amount of crustal contamination is generally not sufficient to produce classic "s-type" granite mineralogy. There seems to be a slight increase in $^{87}Sr/^{86}Sr$ initial ratios with decreasing age, and this trend might be the result of increased upper crustal contamination with time.

The ages calculated from the isochrons may be suspect, for the following reason. Given the high initial ratios and scatter, the isochrons may in part be the result of two-component magma mixing or have been affected by a postsolidification metasomatic process involving mixing with radiogenic ^{87}Sr from the country rocks.

Evidence for mixing processes using initial ratio/total Sr diagrams requires precise estimates of the ages of intrusion. For this reason, and to better achieve the original dating objective, the U/Pb Concordia method has been applied to each pluton for which suitable minerals are available.

U/Pb Geochronology

Polished and etched sections of zircon crystals were examined for most zircon fractions. Many of these had old, inherited zircon cores. U/Pb isotopic analysis of such populations of zircons would not give U/Pb ages of magma crystallization but a date between that of the core and the U/Pb age of the magmatic overgrowth. Some researchers (eg. Pupin 1980) consider that the crystal morphology of zircon is controlled by the chemistry and temperature of the melt. Others have stated (Harrison and Watson 1983) that the chemistry of the melt also determines the Zr saturation level and survival of zircon xenocrysts.

Zircon Morphology and Zr Saturation

A morphological classification scheme (Fig. 11, Pupin 1980) has been applied to each zircon sample on the basis of examination of at least 200 unbroken crystals, except for the Aylmer sample where only 80 grains were examined. The morphological classification is based on the relative development of prismatic and pyramidal crystal faces. These features appear

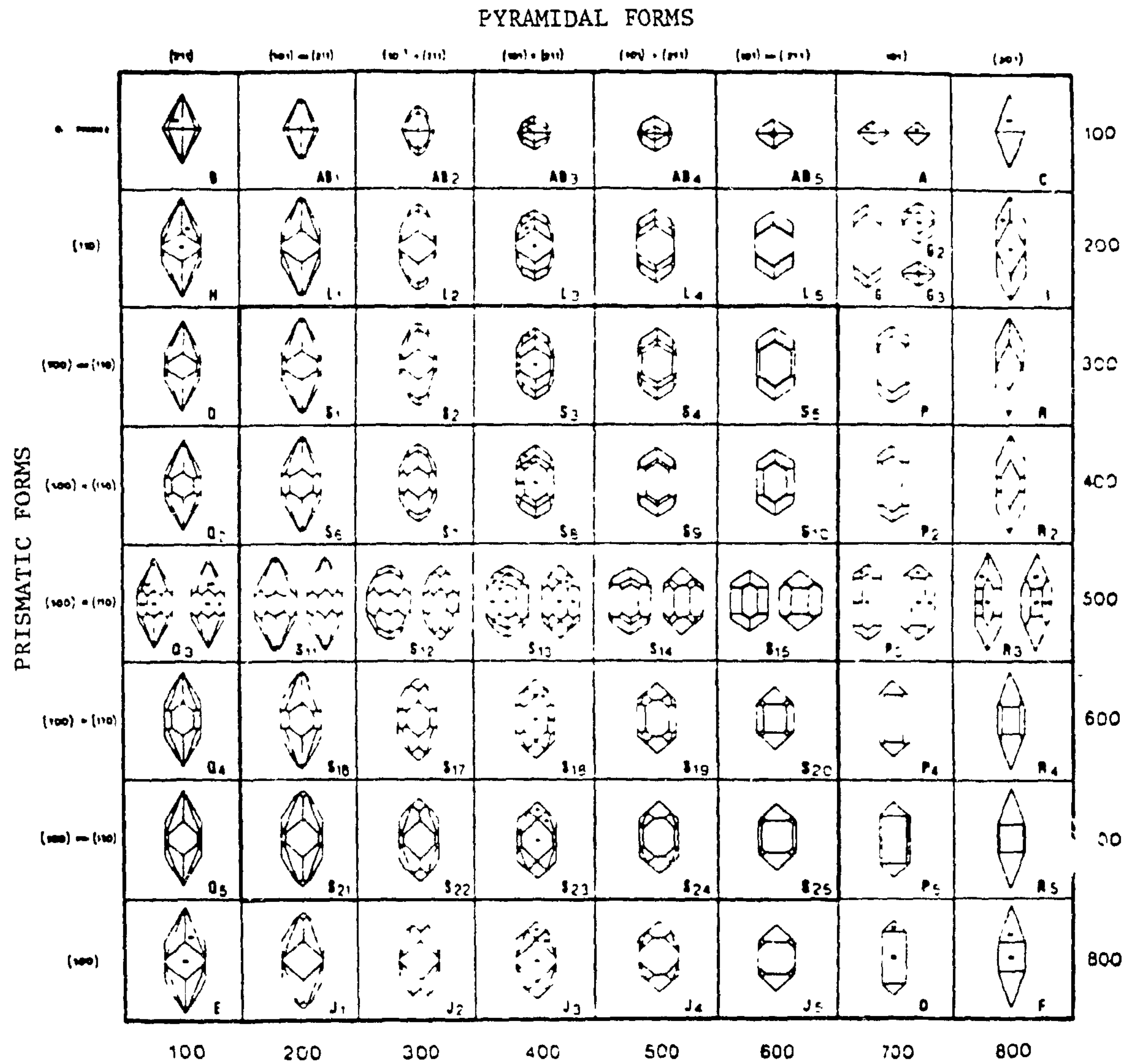

Fig. 11 Zircon morphological classification from Pupin (1980). The horizontal axis is the relative development of either the (101) or (201) pyramidal forms. The vertical axis is the relative development of either the (100) or (110) prismatic forms. Each row and column is assigned an arbitrary number from 100 to 800, identifying each zircon subtype with a unique pair of numbers. These numbers are then used to calculate a weighted average pyramidal and prismatic form that gives the mean zircon subtype.

to reflect both the chemistry and the temperature of the crystallization medium of a zircon population (Pupin 1980). A combination of pyramidal and prismatic forms constitutes a zircon subtype, denoted by a letter-number combination (eg. G1, S2). The mean zircon subtype can be calculated mathematically using the procedure outlined in Pupin (1980). The distribution of zircon subtypes is illustrated in Figs 12a to 12d.

The zircon populations are of the G-subtype and the immediately surrounding subtypes (L5, R1, P2, and S5). These subtypes are dominated by the development of the 110 prismatic and 101 pyramidal faces. According to Pupin (1980) the G-subtype is indicative of crystallization at low temperature in an alkaline melt. The temperature of crystallization was probably low but these rocks are not alkaline (Chapter 2).

The zircons were also sectioned, polished and etched in order to show their internal features. An important internal characteristic of these zircon populations is the presence of inherited zircon cores mantled by a younger magmatic overgrowth (Appendix B, Figs. B1 to B21). The younger magmatic mantle usually results in euhedral crystal faces that can make the zircon appear to be entirely magmatic. Inherited cores were found to be more abundant in the non-zero-degree magnetic fractions, and the zircons containing cores were darker in colour relative to the clear-to-pink completely magmatic zircons.

The preservation of inherited zircon depends on zirconium concentration relative to the saturation level. The stability of

Zircon Population Distribution Diagrams

SCOTSTOWN

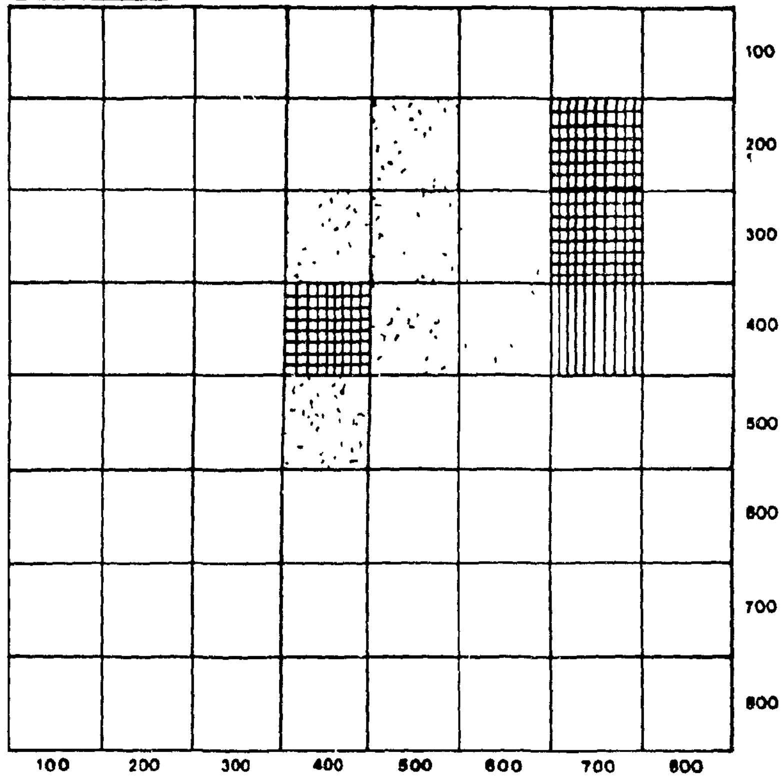

Figure 12a.

LEGEND:

0-2% 2-5% 5-10% 20-40% > 40%

LAC AUX ARAIGNÉES

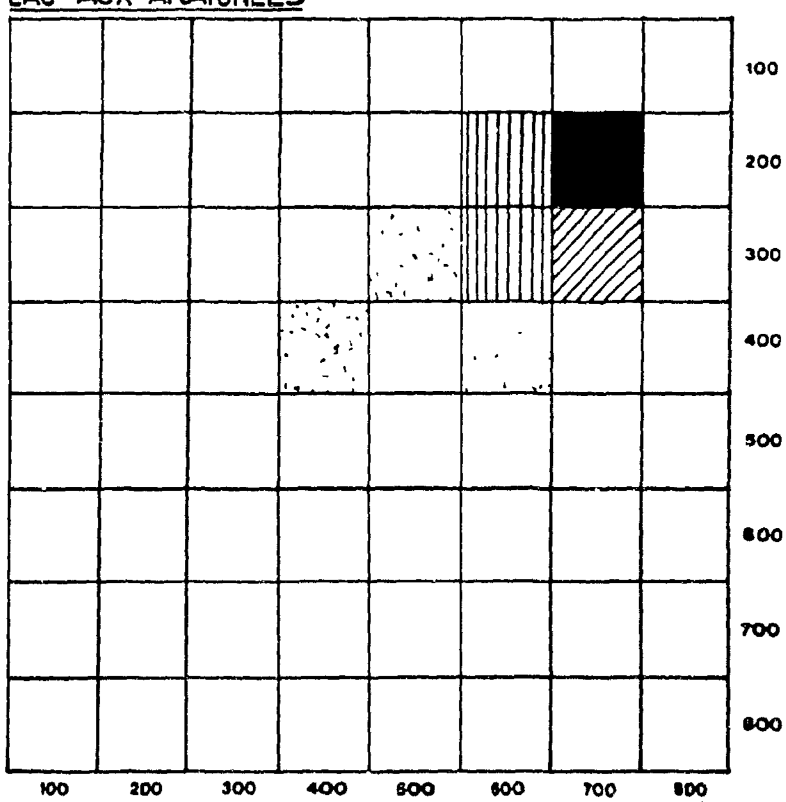

Figure 12b.

Zircon Population Distribution Diagrams

AYLMER

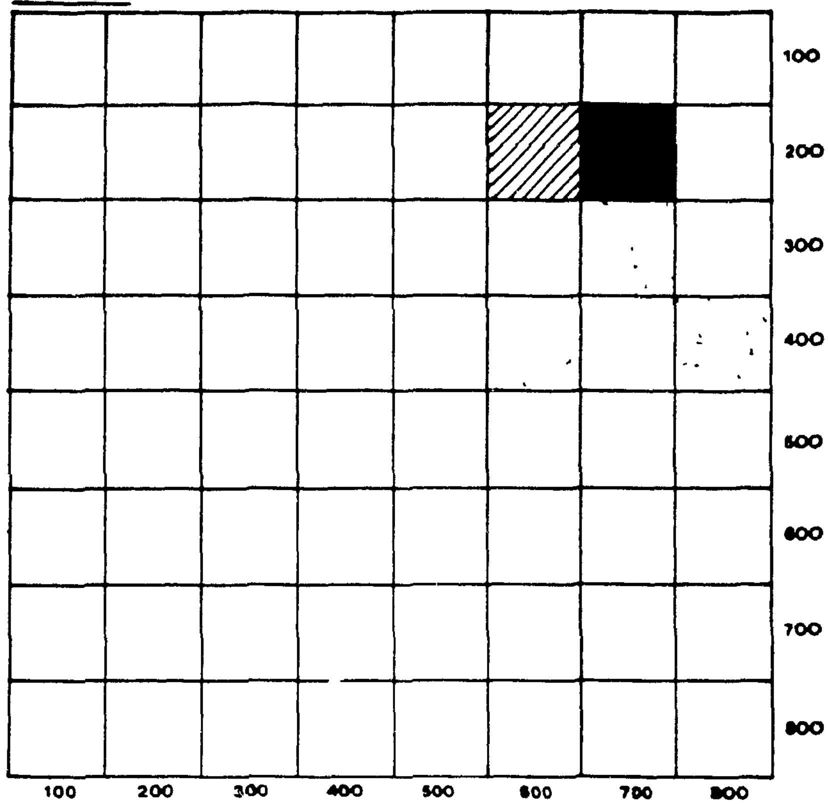

Figure 12c.

LEGEND:

0-2% 2-5% 5-10% 20-40% > 40%

STE.CÉCILE

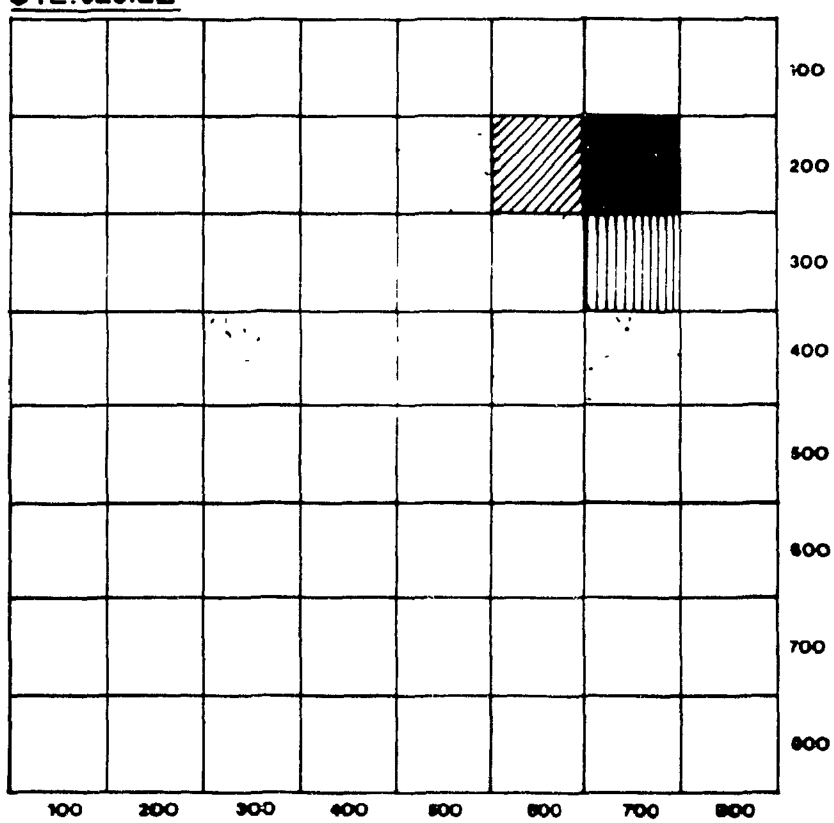

Figure 12d.

zircon during anatexis was experimentally investigated by Watson and Harrison (1983). They found that the saturation of zirconium in crustal felsic melts was a function of both temperature and melt chemistry and could be described by the relationship ·

$$\ln D_{zircon/melt} = -3.80 - [0.85 (M - 1)] + 12900/T,$$

where D is the concentration ratio of Zr in a stoichiometric zircon to that in the melt, T is the absolute temperature and M is the cation ratio (Na + K + 2Ca)/Si x Al, provided the melt contains at least 2% H_2O. Hornblende is a ubiquitous mineral phase in all the plutons. According to Naney (1983), the presence of hornblende in a granodioritic system requires a minimum of approximately 4 wt.% H_2O at 2 Kbar and 2.5 wt.% at 8 Kbar. Therefore it is highly probable that these rocks contained at least 2 wt.% H_2O

The solidus temperature of a granitic melt is a function of pressure. The minimum pressures of emplacement for the different complexes, obtained from the contact metamorphic assemblages (Bourne 1984, 1985, 1986, and Danis 1984, 1985), range from 2 to 4 Kbar. The feldspar phase petrology is in agreement with the above pressure estimates. In this pressure range the granite melting interval is narrow and the granite behaves as a eutectic-like system assuming the melt is water saturated. The solidus temperature for a water-saturated granitic melt at 2 Kbar pressure is 705 degrees Celcius (Wyllie et al. 1976). In a water-saturated granodioritic melt at the same pressure, the solidus has been determined to be 675 degrees Celcius by Naney (1983) and 715 degrees Celcius by Whitney (1975). A temperature of 700 degrees Celcius will be used, and the solidus temperature was not significantly affected by pressure in the studies cited above.

The Zr contents and data used to calculate the M values were obtained from the analyses of Bourne (1984, 1985, 1986) and Danis (1984, 1985) and these are shown in Figs. 13 to 16. The Zr concentrations are greater than those required to saturate the hosts of the zircons, at a temperature of 700 degrees Celcius (Table 3), and this could explain the abundance of inherited xenocrystic cores. The Zr content of the Aylmer sample is sufficient for saturation, but is much lower than for the other plutons. This could explain the near absence of magmatic zircon in this sample.

Zircon fractions were separated from samples of the Scotstown, Lac Aux Araignées, Winslow, and Ste. Cécile plutons. Samples from the other plutons (Aylmer, Beebe, and Stanhope-Averill) did not yield any zircons, or sufficient zircons to be usefully analyzed (we have dated samples as small as 10 ug of mineral). It was possible in all cases to use the same samples for zircon analysis that were used for the monazite and titanite analyses, to make comparisons between the methods as meaningful as possible. Compared to titanite and monazite, the common Pb correction for zircon is small or negligible. Precision is limited by our knowledge of isotopic fractionation or by

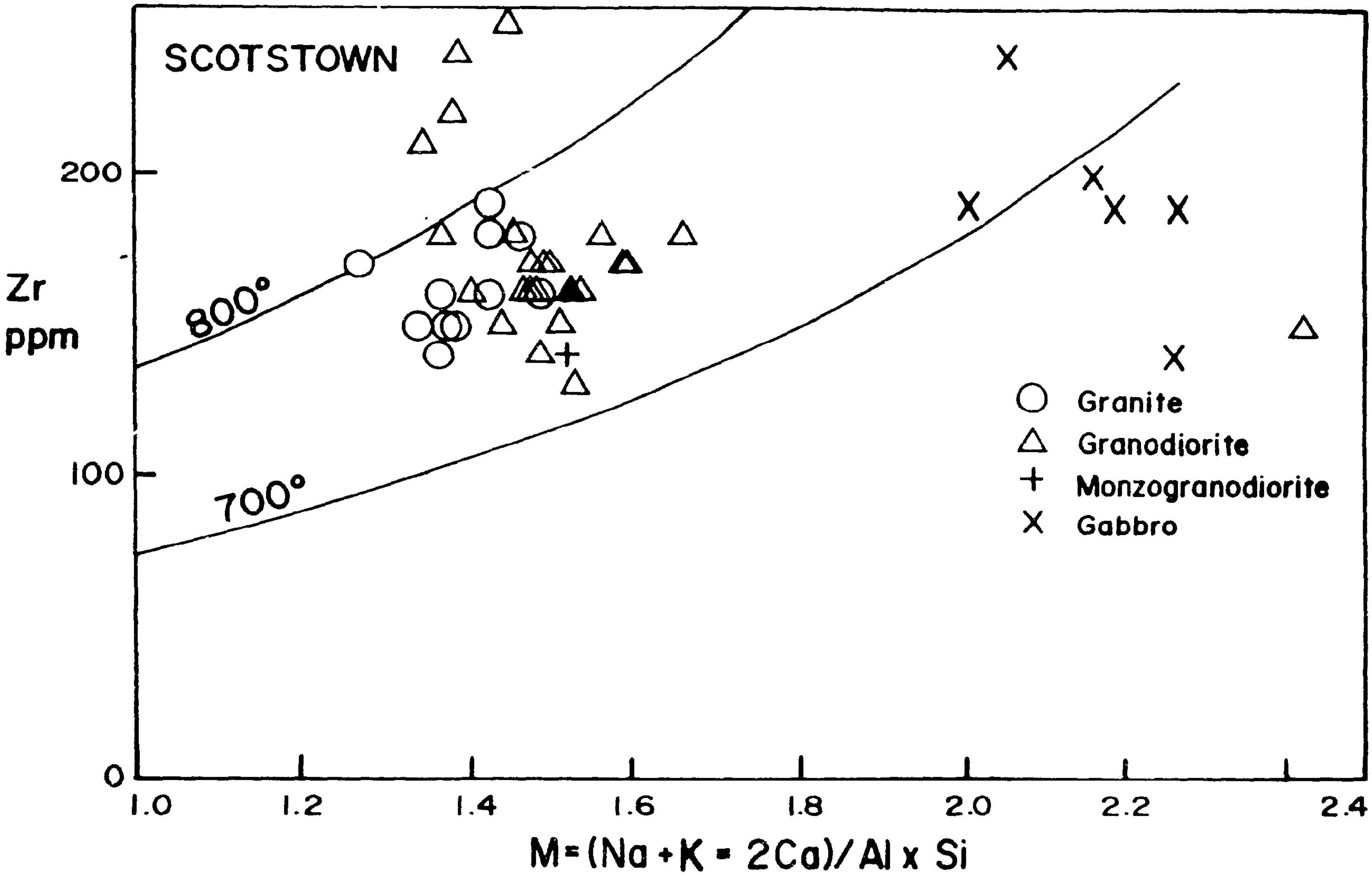

Fig. 13. Scotstown Zr saturation diagram The filled triangle is the sample analyzed for U/Pb mineral dating.

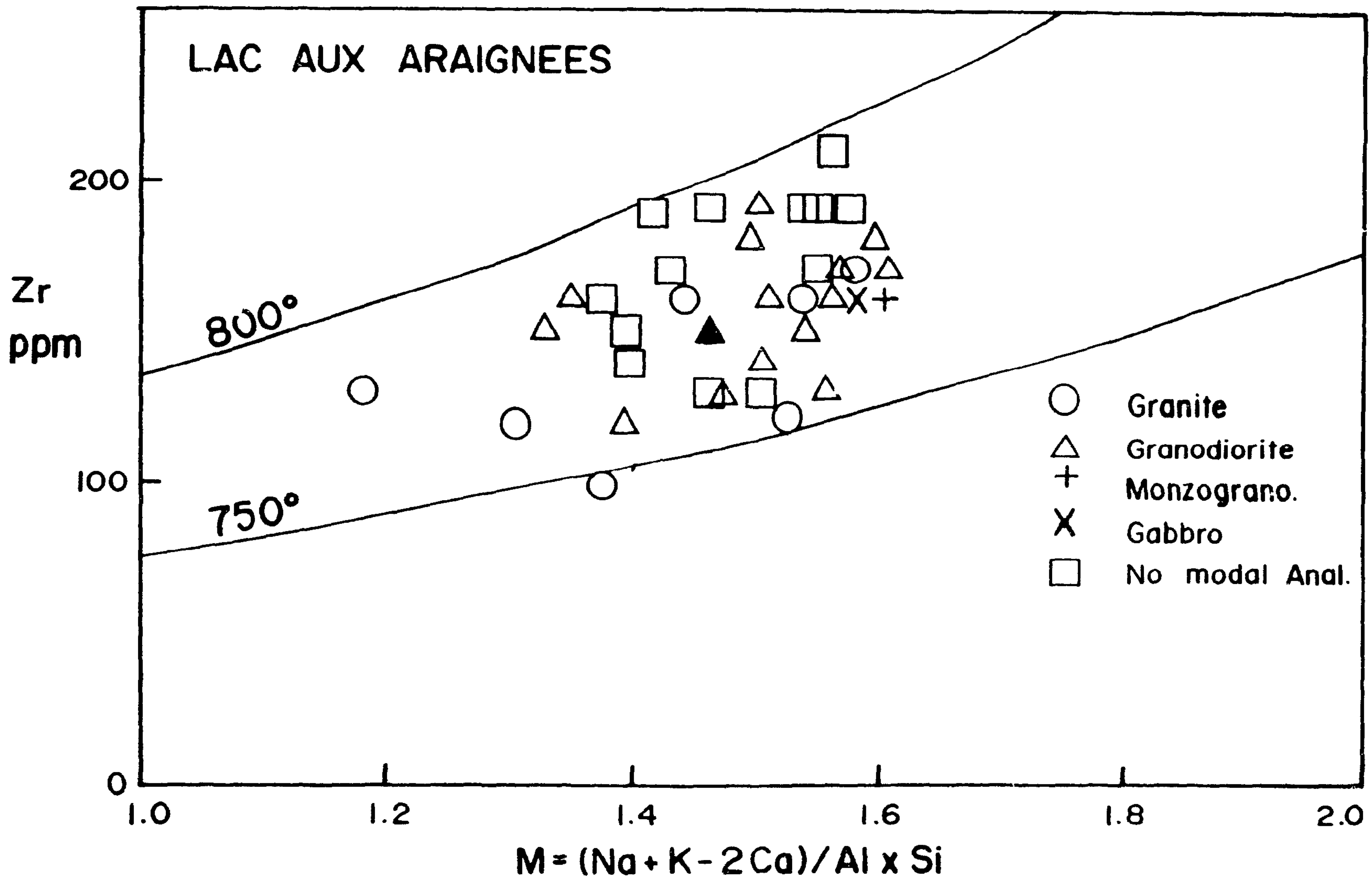

Fig. 14. Lac Aux Araignées Zr saturation diagram. The filled triangle is the sample analyzed for U/Pb mineral dating.

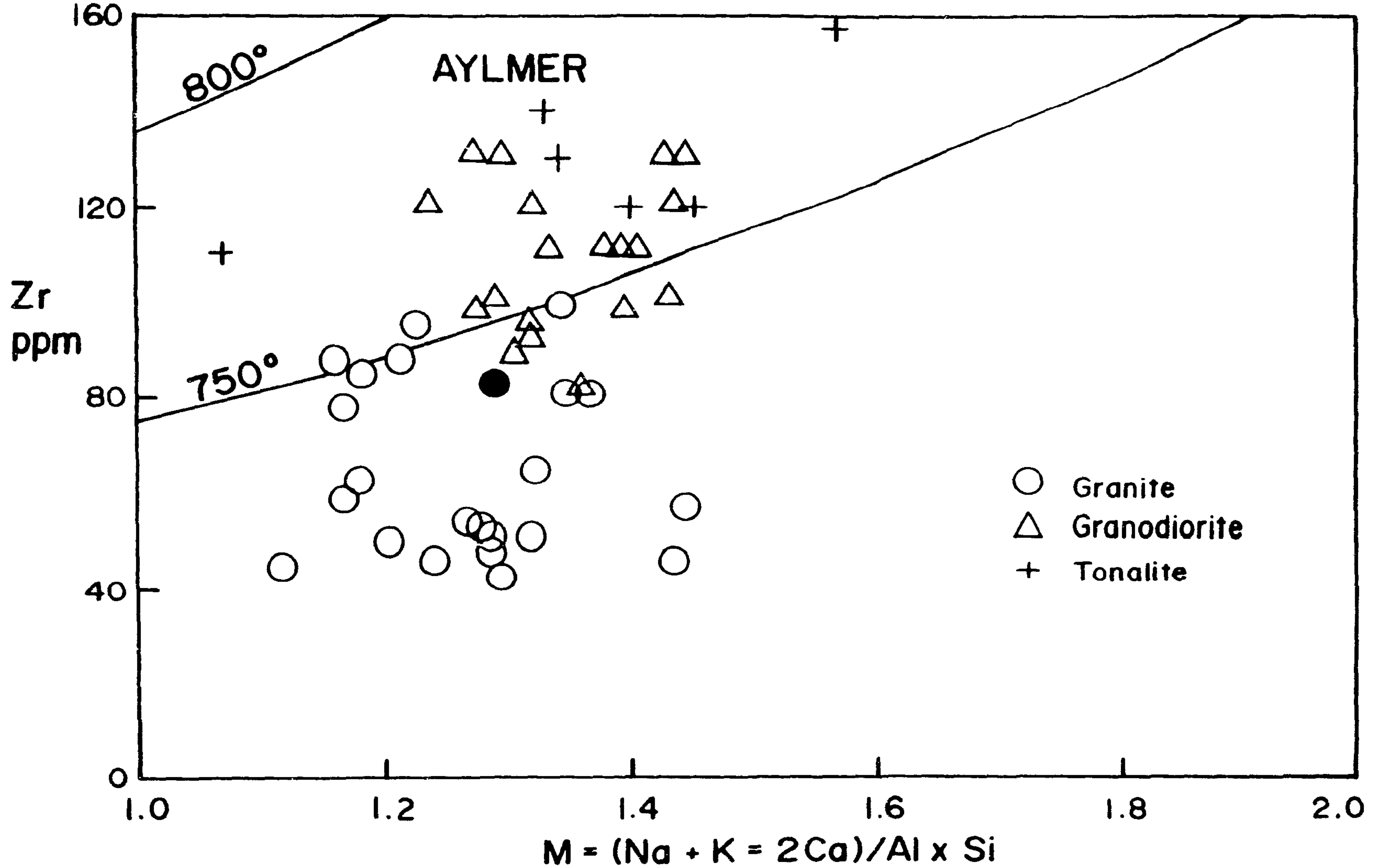

Fig. 15. Aylmer Zr saturation diagram. The filled circle is the sample analyzed for U/Pb mineral dating.

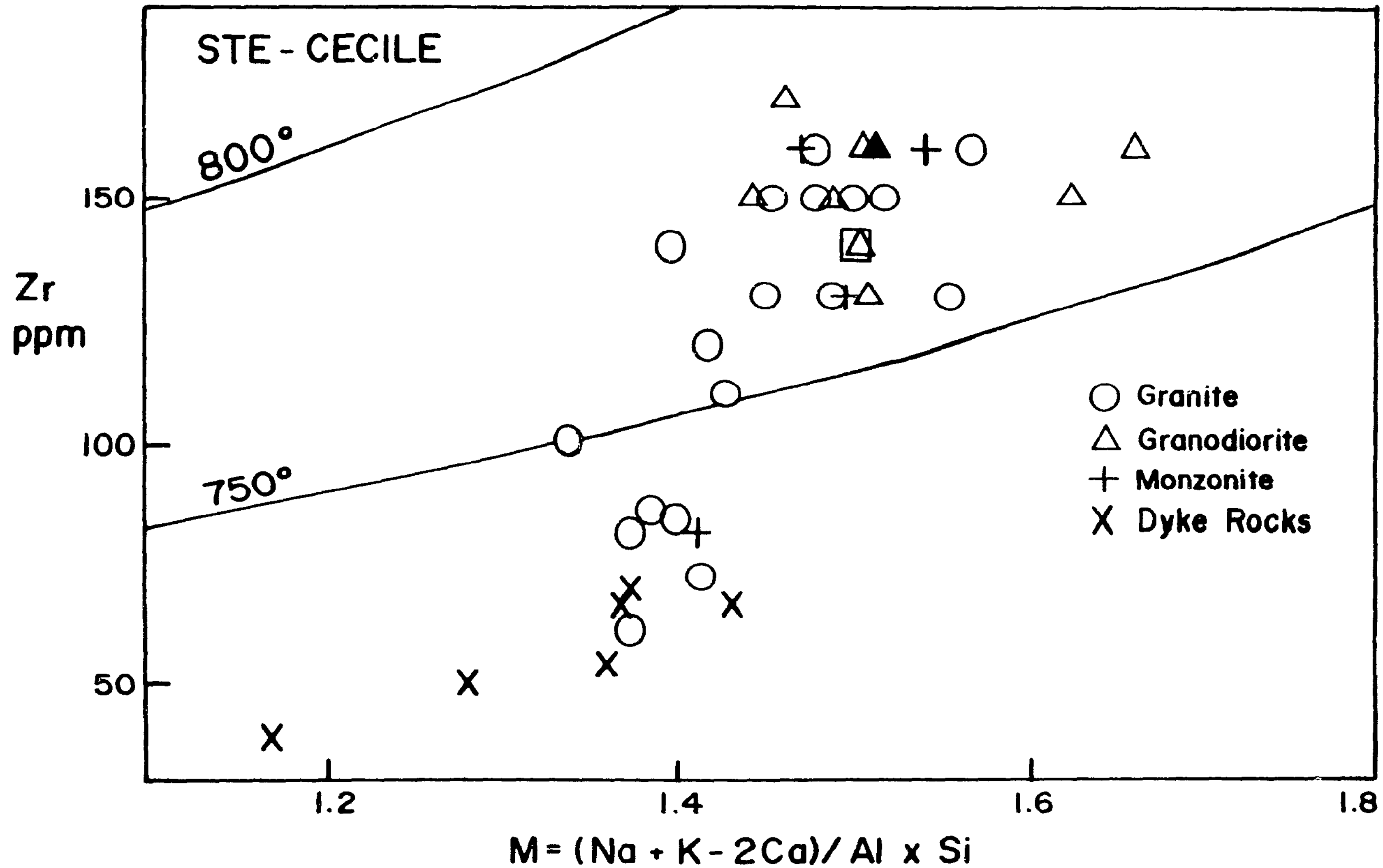

Fig. 16. Ste. Cécile Zr saturation diagram. The filled triangle is the sample analyzed for U/Pb mineral dating.

Table 3. Zr Contents and Saturation Levels for the zircon samples and their respective plutons.

Pluton	Zr Content (ppm)		
	Average of Pluton	Zircon Sample	Of Saturation Level
Scotstown	171	160	55
Lac Aux Araignées	158	150	57
Aylmer	94.5	100	56
Ste. Cécile	132	160	60

measurement error in the case of very small samples.

As described earlier, most zircons from these plutons have cores interpreted to be inherited zircons. These cores are often not visible unless grains are sectioned and polished. Grains were hand-picked to avoid inherited components using simplistic criteria such as lowest magnetism, greatest clarity and crystallinity, and freedom from inclusions. The results to follow show that this approach is somewhat effective for these rocks. The fact that the fractions consist of a small number of carefully selected grains (20 to 40) is probably responsible for the concordance of some points. None were abraded as this would accentuate inheritance problems. The source of inheritance could, however, be of interest.

Dating Titanite and Monazite

The mineral titanite has been observed to give concordant or nearly concordant magmatic ages for igneous rocks (Catanzaro and Hanson 1971), and concordant metamorphic ages for metamorphic rocks (Tilton 1968). It is unlikely that titanite would contain an inherited component because of its low crystallization or melting temperature. Monazite is also used to obtain concordant magmatic ages of granites for situations where zircons have an inherited component (e.g. Zartman and Hermes 1987). However, Parrish (1988) has recently documented several cases of inheritance in monazite.

A disadvantage, relative to zircon, of using titanite and monazite for U/Pb mineral dating is that both minerals incorporate substantial amounts of common Pb, making the initial common Pb correction a much more important factor in accurately determining the age. A further problem with the U/Pb method is that for ages in the approximate range 0-600 Ma, the linear trajectories of lead loss are nearly coincident with the concordia curve. The result is that data may seem to yield concordant ages, i.e. they seem to display closed system behaviour. A second consequence of this near coincidence of concordia and discordia trajectories is that it greatly magnifies errors in $^{207}Pb/^{206}Pb$ ages that are obtained from the intersection of the concordia curve and the recent or continuous loss discordia model lines. Even quite small analytical errors result in large errors in the $^{207}Pb/^{206}Pb$ age. A common approach to this problem is the circular argument that if the minerals titanite and monazite are indeed concordant, then $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages will not be affected by the low-angle intersection problem, and are good age estimates. The problem is that the concordance may be more apparent than real, because of the common Pb correction. These dates can at least be qualified as minimum ages. Only repeated analyses of different fractions of the mineral may resolve whether or not the mineral behaved as a closed system for Pb (Scharer 1986) That is , if points lie within analytical error of each other and of concordia, there may not have been loss of Pb. In most cases the maximum $^{206}Pb/^{238}U$ date will be used here as a minimum age.

Initial common Pb correction

The initial common Pb correction can be determined by either of two methods. The first is to use the Stacey and Kramers (1975) model for a two-stage growth of Pb in the earth's mantle. The second method is to analyze a mineral present at the time of magma crystallization that incorporates Pb but no U in its structure. Such a mineral is potassium feldspar. This second approach gives a more accurate measure of the initial isotopic Pb composition of melts derived from a heterogeneous continental crust. This is especially important when dating titanite and monazite.

In a concurrent study, Robert et al. (1988) determined the initial Pb isotopic compositions of leached K-feldspars from the same intrusions dated in this study, and these have been used for the common Pb corrections. However, only one of Robert's 40 K-feldspar analyses corresponds exactly to a sample from which minerals were separated for dating (Winslow complex, sample W-2). For the other U/Pb mineral samples, her mean common $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values for each pluton were used to represent the common Pb component. These average values are considered to better approximate the common Pb component than Stacey and Kramers (1975) values. The Stacey and Kramers correction consistently gave larger scatter in data points, and some points above concordia. The full range of common Pb values in each pluton was used in the propagation of errors.

Propagation of Error

The common Pb correction especially affects the uncertainty in titanite ages (Dunning 1987). Typical $^{207}Pb/^{204}Pb$ ratios for the titanite analyzed in this study are 20 to 35, and the common $^{207}Pb/^{204}Pb$ component is about 15.52 to 15.58. Therefore, both analytical error and any error in the estimate of the common Pb ratio are amplified significantly when calculating the net radiogenic component. The relative error in this result is the square-root of the sums of squares of the absolute errors in the two error components (analytical and common Pb), divided by the radiogenic component. This additional uncertainty seriously affects the precision of the $^{207}Pb/^{235}U$ and $^{207}Pb/^{206}Pb$ dates. The $^{206}Pb/^{238}U$ date is affected to a much lesser degree because of the relatively high $^{206}Pb/^{204}Pb$ measured ratio.

One could argue that the common $^{207}Pb/^{204}Pb$ ratio in nature has not changed for the last few hundred million years. However, this may not be true of magmas derived from continental crust with variable U/Pb ratios. In any event, the point is to draw attention to serious magnification of error in this study when propagating errors in total and common $^{207}Pb/^{204}Pb$ ratios into errors for the $^{207}Pb/^{206}Pb$ ratio. This further exacerbates the problem of the small angle of intersection between concordia and a trajectory defined by the $^{207}Pb/^{206}Pb$ ratio.

For these reasons (magnification of $^{207}Pb/^{204}Pb$ error; angle of intersection) I consider the $^{206}Pb/^{238}U$ minimum ages to be more useful for titanite (except for the Winslow titanite sample) and to a similar degree for monazite as well, than the $^{207}Pb/^{206}Pb$ ages. When arrays of titanite data show Pb loss, then the maximum $^{206}Pb/^{238}U$ date will be given as the minimum age.

U-Pb Results

Table 4 lists the U-Pb analytical data and Table 5 gives the age results for each mineral sample analyzed. Estimates of closure ages related to crystallization are given for each pluton. These are the highest $^{206}Pb/^{238}U$ ages for the titanite and monazite samples (except for the Winslow sample), and $^{207}Pb/^{206}Pb$ ages for the few concordant zircon samples that have no inherited component. Unlike zircon, the relative concordance of titanite can not be consistently predicted by magnetic properties or grain size. Typically, a single magnetic fraction yields most of the titanite, and the "grains" of this relatively friable mineral are not whole crystals. The term "fractions" is therefore used loosely to represent replicate analyses of small samples, hand-picked to variously represent larger or smaller grains, or those with or without inclusions.

Scotstown Pluton

Sample Sc-8 was collected from the granodioritic phase of the pluton, 150 m from its southeastern margin. The titanite from this sample has a reddish-brown colour with the majority of the grains having some crystal faces.

Table 4. U/Pb analytical data.

Fractions			Concentrations (ppm)		Measured	Atomic Ratios Corrected for Blank & Common Pb[D]				Ages (Ma)	
No.	Properties[A]	Weight[B] (mg)	U	Pb(rad)	$^{206}Pb^{C}$ / ^{204}Pb	^{208}Pb / ^{206}Pb	^{206}Pb / ^{238}U	^{207}Pb / ^{235}U	^{207}Pb / ^{206}Pb	^{206}Pb / ^{238}U	^{207}Pb / ^{206}Pb
	Scotstown										
Z-1	NM0, +70, zircon,NA	0 22	854	50 0	1352	0.088	0 0596	0 4472	0.05442	373 (3)	388 (3)
Z-2	NM0, -70 +123, zircon,NA	0 79	882	56.5	2071	0 091	0.0650	0 4918	0 05486	406 (7)	407 (3)
T-1	M10, +70, titanite, A	1 67	200	16.6	288	0 584	0 0589	0.4447	0 05480	369 (8)	404 (13)
T-2	M10, +70, titanite, A	0 97	163	14.8	140	0 652	0 0620	0 4731	0 05533	388 (8)	426 (10)
T-3	M10, +70, titanite, NA	1 49	183	15 7	237	0.592	0 0603	0 4511	0 05431	377 (3)	384 (9)
T-4	M10, +70, titanite, NA	1 08	210	17 2	260	0 603	0 0571	0 4287	0.05450	358 (3)	392 (6)
	Lac Aux Araignées										
Z-1	NM0, -70 +123, zircon,NA	0 27	904	56 6	1169	0 125	0 0614	0 5053	0 05968	384 (3)	591 (10)
Z-2	M0, -70 +123, zircon, NA	0 32	1379	80 4	1600	0 135	0 0570	0 4259	0 05424	357 (3)	381 (2)
Z-3	M1, +70, zircon, NA	0 33	789	48 6	919	0 122	0 0609	0 4560	0 05428	381 (4)	383 (3)
Z-4	M1, -70 +123, zircon,NA	0 42	1085	65 7	1229	0 135	0 0592	0 4538	0 05625	371 (3)	462 (4)
T-1	M10, +70, titanite,A	0 91	287	17 5	241	0 156	0.0586	0 4318	0 05342	367 (3)	347 (3)
T-2	M10, +70, titanite,NA	0 53	410	24.8	247	0 141	0 0589	0 4408	0 05428	369 (3)	383 (2)
T-3	M10, +70, titanite,A	0 28	373	22 1	268	0 117	0 0587	0 4376	0 05411	367 (3)	376 (2)
T-4	M10, -70 +123, titanite,NA	1 11	348	21.2	328	0 158	0 0584	0 4337	0 05385	366 (4)	365 (18)
	Winslow										
Z-1	NM0, +70, zircon, NA	0 06	285	19 2	42	0 240	0 0602	0 4781	0 05758	377 (3)	514 (2)
Z-2	NM0, -70 +123, zircon, NA	0 11	323	20 5	186	0 136	0.0620	0 4788	0 05604	388 (3)	454 (2)
T-1	M4, -70 +123, titanite, NA	0 96	214	12 4	291	0.108	0 0578	0 4312	0 05413	362 (2)	376 (7)
T-2	M10, +70, titanite, A	0 62	274	16 8	295	0.150	0 0592	0 4423	0.05420	371 (3)	379 (4)
T-3	M10, +70, titanite, NA	1 03	386	22 8	348	0 150	0.0571	0 4260	0 05415	358 (4)	377 (2)
	Aylmer										
M-1	M10, -70 +123,monazite, NA	0 44	1713	1169 2	571	12 106	0 0538	0 4484	0 05435	375 (3)	385 (6)
M-2	M10, -70 +123,monazite, NA	0 26	1316	1007 8	371	13 755	0 0597	0 4531	0 05508	374 (4)	416 (9)

Table 4. Continued

	Ste. Cécile										
Z-1	M0, -70 +123, zircon,NA	0 72	1092	70 0	4772	0 230	0 0580	0 4324	0 05405	364 (3)	373 (1)
Z-2	M1, -70 +123, zircon,NA	0 83	1013	65 1	4622	0 212	0 0590	0 4395	0 05406	369 (4)	374 (1)
Z-3	M2, -70 +123, zircon,NA	0.53	1015	62.0	2141	0 179	0 0576	0 4291	0 05407	361 (3)	374 (2)
T-1	M10, +70, titanite, A	1 79	100	8 9	153	0.718	0.0584	0 4343	0 05392	366 (4)	368 (13)
T-2	M10, +70, titanite, NA	0 92	121	9 9	138	0 577	0 0583	0 4437	0 05523	365 (3)	422 (10)
T-3	M10, +70, titanite, A	1 48	122	10 4	169	0 606	0 0594	0 4492	0 05484	372 (3)	406 (6)
T-4	M10, +70, titanite, NA	1 17	74	7 1	134	0 870	0 0577	0 4357	0 05480	361 (3)	404 (10)
T-5	M10, -70 +123,titanite,NA	1 25	138	11 1	258	0 556	0 0580	0 4344	0 05431	364 (3)	384 (7)

A NM0/ M2 nonmagnetic/ magnetic fractions, 0 and 2 indicate degrees of tilt on a Frantz isodynamic separator,+70.grain size greater than 70 mesh, -70 + 123 grain size greater than 123 mesh but smaller than 70 mesh, A/NA. abraded/non-abraded fractions
B Error in weight +/- 0 001 mg
C Corrected for fractionation, 20 pg blank, and spike
D Corrected for fractionation, 20 pg blank, spike, and initial common Pb determined by Robert et al. (1988)
Errors in brackets are at the 95 % confidence level

Two of the five titanite fractions were abraded in order to reduce possible discordance caused by Pb loss. There is considerable scatter in the position of the data points (Fig. 17) and no correlation between abrasion and degree of discordance. The points are below concordia, either because of Pb loss, or underestimation of the ^{207}Pb component of the common Pb correction. Fraction T-3 is only 1.6 % discordant and gives a $^{207}Pb/^{206}Pb$ age of 384 +/- 9 Ma. Fractions T-1 and T-4 are slightly more discordant and give $^{207}Pb/^{206}Pb$ ages of 404 +/- 13 and 392 +/- 6 Ma, respectively. The wide range of $^{207}Pb/^{206}Pb$ ages illustrates the importance of determining the exact composition of the initial common Pb component and the difficulties inherent in dating titanite of this age using the $^{207}Pb/^{206}Pb$ ratio. Table 5 lists $^{206}Pb/^{238}U$ minimum ages for these samples. Using the criteria defined earlier, the minimum age of emplacement for the Scotstown pluton is given by the sample with the highest $^{206}Pb/^{238}U$ age. This is 388 +/- 8 Ma given by sample T-2.

Two zircon fractions were analyzed from the same sample (Sc-8) used for the titanite dating. Clear, euhedral, and inclusion-free zircons were handpicked from the 0 NM split. Fraction Z-2 consists of grains from the -70 + 123 mesh size fraction, whereas fraction Z-1 is made up of grains greater than 70 mesh.

Fraction Z-1 is concordant at 407 +/- 3 Ma. Fraction Z-2 is 3.9 % discordant, and gives a $^{207}Pb/^{206}Pb$ age of 388 +/- 3 Ma.

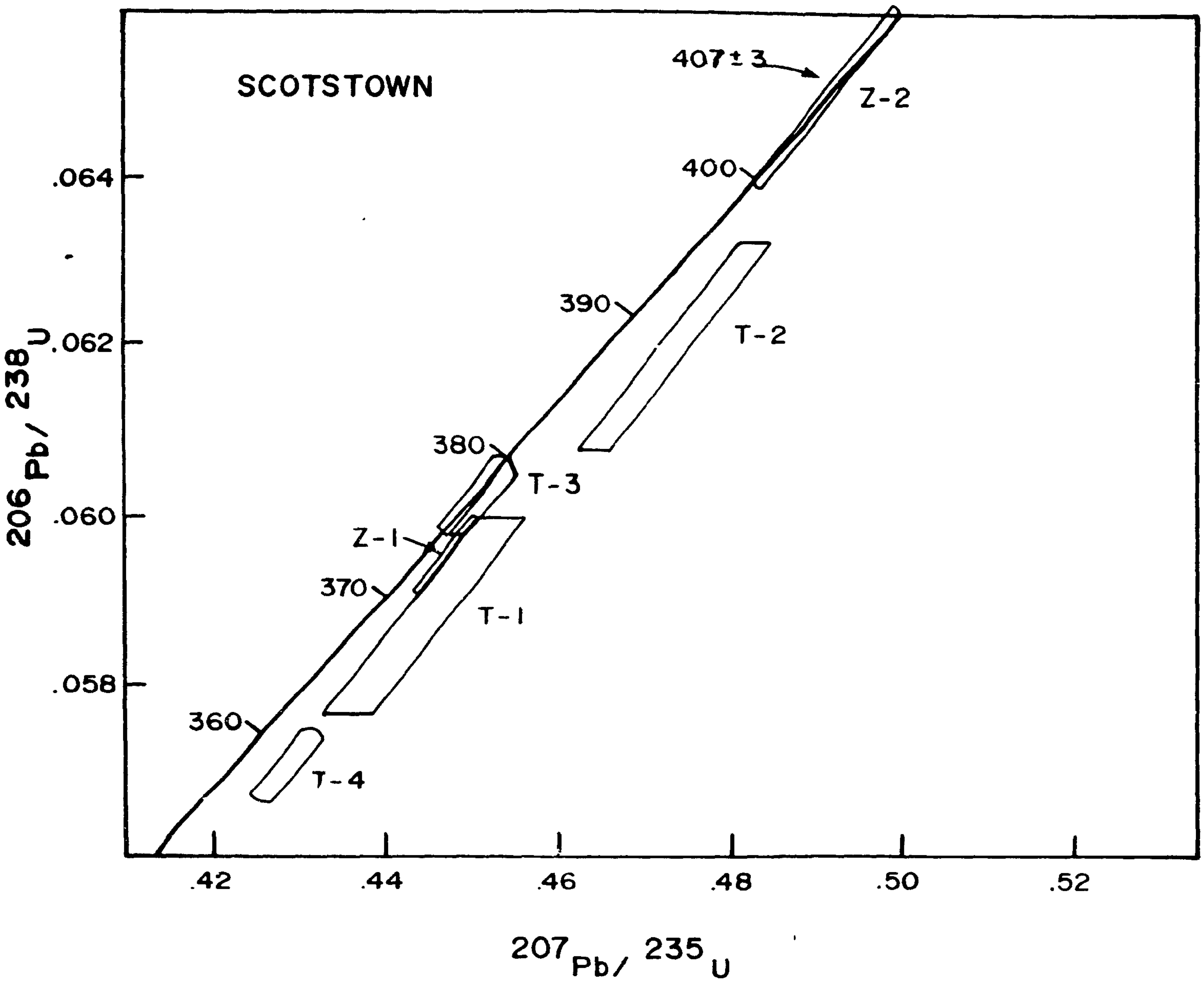

Fig. 17. Concordia diagram for zircon (Z) and titanite (T) samples from the Scotstown pluton.

The latter fraction is interpreted to represent a magmatic zircon population that has lost Pb. This reverse concordance (coarser grains less concordant) is unexpected but it is not an uncommon observation. Uranium contents are similar. The large difference in age between the two samples is unexplained by the error in the ages. The precisely concordant point can not include an inherited component, yet the age is considerably greater than the average titanite date of 376 Ma. The discordance of the titanite samples and their correspondingly much younger $^{208}Pb/^{238}U$ ages are therefore the result of Pb loss as well as possible error in the common Pb correction.

In summary, a crystallization age of 407 +/- 3 Ma is given by the concordant zircon fraction. The titanite samples have lost Pb so that their $^{206}Pb/^{238}U$ ages are lower. They roughly define a discordia so that the error in the common Pb correction is probably not as important a factor as loss of Pb.

Lac Aux Araignées

The sample for the titanite analyses (L-3) was collected from the granodiorite phase of the pluton. The titanite is reddish-brown and is abundant in the 10 degree magnetic fraction.

The four titanite fractions roughly define a horizontal array (Fig. 18). This suggests a variable contribution from an incorrect value of the common $^{207}Pb/^{204}Pb$ ratio. This can be tested by plotting the $^{207}Pb/^{235}U$ ratio against the total measured $^{207}Pb/^{204}Pb$ ratio. There is no correlation, but there

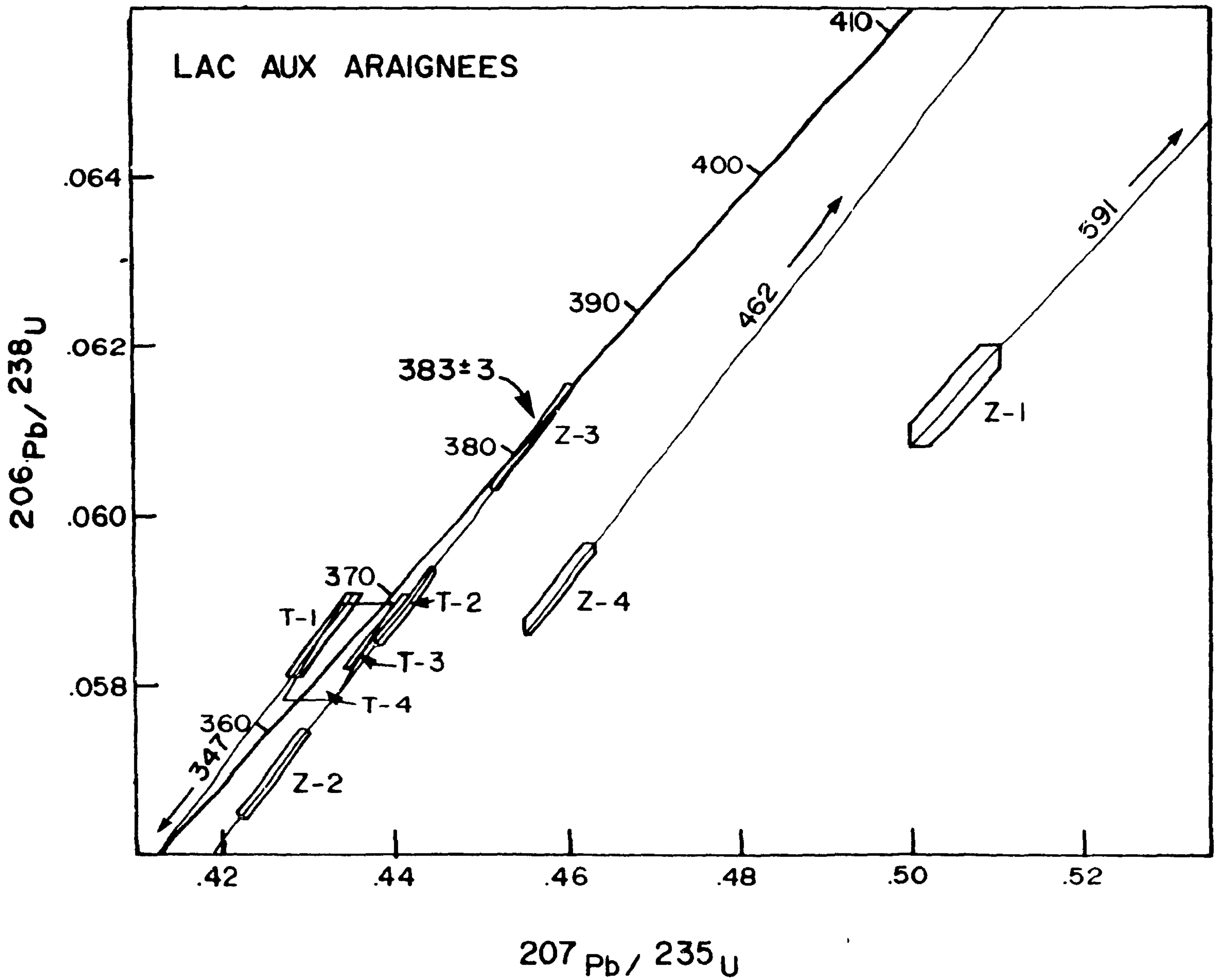

Fig. 18. Concordia diagram for the Lac Aux Araignées zircon and titanite samples.

is for the Scotstown titanites where this possible effect was considered to be minor compared to loss of Pb. In short, the reasons for the apparent discordance of titanite samples are probably quite complex. An additional factor could be the incorporation of small and therefore highly variable numbers of inclusions with a different common Pb composition. This would explain differences between essentially replicate analyses. The average $^{206}Pb/^{238}U$ age is 367 +/- 3 Ma and is interpreted as the minimum age of emplacement.

Four zircon samples with "magmatic-like" features (clear, euhedral, inclusion-free) were selected from the same sample (L-3). These are the 0 NM, OM and 1 M fractions of grain size -70 to +123 mesh , and the + 70 size of the 1 M fraction.

Fraction Z-3 (+ 70 mesh, 1 M) is concordant at 383 +/- 3 Ma. Fraction Z-2 (- 70 to + 123 mesh, 0 M) is a discordant point that gives a $^{207}Pb/^{206}Pb$ age of 381 +/- 2 Ma. This age is very similar to the concordant age of fraction Z-3, but this is probably a coincidence given the Scotstown experience. Fractions Z-1 and Z-4 are discordant, and clearly have an inherited component. The erroneous $^{207}Pb/^{206}Pb$ ages are 591 +/-10 and 462 +/- 4 Ma, respectively. In most documented cases involving an older zircon component, the coarser zircons contain higher proportions of old inherited Pb than do the smaller grains (e.g. Aleinkoff et al. 1981). In this case, the reverse relationship is true. Ayuso et al. (1984) have also experienced the inverse relationship observed here.

Grains of these samples were sectioned, polished and etched, as well as grains from the 2 M fraction. Old, rounded, metamict cores were only observed in the 2 M fraction and no correlation was observed between grain size and size of core, to some degree supporting the suggestion of more new growth for the larger grains showing less inheritance. Although no cores were observed in the sectioned zircons from fractions Z-1 and Z-4 the inheritance could be caused by a single grain, and it is not practical to section large numbers of grains to prove this point. The two fractions lie on a discordia curve with an upper intercept of 2500 Ma and a lower intercept of 367 Ma. However, the concordant $^{207}Pb/^{206}Pb$ age of 383 +/- 3 Ma should represent the age of magma crystallization as far as zircon is concerned. Fractions Z-1 and Z-4 therefore should lie on a discordia with 383 Ma as its lower intercept, and not 367 Ma. One likely explanation for the position of fraction 1 is Pb loss since 383 Ma. Similar lead loss for fraction Z-1 would result in an age for the inherited component of less than 2500 Ma, and so no significance should be attributed to this upper intercept age.

The 16 Ma age difference between the zircon (383 Ma) and titanite (367 Ma) ages is probably too large to be the result of a complex cooling history. As in the case of the Scotstown complex, the titanite samples have probably experienced Pb loss resulting in younger $^{208}Pb/^{238}U$ ages compared to the concordant zircon age. The horizontal spread of the titanite samples may be attributed to an incorrect $^{207}Pb/^{204}Pb$ common Pb correction, but this is not supported by trial calculations using different $^{207}Pb/^{204}Pb$ common Pb values. The concordance of the average titanite data, but at a young age level may be due to an average overestimation of the common $^{207}Pb/^{204}Pb$.

Winslow

The Winslow (W-2) titanite sample was obtained from a roadside outcrop of tonalite. This is the only U/Pb sample for which the exact composition of its common Pb component is known precisely from the measurements of Robert et al. (1988). Three titanite fractions were analyzed (Table 4 and Fig. 19). In this case the abraded fractions are more concordant. Fraction T-3 is the most discordant (4.8%) point and this may be related to its high Uranium content (386 ppm). In contrast to the two previous concordia diagrams, the points do not scatter but fall on the same discordia curve with very similar $^{207}Pb/^{208}Pb$ ages of 376 +/- 7 to 379 +/- 4 Ma. The lack of uncertainty in the common Pb correction has presumably reduced the variation in the $^{207}Pb/^{206}Pb$ ages, supporting earlier suggestions with regard to the effect of the common Pb correction.

Two zircon fractions from tonalite sample W-2 were analyzed. Both are from the 0 NM separate but fraction Z-2 is -70 to + 123 mesh and fraction 1 is +70 mesh. The grains selected were colourless, crack-free, and euhedral.

Both fractions are discordant (Fig. 19), and their

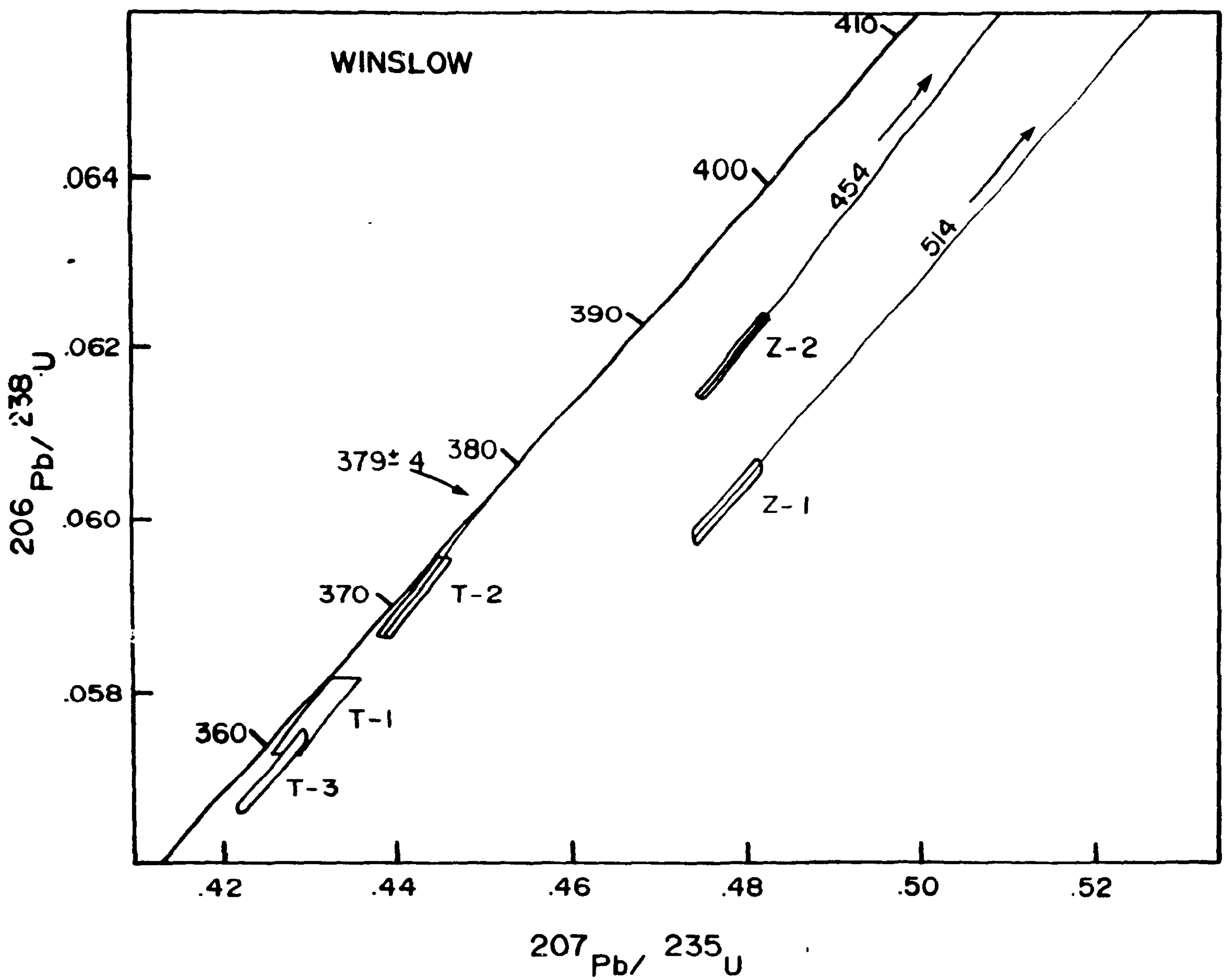

Fig. 19. Concordia diagram for titanite samples from the Winslow pluton.

$^{207}Pb/^{206}Pb$ ages are 454 and 514 Ma. If we discount the likelyhood of these ages, the discordance is partly the result of an inherited component present within the zircon as old xenocrystic cores. A discordia line through fraction Z-1 with a lower intercept of 377 Ma (average titanite age) gives an upper intercept age of 1,800 Ma (average age of inheritance). Fraction Z-2 has clearly lost Pb since 377 Ma because its upper intercept age is undefined (the discordia line is horizontal). Hence, the finer-grained fraction Z-2 has most likely lost Pb as well, so that its upper intercept "inheritance date" would be much less than 1800 Ma. The $^{206}Pb/^{204}Pb$ measured ratios and total U (ppm) values (Table 4) are extremely low and are not typical of zircons analysed in this study. The low uranium levels are consistent with the occurrence of these zircons in tonalite.

Ste. Cécile

The Ste. Cécile titanite sample was obtained from a granodiorite (C-26). The titanite is reddish-brown and very abundant in the 10 M fraction. It is coarsed-grained (> 70 mesh) and euhedral to subhedral in form.

The titanite fractions have low total uranium contents, and consequently low $^{207}Pb/^{204}Pb$ measured ratios (Table 4). This makes the initial common Pb correction a more critical factor, and may account for the bias towards a cluster of points just below concordia (Fig. 20). The wide range (368 +/- 13 to 422 +/- 10 Ma) of $^{207}Pb/^{206}Pb$ ages reflects again the problem of low

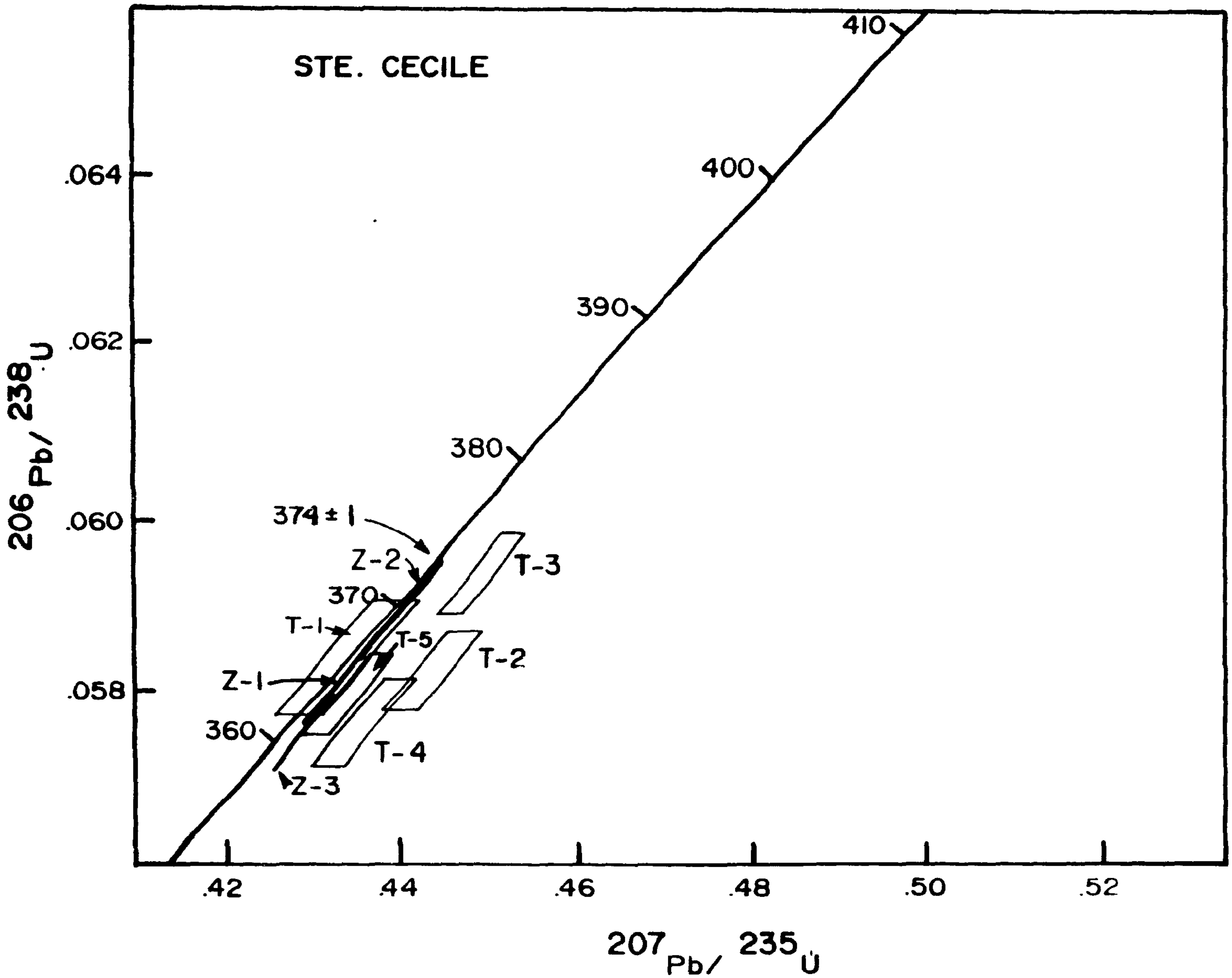

Fig. 20. Concordia diagram for titanite and zircon samples from the Ste. Cécile pluton.

angle of intersection and the apparently variable bias towards high $^{207}Pb/^{204}Pb$ values. The $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages vary little (361 +/- 3 to 372 +/- 4 Ma and 366 +/- 4 to 372 +/- 3 Ma, respectively). Fraction T-3 has the oldest $^{206}Pb/^{238}U$ age of 372 +/- 3 Ma.

Three zircon fractions were analyzed (Table 4, Fig. 20). Fractions Z-1, Z-2, and Z-3 gave identical $^{207}Pb/^{206}Pb$ ages of 374 +/- 1 to 2 Ma. They also have the highest measured $^{206}Pb/^{204}Pb$ ratios (2100 to 4800). Fraction Z-2 (1 M) is the most concordant point. The ages are very similar to the maximum titanite $^{206}Pb/^{238}U$ age.

Aylmer

The Aylmer pluton samples tested did not have significant quantities of either zircon or titanite. However, monazite is abundant. The treatment of the data for monazite is similar to that for titanite, but the common Pb levels are typically lower. A potential problem is the recent documentation of inherited Pb in this mineral (Parrish 1988). The monazite was obtained from a sample of granodiorite (A-1) in the northern part of the pluton. The monazite grains are turbid to clear yellow and are tabular euhedral to subhedral crystals.

The higher uranium concentration compared to titanite (Table 4) results in higher $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios that are less sensitive to the common Pb correction. Both monazite samples are non-abraded and from the same sieved

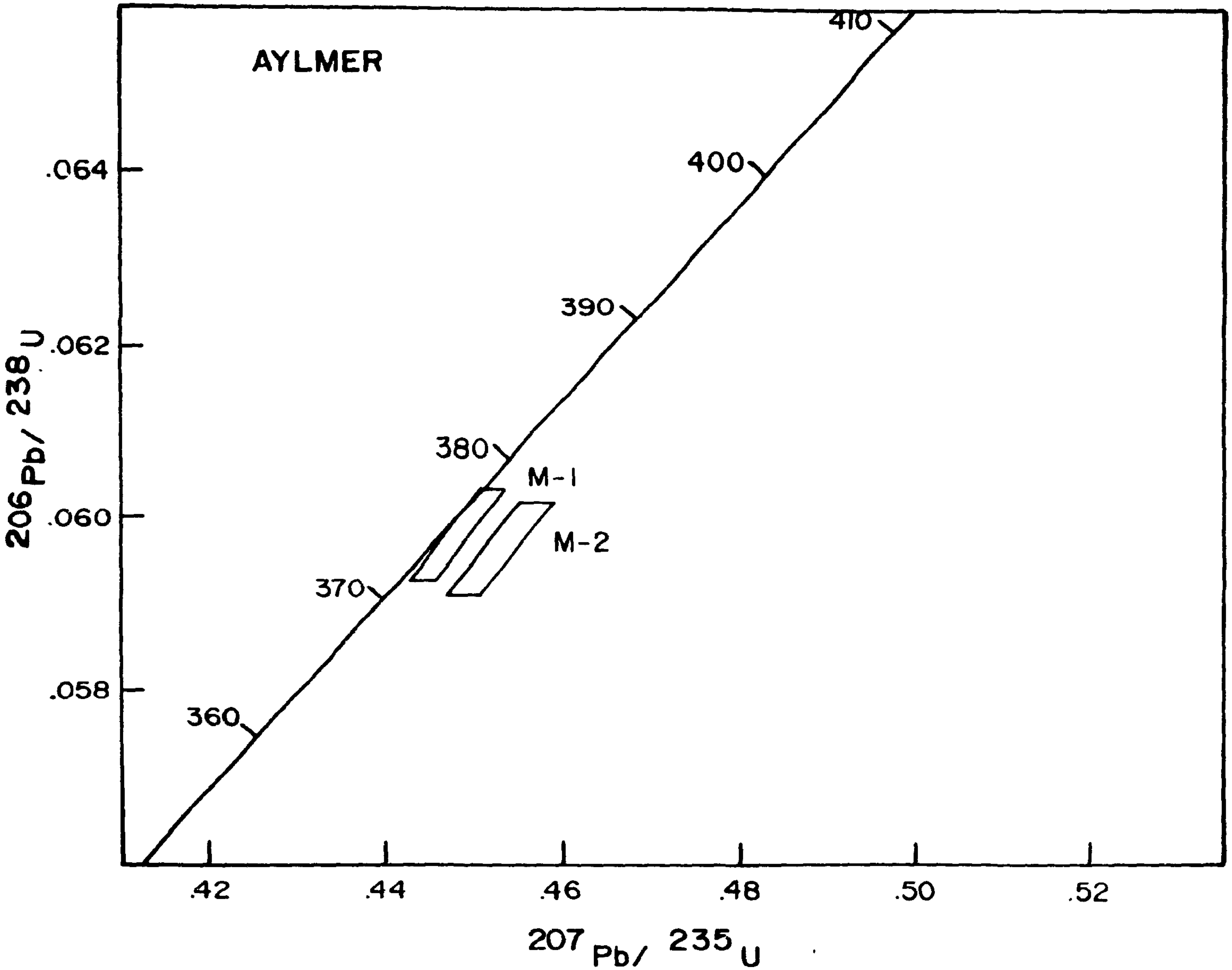

Fig. 21. Concordia diagram for monazite samples from the Aylmer pluton.

fraction. Sample M-1 is the more concordant of the two. The $^{207}Pb/^{206}Pb$ ages are very different (385 +/- 6 and 416 +/- 9 Ma) but their $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages are nearly identical ($^{206}Pb/^{238}U$ ages of 375 +/- 3 and 374 +/- 4 Ma, and $^{207}Pb/^{235}U$ ages of 376 +/- 5 and 379 +/- 6, respectively, Figure 21). The older $^{206}Pb/^{238}U$ age of 375 +/- 3 Ma for the more concordant monazite fraction (1), will be used as the estimate of the minimum age of emplacement.

Summary of U/Pb Age Data

Table 5 is a summary of the U/Pb ages obtained from the titanite, monazite, and zircon analyses. Where comparisons are possible between zircon and titanite data, the titanite $^{206}Pb/^{238}U$ ages are younger. This is probably a result of Pb loss when the data define discordia lines (Winslow and possibly Scotstown). Scattered distributions of data (Lac Aux Araignées, Ste. Cécile) may be caused by a combination of Pb loss and incorrect common Pb correction. This is supported by the coherent behaviour of the Winslow samples for which exact common Pb values were available.

Best estimates for ages of emplacement, in decreasing order of confidence, are : Ste. Cécile - 373 +/- 1 Ma(Z),, Lac Aux Araignées - 383 +/- 3 Ma(Z), Aylmer - 375 +/- 3 Ma(M), Winslow - 377 +/- 6 Ma(T), Scotstown - 407 +/- 3 Ma(Z). The reason for ranking Scotstown last is that its greater age is based on one concordant zircon sample that is at variance with both titanite

Table 5. U/Pb Mineral Ages.

SAMPLE	206 Pb/238 U Age	207 Pb/235 U Age	207 Pb/206 Pb Age
Scotstown			
Zircon:			
Z-1	373 (3)	375 (3)	388 (3)
Z-2	406 (7)	406 (7)	407 (3)*
Titanite:			
T-1	369 (8)	374 (9)	404 (13)
T-2	388 (8)	393 (8)	426 (10)
T-3	377 (3)	379 (3)	384 (9)
T-4	358 (3)	362 (3)	392 (6)
Lac Aux Araignées			
Zircon:			
Z-1	384 (3)	415 (3)	591 (10)
Z-2	357 (3)	360 (3)	381 (2)
Z-3	381 (4)	381 (4)	383 (3)*
Z-4	371 (3)	383 (3)	462 (4)
Titanite:			
T-1	367 (3)	364 (4)	347 (3)
T-2	369 (3)	370 (4)	383 (2)
T-3	367 (3)	368 (4)	376 (2)
T-4	366 (4)	366 (4)	365 (18)
Winslow			
Zircon:			
Z-1	388 (3)	397 (3)	454 (2)
Z-2	377 (3)	397 (3)	514 (2)
Titanite:			
T-1	362 (2)	364 (4)	376 (7)*
T-2	371 (3)	371 (3)	379 (4)*
T-3	358 (4)	360 (3)	377 (2)*
Aylmer			
Monazite:			
M-1	375 (3)*	376 (3)	385 (6)
M-2	374 (4)	379 (4)	416 (9)
Ste. Cécile			
Zircon:			
Z-1	364 (3)	365 (3)	373 (1)
Z-2	369 (3)	370 (3)	374 (1)*
Z-3	361 (3)	363 (3)	374 (2)
Titanite:			
T-1	366 (4)	366 (6)	368 (13)
T-2	365 (3)	372 (5)	422 (10)
T-3	372 (3)	376 (4)	406 (6)
T-4	361 (3)	367 (5)	404 (10)
T-5	364 (3)	366 (4)	384 (7)

* : The best age estimates

and another zircon fraction. Where I have had to use titanite and monazite data, these are the most concordant of the whole study and the least affected by uncertainty in the common Pb ratios. Other zircon samples contained an inherited component, even in the least magnetic fractions. Inherited zircons can sometimes be used to identify their source. The upper intercept ages of 2500 Ma (Lac Aux Araignées) and 1800 Ma (Winslow) are average ages of inheritance, because of possible recent Pb loss. Zircons inherited from the postulated Grenville basement (Spencer et al. 1987) would give ages of about 1000 to 1200 Ma, but Naylor et al. (1973) reported a U/Pb zircon age of 1600 Ma for the quartz-feldspar gneisses of the Chain Lakes Massif.

Sr Mixing Diagrams

The moderately high initial ratios and the considerable scatter of the Sr isotopic data for most suites analyzed could be the result of a radiogenic and heterogeneous source region, or mixing with a radiogenic contaminant. The contaminant should be most effective in raising the $^{87}Sr/^{86}Sr$ ratio when the magma or rock contains little Sr. For this reason, a graph of initial $^{87}Sr/^{86}Sr$ against 1/Sr should yield a positive correlation when mixing has occurred (see Faure 1986, chapter 9 for a more complete explanation).

Initial ratios for individual samples were calculated using the U/Pb mineral ages, and plotted against 1/Sr, for each pluton. Only Scotstown (Fig. 22) yielded anything approaching a

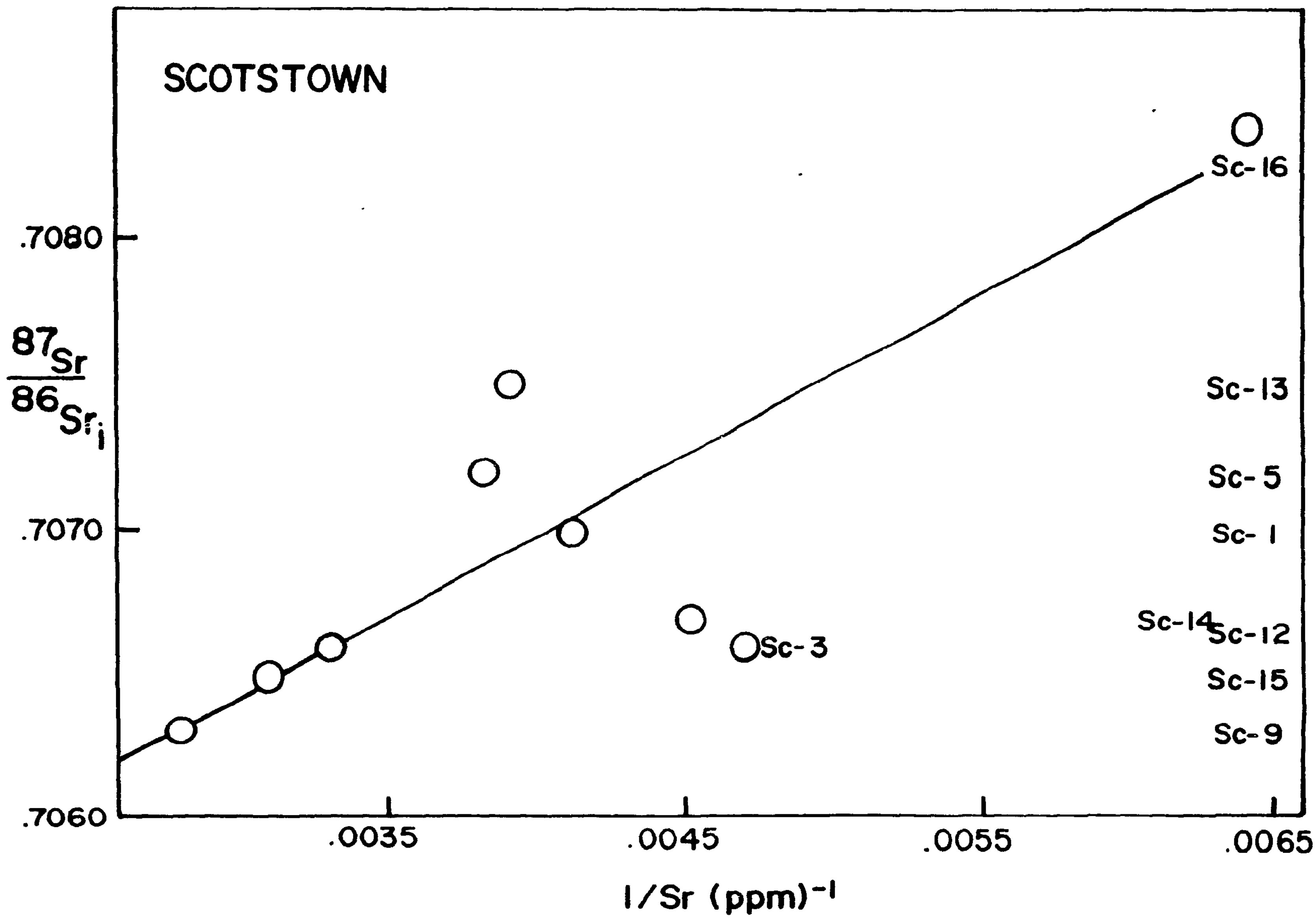

Fig. 22. Scotstown Sr mixing diagram.

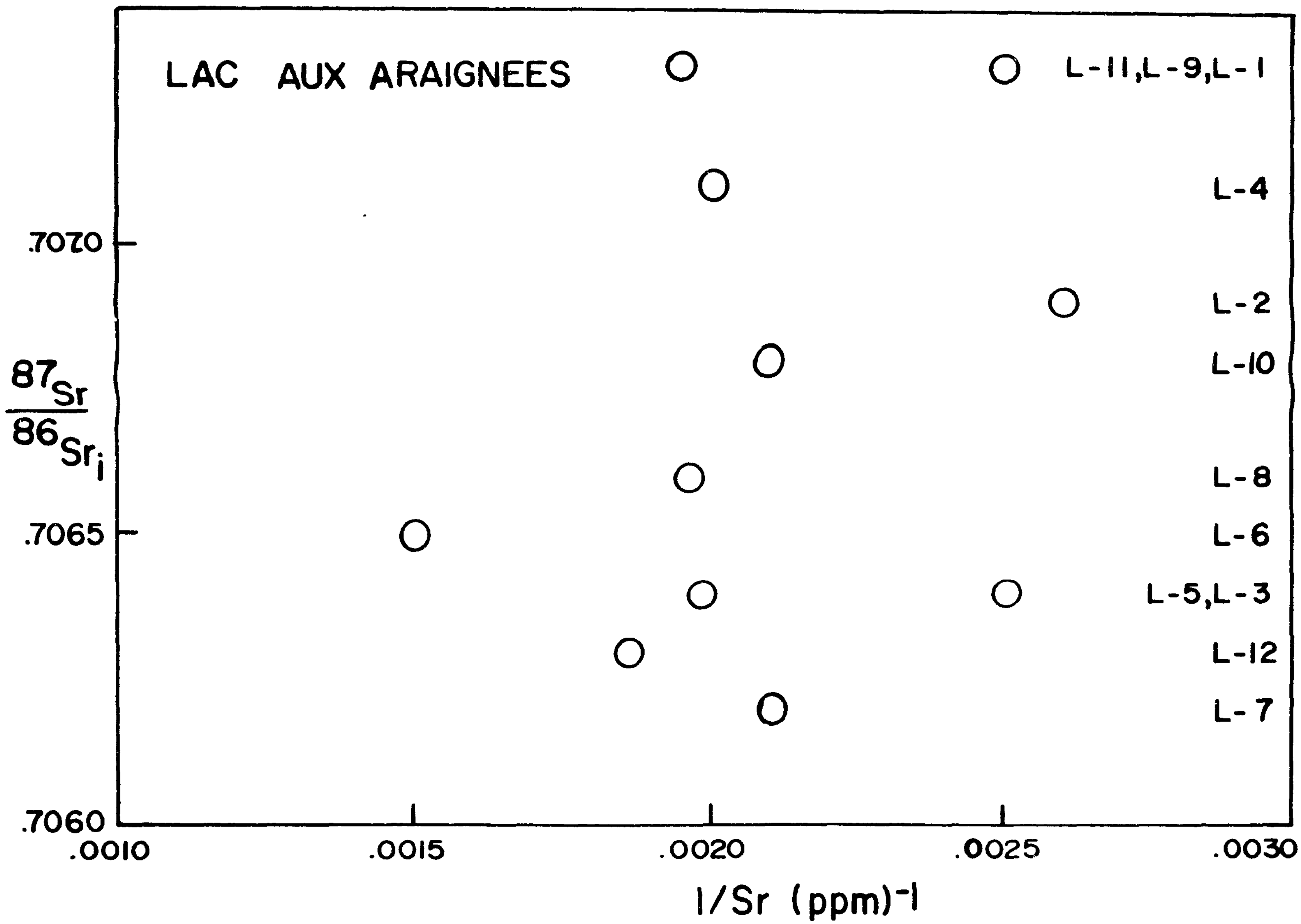

Fig. 23. Lac Aux Araignées Sr mixing diagram.

correlation. The diagram for Lac Aux Araignées (Fig. 23) is typical of most of the other plutons. The graph for Beebe (not shown) is a vertical or "non-correlation". That is, highly variable initial ratios for constant Sr content. These observations would favor a heterogeneous source region rather than contamination or alteration at the present intrusive level, yet variations are observed in rocks that are close to each other with no visible contacts. The alternative is that the degree of contamination is more important than the level of Sr in the rock in determining anomalies in the $^{87}Sr/^{86}Sr$ ratio.

There is a correlation for Scotstown, but the sampled sedimentary xenolith (Sc-3) is far from the trend, is not especially radiogenic, and is therefore not representative of the contaminant.

CHAPTER 4

DISCUSSION AND CONCLUSIONS

Comparative Geochronology

Table 6 lists the U/Pb and Rb/Sr results of this study as well as K/Ar and Rb/Sr dates reported by other researchers. It was not possible to apply both the U/Pb and Rb/Sr methods to all the plutons, but the southernmost Beebe and Stanhope plutons and the older Moulton-Hill granite were not the prime focus of this study.

Efforts to date zircons were not entirely successful because of the common occurrence, even in the least-magnetic, euhedral fractions, of an inherited radiogenic Pb component. Zircon grains were sectioned and etched to reveal internal structure such as old cores, and many were found. It is only practical to section a few grains from each zircon fraction, and these are not the grains actually analyzed. Of the apparently core-free populations analyzed, about half still had an inherited component, perhaps caused by the inclusion of one or more grains with cores. A few, perhaps insufficient, analyses yielded concordant data, and these dates are used to help evaluate the U/Pb-titanite method applied to the same samples, and to those samples that contained no zircon.

The morphological classification of Pupin (1980) was also applied, in part to help select material for analysis. The

Table 6. Comparative Geochronology. All ages are in Ma, and errors in brackets are at the 95 % confidence level.

PLUTON	ZIRCON ^{207}Pb* / ^{206}Pb	TITANITE MONAZITE ^{206}Pb / ^{238}Pb	K/Ar	Rb/Sr Whole-Rock
Scotstown	407 (3)	388 (8)	----	410 (38)
Lac Aux Araignées	383 (3)	369 (3)	----	402 (62)
Winslow	-----	371 (3)	----	298 (670)
Aylmer	-----	375 (3)	379	393 (42)
Ste. Cécile	374 (1)	372 (3)	362	364 (14)
Stanhope-Averill	-----	------	346 (8)	363 (53)
Beebe	-----	------	-----	350 (60)

* concordant zircon ages

populations were, however, quite uniform. The method also erroneously classified the rocks as alkaline, although the immediate environment of the late-crystallizing zircons could have been alkaline. The same morphological scheme gives a temperature of crystallization of 600 +/- 50 degrees C, somewhat consistent with the chemical data.

Other researchers have found that U/Pb titanite analyses often give concordant points on a concordia diagram, corresponding to either crystallization or metamorphic ages, depending on the history of the rock. However, the precise degree of concordance may be difficult to determine because of uncertainty in the large common Pb correction. In the present study the proportion of common Pb in the titanites is especially large for rocks of this age. This makes it easier to detect problems associated with the correction, so that the results may be of use to others analyzing minerals with a lower proportion of common Pb.

The common Pb correction especially affects the $^{207}Pb/^{204}Pb$ ratio, and can result in a horizontal scatter of points on the concordia diagram. This results in imprecise age estimates based on the $^{207}Pb/^{206}Pb$ ratio. The common Pb in these titanites is partly or completely derived from continental crust: use of the Stacey-Kramers model for the correction yielded even less reproducible, and biased $^{207}Pb/^{206}Pb$ ages. For these reasons, it is best to measure the composition of common Pb in the sample, and to use the $^{206}Pb/^{238}U$ age because the ^{206}Pb content is less affected by the common Pb correction. This age is qualified as a minimum age in this study because titanite samples gave dates 6 to 30 Ma younger than coexisting concordant zircons. Barring a protracted thermal history, the implication is small but significant Pb loss. This is clear for the Winslow samples that fall on a single discordia, and these are the only samples for which the common Pb composition was measured for coexisting potassium feldspar. For the other plutons, only an average Pb composition was available, and the points scatter more widely. The common Pb values used are slightly less radiogenic than the equivalent Stacey-Kramers values, which is not unexpected for a high grade crustal source. The result is that application of the Stacey-Kramers model sometimes makes data more concordant, but the scatter is increased, and several points lie above concordia.

By chance, those samples that did not have zircons or did not yield concordant zircons, are those for which concordant titanite or monazite data were obtained. It is therefore likely that the ages of crystallization listed are unbiased estimates relative to each other.

In spite of difficulties with the U/Pb dating, this method gave much more precise and credible results than the Rb/Sr method. Where the Sr isotopic heterogeneity is least (Ste. Cécile), the Rb/Sr age of 364 +/- 14 Ma is close to the U/Pb age of 374 +/- 1 Ma. The Scotstown Rb/Sr age of 410 +/- 38 Ma should include a mixing component because of a positive correlation between initial Sr ratios of individual samples and the reciprocal of their Sr contents. This mixing effect must be small, i.e. within the Rb/Sr error, because this age is essentially the same as the U/Pb zircon age. The other mixing diagrams produced no correlations, so that the isotopic heterogeneity may be the result of a very variable degree of alteration, rather than uniform alteration of rocks with different Sr contents.

Source of the Magmas: Sr and Pb Evidence

The $^{87}Sr/^{86}Sr$ initial ratios for the seven suites range from 0.7065 to 0.7102. Individual samples vary more widely, but this is considered to be the result of alteration at the level of emplacement, because the variations can occur over short distances in otherwise homogeneous rocks. The initial ratios of the suites are clearly higher than those of oceanic mantle (0.702-0.704). The isotopic composition of the sub-continental mantle is less well known and variable (Allègre et al. 1981), and could consist of long-lived mixtures of mantle and so-called orogene reservoirs (Zartman 1984). The continental mantle in this region may even be depleted, by extrapolation of results of Bell et al. (1982) and Larocque (1986).

The alternative to an enriched mantle source is derivation within the lower continental crust. Seismic evidence (Spencer et al. 1987) shows that there is a Grenville-like basement beneath the Appalachians in this area, and still older gneisses (1.6 Ga) occur just east of the Lac Aux Araigneés pluton (Naylor et al. 1973). The peraluminous chemistry of the plutons, and of lesser significance, the abundance of inherited zircons favor an origin by melting of continental crust. The average $^{87}Sr/^{86}Sr$ ratios of high-grade metamorphic rocks in the Grenville Province are greater than 0.710 (eg. Doig 1977) 400 Ma ago, but at the present level of exposure. There is a slight trend of increasing initial ratios with decreasing age, possibly reflecting partial melting at higher crustal levels.

In an analagous study of granitic rocks in the central Gaspé region of Québec, Larocque (1986) also obtained moderately high and variable Sr initial ratios. However, one associated gabbroic phase had an initial ratio of 0.7041 , showing that melting began in a depleted continental mantle, but then progressed to widespread melting of continental crust.

Robert et al. (1988) has determined the Pb isotopic composition of representative samples of the seven plutons studied here, and Ayuso (1986) measured the Pb isotopic composition of plutons in the Connecticut-Valley Gaspé synclinorium in northern Maine. Except for the Beebe and Stanhope plutons that are slightly more radiogenic, the results are very similar, and this indicates that the source of the granites is continental lithosphere and is not dominated by oceanic material (Ayuso 1986). The Pb isotopic nature of the subcontinental mantle is probably complex, but the data do not preclude derivation from lower continental crust.

History of Plutonism

Although the five ages are not a large statistical sample, they do represent the volumetrically significant Acadian plutons of the Southern Québec Appalachians, and cover a distance of 60 Km across the trend of the Appalachians. The pattern of ages does not show a significant geographic trend and so does not support an origin by subduction of oceanic crust. The ages can be separated into an early plutonic event represented by Scotstown (407 +/- ? Ma) and a later group represented by Lac Aux Araigneés, Winslow, Aylmer and Ste. Cécile at 383 +/- 3, 377 +/- 6 Ma, 375 +/- 3 Ma and 374 +/- 1 Ma, respectively. Lyons and Livingston (1977) also reported this range (360 to 410 Ma), using the Rb/Sr isochron method for the New Hampshire Plutonic Series.

Larocque (1986) obtained a bimodal distribution of ages of about 360 Ma and 380-385 Ma for a group of mildly alkaline granitic rocks of the central Gaspé region. She related this magmatic activity to a tensional environment in a strike-slip zone in the foreland of a collided plate. Deep fractures could have promoted melting of both mantle and crust, and facilitated passage of magma to shallower levels. Although some of the Southeastern Québec plutons are close to major faults, low Sr initial ratios were not observed, and the rocks are not alkalic. The magmatism in Southeastern Québec is most probably the result of partial melting of Rb- and U-depleted Grenville lower crust, in response to crustal thickening during the Acadian Orogeny. The partial s-type signature of the granitoid complexes is probably the result of small-scale, high level contamination from Silurian metasedimentary rocks.

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APPENDIX A

Harker Variation Diagrams

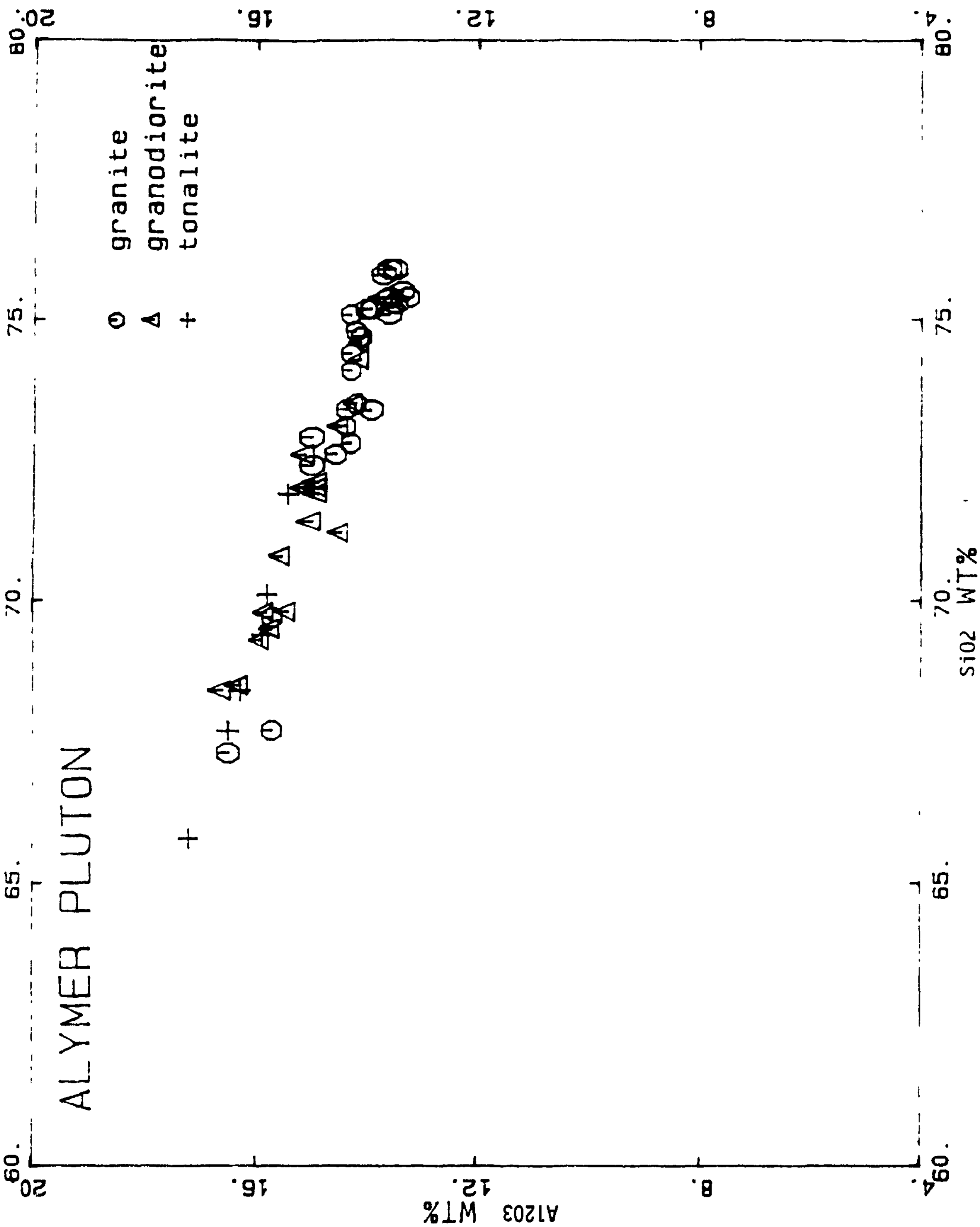

ALYMER PLUTON
granite
granodiorite
tonalite
SiO2 WT%
Al2O3 WT%
60.
65.
70.
75.
80.
20.
16.
12.
8.
4.

Fig. A1

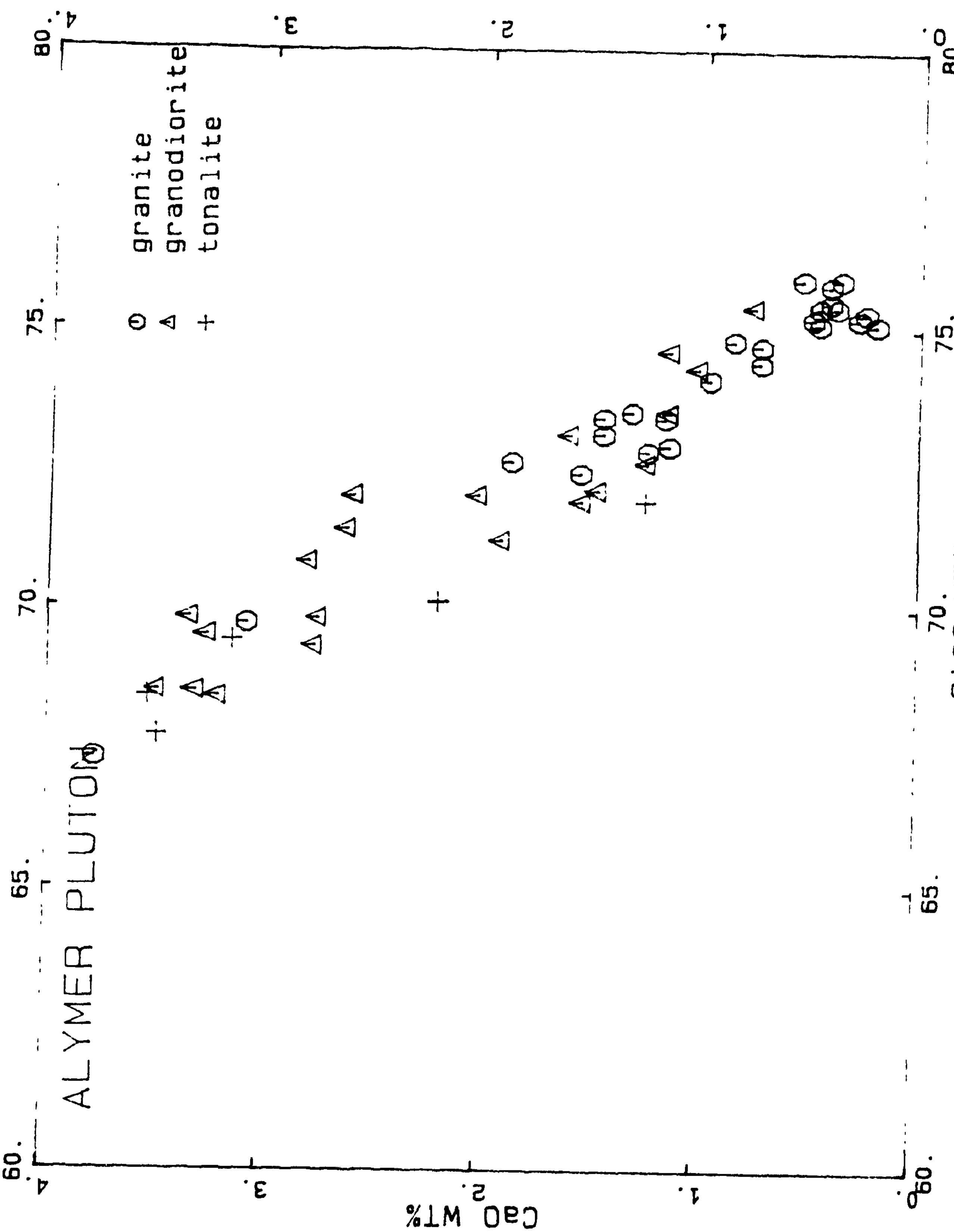

ALYMER PLUTON
granite
granodiorite
tonalite
SiO2 WT%
CaO WT%
60.
65.
70.
75.
80.
0.
1.
2.
3.
4.

Fig. A2

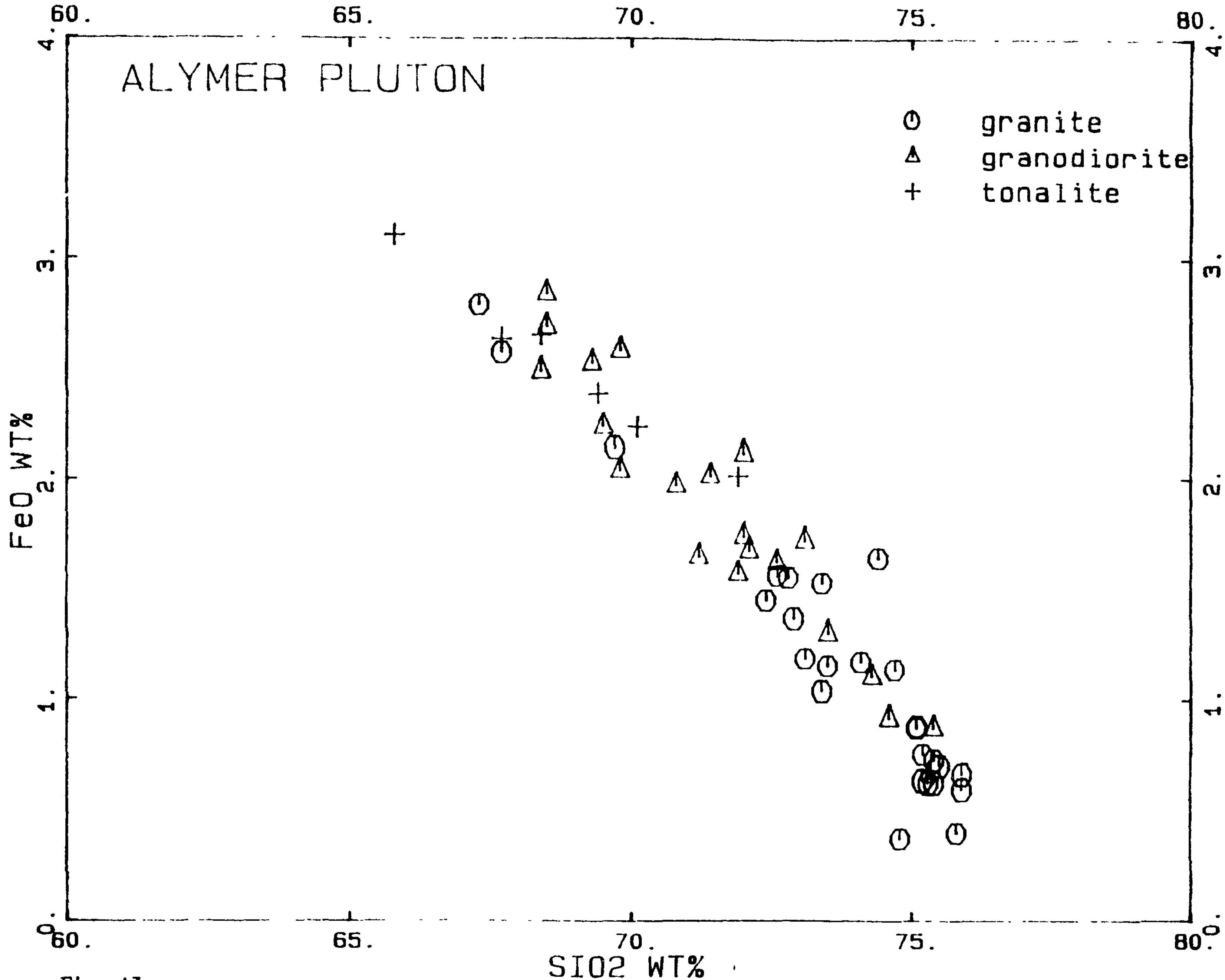

ALYMER PLUTON
granite
granodiorite
tonalite
FeO WT%
SIO2 WT%
60.
65.
70.
75.
80.
0.
1.
2.
3.
4.

Fig. A3

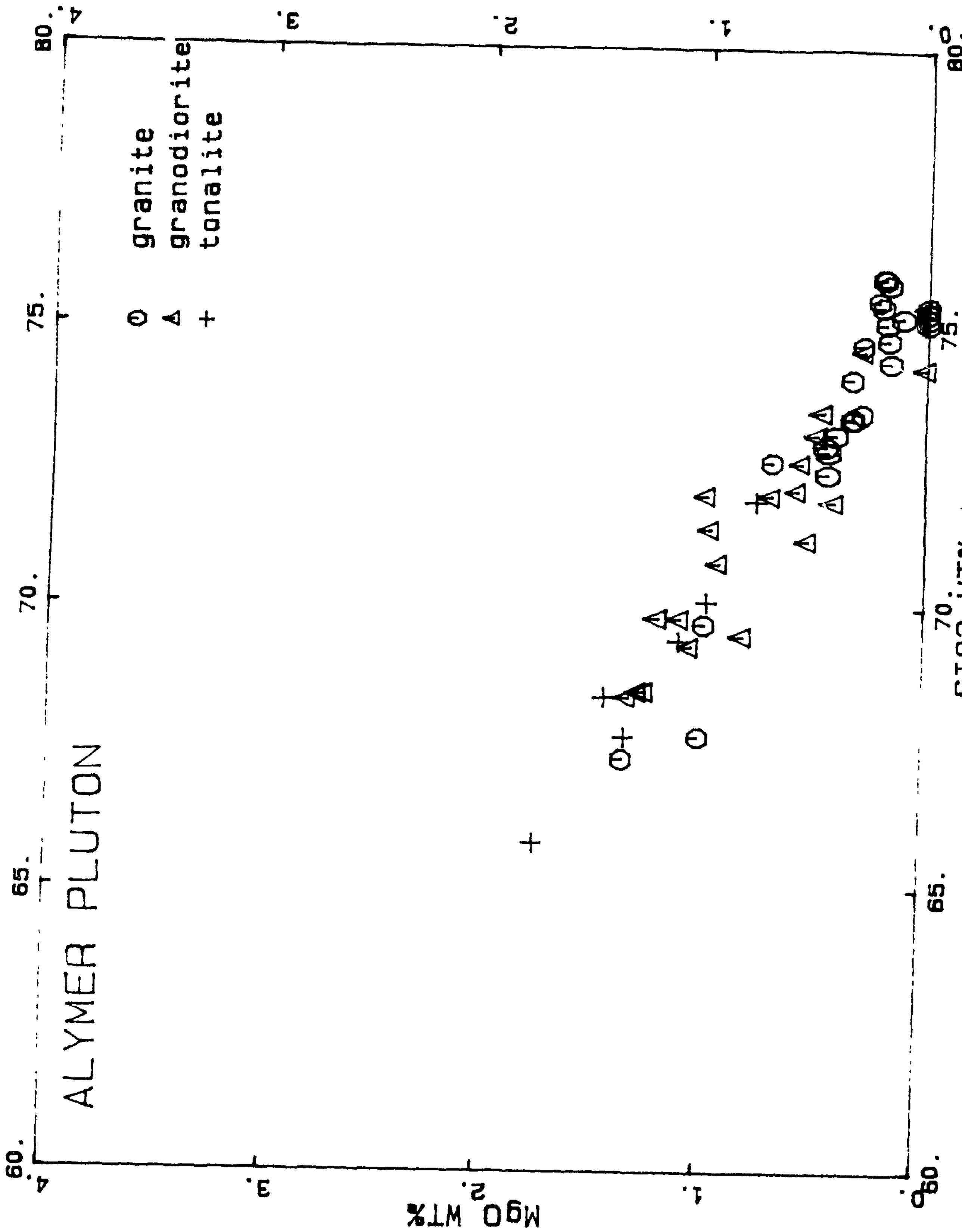

ALYMER PLUTON
granite
granodiorite
tonalite
SIO2 WT%
MgO WT%
60.
65.
70.
75.
80.
0.
1.
2.
3.
4.

Fig. A4

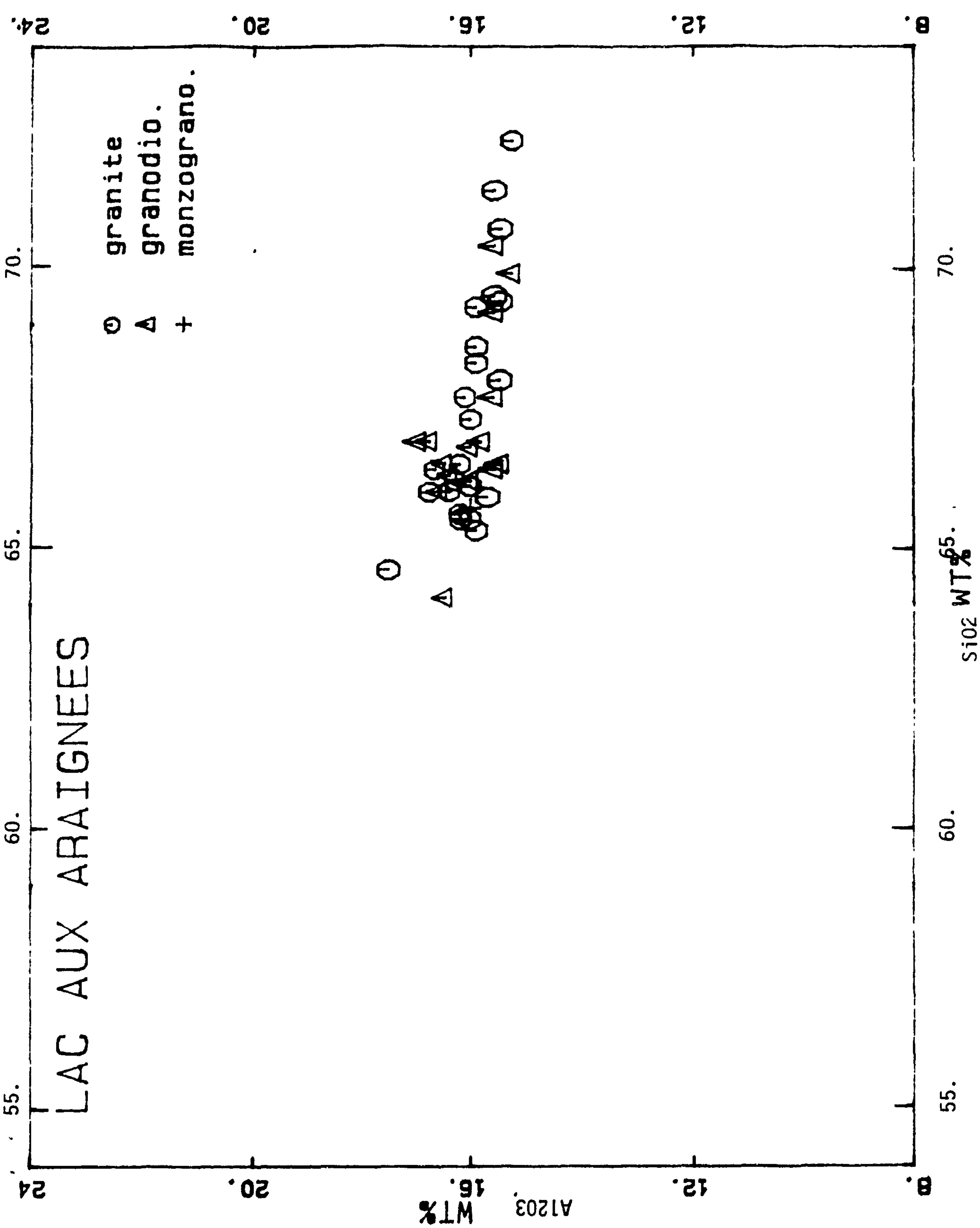

LAC AUX ARAIGNEES
granite
granodio.
monzograno.
SiO2 WT%
Al2O3 WT%
55.
60.
65.
70.
24.
20.
16.
12.
8.

Fig. A5

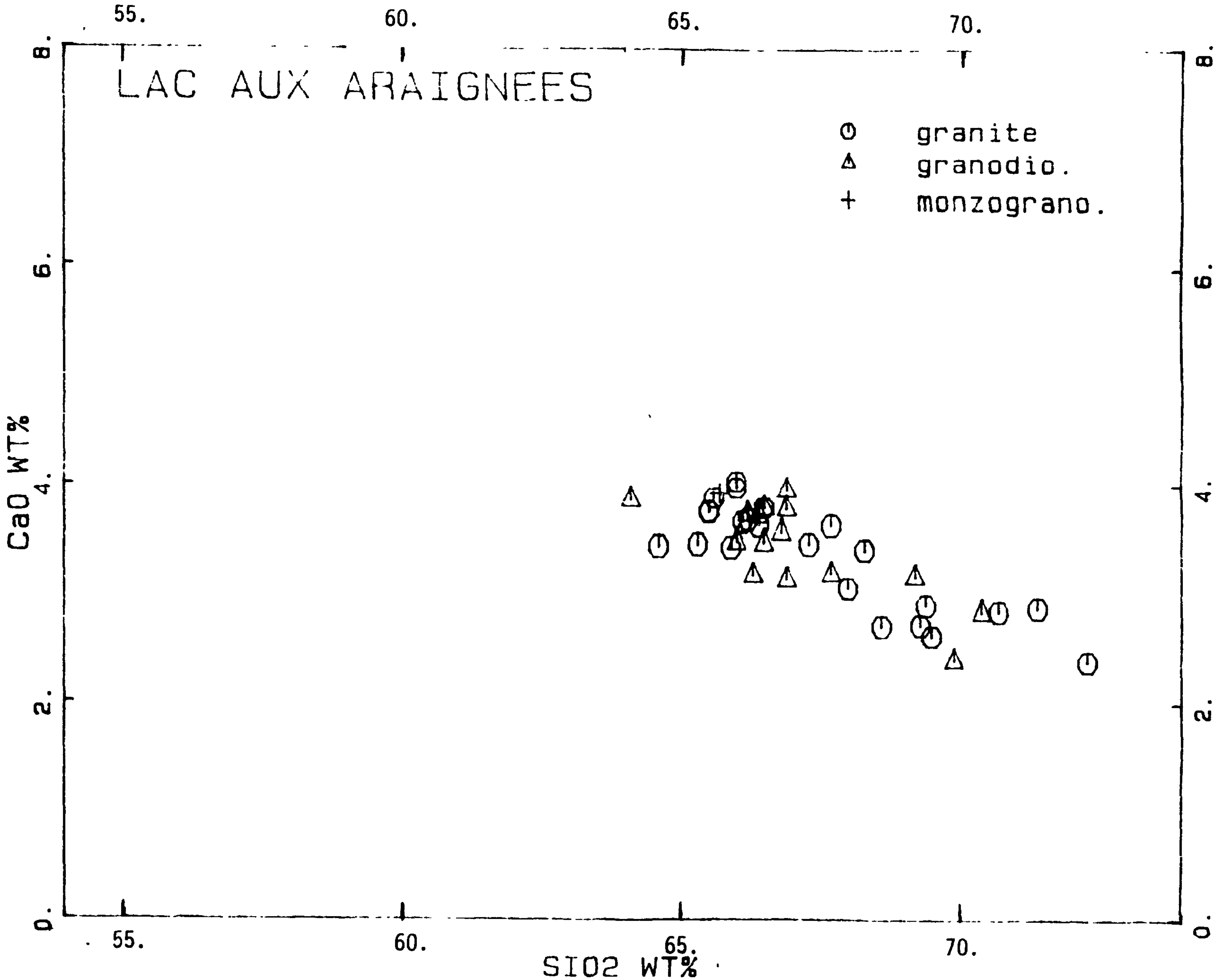
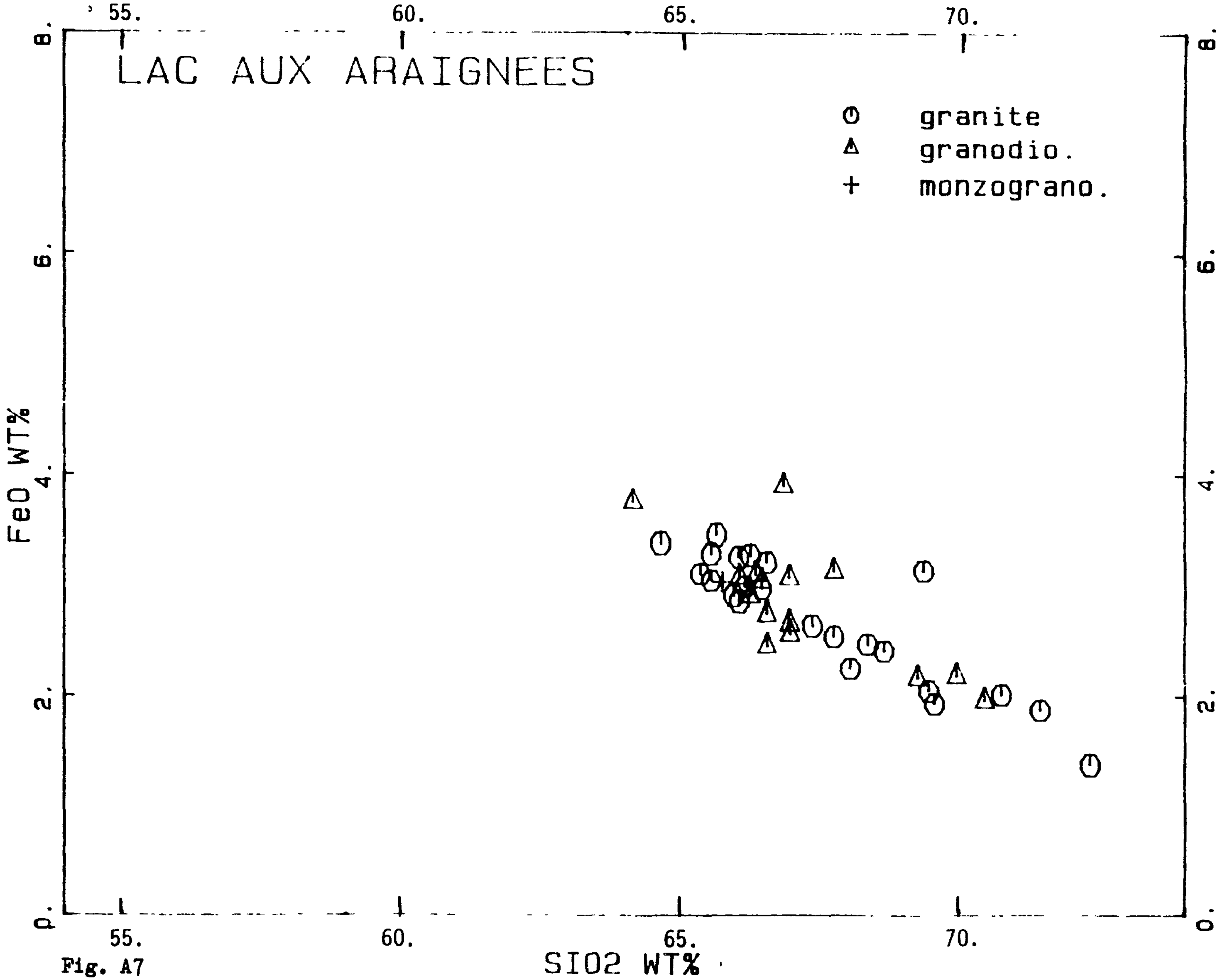

LAC AUX ARAIGNEES
granite
granodio.
monzograno.
CaO WT%
SIO2 WT%
55.
60.
65.
70.
0.
2.
4.
6.
8.

Fig. A6



LAC AUX ARAIGNEES
granite
granodio.
monzograno.
FeO WT%
SIO2 WT%
55.
60.
65.
70.
0.
2.
4.
6.
8.

Fig. A7

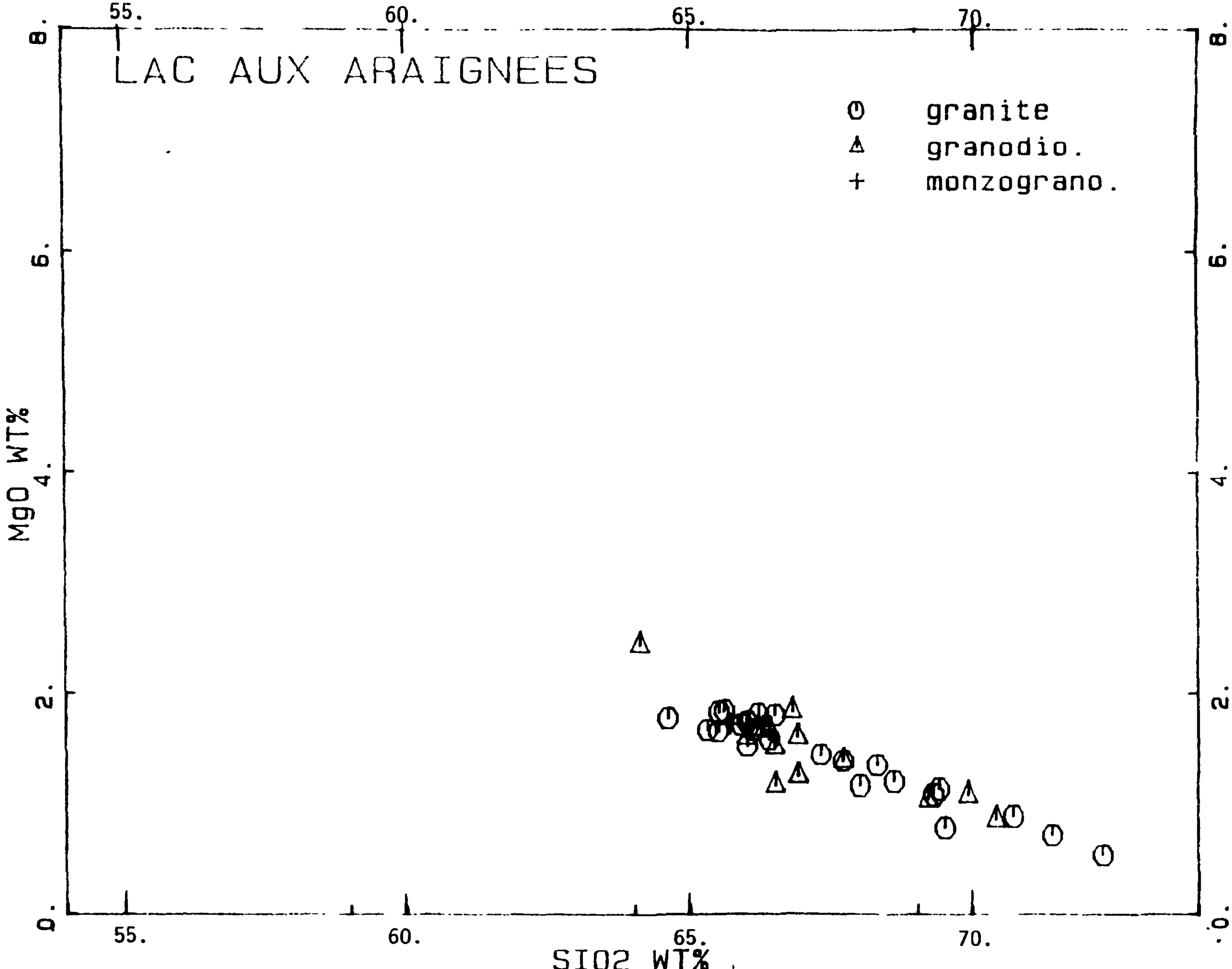

LAC AUX ARAIGNEES
granite
granodio.
monzograno.
MgO WT%
SIO2 WT%
55.
60.
65.
70.
0.
2.
4.
6.
8.

Fig. A8

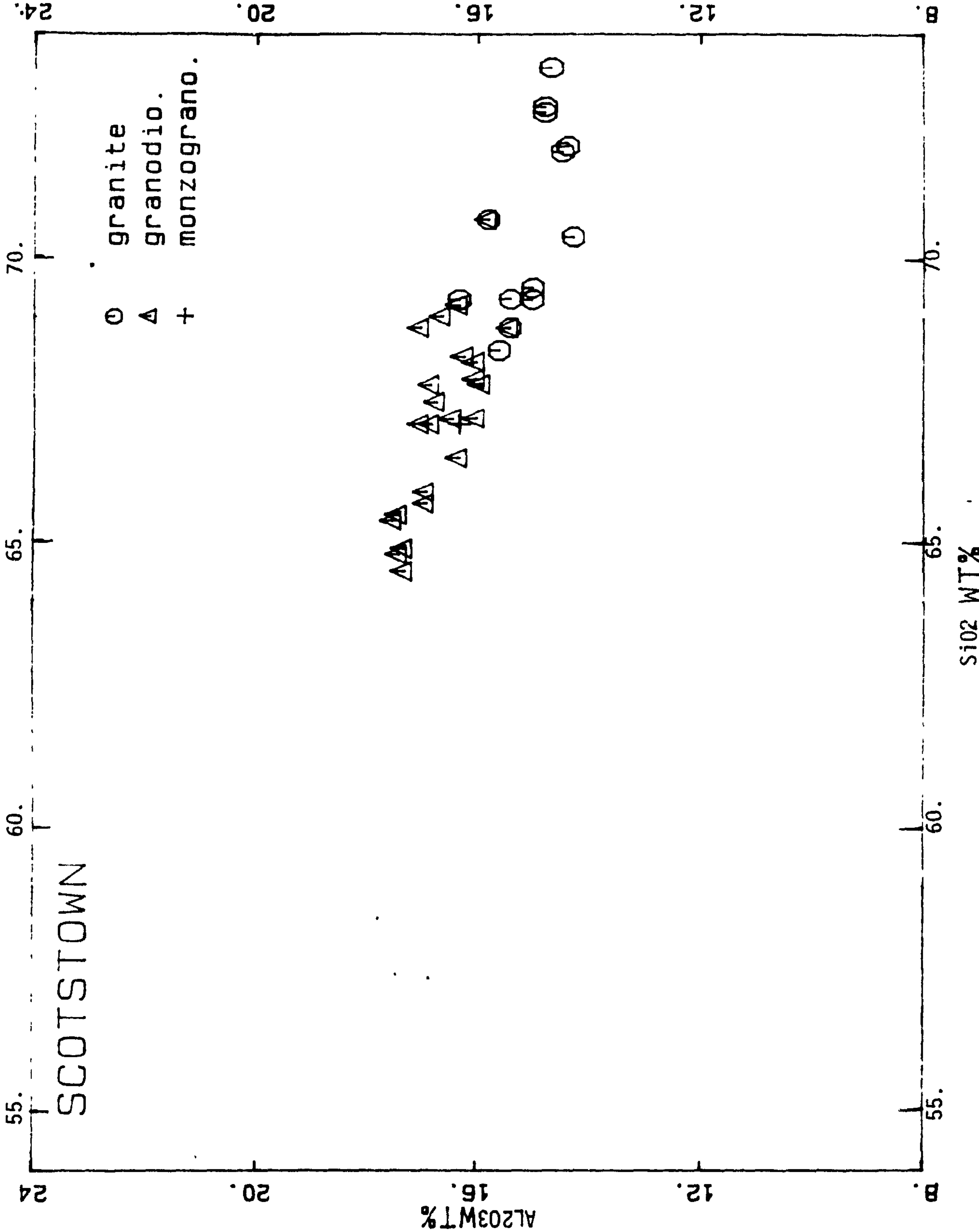

SCOTSTOWN
granite
granodio.
monzograno.
SiO2 WT%
AL2O3WT%
55.
60.
65.
70.
24.
20.
16.
12.
8.

Fig. A9

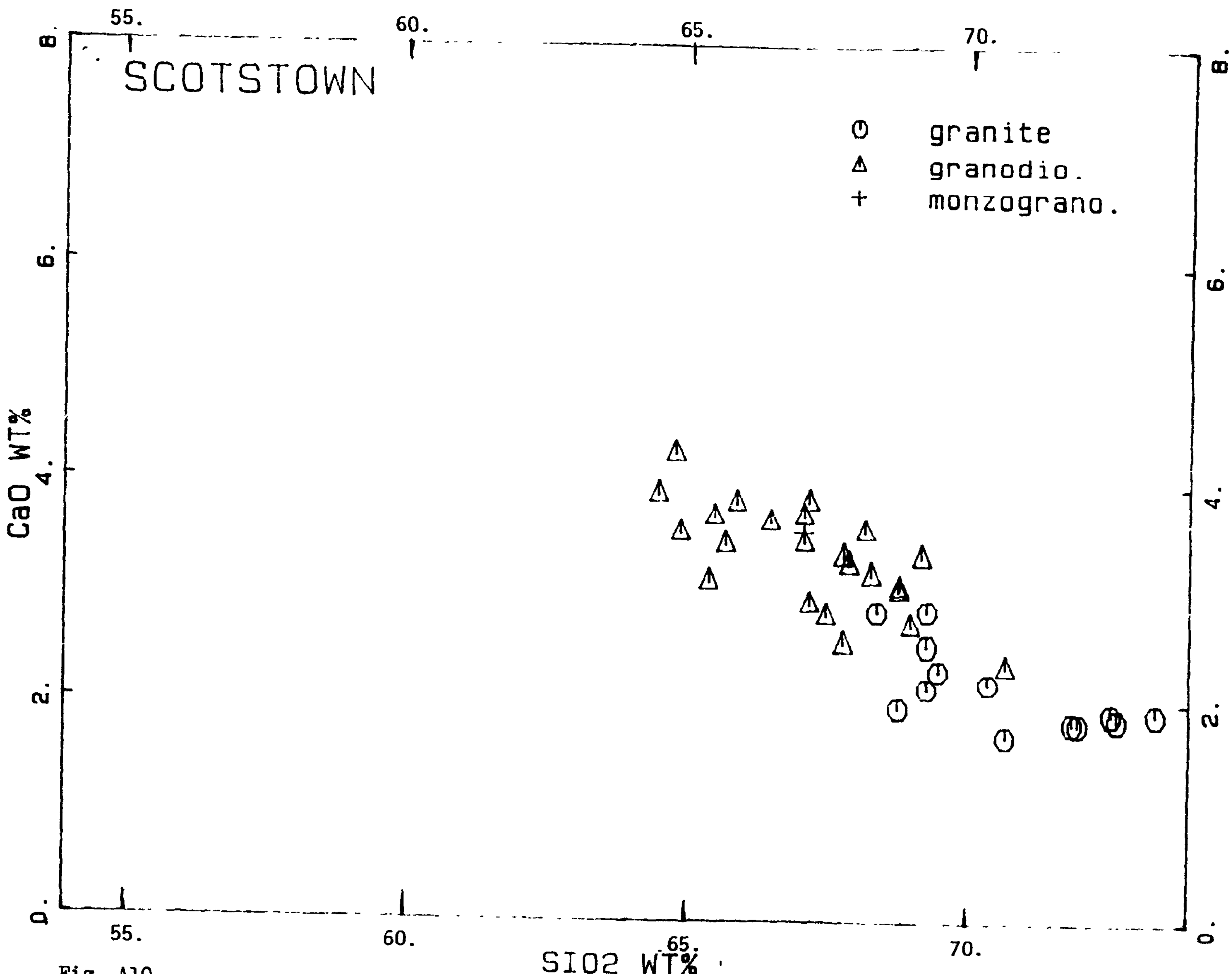

SCOTSTOWN
granite
granodio.
monzograno.
55.
60.
65.
70.
0.
2.
4.
6.
8.
CaO WT%
SIO2 WT%

Fig. A10

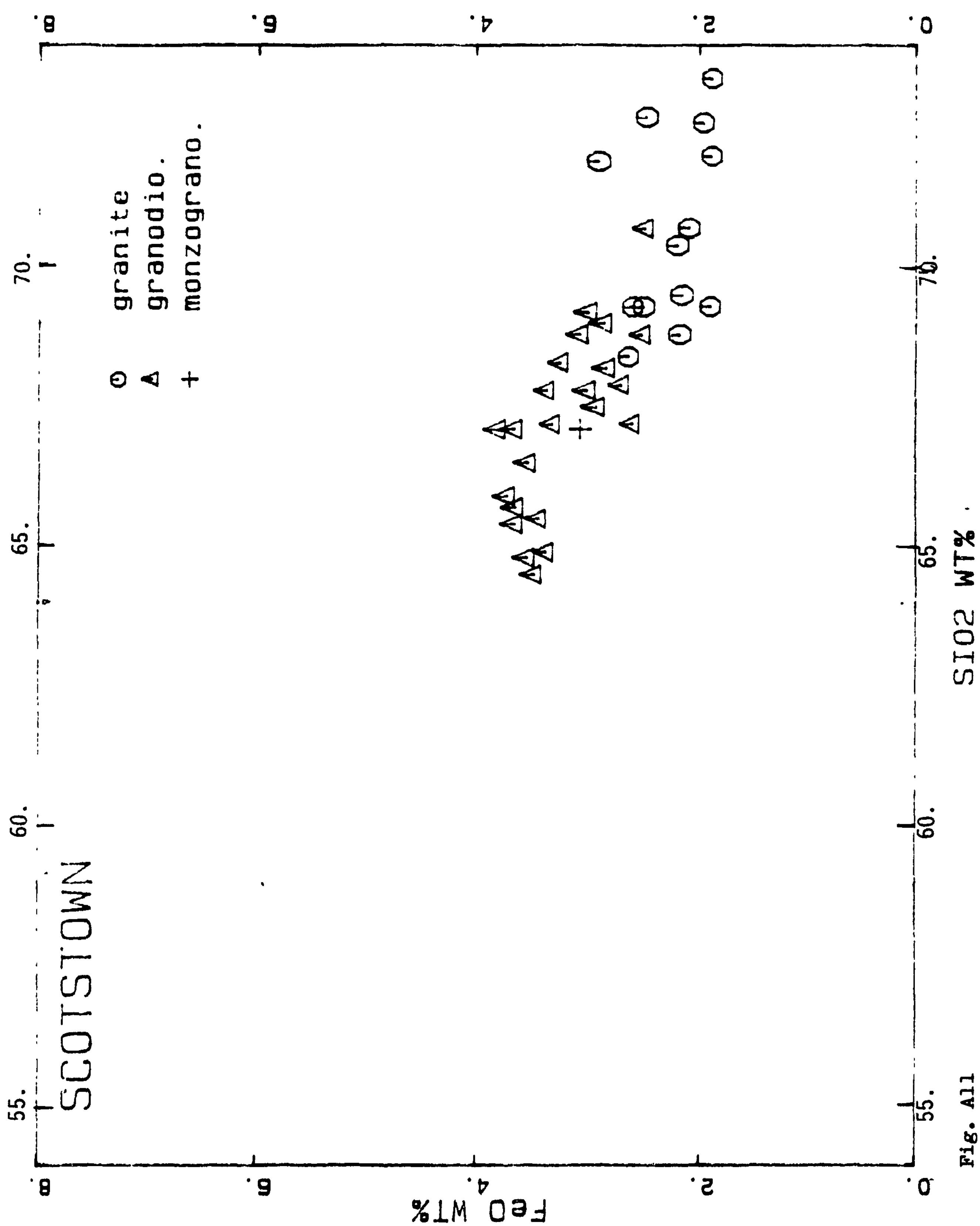

SCOTSTOWN
granite
granodio.
monzograno.
SIO2 WT%
FeO WT%
55.
60.
65.
70.
0.
2.
4.
6.
8.

Fig. A11

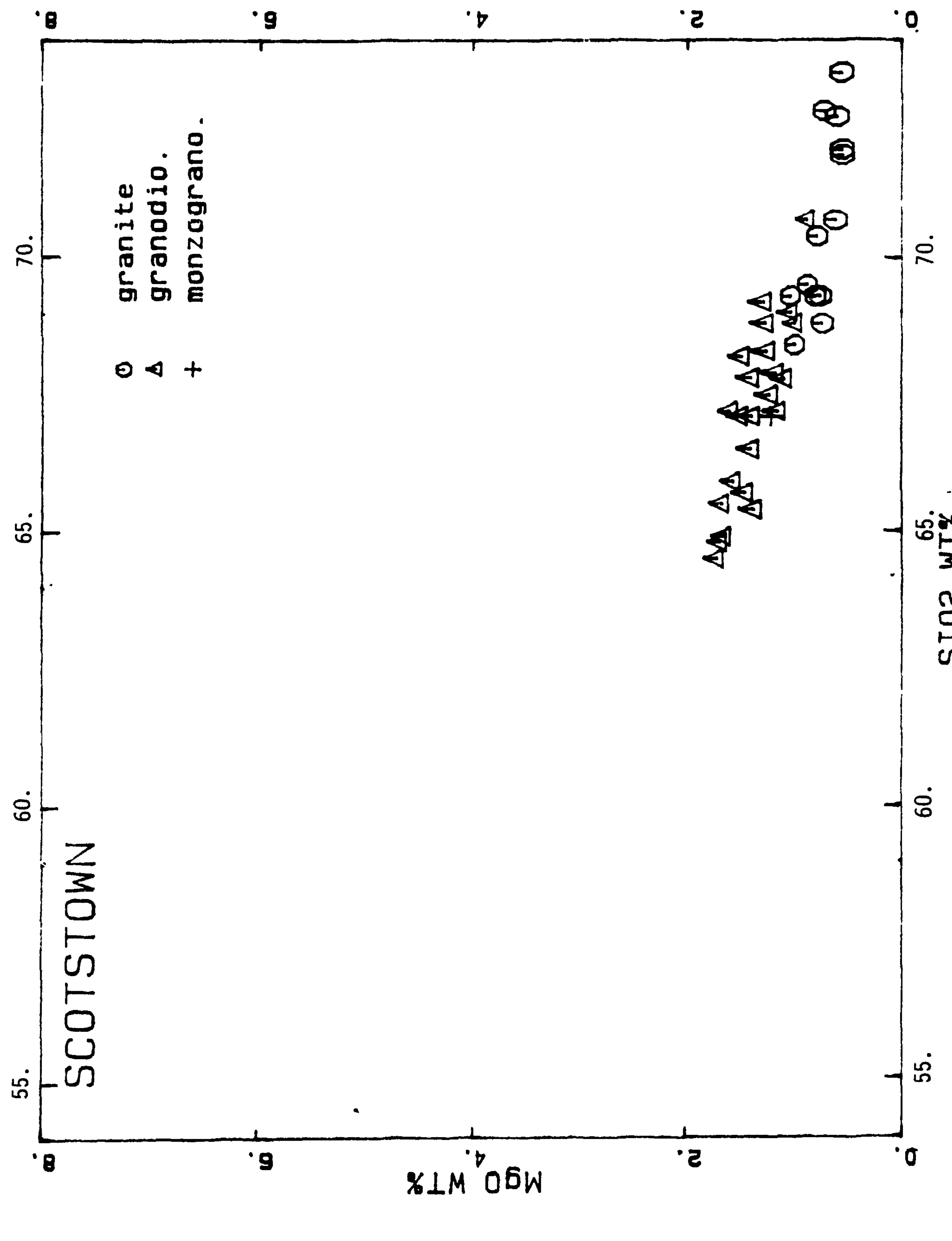

SCOTSTOWN
o granite
Δ granodio.
+ monzograno.
SIO2 WT%
MgO WT%
55.
60.
65.
70.
0.
2.
4.
6.
8.

Fig. A12

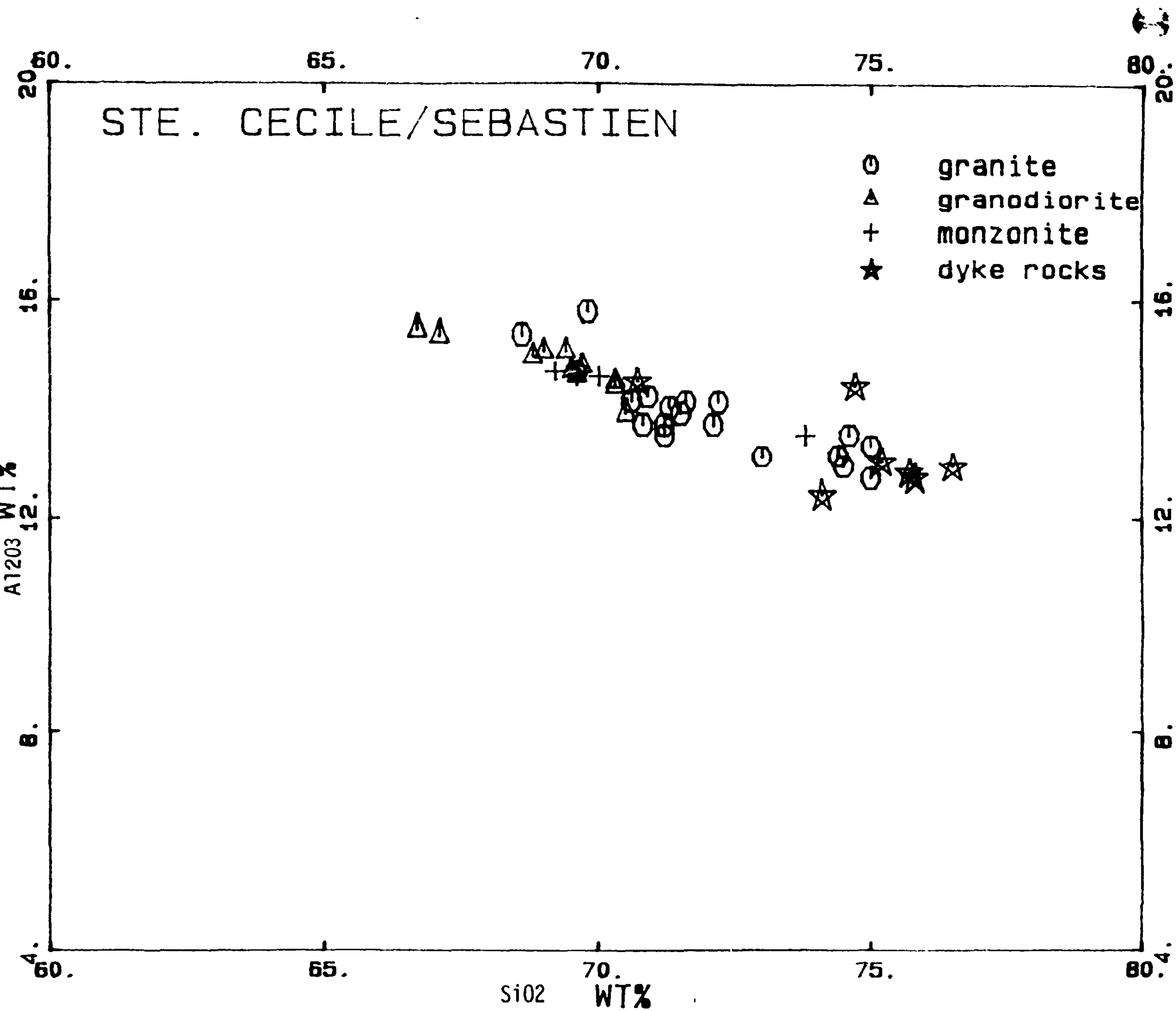

STE. CECILE/SEBASTIEN
granite
granodiorite
monzonite
dyke rocks
Al203 WT%
SiO2 WT%
60.
65.
70.
75.
80.
4.
8.
12.
16.
20.

Fig. A13

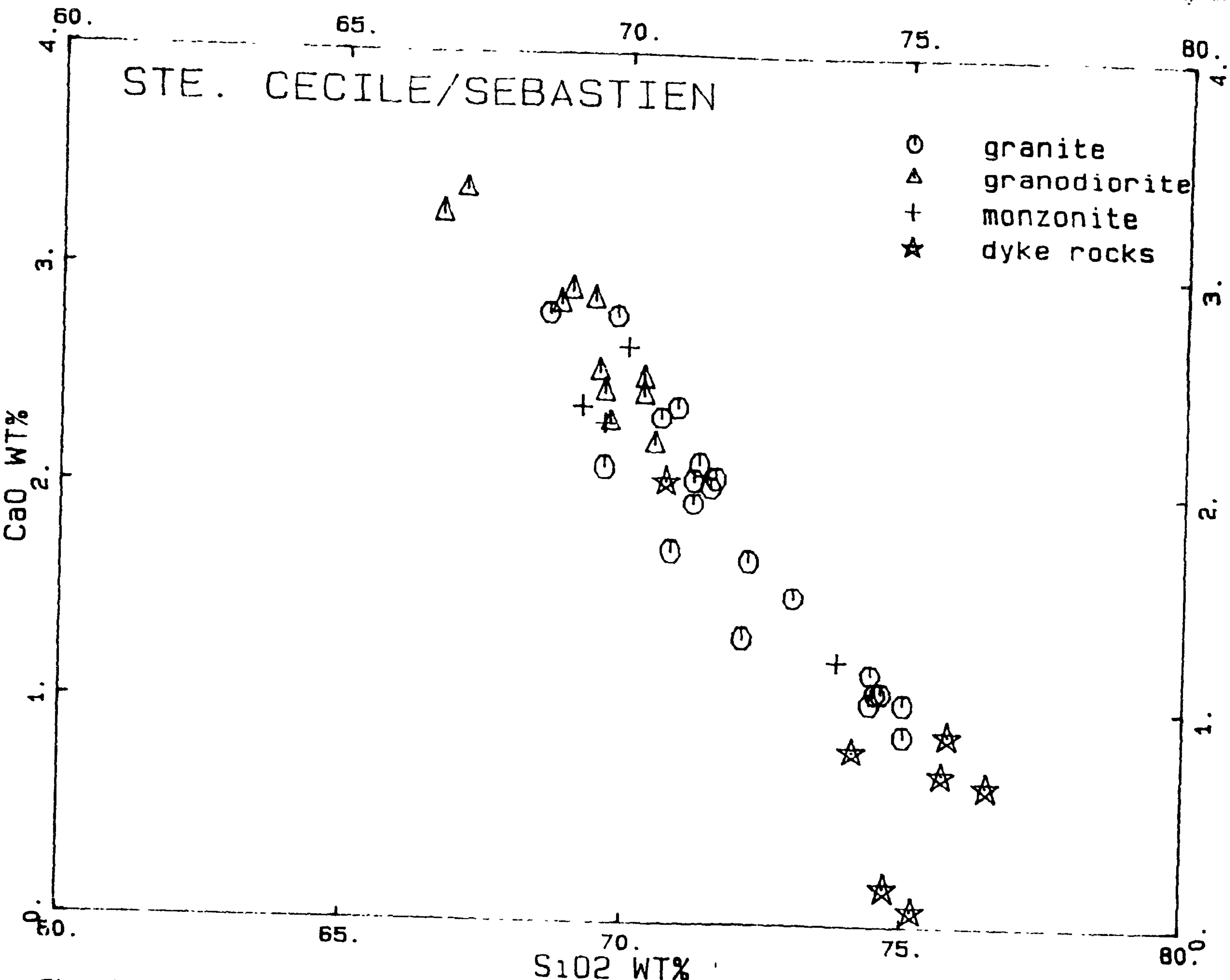

STE. CECILE/SEBASTIEN
granite
granodiorite
monzonite
dyke rocks
CaO WT%
SiO2 WT%
60.
65.
70.
75.
80.
0.
1.
2.
3.
4.

Fig. A14

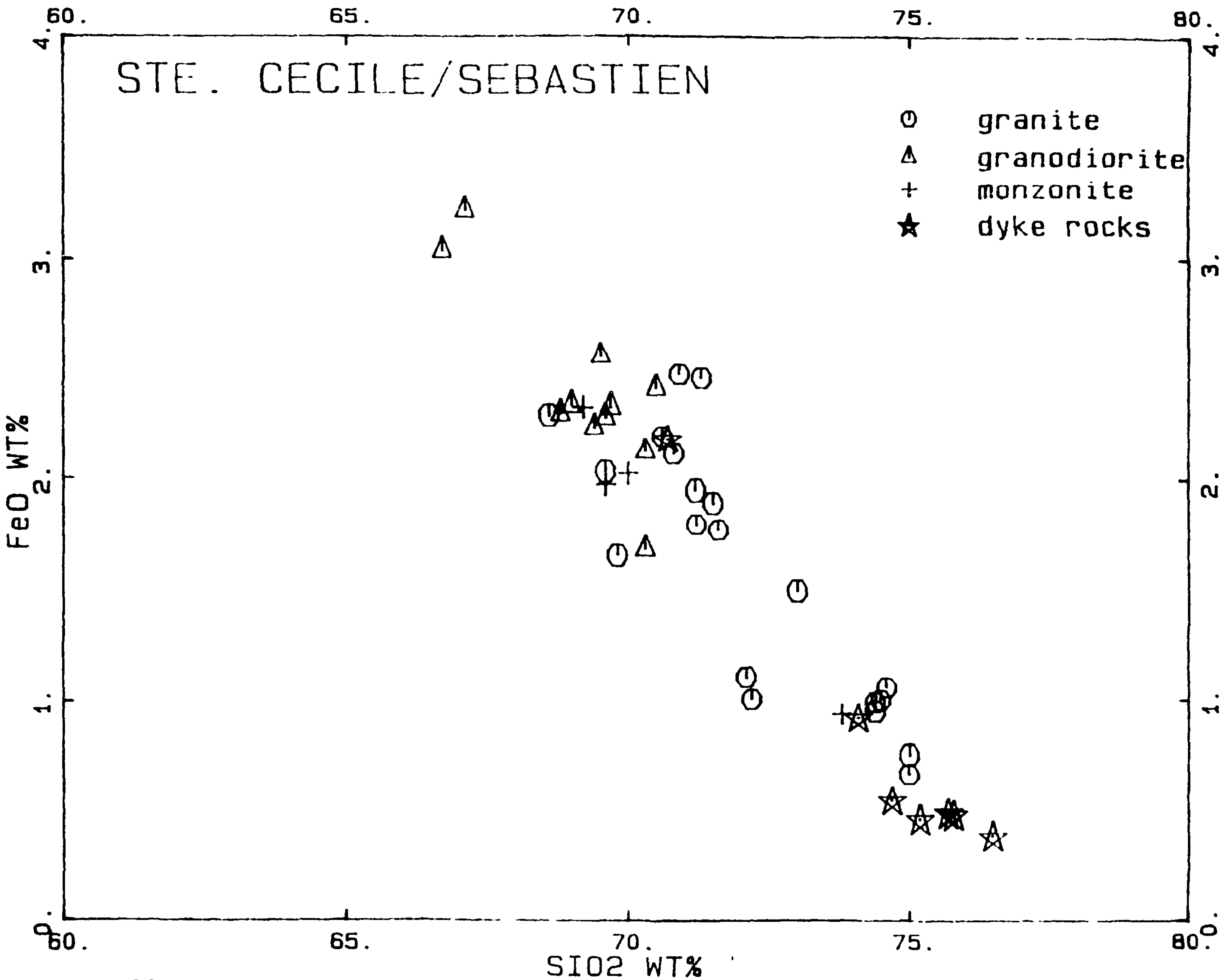
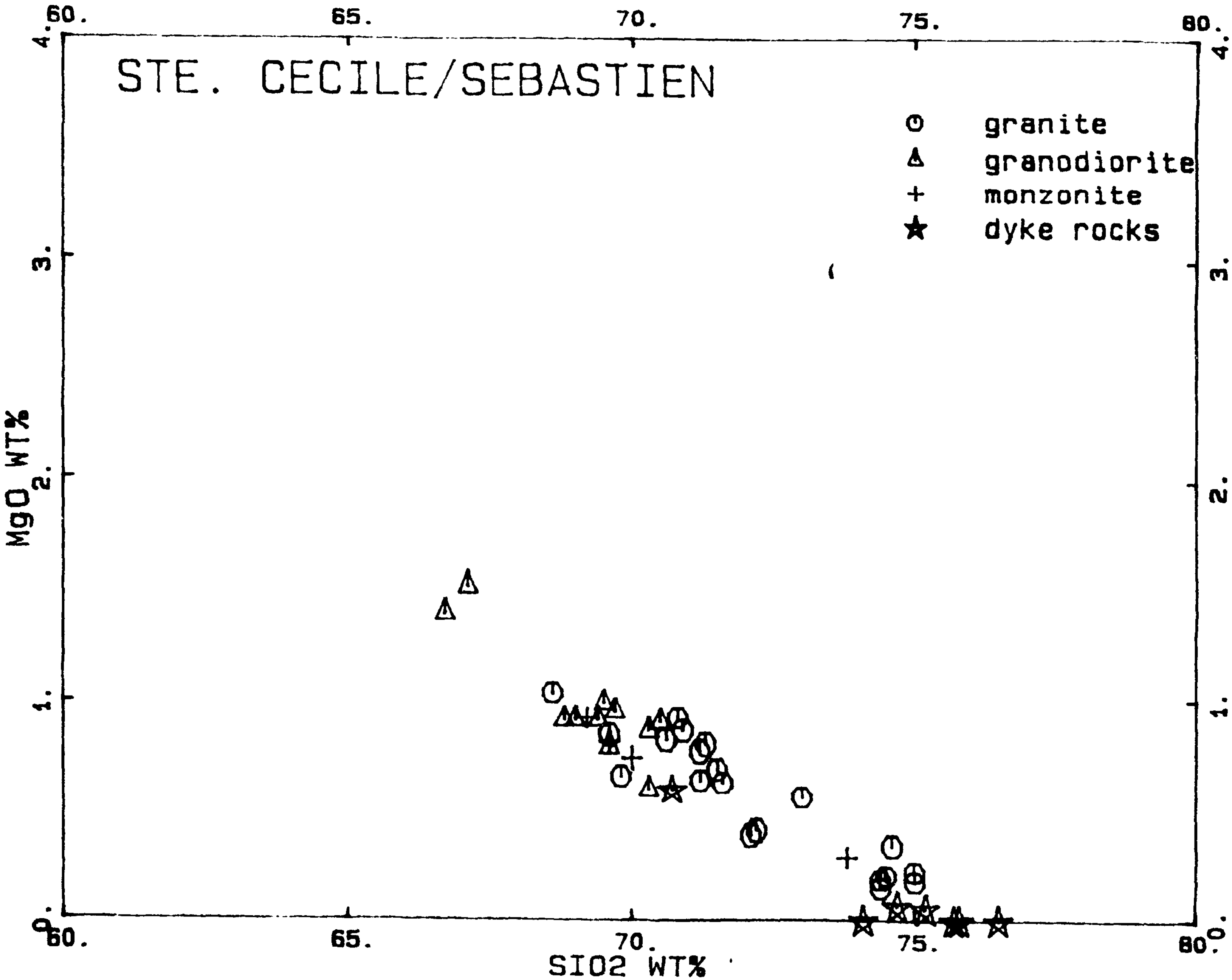

STE. CECILE/SEBASTIEN
granite
granodiorite
monzonite
dyke rocks
FeO WT%
SIO2 WT%
60.
65.
70.
75.
80.
0.
1.
2.
3.
4.

Fig. A15



STE. CECILE/SEBASTIEN
granite
granodiorite
monzonite
dyke rocks
MgO WT%
SIO2 WT%
60.
65.
70.
75.
80.
0.
1.
2.
3.
4.

Fig. A16

APPENDIX B

Representative zircon grains were mounted in epoxy, sectioned and polished, and etched with HF vapor. The grains were examined and photographed in reflected light. The HF vapor preferentially attacks altered areas, and along fractures. By altered areas is meant areas that have experienced various degrees of radiation damage (metamictization), which is a function of the content of uranium, and age. The etching process results in a darkening of the more metamict parts of the grain. In this study, all inherited cores are dark brown. Both dark and light overgrowths are observed, presumably a function of uranium content. The scale-bar next to each photograph represents 0.1 mm.

Fig B1 Highly fractured zircon from the Scotstown 1 M fraction A small zircon has attached itself at the lower left hand side Both the zoned inner portion of the main grain and the overgrowth are interpreted to be products of crystallization of the pluton

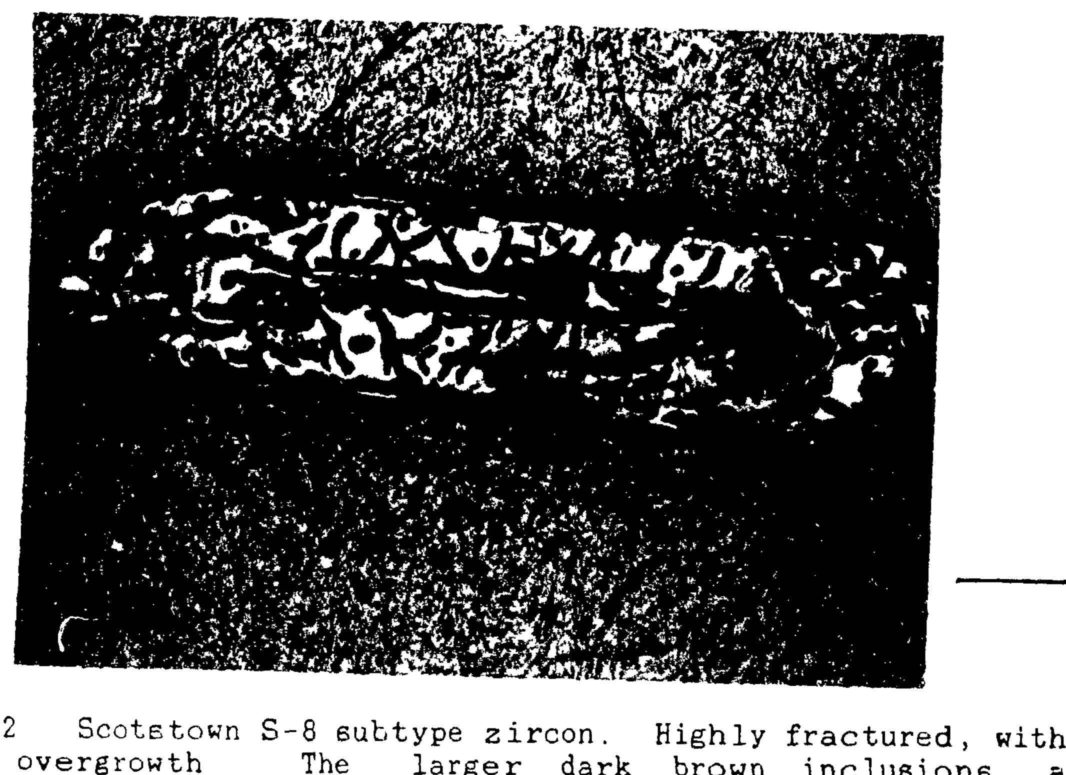


Fig. B2 Scotstown S-8 subtype zircon. Highly fractured, with a thin overgrowth The larger dark brown inclusions are interpreted to be resorbed inherited zircon

Fig. B3. Lac aux Araignées G subtype zircon from the 2 M fraction. Dark brown inherited zircon (?) surrounded by clear but fractured zircon, followed by brown zoned zircon growth at the pyramidal terminations

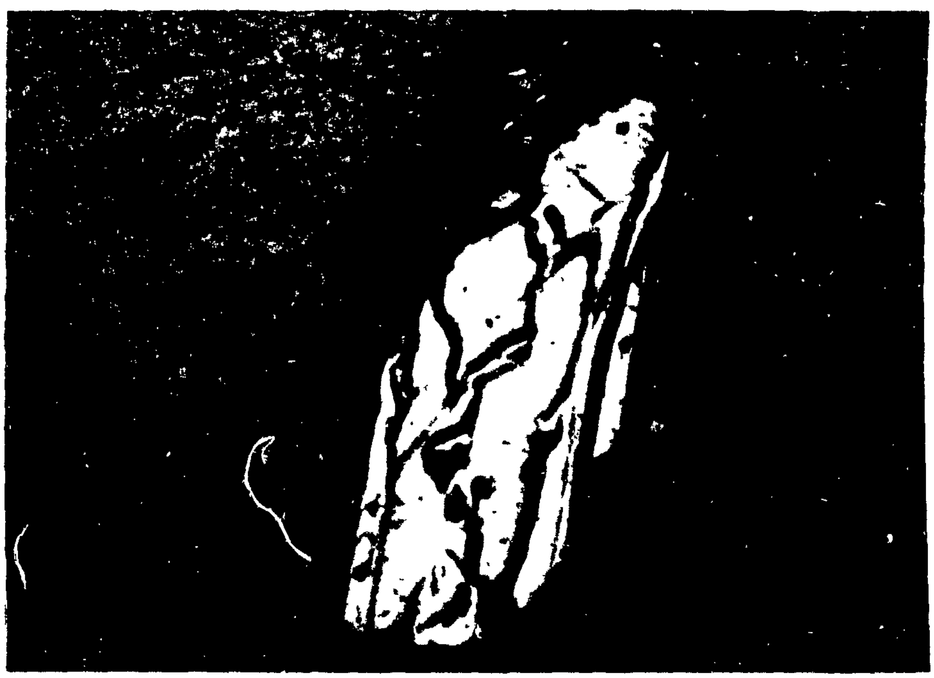


Fig. B4. Part of a Lac aux Araignées zircon from the 1 M fraction. Dark overgrowth on a clear, fractured magmatic core.

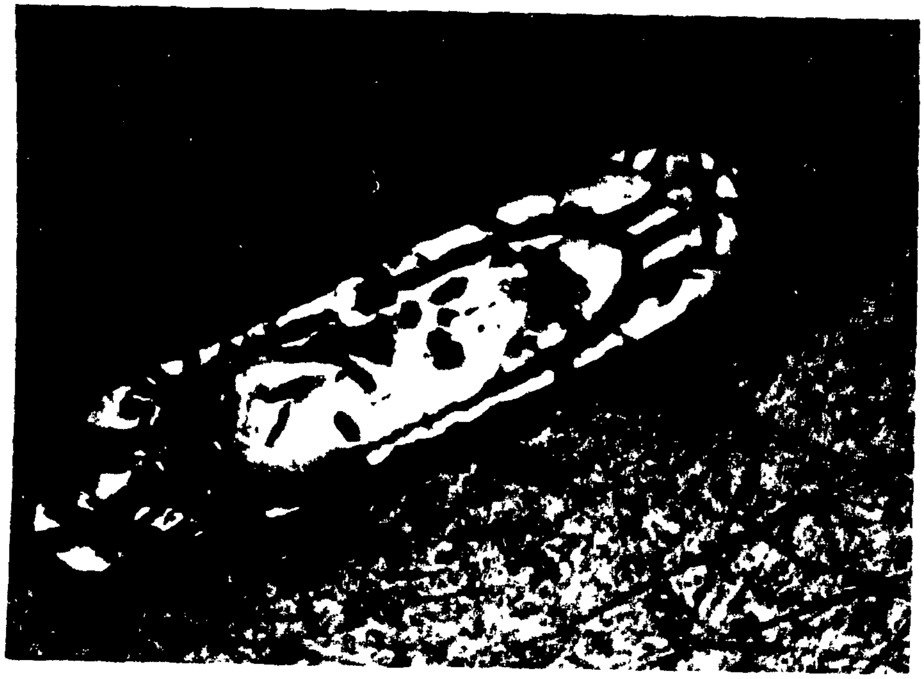


Fig. B5 Lac aux Araignées G subtype zircon from the 1 M fraction Relatively clear magmatic core mantled by a highly fractured clear overgrowth

Fig. B6. Ste. Cécile zircon from the 2 M fraction. Probably early growth of clear zircon followed by a more uranium-rich zoned overgrowth.

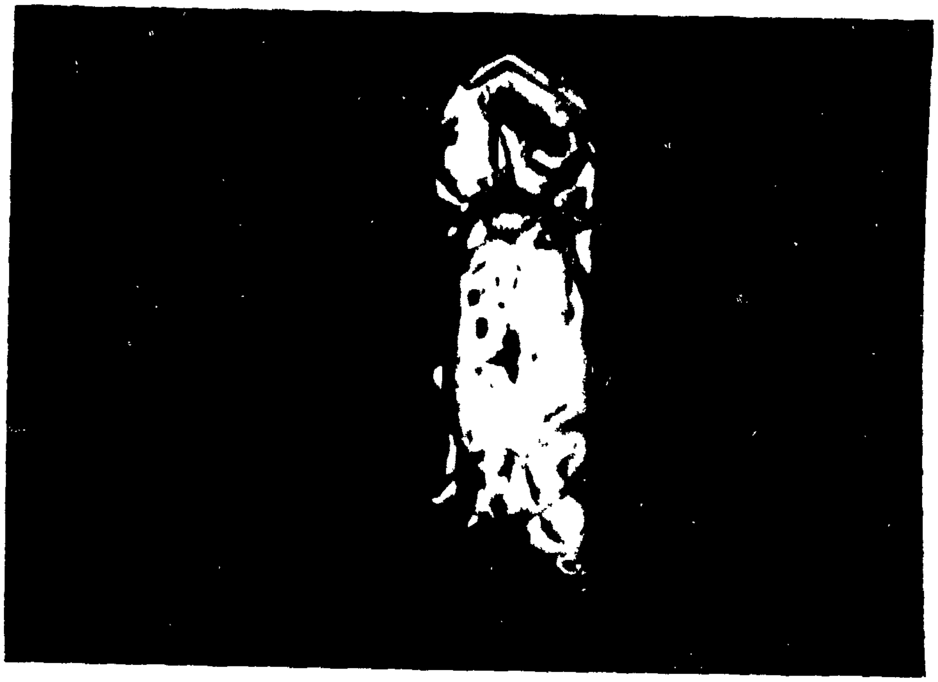


Fig. B7 Lac aux Araignées zircon from the 2 M fraction. Essentially a single stage of growth, incorporating an unknown mineral (top of grain).

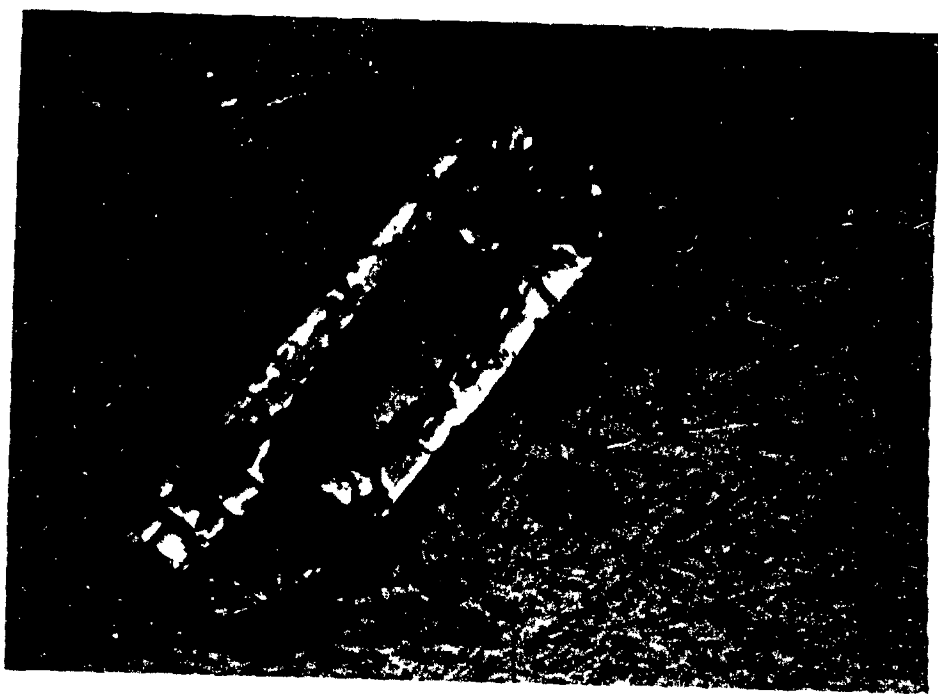


Fig. B8. Lac aux Araignées G subtype zircon from the 2 M fraction. A large inherited zircon core is mantled by pink zircon, followed by brown pyramidal growth or alteration.

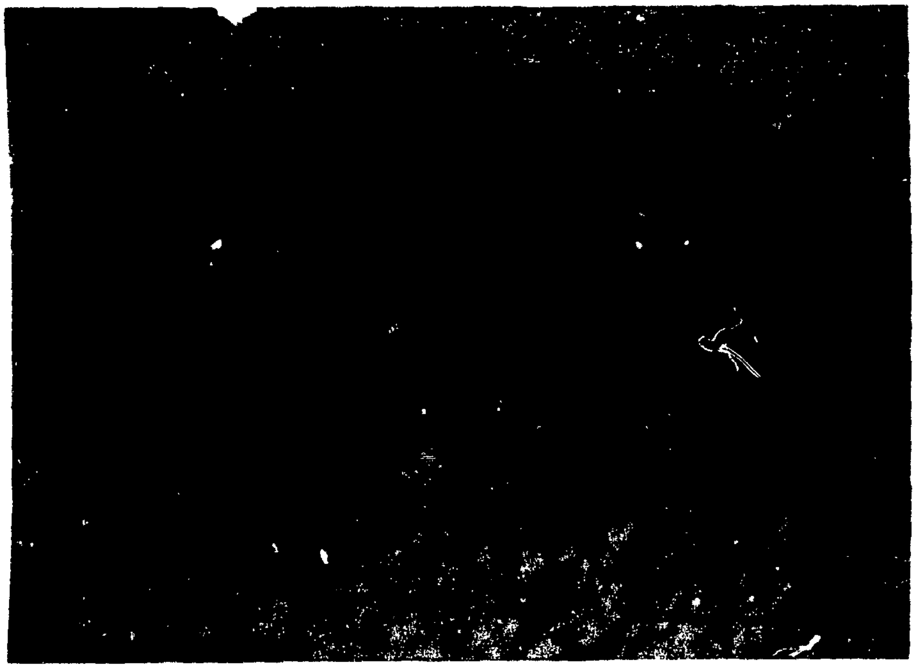


Fig B9. Intergrown inherited zircons with no new growth. From the Aylmer 4 M fraction. The zirconium contents of Aylmer rock samples were the lowest of the plutons analyzed.

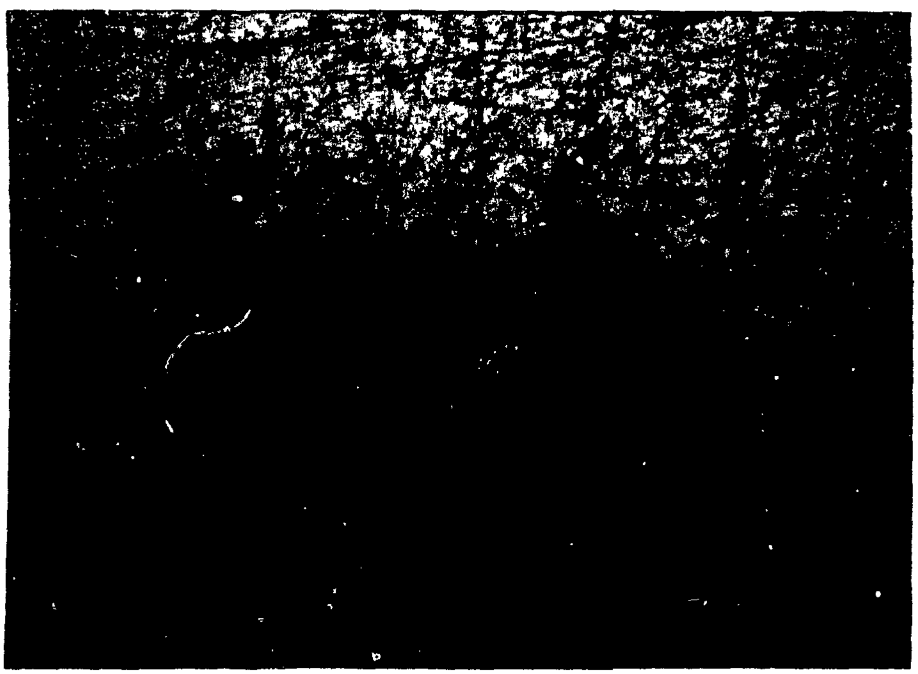


Fig. B10. Another fragment of inherited zircon from Aylmer, with no new growth.

Fig. B11 One of the very few magmatic zircons from Aylmer (3 M fraction). Note the several periods of growth and small size.

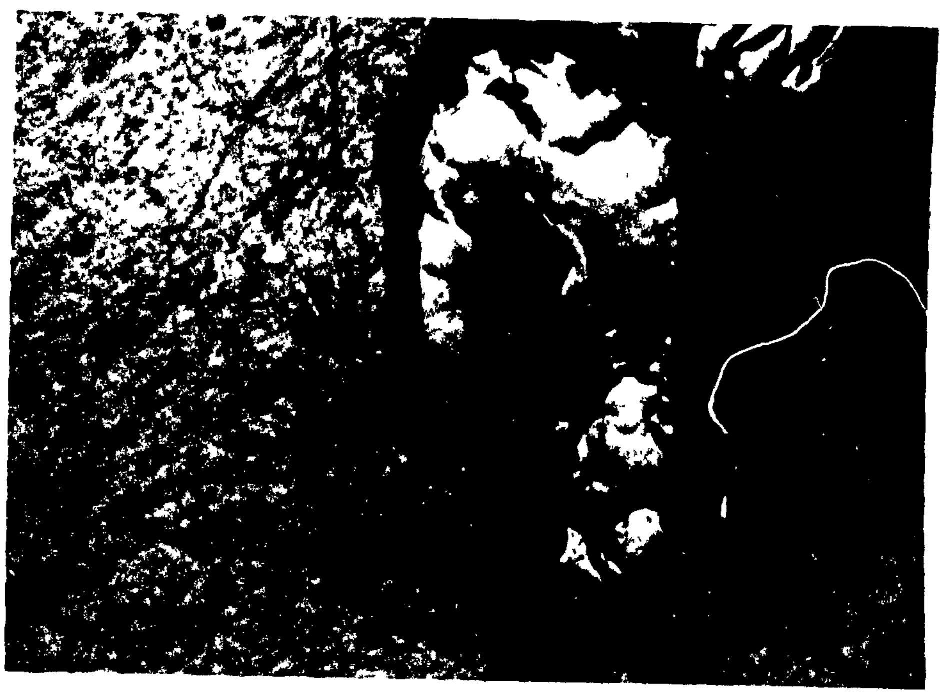


Fig. B12. Intergrowth of two magmatic zircons from the Ste. Cécile 4 M fraction. The larger grain encloses a dark brown inherited zircon.

Fig. B13 Ste Cécile 4 M zircon consisting of a partly disolved inherited core and a mantle of new, uranium-poor zircon.

Fig. B14. Ste. Cécile, 3 M fraction. Intergrown zircons with brown cores interpreted to be new magmatic growth. The darker inclusions are probably inherited zircon fragments.

Fig. B15 Ste. Cécile, G subtype, 3 M fraction. Similar to B15: Minor inherited fragments (?) in a uranium-rich, zoned magmatic core, surrounded by a fractured uranium-poor mantle.

Fig. B16. Ste. Cécile, 1 M fraction. Inherited core with sharp edges, but disolved and replaced along a fracture (?) by the magmatic overgrowth.

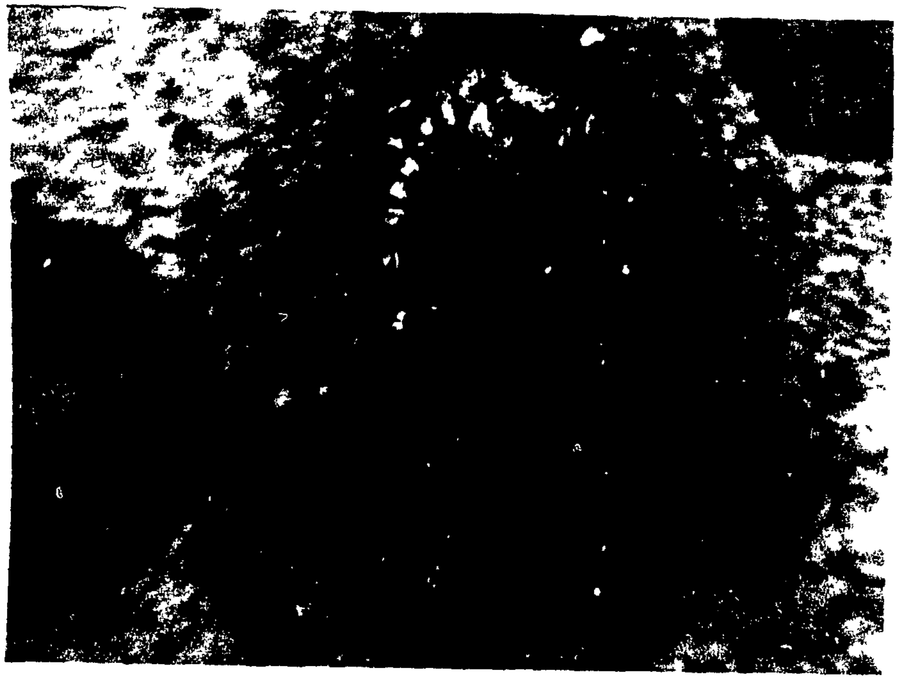


Fig B17 Ste Cécile, 1 M fraction Mostly an inherited core with a thin mantle of new zircon.

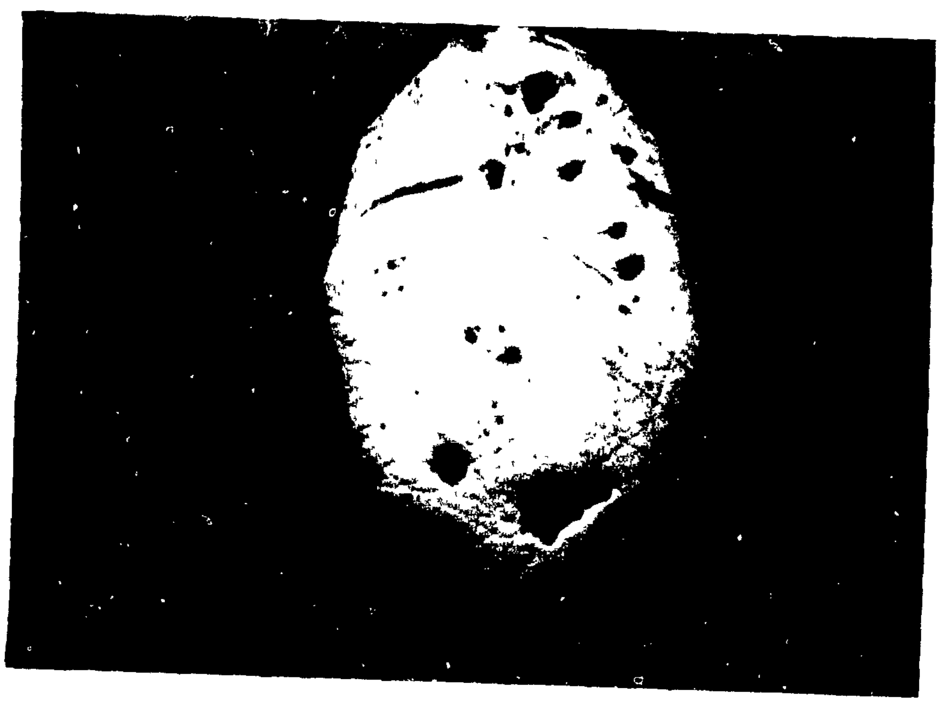


Fig. B18. Lac aux Araignées, 2 M fraction. One of a small number of almost equidimensional, unzoned, uranium-poor zircons.

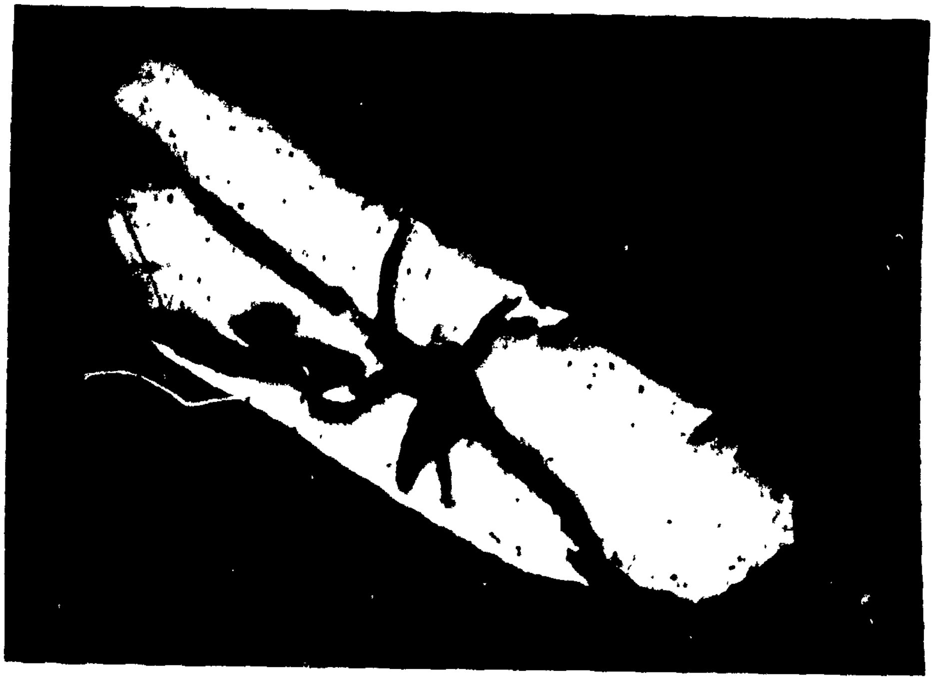


Fig B19 Lac aux Araignées, 1 M fraction Intergrowth of two homogeneous (like B19), but elongated zircons.

Fig. B20. Ste. Cécile, 3 M fraction. Colorless G subtype zircon with marked igneous zoning.

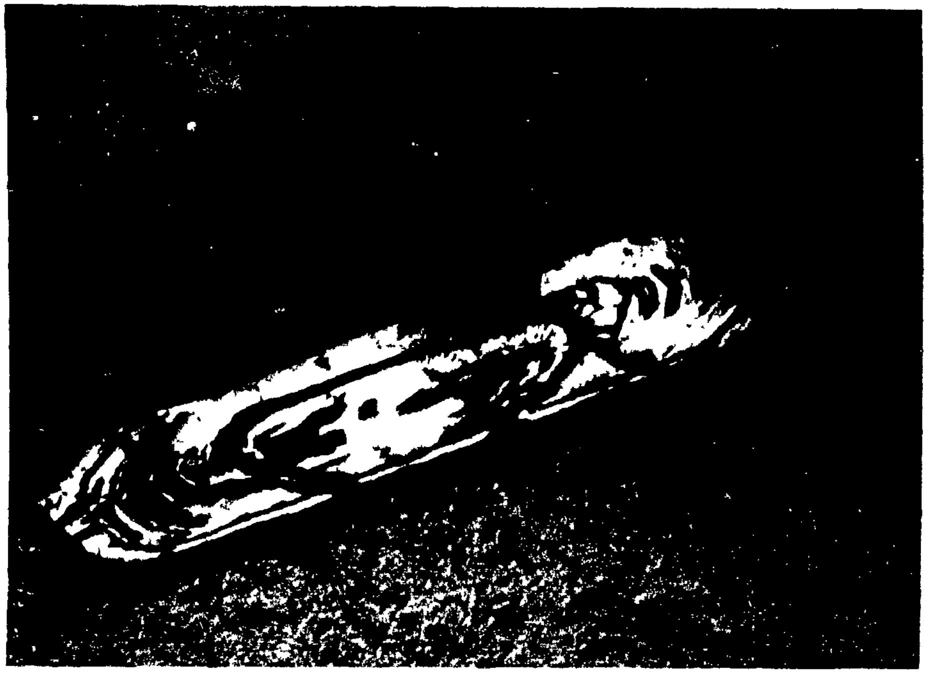


Fig B21. Ste. Cécile, 3 M fraction. Similar to B21 but fractured.