STRUCTURE, METAMORPHISM, AND GEOCHRONOLOGY OF THE SINGIS-NIKKALUOKTA REGION, ARCTIC SCANDINAVIAN CALEDONIDES

by

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Abstract

Rocks of the Scandinavian Caledonides have conventionally been grouped into five main complexes: The Autochthon and Parautochthon, the Lower Allochthon, the Middle Allochthon, the Upper Allochthon (Seve and Köli Nappes), and the Uppermost Allochthon (Gee, 1975). The rocks of the Singis-Nikkaluokta transect fit into these broad categories, however intra-nappe correlations within these units along strike of the orogen are sometimes problematic. The Singis-Nikkaluokta portion of the transect contains rocks from the Lower Köli Nappe, the Seve Nappe, the Middle Allochthon, and the Autochthonous-Paratochthonous Baltic Shield. In this study the rocks of the Singis-Nikkaluokta area are described and grouped into a specific tectonostratigraphy and then regional correlations and implications are discussed.

The deformational history of the Singis-Nikkaluokta region may be subdivided into eight deformational events which are associated with two major tectonothermal events. Deformations 1 and 2 are Finnmarkian, and are associated with the Late Cambrian to Early Ordovician metamorphism of the Seve Nappe. Deformation 3 is associated with the post-Ashgillian Scandian metamorphism of the Lower Köli Nappe. The juxtaposition of the Köli and Seve produced the fabrics associated with the fourth deformational event. Emplacement of the Upper Nappe Complex onto the rocks of the Baltic shield produced structures assigned to D5, D6, and D7. The final deformational event (D8) is correlated with late stage west vergent motion along the Seve-Köli contact.

Several samples from units within the Seve Nappe of the Singis-Nikkaluokta region contain assemblages which allow the application of well calibrated quantitative thermobarometers. Quantitative thermobarometry and garnet zoning profiles on Seve quartzofeldspathic gneiss samples with appropriate assemblages yields important constraints on the "Finnmarkian" history of the Seve Nappe of the Singis-Nikkaluokta region. The metamorphic results from this study area include: 1) Eclogite grade rocks of the Aurek Assemblage yield temperatures and pressures in excess of 12 kb and 730° C. 2) The temperatures and pressures obtained in this study for seven samples from the Savopakte Assemblage of the Seve Nappe range from 571-766° C and 8.9-13.6 kb. When combined with $^{40}Ar/^{39}Ar$ data these pressures correspond to burial depths of approximately 30-45 km during the Finnmarkian (490 Ma) for the outer margin of Baltica. Uplift rates of .2-.4 mm/yr during the Finnmarkian are obtained 3) Within the Vidja Assemblage of the Seve Nappe a pressure and temperature of 7.3±1.7 kb and 616±60° is obtained. These conditions are consistent with the interpretation of a late Finnmarkian (450 Ma) intra-Seve juxtaposition of the Vidja and Aurek Assemblages after approximately 20-30 km of slow uplift from the peak pressures recorded during the early Finnmarkian. and, 4) Garnet zoning occurs in samples whose rim equilibrium temperatures are less than 650° C. Samples used in thermobarometry whose rim temperatures exceed 650° C do not exhibit zoning. This is consistent with several studies which indicate that homogenization of garnet growth zoning by intragranular volume diffusion is possible

$^{40}Ar/^{39}Ar$ geothermochronology has become an indispensable tool in the analysis of multiply deformed and metamorphosed regions. This technique is especially useful within the Scandinavian Caledonides which experienced deformation and metamorphism as a result of two major tectonothermal pulses during the early and middle Paleozoic. A detailed $^{40}Ar/^{39}Ar$ geochronology study of the Singis-Nikkaluokta area allows examination of the timing of tectonothermal activity within the Lower Köli Nappe, the Seve-Köli shear zone, the Seve Nappe, and the shear zone rocks of the Middle Allochthon. The results obtained indicate: 1) The high grade metamorphism and associated deformation of the Seve units was a late Cambrian to early Ordovician event (Finnmarkian) in which the rocks cooled below the respective closure temperatures for hornblende at ≈ 490 Ma and muscovite at ≈ 454 Ma. 2) Assuming a simple linear cooling model a cooling rate of 3-6° C/Ma. was obtained for the older tectonothermal event. 3) There is evidence for a late stage Finnmarkian (450 Ma.) relatively high grade shear zone separating different tectonostratigraphic elements within the Seve. 4) The Scandian phase of deformation and metamorphism partially reset some of the Seve hornblendes and a majority of the muscovites which indicate that the rocks effected by the Finnmarkian event felt a second tectonothermal pulse of more than 350° C beginning at ≈ 430 Ma. and, 5) During the Scandian event all of the far travelled allochthonous tectonic units were juxtaposed and the Middle Allochthon mylonites were formed as these nappes were emplaced above the Baltic Shield. The tectonic units of the Singis-Nikkaluokta transect were assembled prior to regional cooling through the closure temperature of muscovite.

This study provides some of the first integrated P-T-t constraints for the evolution of the Finnmarkian tectonothermal event within the northern Scandinavian Caledonides. While these constraints are consistent with the models proposed by Dallmeyer and Gee (1986) and Stephens and Gee (1989), the results obtained in this study provide some additional constraints which need to be considered in future tectonic models. These constraints include: 1) The metamorphic conditions obtained for the Savopakte Assemblage of the Seve Nappe record high pressures and high temperatures during the Finnmarkian. and 2) Constraints provided by this study indicate that Finnmarkian uplift rates of .2-.4 mm/yr were likely for marginal Baltica after peak metamorphism. Rates of this magnitude may be accounted for solely by slow erosion and do not require (but do not preclude) more complex tectonic interpretations. A tectonic model provided by the Late Cenozoic thrust belts of the Apennine Carpathian, and Hellenic systems of the mediterranean region, may lead to new insights into the Early Paleozoic evolution of the Scandinavian Caledonides. This modern analog is attractive for the evolution of the Caledonides because it helps explain several salient points: 1) The overriding plate is a zone of extension allowing for the elevation of geotherms; therefore explaining the high temperatures at high pressures recorded within the Seve. 2) Although evidence for arc-related volcanic rocks has been documented (Stephens and Gee, 1985), there exists no evidence within the Scandinavian Caledonides of the volcanic arc. The Apennine model while containing arc-type volcanism in the overlying plate, does not require the presence of a massive volcanic-arc. The arc region is extended during its development and may be disrupted and spread across a broad region of extension. 3) Within the Mediterranian systems the extended area is often a zone of subsidence, thus a topographic high with associated rapid erosion rates are not necessary. The low (.2-.4 mm/yr) uplift rates obtained in this study may be consistent with this interpretation.

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Chapter 1
Introduction

The Scandinavian Caledonides are an ideal setting in which to examine the effects of continent-continent collision at middle to deep crustal levels. They formed as a result of the Early to Middle Paleozoic closure of Iapetus and the ensuing eastward obduction of a complex package of oceanic and continental lithologies over the Baltic Shield. Although the mountain range is deeply eroded, many of the obducted lithologies are preserved, which allows for an examination of the complicated history related to orogenesis of the different tectonic units within the Caledonides (Fig.1-1). Broad reviews of the geology of the Scandinavian Caledonides are discussed in Gee (1975, 1978) and within Zachrisson (1979). Particularly comprehensive and useful are the papers discussing the tectonostratigraphy for the central-north Scandinavian Caledonides found in Stephens et. al. (1985) and Stephens and Gee (1989). Regional syntheses of the Arctic Swedish Caledonides are provided by Kulling (1964, 1972). A 1: 2,000,000 tectonostratigraphic map (Gee et. al., 1985) provides a visual overview of the areal distribution of the major nappe units.

In general the nappes of the Scandinavian Caledonides may be grouped into three major tectonostratigraphic elements. These include: 1) the Autochthon-Parautochthon, 2) the Middle Allochthon, and 3) the Upper Allochthon (which is often referred to as the Upper Nappe Complex).

The Autochthon-Parautochthon consists of a thin platform sequence of Vendian to Early Ordovician age consisting primarily of sandstones and black shale which lie unconformably on the Precambrian crystalline basement of the Baltic Shield. Stratigraphic correlation of the sedimentary sequences in the Autochthon-Parautochthon with sedimentary rocks which occur within the overlying Lower and Middle Allochthons provide evidence for a passive margin sequence during the Cambrian which thickened to

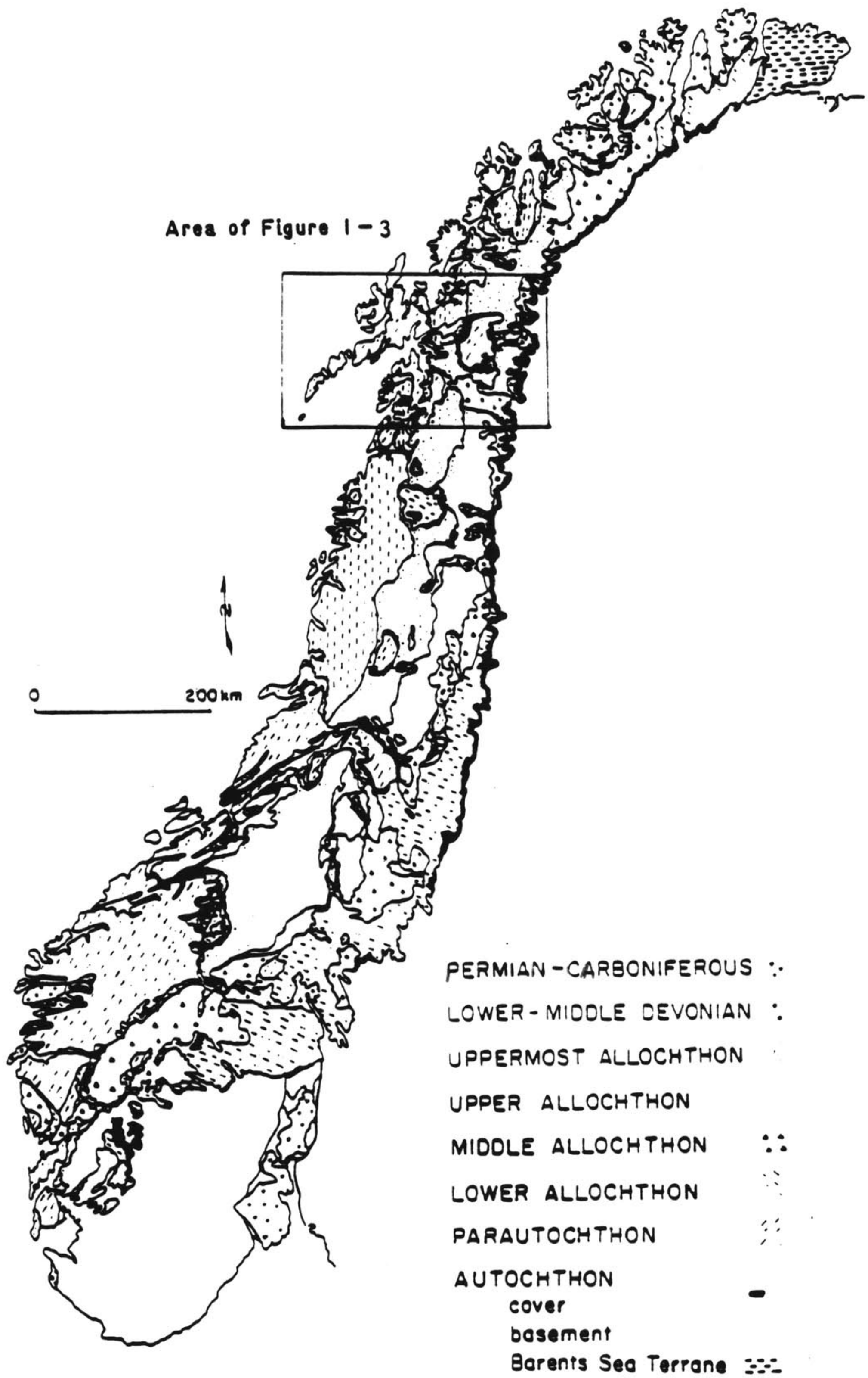


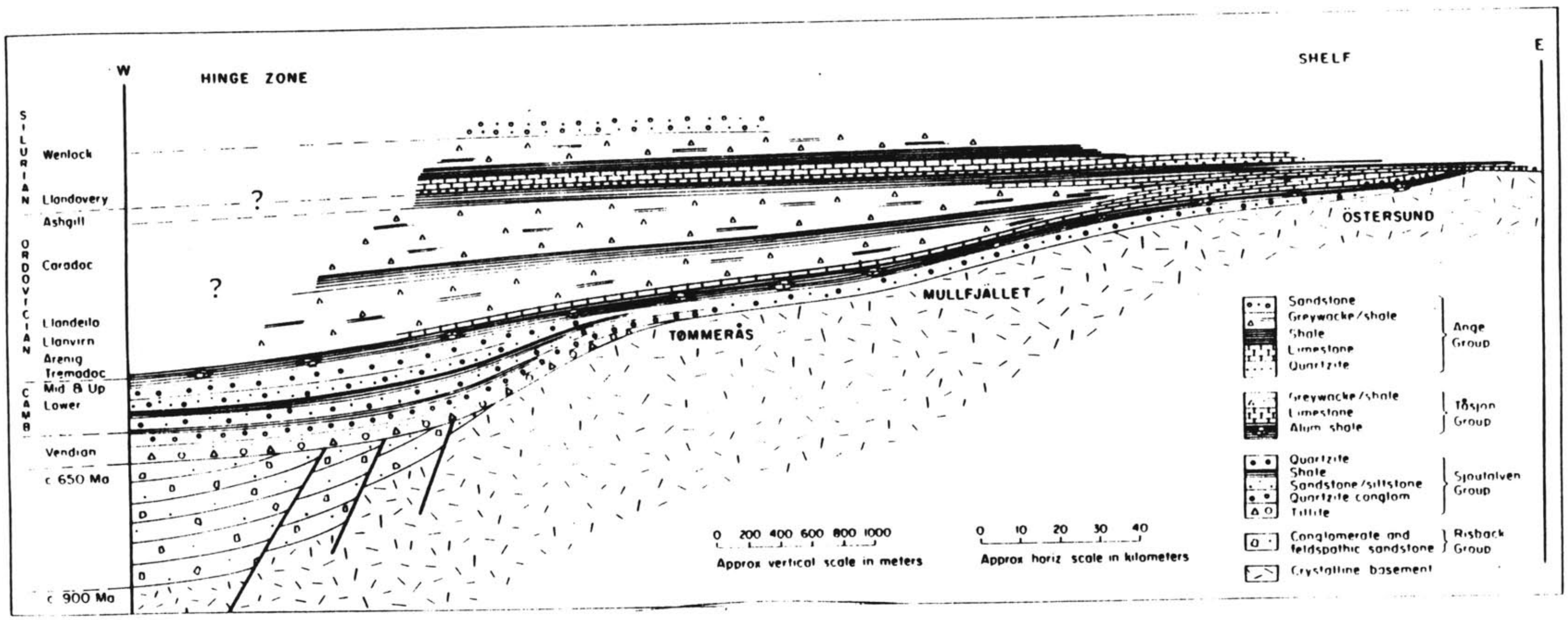
Figure 1 - 1: The Scandinavian Caledonides

the west (Stephens and Gee, 1985)(Fig. 1-2). Rocks of the Autochthon-Parautochthon are preserved within the Baltic Shield east of the present erosional front of the orogen, within windows through the Nappe pile in the central sections of the mountain belt, and along the west coast of Norway.

Separating the far-travelled units in the Upper Allochthon from the autochthonous to parautochthonous rocks of Baltica is a shear zone which has been split into two main units: the Lower Allochthon, and the Middle Allochthon. The Lower Allochthon consist of tillites, shallow marine sandstones, quartzites, uraniferous black shales, and limestones. This sedimentary package termed the Jämtland Supergroup (Gee, 1975) ranges from late Proterozoic to Mid-Ordovician in age and represents the imbricated miogeoclinal wedge of Baltica. The Middle Allochthon is composed primarily of a variably deformed package of granitoids and sediments of Baltic affinity which have undergone in places extreme mylonitization. The Lower Allochthon thins to the North and at the latitude of the Lofoten-Nikkaluokta transect (68°) all rocks between the Autochthon-Parautochthon and the Upper Allochthon have been grouped into the Middle Allochthon. To the south of our transect, in the Akkajaure area, Björklund (1985, 1989) has completed an extremely detailed examination of the Middle Allochthon rocks. He has established that the Middle Allochthon is composed of six rather thin, continuous slivers of sheared Baltic Shield crystalline and sedimentary rocks. Recent mapping by Burchfiel and Royden (1986, 1987) northwest of Akkajaure near the Tysfjord culmination indicate that some of the slivers discussed by Björklund may in fact be caused by repetition due to isoclinal folding with fold axes parallel to S60E,the main transport direction of the nappes, which suggests some degree of south directed movement (Burchfiel, 1989).

Rocks of the Upper Allochthon all have been derived from west of the present Norwegian coast and consist of a complex variably metamorphosed and deformed package which include, ophiolites, metasedimentary rocks, and metavolcanic rocks. In central and northern Scandinavia the rocks have been divided into the Seve, Köli, and Rodingsfjallet

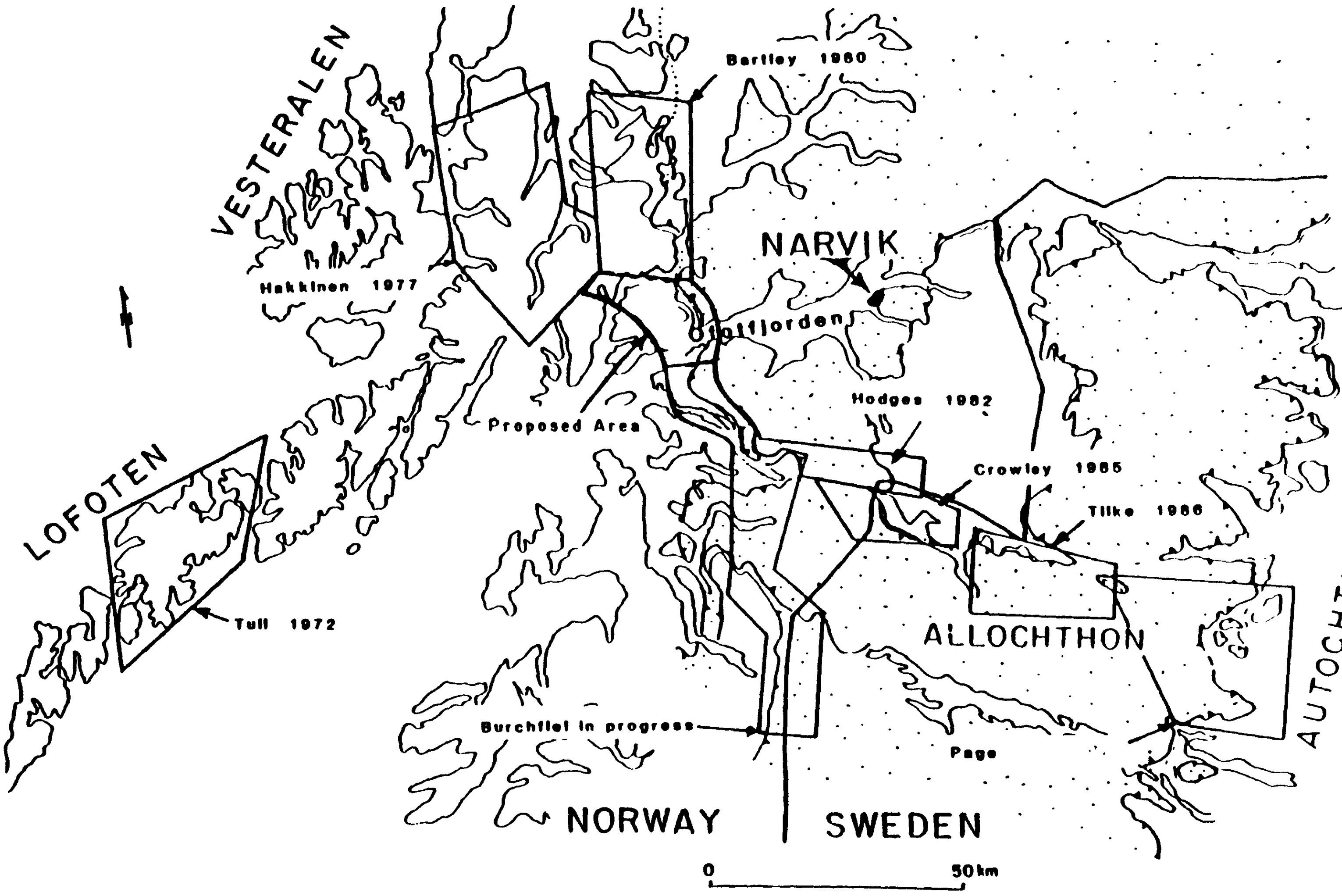
Figure 1-2: Pre-tectonic reconstruction of the Jämtland Supergroup Stratigraphy; from Stephens and Gee (1985)



nappes which themselves consist of a complex package of different rock types. The geologic and tectonic relationship within and between these nappe units and with respect to the rocks of the Baltic Shield has been a focus of much of the recent work within the Caledonides (e.g. Stephens and Gee, 1989; Stephens et. al. 1985; Dallmeyer and Gee, 1986; MIT transect Ph.D. dissertations: Bartley, 1980; Hodges, 1982; Crowley, 1985; Tilke, 1986; This study). These studies have begun to decipher the complex geologic history of the Scandinavian Caledonides and have led to new tectonic models which incorporate the results from a wide variety of geological sub-disciplines.

A geologic examination through the Scandinavian Caledonides along a nearly 200 km transect from the Lofoten Islands in Norway eastward to Nikkaluokta in Sweden (Fig. 1-3) will be concluded with this study. This transect has been studied in a series of Ph.D. dissertations beginning at Rice University and continuing at MIT over the past 18 years under the supervision of Dr. Clark Burchfiel focusing on the processes that occur at lower to mid-crustal levels during continent-continent orogenesis. The transect began with the examinations of Tull (1972, 1977) and Hakkinen (1977) on the Caledonian effects on the crystalline basement of Vestvågöy and western Hinnöy. These studies were followed by the dissertations and related publications of Bartley (1980, 1981, 1982), Hodges (1982a,b, 1984, 1985), Crowley (1985), Tilke (1986), and this study, which examined the complex relationships between and within the Upper Nappe Complex (UNC) and the contact relations between the UNC and the basement of the Baltic Shield. These studies have all utilized (and in some cases developed, ie Hodges and Royden, 1984; Royden and Hodges, 1984) a wide variety of techniques including: field mapping, isotope geochronology, geochemistry, petrography, and quantitative geothermobarometry, to better constrain the geologic history of this complex orogen.

Figure 1-3: Lofoten-Nikkaluokta transect.



Purpose of this study

The Singis-Nikkaluokta portion of the transect represents the eastward completion of the MIT transect to the present day erosional front of the Caledonide mountain belt. The tectonic units represented in this area include: The Upper Allochthon (consisting of the Lower Köli and the Seve Nappes), the Middle Allochthon, and the Autochthon-Parautochthon. The purpose of this study includes:

1) The continuation of field mapping and structural observations to the erosional front of the orogen combined with definition and regional correlation of the tectonostratigraphy of the nappe units.
2) The first detailed examination of the Seve Nappe in the MIT transect
3) The application of isotope geochronology to establish timing of deformation and metamorphism within the different nappe units.
4) Application of quantitative geothermobarometry to establish P-T conditions within the different tectonic units.
5) Integration of the results from the objectives listed above to constrain the geologic history of a portion of the Scandinavian Caledonides.

The nature of the Finnmarkian Orogeny within the Caledonides is a question which may first be addressed and constrained for the transect by the rocks exposed within the Seve Nappe in the Singis-Nikkaluokta region. The Cambro-Ordovician Finnmarkian events are thought to be related to convergent activity that preceeded and was largely overprinted by the Scandian events of Silurian-Devonian age. Due to a recent reinterpretation of the type Finnmarkian (Krill and Zwaan, 1987, 1989) there has been some debate as to what exactly should be termed Finnmarkian (Gee, 1987; Roberts et al, 1985). The definition which will be used in this study follows the usage of Stephens and Gee (1989) which describes the Finnmarkian as relating to metamorphism and deformation of units that were proximal to the Baltoscandian margin during Late Cambrian to Early

Ordovician time. The detailed geochronologic and thermobarometric examination of the Seve Nappe in this study has led to an understanding of the conditions and timing of deformation during the Finnmarkian that when coupled with results obtained for the Scandian phase of deformation place new constraints on the understanding and modeling of the complex polyphase nature of orogenesis within the Caledonides.

Field Methods

Field work was performed during the summers of 1985-1987. Field mapping was done on 1:25,000 scale maps which were enlarged from the 1:100,000 topographic Kebnekaise sheet (29I) published by Statens Lantmäteriverk in 1984. The contour interval for this map is 20 m. The field maps were compiled on a 1:25,000 mylar upon completion of the 1987 field season with a simplified version (Plate 1) included in this dissertation. Mapping was usually accomplished by establishing a base camp for a week to ten days with day hikes radiating away from camp. Access into the area was either by hiking from Nikkaluokta or by helicopter. The area is defined by Kaitumjaure to the south, to the north by an almost 30 km valley leading west from Nikkaluokta (just south of Sweden's highest peak, Kebnekaise-2117 m) to the Singis window, to the east by the erosional front of the orogen, and to the west near lake Vidjajaure to the central part of the Singis window. The physiography of the area is typically a product of glaciation with generally good (70%) exposure. Wildlife in the area include reindeer, fox, wolverine, hare, ptarmigan and various birds of prey including hawks, eagles and falcon.

Chapter 2

Tectonostratigraphy of the Singis-Nikkaluokta Area

The rocks of the Scandinavian Caledonides have conventionally been grouped into five main complexes: The Autochthon and Parautochthon, the Lower Allochthon, the Middle Allochthon, the Upper Allochthon, and the Uppermost Allochthon (Gee, 1975; Stephens, 1985). The rocks of the Lofoton-Nikkaluokta transect fit into these broad categories; however intra-nappe correlations within these units along strike of the orogen are sometimes problematic. The Singis-Nikkaluokta portion of the transect contains rocks from the Upper and Middle Allochthons as well as the Autochthonous-Paratochthonous Baltic Shield. The tectonic units within the study area from the Upper Allochthon can also be grouped within the tectonostratigraphic scheme first developed for the Central Scandinavian Caledonides, which divides the Upper Allochthon into the Köli and Seve Nappes. In this chapter the rocks of the Singis-Nikkaluokta area are described and grouped into a specific tectonostratigraphy and then regional correlations and implications are discussed. Figure 2-1 shows both the regional and the specific unit names for the rocks exposed in the Singis-Nikkaluokta transect.

Upper Allochthon Units

Köli Nappe

Salka Group

The rocks of the Köli Nappe make up the structurally highest level of the tectonostratigraphic package of the Singis-Nikkaluokta transect. Tilke (1986) assigned the rocks in this region to the Salka Group. The Salka group consists of greenschist grade calc-schists, graphitic schists, and chloritic psammites. Stephens (pers. comm.) notes the

Figure 2-1

Upper Allochthon	Köli	Salka Group
	Seve	Vidja Assemblage Aurek Assemblage Savotjåkka Assemblage
Middle Allochthon		Matert Shear Zone Paltavare Shear Zone
Autochthonous-Parautoch. Seds	Tornetrask Fm.	Upper Sandstone Member Red+Green Siltstone Member Lower Sandstone Member
Precambrian Basement	Grunfjell Gp.	

similarity of the rocks in the study area with those of the lower Köli nappes further south in both the Padjalanta region and in the central Scandinavian Caledonides, suggesting that these rocks may be correlated throughout the Caledonides (the same may not be said for the rocks at structurally higher levels from the Lofoten-Nikkaluokta transect). Tilke (1986) further subdivided the Salka Group into the Rusjka Calcareous Schist, the Rusjka Graphitic Schist, and the Patta Quartzite.

Patta Quartzite

The Patta Quartzite was originally named by Kulling (1964) for exposures on Peak Pattajakka which does not appear on the 1:50,000 tectonostratigraphic map (Plate 1), but lies approximately 5 km southwest of Vidjajaure in the western part of the study area. Only the lower 100 meters of the Patta Quartzite were examined in this study. They consist of green to light gray foliated psammite which contains quartz+plagioclase+chlorite+muscovite with minor amounts of biotite and Fe-oxides. Some horizons also contain chloritoid porphyroblasts and pseudomorphs of garnet. Garnet is also present, but mostly has undergone retrograde replacement by chlorite. The lower contact of the Patta Quartzite with the Rusjka Schists is well defined by the more resistant nature of the Patta Quartzite which typically forms an easily discernible ledge just above the contact with the much less resistant schists.

Rusjka Graphitic Schist

The Rusjka Graphitic Schist (RGS) was first mapped by Kulling (1964) and named within the study area by Tilke (1986). The RGS makes up a marker horizon which has been mapped by Kulling (1964) from the Tornetrask area 60 km to the north-northeast of the study area to near Akkajaure approximately 20 km to the south. In the study area it ranges from 10 to 40 meters thick. Weathered surfaces are rust coloured in outcrop, while fresh surfaces are dark black with abundant quartz stringers. No samples were collected from the RGS for this study; however, Tilke (1986) describes a thin-section from this unit that consists of a well foliated quartz-muscovite-graphite-albite schist. The contact between the underlying Rusjka Calcareous Schist and the RGS is generally marked by a bench formed by the slightly more resistant Rusjka Calcareous Schists.

Rusjka Calcareous Schist

The Rusjka Calcareous Schist (RCS) was named by Tilke (1986) for exposures southeast of Rusjka, a mountain just north of the northwest end of the study area. Tilke described the unit as a heterogeneous assemblage dominated by chloritic psammite with discontinuous lenses (up to a few hundred meters) of marble, garnet-muscovite-biotite schists (which contain rotated garnets), garnet-hornblende-calcite schist, graphitic schist and greenschist. The RCS has a variable thickness within the study area but is approximately 250 meters thick just south of Vidjajaure in the western part of the study area (Plate 1). There were no marble lenses within the study area; however, in Tilke's area, the marbles consist of gray to light brown weakly foliated ankeritic zones with dark brown pelitic laminae (Tilke, 1986). Thin-sections of the garnet-mica schists consist predominantly of quartz, plagioclase, muscovite, biotite,and garnet, but also include minor amounts of chlorite and Fe-oxides. The greenschists are dark green and well foliated in outcrop and in thin-section (Tilke, 1986) consist of porphyroblastic zoisite in a matrix of actinolite, epidote, white mica, chlorite, and quartz. Within the study area, the RCS makes up the hanging wall of the Rusjka fault which separates the Köli Nappe from the underlying Seve Nappe.

Seve Nappe

The Seve Nappe within the study area consists of an assemblage of high grade amphibolites, quartzofeldspathic gneisses, meta-gabbros with minor amounts of metacarbonates and quartzites. The rocks have been subdivided into three main units: The Vidja Assemblage, the Aurek Assemblage, and the Savopakte Assemblage. This differs slightly from the tectonostratigraphic classification of Tilke (1986) which groups all of these units into the Aurek assemblage.

Vidja Assemblage

The Vidja Assemblage is named for the exposures of this unit on the east side of Vidjajaure in the western part of the field area (Plate 1). It is composed of three lithologically distinct and interlayered rock types: 1) a light grey, massive, weakly foliated, quartzofeldspathic gneiss, 2) an orange to rust-coloured, well-foliated, more micaceous, quartzofeldspathic gneiss, and 3) a dark green, strongly lineated amphibolite. A few kilometers to the north, in the area mapped by Tilke (1986), there is a unit called the Vidja Biotite Gneiss which overlies the Vidja quartzofeldspathic gneisses but is tectonically cut out to the south by the Rusjka Fault before entering the mapped area. The Vidja Assemblage has an approximate maximum thickness of 2000 meters within the study area; however, the thickness varies considerably along strike because parts of this unit are tectonically removed by the overlying Rusjka fault. Outcrop of the Vidja Assemblage becomes more areally extensive to the south (see Kulling's map, 1964). In the following sections the different units of the Vidja Assemblage are described from the structurally highest to lowest levels

Vidja Amphibolite

The Vidja Amphibolite is exposed in the western part of the field area along the stream Vidjajåkka at the southern end of lake Vidjajaure (Plate 1). It extends discontinuously along strike to the north through the area mapped by Tilke (1986) and is approximately 50-100 meters thick. In outcrop it is dark green with a well-defined lineation (N60W, Fig.2-2) and foliation. In thin section, the Vidja Amphibolite contains

Figure 2-2: N60W mineral lineation within the Vidja Amphibolite.

Figure 2-3 Well-foliated Vidja Muscovite Gneiss near Vidjajaure on the west slope of Sangartjåkka.

hornblende, plagioclase, epidote,and calcite. Tilke (1986) notes that the Vidja Amphibolite in the area he sampled north of Vidjajaure sometimes contains garnets which are poikilitic, porphyroclastic, and retrogressed.

Vidja Muscovite Gneiss

The Vidja Muscovite Gneiss is exposed in the western part of the study area structurally below the Vidja Amphibolite and above the Aurek Assemblage (Plate 1). Its basal contact with the Aurek Assemblage is very sharp and well defined by the more resistant gneiss which typically forms ledges overlying the Aurek Assemblage Amphibolite. Tilke (1986) grouped the Vidja Muscovite Gneiss, the Vidja Quartzofeldspathic Gneiss (described below), and a unit he termed the Vidja Biotite Gneiss into one unit called the Vidja Gneiss. This tectonostratigraphic classification has been modified slightly to better distinguish the different gneiss units. Tilke (1986) described a gradational contact between the muscovite-rich gneiss unit and the quartzofeldspathic gneiss; however, in this study a clear contact could be mapped between the two units and it appears that the interlayering of the muscovite-rich unit with the quartzofeldspathic gneiss unit may be caused by large scale isoclinal folding (see structure chapter). The Vidja Muscovite Gneiss (Fig. 2-3) is a well-foliated, orange-to rust-brown-coloured unit that typically contains 2-3 cm muscovite porphyroblasts. In thin-section the rock consists predominantly of quartz+plagioclase+muscovite+biotite+garnet with minor amounts of secondary chlorite and zoisite. There are two distinct fabrics within the rock (see structure section) with the second foliation defined by planes formed by muscovite, biotite and occasionally chlorite. This second foliation is also associated with retrogressed and porphyroclastic garnets which originally grew during the development of the first foliation. The zoisite is prismatic and is present as overgrowths primarily of plagioclase, while the chlorite is typically associated with the micas and the garnet. The intensity of the second foliation increases toward the contact with the Rusjka Fault.

Vidja Quartzofeldspathic Gneiss

The Vidja Quartzofeldspathic Gneiss (VQG) has a maximum structural thickness of 500 meters and appears between two limbs of the Vidja Muscovite Gneiss within the western part of the study area (Plate 1). In outcrop the VQG is light gray and in thin-section it contains plagioclase+quartz+muscovite+biotite+garnet+kyanite with minor amounts of Fe-oxides and zoisite. The VQG preserves relict sedimentary cross bedding (Fig.2-4) and contains a deformed pebble conglomerate (Fig.2-5). Although the VQG is similar to the Vidja Muscovite gneiss it may be distinguished in the field by its colour and its lack of large muscovite porphyroblasts, and in thin-section by the presence of kyanite and significantly less mica.

Aurek Assemblage

The Aurek Assemblage consists of garnet amphibolites surrounding high grade meta-gabbro and associated relict eclogites. It is named for exposures on peaks Stuor and Unna Aurek in the western part of the field area (Fig.2-6). The Aurek Assemblage has a thickness of up to 1300 M.

Aurek Gabbro

The Aurek Gabbro constitutes the high resistant peaks of Stuor and Unna Aurek (Plate 1). It does not extend north of the Singis window and pinches out with a series of small scale (<100 meters) gabbro boudins encased in an amphibolite sheath (Fig.2-7). The Aurek Gabbro is predominantly white and olive green with orange to rust-brown regions (Fig. 2-8). The internal parts of the gabbro are massive and unfoliated whereas its external parts are sheared and have a foliation parallel to the main regional foliation in the overlying Vidja Gneiss. Besides having a primary igneous texture, parts of the gabbro also show an early Caledonian fabric associated with the M1 metamorphism at eclogite grade. The Aurek

Figure 2-4: Overturned cross bedding preserved within the Vidja Quartzofeldspathic Gneiss, on the east slope of Sangartjåkka.


Nikon

Figure 2-5: Stretch-pebble conglomerate with the long-axis of the deformed pebbles oriented N60W. Photo taken on the east slope of Sangartjåkka.

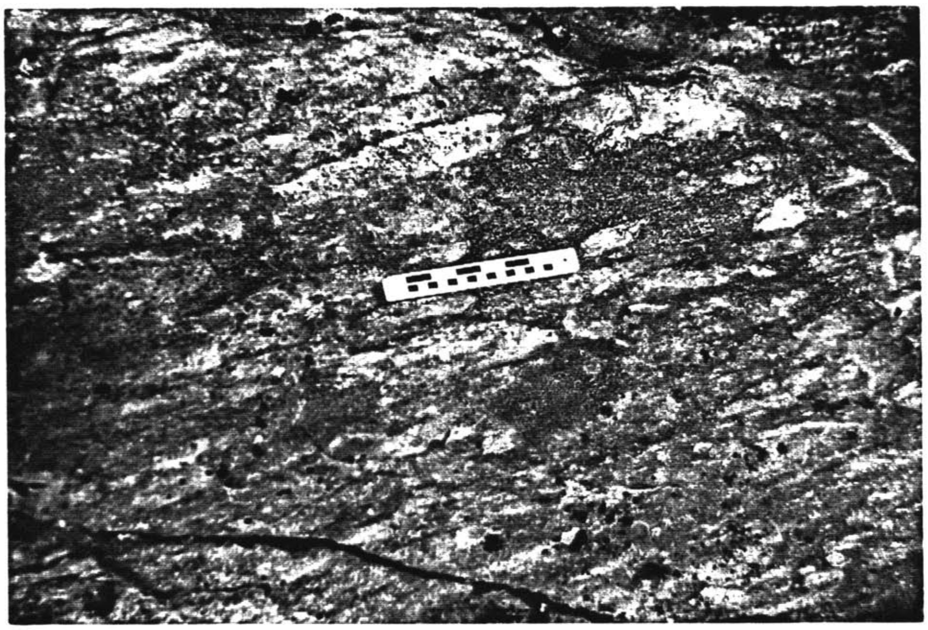


Figure 2-6: Upper photograph-View looking north towards Unna Aurek showing the western-portion of the Aurek Assemblage Gabbro in contact with the Vidja Muscovite Gneiss.

Lower photograph-View Looking north from easternmost portion of Unna Aurek towards the Aurek Gabbro on Stuor Aurek.

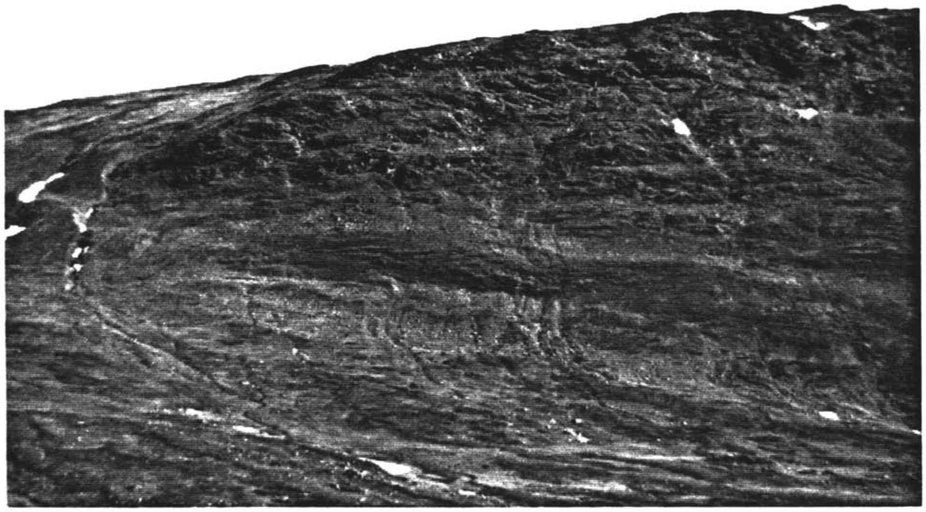


Figure 2-7: Aurek Assemblage meta-gabbro boudin. View looking north at eastern end of Sangarvagge.

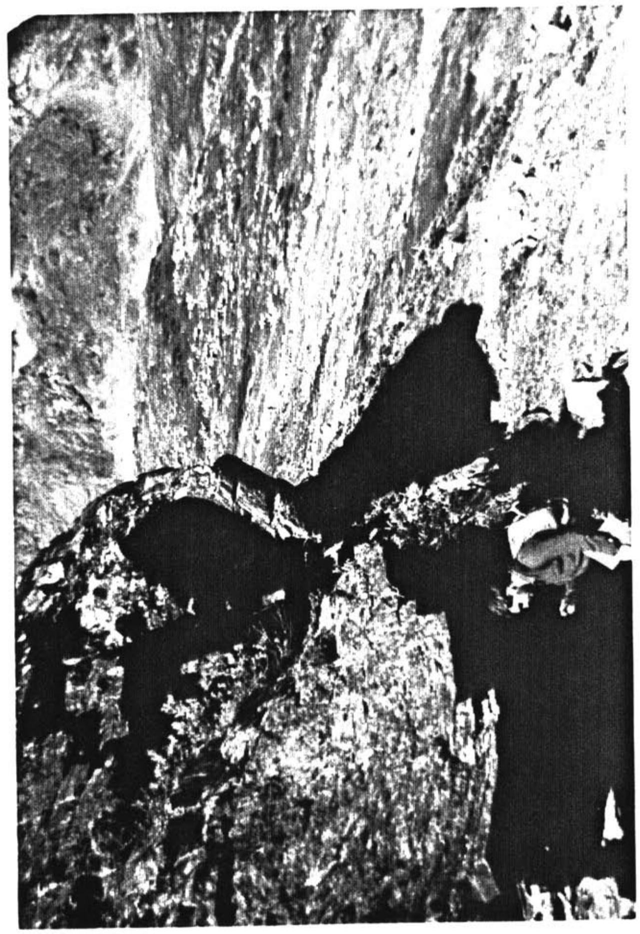
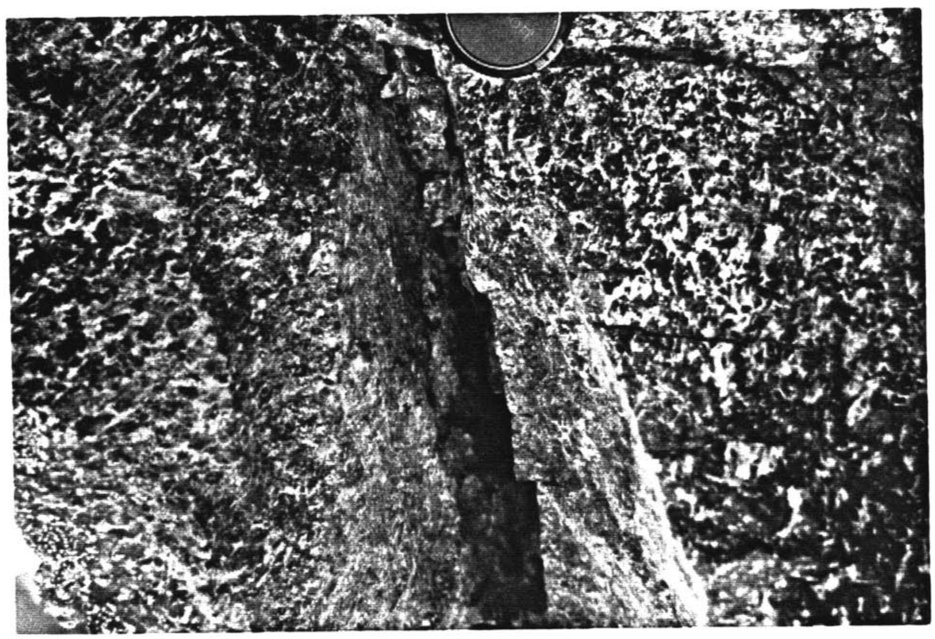


Figure 2-8: Weakly foliated Aurek Gabbro from Stuor Aurek.



Gabbro contains a primary igneous cumulate layering on the scale of a few hundred meters and in some places on a meter scale. The attitude of the cumulate layers (N50E, 60N) is discordant to and cut by many of the Caledonian aged regional foliations. As described in Tilke (1986), the primary igneous mineralogy of the Aurek Gabbro is a medium-grained (1-5mm), granoblastic plagioclase-olivine-augite-magnetite gabbro. The rust weathering ridges that make up the other part of the cumulate layering consist primarily of olivine. In places the gabbro has been variably metamorphosed under eclogite conditions. These regions have a very complex mineralogy which is discussed within the metamorphic chapter. Following eclogite metamorphism the gabbro underwent amphibolite grade metamorphism. The effects of this later metamorphism are best developed near the sheared margins of the gabbro body. These amphibolite grade rocks of the Aurek Gabbro consist of hornblende+plagioclase+zoisite+calcite. Tilke (1986) also describes some shear zone samples which consist of hornblende+scapolite+plagioclase and garnet.

Aurek Amphibolite

The Aurek Amphibolite surrounds the Aurek Gabbro and varies from 50 to 100 m thick. In outcrop the Aurek Amphibolite is dark black to green with minor discontinuous small (1-10 m) lenses of gabbroic rock. The Amphibolite is well foliated and in thin-section consists of hornblende+plagioclase+garnet+zoisite+Fe-oxides±biotite. Tilke (1986) also reports an assemblage of actinolite+scapolite+calcite quartz+garnet. Tilke (1986) interpreted the Aurek Assemblage as a reaction skarn (Brady, 1977) between the mafic Aurek Gabbro lenses and the quartzofeldspathic rocks of the surrounding Vidja gneiss. Argon geochronology (see argon chapter) suggests that the Aurek Amphibolite may be a late Finnmarkian shear zone that juxtaposed the Vidja Gneiss and the Aurek Gabbro.

Savotjåkka Assemblage

The Savotjåkka Assemblage is named for exposures on the peak Savotjåkka in the north-central part of the study area, just west of the Savovagge Valley (Plate 1). It comprises much of the exposed portions of the Upper Nappe Complex within the field area. The Savotjåkka Assemblage consists of interlayered garnet amphibolite and quartzofeldspathic gneiss with minor discontinuous lenses of meta-gabbro and carbonate rocks. The layering of the quartzofeldspathic gneisses within the garnet amphibolites is both on a large (km) and small (few meters) scale. The basic mineralogy and appearance of the units will be discussed below. The units will also be discussed in the relevant sections in the structure, metamorphic and geochronologic chapters.

Savotjåkka Amphibolites

The Savotjåkka Amphibolites (SA) are dark green to black in outcrop. The rocks are well foliated with a general regional attitude of N10-30°E 30°N (Fig. 2-9). The lithology of the amphibolites is variable and ranges from hornblende+plagioclase+fe oxides to hornblende+plagioclase+fe oxides ±garnet,biotite, epidote, zoisite, sphene and calcite. The hornblendes are generally prismatic while garnets are porphyroblastic and sometimes poikilitic. Samples located near the Middle Allochthon shear zones are often mylonitized and retrogressed to greenschist grade and have a mineralogy that includes chlorite, actinolite, epidote and porphyroclasts of garnet.

Savotjåkka Quartzofeldspathic Gneiss

The Savotjåkka Quartzofeldspathic Gneiss (SQG) is usually a light gray or rusty orange colour with a well developed axial planar foliation (Fig.2-10). The gneisses are compositionally variable and include rocks consisting primarily of quartz+plagioclase+muscovite to rocks consisting of quartz+plagioclase+muscovite and including some of the following minerals: garnet, biotite, epidote, zoisite, calcite, Fe-

Figure 2-9: Well-foliated garnet-amphibolite from the Savotjåkka Assemblage. View looking northwest on the southwest slope of Liddopakte.

Figure 2-10: Flaggy quartzofeldspathic gneiss with a N0W 25°W foliation from the Savotjåkka Assemblage near the peak of Läipetjäpetjåkka.

oxides, and sphene. Near the contact with the Middle Allochthon shear zone retrograde chlorite is often present replacing garnet and biotite. The mineralogy and pressures and temperatures of the SQG will be discussed in greater detail in the metamorphic chapter.

Manak Gabbro

The Manak Gabbro is named for exposures on the peak Manak in the south central part of the area (Fig. 2-11). It is medium to coarse-grained and is white and olive green on fresh surfaces. The Manak Gabbro is intruded by fine-grained diabase dikes. Placement of this unit in the Upper or Middle Allochthon is somewhat problematic because while lithologically the Manak Gabbro is quite similar to the unmetamorphosed portions of the Aurek Gabbro it is relatively unmetamorphosed and is contained in places within rocks which are mylonitized and appear in all ways similar to parts of the Middle Allochthon mylonites. The Manak Gabbro has been placed in the upper allochthon in this study because of geochronologic aurguments developed within the Argon chapter (Chapter 6) which indicate that a muscovite collected from the Savotjåkka Assemblage directly above the Manak assemblage gives a Finnmarkian age which was not reset during the Scandian emplacement onto the Middle Allochthon.

Middle Allochthon Units

The Middle Allochthon consists of a heterogeneous assemblage of variably mylonitized sediments and Baltic Shield crystalline rocks. Within the study area, the Middle Allochthon have been split into two units: the Matert Shear zone and the Paltavare Shear Zone. The Matert Shear zone was first named by Tilke (1986) for rocks which are exposed in the western half of the Singis window. The Paltavare Shear Zone was named for exposures on peak Paltavare in the southeast section of the field area (plate 1). Contact relationships between the Middle Allochthon and both the overlying and underlying units

Figure 2-11: View looking southwest of the Manak Gabbro, peak Manak in the foreground.

Figure 2-12: Contact betwen the overlying Seve assemblage (high peak to the right of the photograph) and the Manak Assemblage (lower peak to the left). This package structurally overlies the Middle Allochthon. View looking southwest towards Skartavartoh from Paikejaurasj.

are very sharp and easily discernible in the field. Within the top few tens of meters of the shear zone retrogressed and highly strained slivers of the Upper Allochthon are quite common. The structural relationship between the Matert Shear Zone and the Paltavare Shear Zone cannot be determined from field relationships. The two were differentiated because of the greater structural thickness of the shear zone rocks in the front of the range as well as on minor stratigraphic differences.

Matert Shear Zone

Rocks of the Matert Shear Zone along the western margin of the Singis window (Plate 1) consist predominantly of a relatively thin (20-50 m) matrix schist that consists of either a graphite, quartz, muscovite schist or a quartz muscovite schist, both of which may have subordinate chlorite, epidote, calcite or apatite (Tilke 1986). The north-central part and the eastern section of the Singis window consists of slivers of variably deformed granitic rock containing an S-C fabric that defines an east-southeast vergent direction of transport. In the northeast section of the Singis window, sheared discontinous slivers of upper allochthon lithologies are incorporated within the Middle Allochthon. These slivers consist of retrogressed amphibolite and garnet-bearing muscovite gneiss whose original foliation has been transposed by a mylonitic foliation associated with the development of the Middle Allochthon.

Paltavare Shear Zone

Rocks of the Paltavare Shear Zone (Plate 1) consist primarily of variably mylonitized granitic rock with lesser amounts of mylonitized quartzite and phyllonite. Mostly the original rock has been completely sheared and recrystallized such that field identification of the protoloth is extremely difficult (Fig. 2-13) The granites often show excellent examples of strain localization and may pass from unfoliated to completely mylonitized and recrystallized within a few meters (see Fig. 3-9, in structure section).

Figure 2-13: Banded ultramylonite from the Paltavare Shear Zone of the Middle Allochthon. Photograph taken on peak Paltavare.

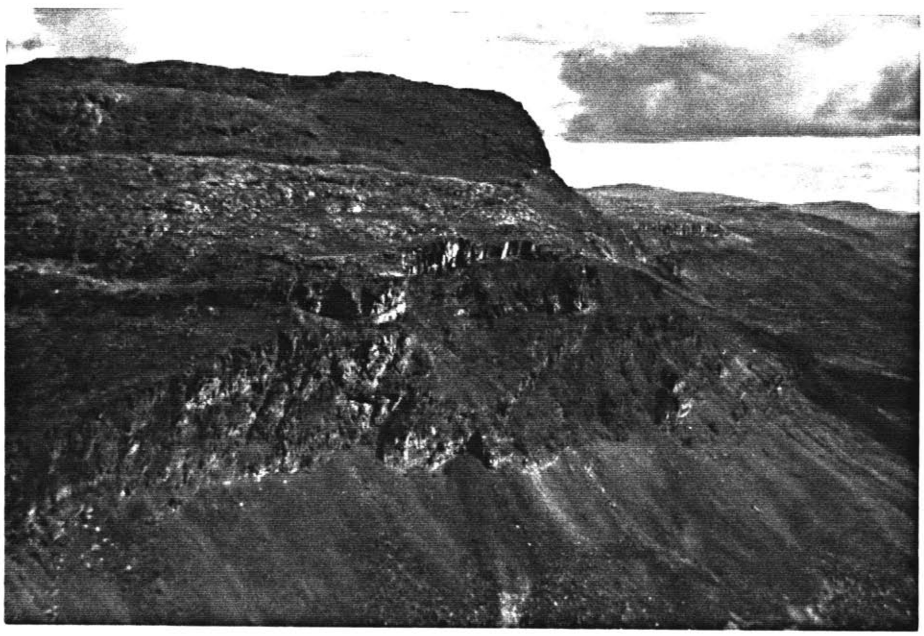
Within the Paltavare Shear Zone in the north-central section of the study area (Plate 1) is a distinctive discontinous lens of black micaceous phyllonite whith a maximun thickness of 100 meters. The quartzites are typically weakly banded and in thin-section are almost completely recrystallized.

Autochthon-Parautochthon

Dividal Group

The Dividal Group consists of a sedimentary sequence of sandstones, siltstones, and conglomerates of Vendian-Cambrian age that lie unconformably on the Proterozoic basement of the Baltic Shield foreland. Thelander (1982) subdivided the Dividal Group into two formations, the Tornetrask Formation and overlying Alum Shale. In the type area Thelander subdivided the Tornetrask Formation into six members. Tilke (1986) correlated three of these members with rocks exposed within the MIT transect area. The three members are: a Lower Sandstone member of quartzite, sandstone, and conglomerate, A Red and Green siltstone member, and an Upper Sandstone member of blue-gray siltstone and blue quartzite. In the study area these sedimentary rocks are exposed in both the foreland and within the Singis window (Plate 1). Above the crystalline basement in the Singis window a basal conglomerate is sometimes present. The Dividal Group rocks within the Singis window have been tectonically folded and faulted and contain a pervasive schistosity near the contact with the overlying Matert Shear Zone. At the eastern front of the range only blue-gray siltstone and blue quartzite of the Upper Siltstone Member is exposed and these rocks also have a well developed schistosity near the contact with the Middle Allochthon mylonites (Fig. 14).

Figure 2-14: View looking north along the present day erosional front of the orogen. The massive ledge forming rocks are composed of the Middle Allochthon which structurly overlies sediments of the Autochthon-Parautochthon.



Crystalline Basement

A detailed analysis of the crystalline basement rocks in the Singis-Nikkaluokta area was not attempted in this study because: the crystalline rocks of the foreland are not exposed in the low lying parts of the study area which are covered by tundra; and the crystalline rocks of the Singis window have been discussed in detail by Tilke (1986). Gunner (1981) correlated the Proterozoic rocks in the Rombak-Sjangeli window, west of the mapped area, with the rocks in the Baltic foreland. An Rb/Sr age of 1690±90 Ma. for rocks in the Rombak-Sjangeli window was determined by Heier and Compston (1969). Tilke (1986) noted that greenschist alteration and strain of the basement rocks are prevalent throughout the study area.

Regional Correlations

Köli Nappe

The greenschist grade psammites of the Salka Group may be regionally correlated with metasedimentary rocks in the Lower Köli Nappe which contain fossils of Ashgillian age (Kulling, 1972) in the central part of the Scandinavian Caledonides. Reconnaissance mapping by Stephens (pers. comm.) notes the similarity of lithologies within the study area with rocks from the Lower Köli in other regions throughout the Caledonides.

Seve Nappe

The Seve Nappe extends for more than 800 km along the strike of the Scandinavian Caledonides and consists predominantly of a complex variably metamorphosed package of psammitic and pelitic schists, amphibolites, dike intruded sediments and some larger mafic igneous massifs. Many units within the Seve Nappe have been interpreted to have been derived from the westernmost portions of the Baltoscandian Margin (Gee, 1975). Many recent studies have focused on mapping and petrochemical analyses of mafic dike swarms and sheeted dike complexes within the Seve which have been interpreted as being related to initial rifting along Iapetus (Svenningsen, 1987; 1989, Andreasson, 1986;1987, van Roermund, 1985). Svenningsen (1989) obtained a Sm-Nd crystallization age of ca. 600 Ma for sheeted dikes found within the Sarektjåkka Nappe of the Seve in the Sarek area about 75 km south of the area in this study. This age is interpreted to be the age of Iapetus rifting with the dikes intruding a sedimentary sequence on the western margin of Baltica.

The Seve rocks of the Singis-Nikkaluokta region contain high grade amphibolite, paragneiss, and eclogitized meta-gabbro. Preliminary reconnaissance mapping by Andréasson and Gee (1989) indicates that rocks of the Kebnekaise Massif, just to the north of the study area, contain dike swarms intruding meta-sedimentary rocks that structurally overlie the higher grade paragneisses of the Seve units of this study. The dike-intruded unit of the Kebnekaise area is very distinctive and can be correlated with the Sarektjåkka unit (Andreasson, 1986) which makes up part of the Sarek lens of Zachrisson and Stephens (1984) in the Sarek area 75 km to the south. The unit structurally below the Sarektjåkka Nappe (or the Sarek Lens) in the Sarek National Park contains quartzite, eclogites, amphibolites, and psammitic schist and has been assigned to the Mikka Nappe in the area mapped by Svenningsen (1989). This unit is also correlated with the Juron quartzites of Kulling (1982) which makes up part of the Vaimok lens defined by Zachrisson and Stephens (1984). The structural position of the Seve units in this study below the dike intruded units of the Kebnekaise massif, which are reliably correlated with the Sarek lens, together with the presence of eclogites indicate that the Seve in the study area may be correlated with the Vaimok lens (or Juron Quartzite of Kulling) on a regional scale.

Middle Allochthon

The rocks of the Matert Shear Zone and Paltavare Shear Zone are lithologicaly similar to rocks of the Akkajaure Nappe Complex described by Björkland (1989) for the excellent exposures of the Middle Allochthon near Akkajaure 30 km to the south of the present study area. There Björkland has observed six variably deformed slivers of sheared sediments and crystalline basement of Baltic affinities which may be traced more than 150 km from the Caledonian front to near the Norwegian coast.

Basement Sediments and Crystallines

The sedimentary cover rocks and the crystalline basement of the study area may easily be correlated throughout the region with the Dividal Group of Vendian- Cambrian age which unconformably overlies the Proterozoic basement throughout the Northern Caledonide foreland.

Chapter 3

Caledonian Structure of the Singis-Nikkaluokta Area

Caledonian structures of the Singis-Nikkaluokta area are the products of eight deformational events (Table 3-1) associated with two major tectonothermal events. When presenting structural data there are several different methods from which to choose. Tilke (1986) chose to present his data by splitting his map area into distinct structural domains and described and classified the deformation within each domain such that he would have AAD1 and SGD1 to represent the first deformation within the Aurek Assemblage and the Salka Group respectfully. Other workers in the MIT transect have chosen to present their structural data by describing the effects of each deformation on whichever units contain evidence for that specific event. In this chapter, each of the deformational events from the oldest to the youngest will be discussed with representative photographs and stereonet plots given when needed.

D1: Deformation associated with eclogite-grade metamorphism.

The meta-gabbros of the Aurek Assemblage on Stuor and Unna Aurek in the western part of the study area (Plate 1) show evidence for an early (pre-490 Ma) eclogite-grade metamorphism and associated weak foliation with no consistent orientation which is superimposed on the original igneous layering and texture. The eclogite metamorphism of this unit is discussed in detail in the metamorphic chapter of this thesis. The meta-gabbro has a lens-shaped geometry and is encased within garnet amphibolite on the margins with several smaller boudin like bodies of gabbro within the amphibolite to the south of Stuor Aurek. The gabbro body becomes progressively sheared towards its contact with the surrounding garnet amphibolites.

Table 3-1 DEFORMATIONAL EVENTS IN THE SINGIS-NIKKALUOKTA AREA

D1: Deformation associated with the high grade eclogite metamorphism of the Aurek Assemblage meta-gabbro.

D2: Deformation and associated upper amphibolite grade metamorphism within the Seve Nappe. Main isoclinal axial planar foliation N10-25E 25W. Intersection and mineral lineations N60W 10.

D3: Deformation and associated greenschist metamorphism within the Lower Köli Nappe. Isoclinal axial planar foliation N20-30E 25W, mineral and intersection lineations oriented N60W 0-10.

D4: Juxtaposition of Köli and Seve Nappes. Transposition of D2 fabric within Seve. Sygmoidal inclusion trails within Köli garnets indicate SE directed thrusting.

D5: Emplacement of Upper Allochthon Nappe complex onto Baltic shield. Formation of Middle Allochthon mylonites during S60E thrusting.

D6: Gentle N60W warping on both local and regional scale

D7: Late N30E warping of entire Nappe package

D8: West-vergent backfolding or normal faulting(?) along Seve-Köli contact.

D2: Dominant Deformation and Metamorphism within the Seve Nappe

The D2 event is the main foliation producing event associated with high-grade metamorphism in the Seve Nappe. The regional foliation is axial planar to tight isoclinal folds with a mean orientation of fold axes oriented N60W 10° to S60E 10°. Mineral and intersection lineations are consistently parallel to these fold axes (Fig. 3-1). Isoclinal fold axes that parallel the inferred transport direction is widely observed throughout the Scandinavian Caledonides and other high-grade deformed regions (Björklund, 1989; Tilke, 1986). Clasts in highly deformed pebble conglomerate present within the Vidja Assemblage show elongation also parallel to the regional N60W transport direction (Fig. 2-5). The isoclinal folding is observed on both the meter and kilometer scales. Within the Vidja Assemblage in the western part of the study area large scale folds have been mapped (Plate 1). The S2 foliation ranges from N20E 25W in the eastern part of the study area to N15W 30W within the western Seve (Figs. 3-2, 3-3). The metamorphism is synkinematic with the isoclinal folding as the minerals within the hinges of the folds show no evidence of post-growth D2 deformation. The main foliation in the garnet amphibolites is defined by mafic-felsic segregations, while the foliation planes in the quartzofeldspathic gneisses are typically micaceous. Near the Singis window, in the area mapped by Tilke, the main S2 foliation (AAD1 of Tilke) has been overprinted and transposed by lower grade D4 and D5 foliations in association respectively with the juxtaposition of the Seve and Köli Nappes and the emplacement of the Seve-Köli Nappe Complex onto the Baltic Shield (AAD2, AAD3), such that most of the original fabric and mineralogy has been altered. From Tilke's area near the Singis window south into the area mapped in this study, more of the D2 fabrics are preserved; however, rocks near the Rusjka fault show a lower grade retrogressive foliation which transposes the original S2 foliation into parallelism with the strike of the Rusjka fault. Timing of the D2 deformation is given by Ar^{40}/Ar^{39}

Figure 3-1: Seve isoclinal fold axes and lineations

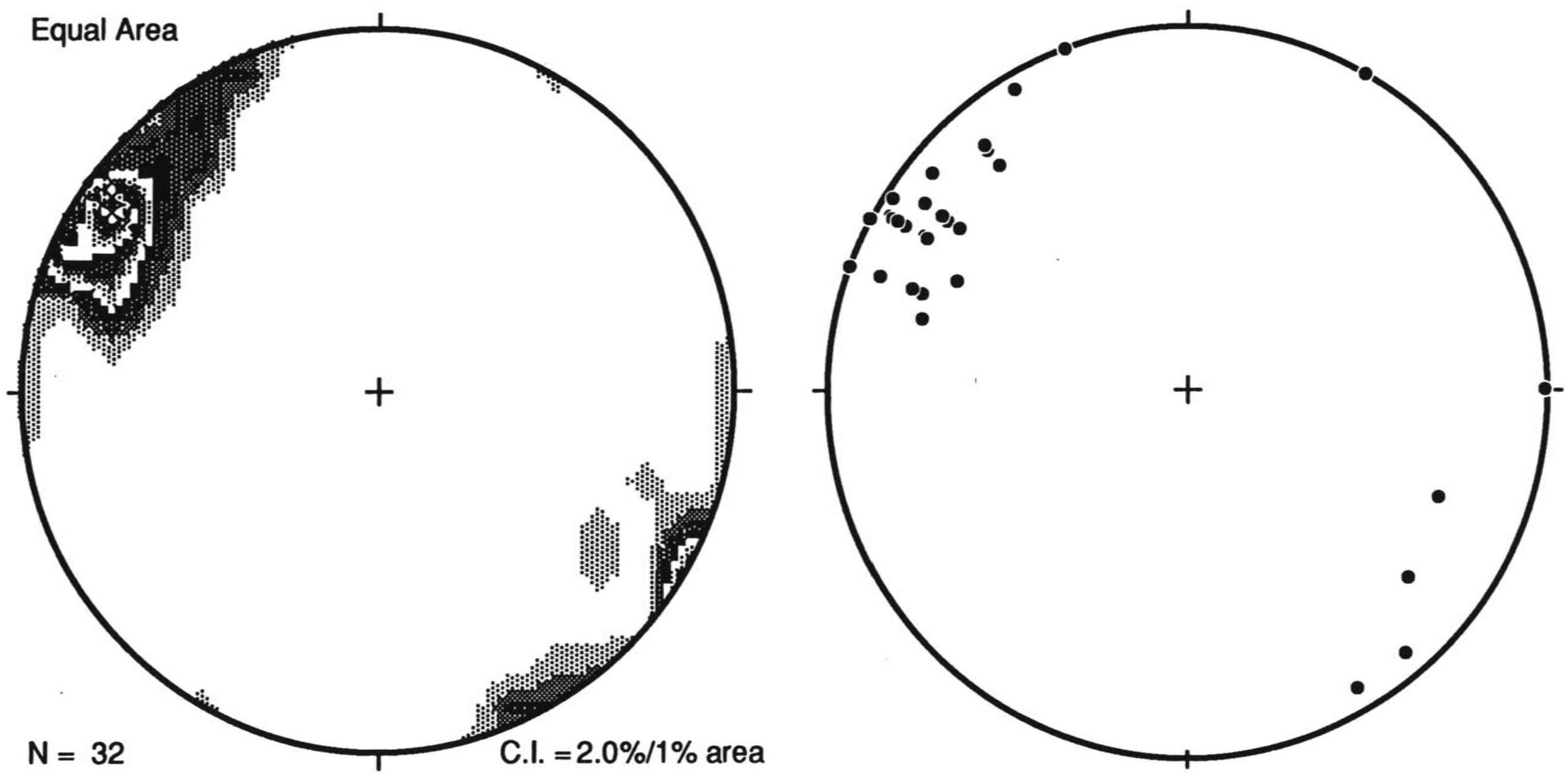


Figure: 3-2

EAST SEVE D2 FOLIATION

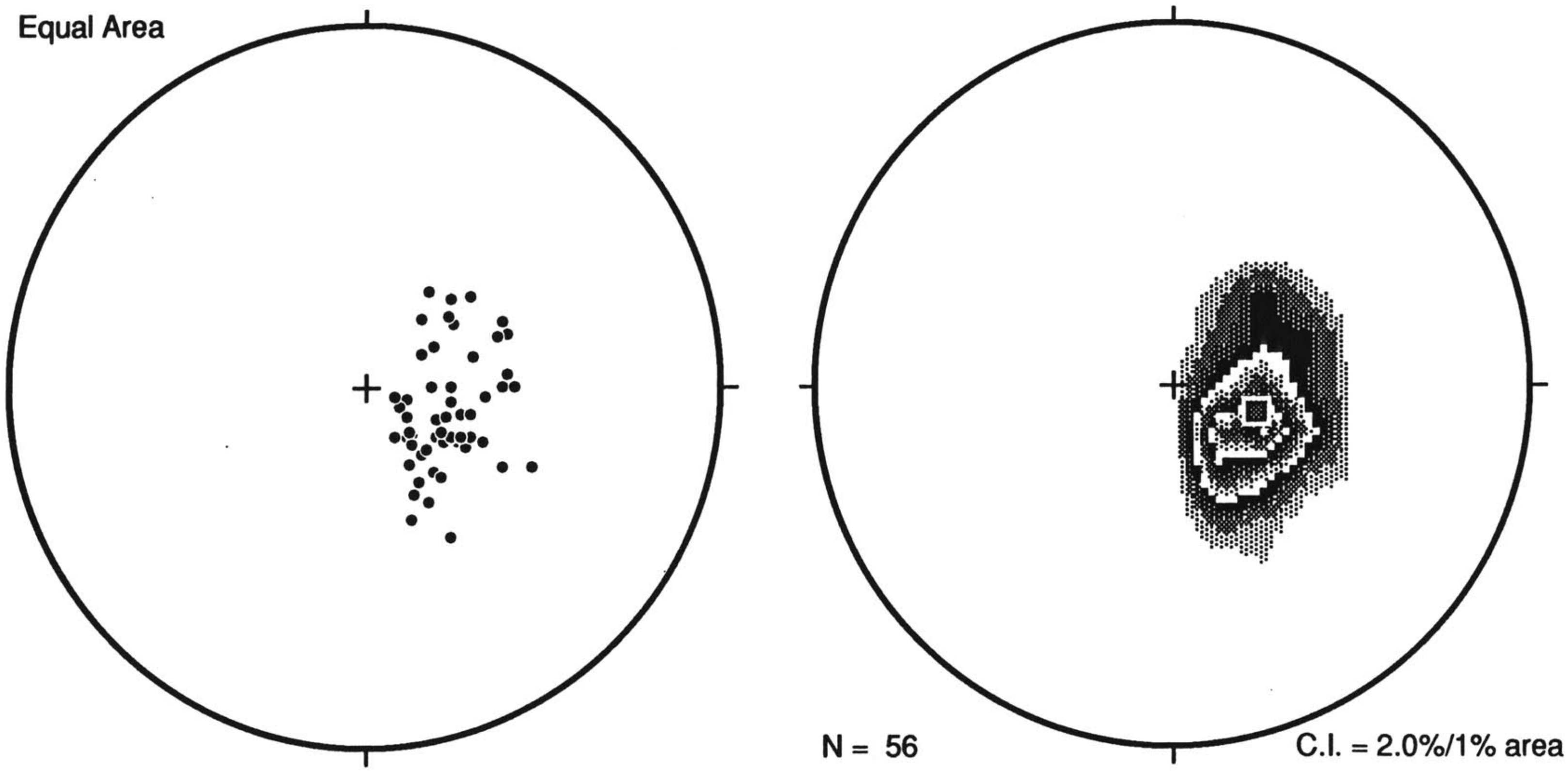
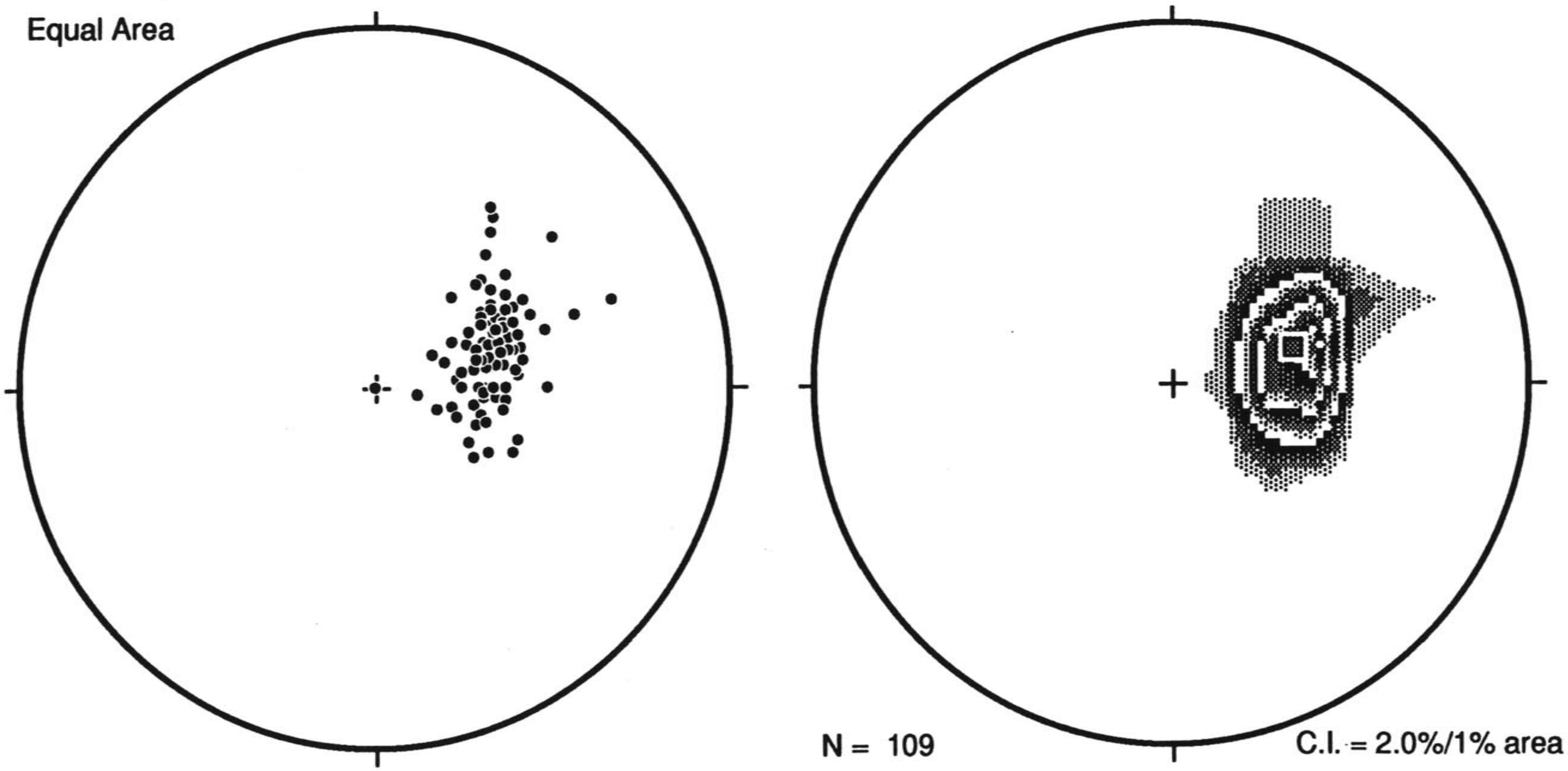


Figure 3-3

WEST SEVE D2 FOLIATION



geochronology (see Ar chapter) on synkinematic hornblendes that yield Early Ordovician (Finnmarkian) ages for cooling below 500° C.

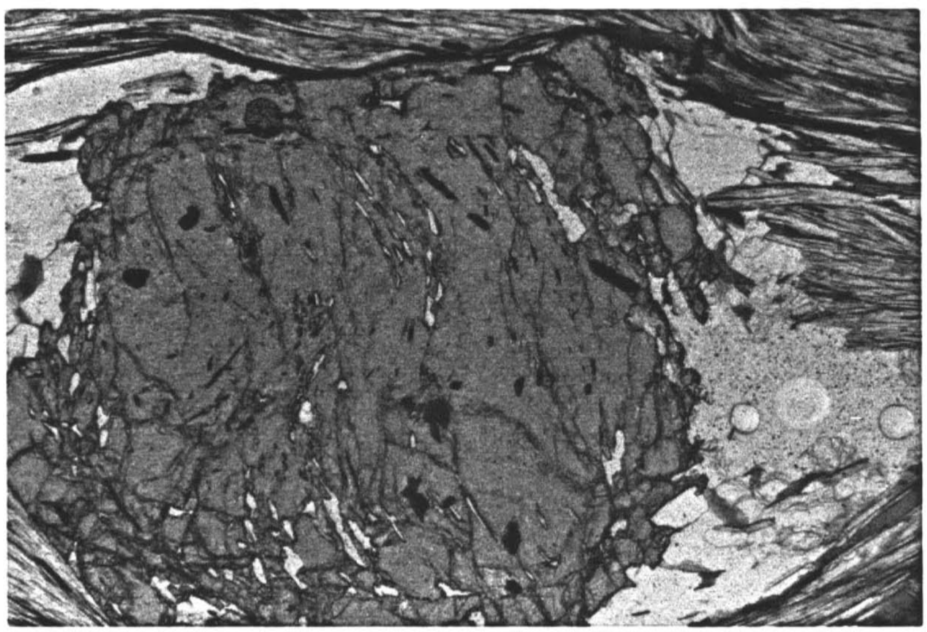
D3: Dominant Metamorphism and Deformation within the Köli Nappe.

The S3 foliation formed within the lower Köli Nappe (Salka Group) has essentially the same relationships to isoclinal folds and lineations as described for the D2 structures in the Seve Nappe. The two foliations can be differentiated in the field by the lower metamorphic grade of the synkinematic minerals of the greenschist grade Salka Group and in the lab by Ar^{40}/Ar^{39} geochronology which demonstrates that the greenschist metamorphism associated with deformation of the the Lower Köli is Early Silurian in age. The age difference is supported by the Early Ordovician ages in the Seve. Regional stratigraphic correlation of the Lower Köli rocks with rocks which contain fossils of post-Finnmarkian Ashgillian age (see stratigraphy chapter). The main S3 foliation has an attitude of N0-30E 25-30W and is also axial planar to isoclinal fold axes which trend N50-60W, parallel to associated mineral and intersection lineations.

D4: Juxtaposition of Köli and Seve Nappes

The Köli Nappe was thrust onto the Seve Nappe within the study area along the Rusjka fault during Early Silurian time (see Ar chapter). Towards the Rusjka fault, the rocks of the Köli Nappe become strongly affected by D4 deformation such that most of the D3 foliation is transposed into parallelism with the foliation in the fault zone. Within the base of the Salka Group of the Lower Köli Nappe, sygmoidal inclusion trails within garnet indicate syntectonic garnet growth with the rotation recorded in the garnets indicating southeast directed shear (Fig. 3-4). The underlying Vidja Gneiss of the Seve contains a penetrative biotite grade schistosity which transposes the older S2 foliation with increasing

Figure 3-4: Garnet collected from the Seve-Köli shear zone containing sygmoidal inclusion trails which indicate top to the right (SE) directed shear.



intensity near the contact with the Rusjka Fault (Fig. 3-5). Tilke (1986) documented a slight increase from biotite-chlorite grade to garnet grade metamorphism of the Salka Group rocks towards the contact with the Rusjka fault coupled with the biotite grade retrogression of parts of the Vidja Gneiss unit of the Seve Nappe in an area just to the north of the present study area. Tilke attributed this pairing of lower grade rocks with an increase in metamorphism toward the fault to be related to shear heating along the Rusjka Fault. Ar^{40}/Ar^{39} muscovite ages (Ar chapter, this study) for samples collected within the shear zone give ages of 432-425 Ma.

D5: Emplacement of Upper Allochthon on Baltic Shield

The D5 deformation is related to the emplacement of the Upper Allochthon onto the Baltic Shield concomitant with formation of the Middle Allochthon mylonites. It effects the entire tectonostratigraphic package in the Singis-Nikkaluokta region. The Middle Allochthon mylonites of the Matert Complex and the Paltavare Complex formed during this event and yield Ar^{40}/Ar^{39} muscovite ages of approximately 430-425 Ma.. These ages are, within scatter, indistinguishable from those associated with the D4 juxtaposition of the Seve and Köli Nappes; however, within the Singis Window (Plate 1) the S5 foliation clearly transposes the S4 foliation. This D5 deformation was coaxial with both the D2 deformation which affected the Seve and the D3 which affected the Köli. Stereonet plots (Fig. 3-6) of the S5 mylonitic foliation, which is axial planar to intrafolial isoclinal folds (Fig. 3-7), show the mean foliation within the southern Paltavare complex to be N28E 22W and the isoclinal fold axes and both mineral and intersection lineations to be oriented 13°, N55E (Fig. 3-8). The slight girdle distributed about the mean in the stereonet shown in figure 6 is caused by later D6 gentle warping along N60E axes. The mylonitization within the Middle Allochthon is highly variable. Figure 3-9 shows a typical Middle Allochthon example of shear localization in which a granitoid rock of Baltic affinity ranges

Figure 3-5: Sample from the Vidja Assemblage collected near the Rusjka Fault containing both a S2 and a later S4 biotite-grade retrogression associated with the juxtaposition of the Köli and Seve Nappes.

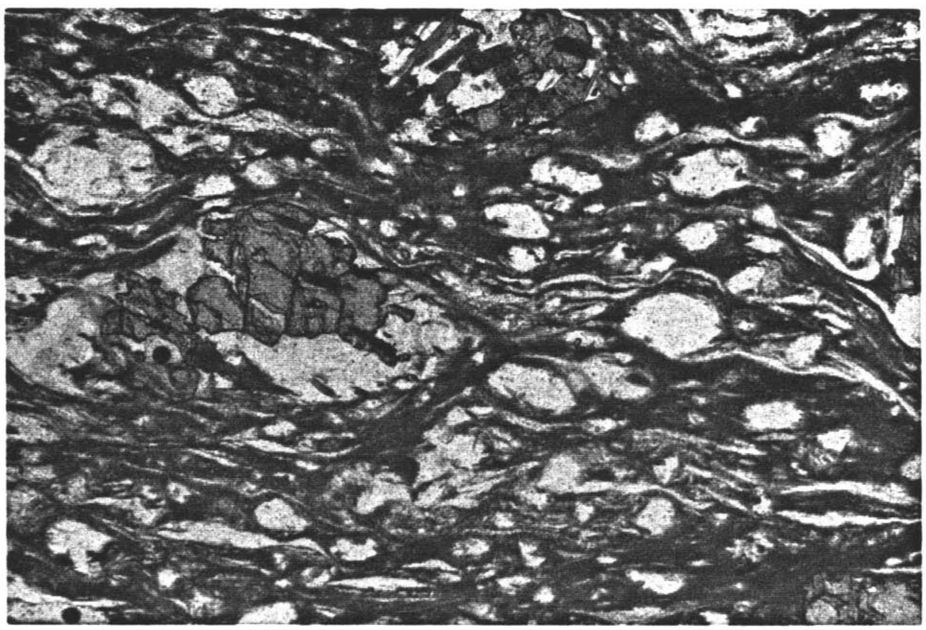


Figure 3-6
Middle Allochthon S5 Foliation

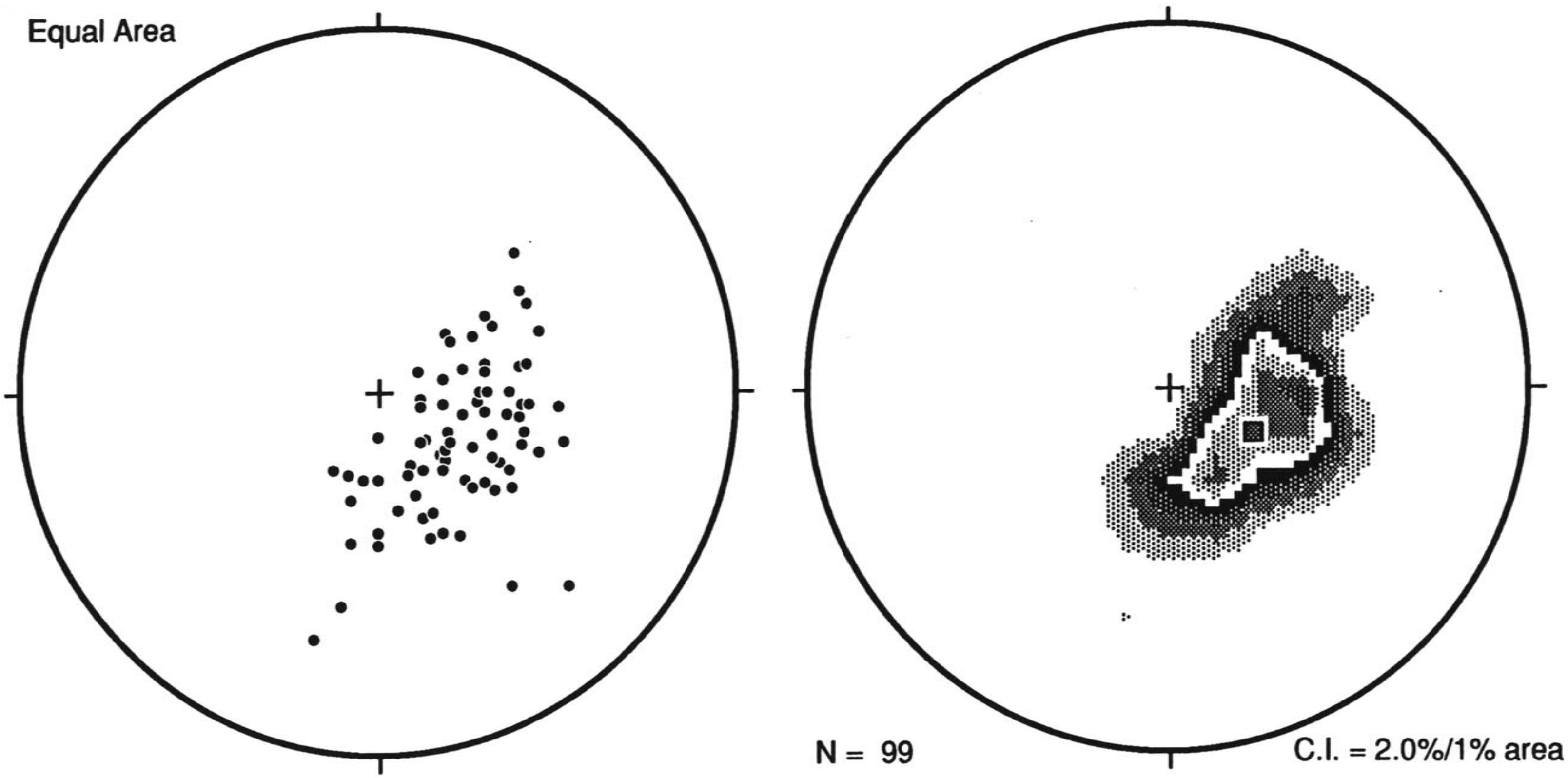


Figure 3-7: Banded ultramylonite containing isoclinal axial planar intrafolial folds. Fold axes have a N60W orientation.

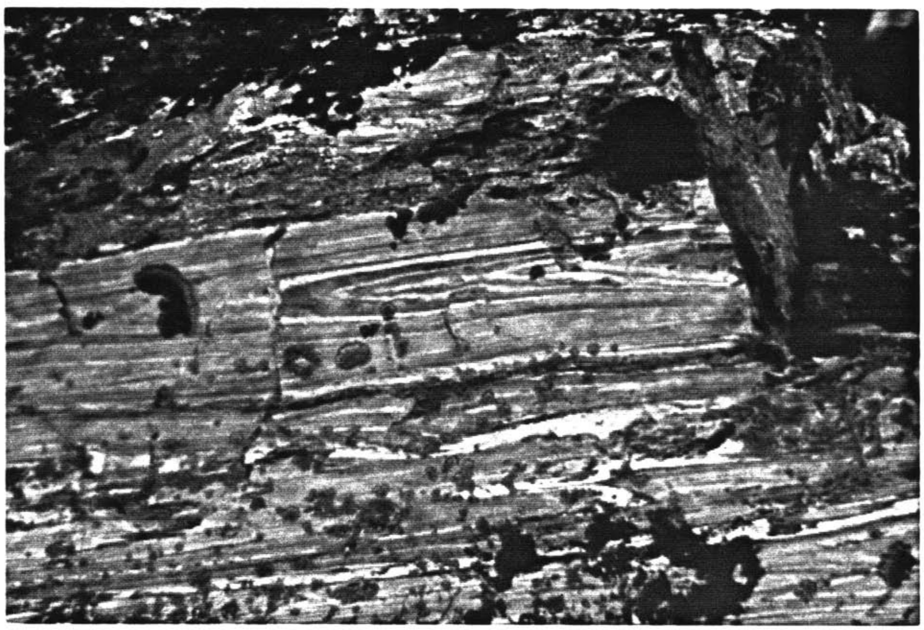


Figure 3-8
Middle Allochthon Isoclinal Fold Axes

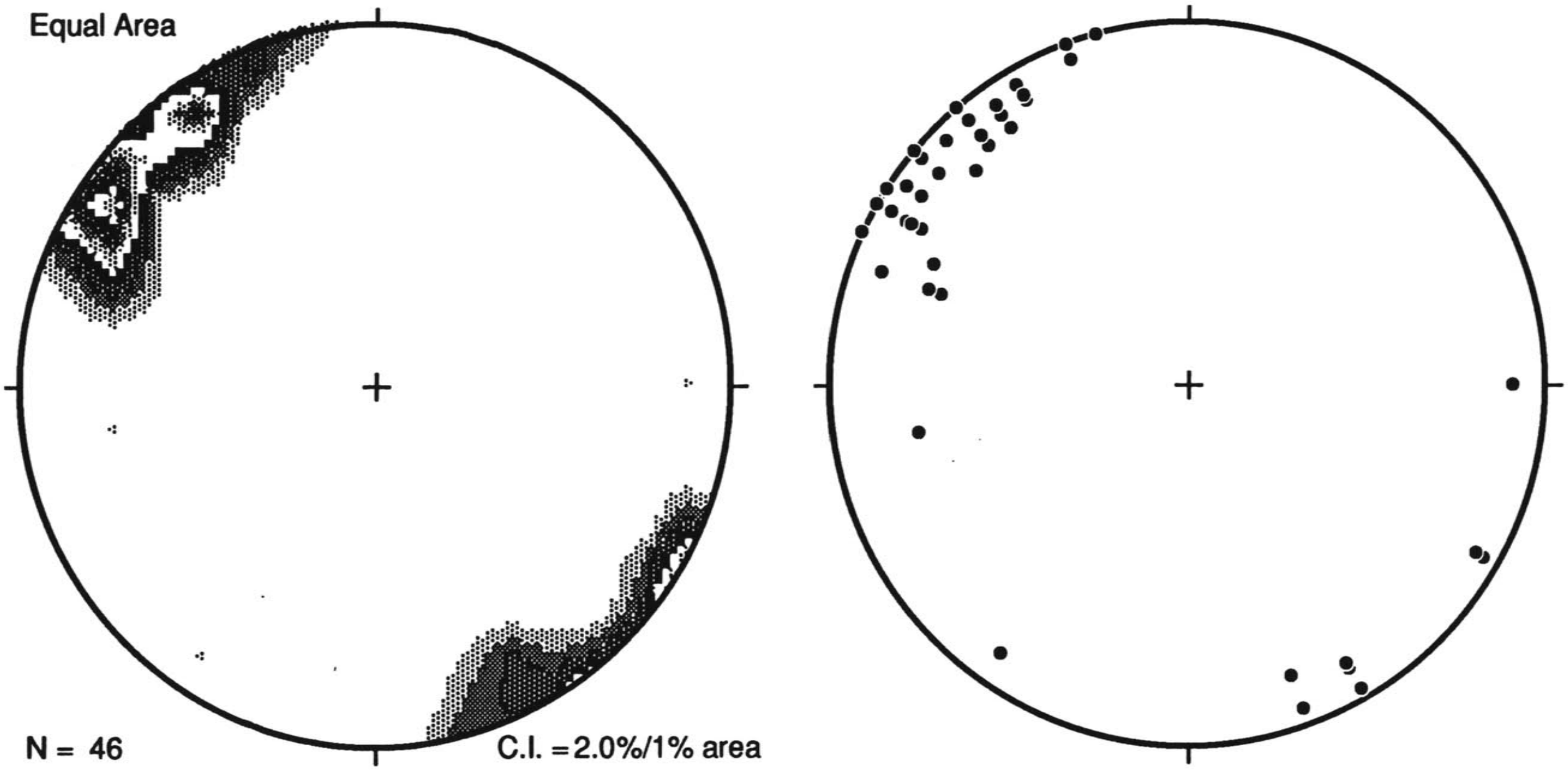


Figure 3-9: Common example of strain localization within the Middle Allochthon. In the lower portion of the photograph, asymmetric augen give a top to the right (SE) directed shear sense.

from only weakly deformed to a completely recrystallized fine grained ultramylonite that in places may have behaved superplastically (Fig. 3-10). The process of mylonitization in the granitoid rocks typically begins with progressive grain size reduction involving both cataclasis and recrystallization of the initial igneous mineralogy producing a well-foliated rock, commonly having a well-developed quartz-feldspar aggregate lineation. Within the Middle Allochthon of the Paltavare Complex (Plate 1) is a black micaceous phyllonitic unit which contains abundant quartz stringers and in places floating quartzite isoclinal fold hinges (Fig. 3-11). The asymmetry of quartz aggregate pressure shadows around quartz or feldspar porphyroclasts indivates SE-directed shearing. The phyllonite unit contains an S-C fabric typically defined by a shear plane and mica fish with an orientation consistent with a southeast directed shear sense. S-C fabrics within the deformed granitoid rocks are also quite common. Typically these consist of a shear plane defined by the mylonitic foliation combined with a schistosity defined by the long dimensions of mica fish. An excellent detailed description of the structural complexities within the variably deformed Middle Allochthon mylonites of the Akkajaure-Tysfjord region to the south of the study area may be found in Björklund (1989).

The rocks of the Upper Nappe Complex have been retrogressed and their original foliations have been transposed and sheared into parallelism with the contact of the Middle Allochthon. Figure 3-12 shows an example from just north of the Singis window where the higher grade rocks of the Seve Amphibolite have chlorite pseudomorphs replacing garnet and their original S2 foliation transposed into S5.

The autochthonous to parautochthonous rocks of the Singis window and those at the Caledonian front have also been highly deformed during D5 deformation. Structural features include SE-vergent, tight to isoclinal folds whose axes trend approximately 0°, N20E. Within the eastern half of the Singis Window, there is a basement involved thrust, with an attitude consistant with SEE directed transport, which places the Precambrian crystalline rocks of the Baltic Shield over autochthonous sedimentary rocks. There are also

Figure 3-10: Photomicrograph of a completely recrystallized banded mylonite from the Middle Allochthon. Field of view is approximately 4 cm.

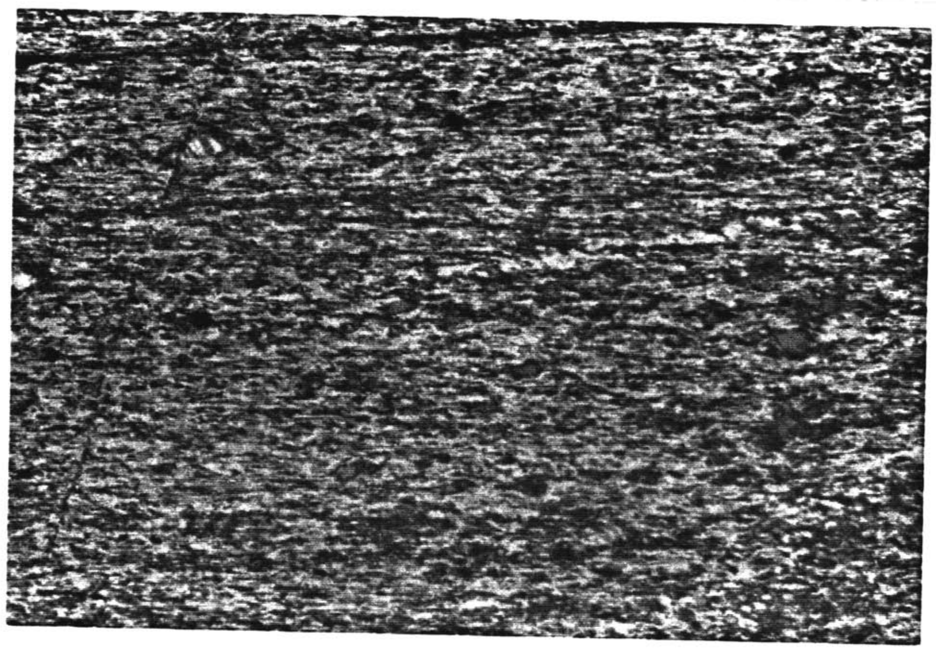
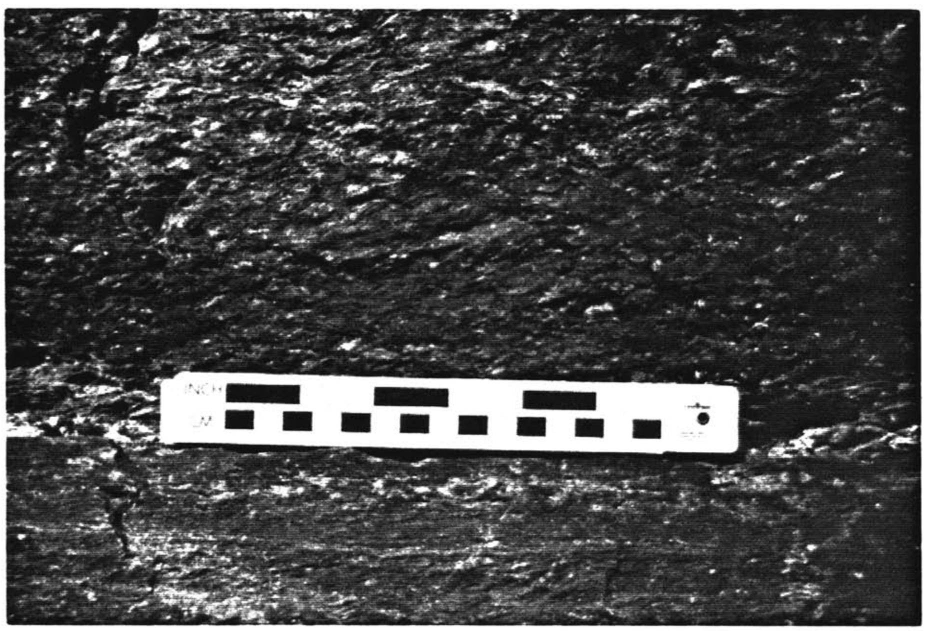


Figure 3-11: Phyllonite from the Paltavare complex near Kärkevarto, containing quartz stringers and occasional floating hinges.

Figure 3-12: View looking north from the Singis window at the Seve-Middle Allochthon contact. The upper 2/3 of the photograph consists of retrogressed Seve, containing small chloritized garnets. The lower portion of the photograph consists of the Middle Allochthon in which a weak S-C fabric is observed.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shallow-dipping (10-30°) thrusts within the sedimentary rocks in the Caledonian front. There is a well developed S5 schistosity in the sedimentary rocks throughout the study area that is the oldest fabric found in rocks of the Autochthon-Parautochthon.

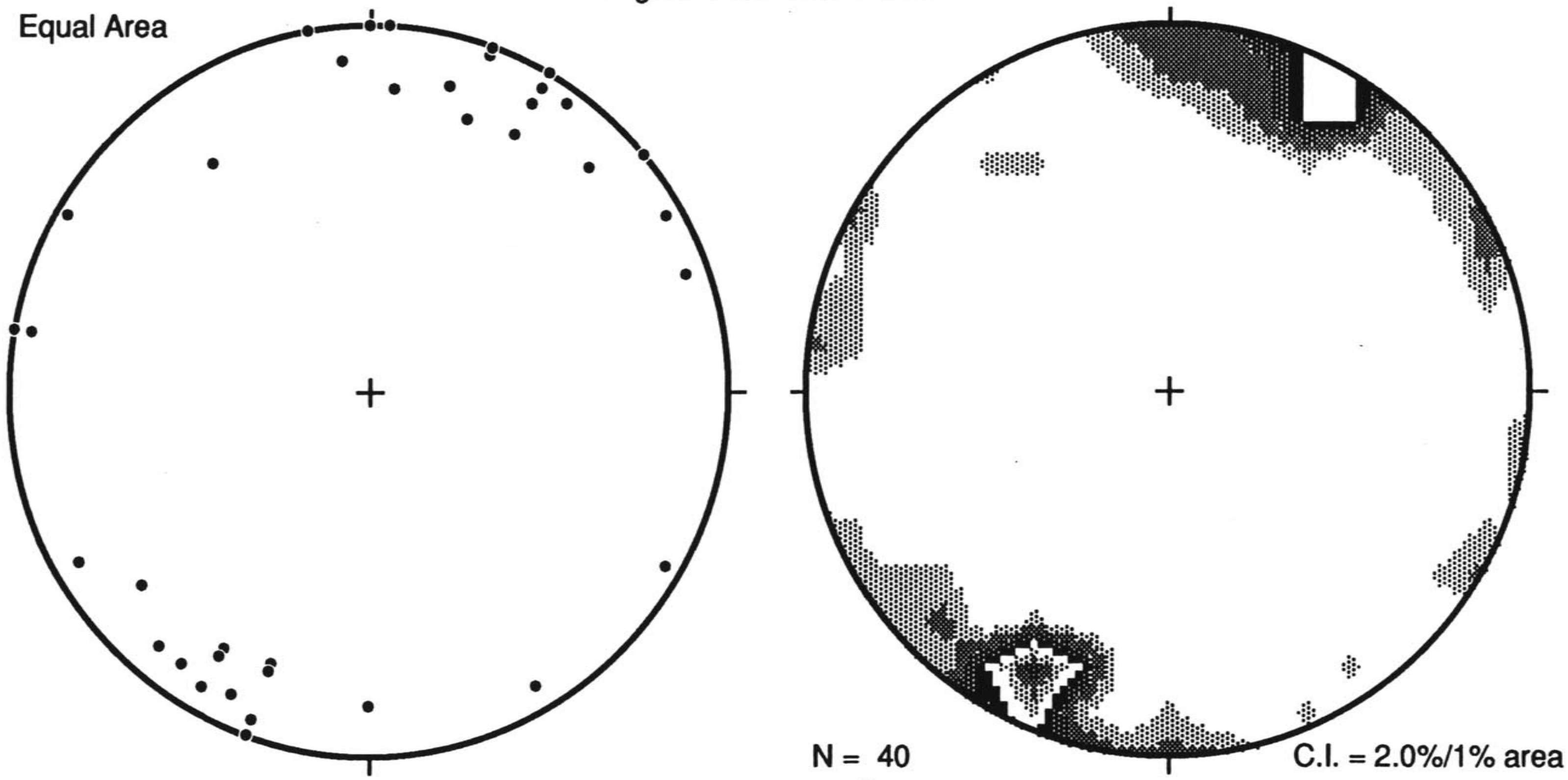
D6: Late Gentle Warping along N60W Axes

The entire Nappe Complex in the Singis-Nikkaluokta transect has been folded by late broad folds whose fold axes trend N40-60W. These folds range in scale from local to regional and have steep to vertical axial planes. They are particularly well developed within the sedimentary rocks of the Singis Window, but are common throughout the study area. The regional-scale F6 folds often have wavelengths of more than 40 km and they are partly responsible for the general outcrop pattern of the tectonostratigraphic elements within the Caledonides. A good example of a regional scale D6 fold is in the Akkajaure area to the south of the present study area, where the Middle Allochthon mylonites of the Akkajaure Nappe Complex are exposed for over 100 km along a N60W trend along the crest of a large regional D6 antiform.

D7: Late Warping along N30E Axes

All tectonostratigrtaphic elements within the Singis-Nikkaluokta area have been affected by late broad F7 folds with N20-30E fold axes (Fig. 3-13) orthogonal to the inferred transport direction of the nappe complex. These folds are associated with late-stage shortening of the nappe complex.

Figure 3-13: Late Folds



D8: West vergent motion at the Seve-Köli contact

Along the Rusjka fault in the western part of the study area there is evidence for late west-vergent motion of the tectonostratigraphically higher Köli Nappe over the lower Seve Nappe with associated asymmetric folding and retrogression of rocks in the shear zone (Fig. 3-14). Asymmetric quartz pressure shadows around garnet (Fig. 3-15) are consistant with west-directed movement. A well defined mineral lineation defined by these quartz pressure shadows has a general N70W trend. Tilke (1986) performed a Hansen Analysis (Hansen, 1971) and found the bisectrix of the fold axes girdle trended N74W 45 for the west-vergent movement direction on the fault. This west-vergent motion may be the result of normal faulting due to gravitatonal collapse of the entire orogen (Tilke, 1986), however much more work throughout the Scandinavian Caledonides is needed to confirm this hypothesis.

Conclusions

The deformational history of the Singis-Nikkaluokta region may be subdivided into eight deformational events. Deformations 1 and 2 are Finnmarkian, and are associated with the Late Cambrian to Early Ordovician metamorphism of the Seve Nappe. Deformation 3 is associated with the post-Ashgillian Scandian metamorphism of the Lower Köli Nappe. The juxtaposition of the Köli and Seve produced the fabrics associated with the fourth deformational event. Emplacement of the Upper Nappe Complex onto the rocks of the Baltic shield produced structures assigned to D5, D6, and D7. The final deformational event (D8) is correlated with late stage west vergent motion along the Seve-Köli contact.

Figure 3-14: View looking north along the Seve-Köli shear zone showing the late west-vergent folds (F8).

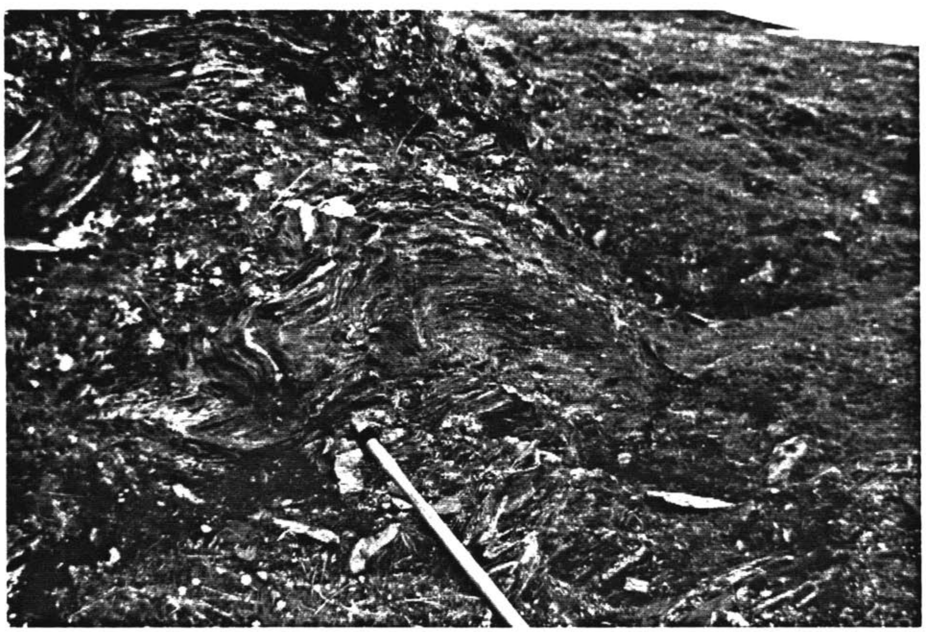
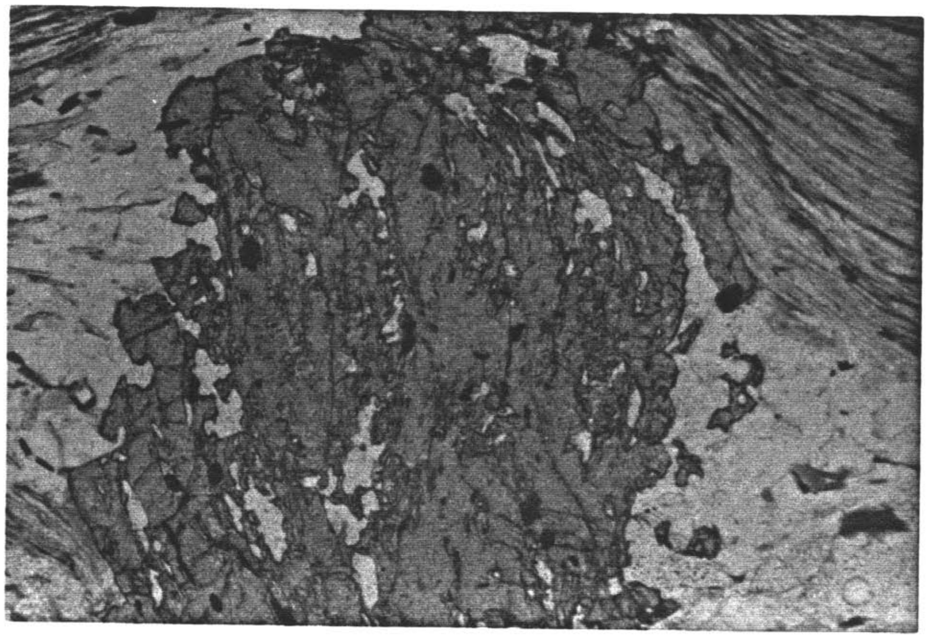


Figure 3-15: Quartz pressure shadows around garnet from the Seve-Köli shear zone (upper left and lower right of photograph) consistent with top to the left (west) shear.



Chapter 4

Metamorphism of the Singis-Nikkaluokta Region

Introduction

Rocks of the different tectonic nappes within the Singis-Nikkaluokta region have experienced different degrees of metamorphism ranging from lower greenschist facies to eclogite facies. Structural relationships and $^{40}Ar/^{39}Ar$ geochronology indicate a complex geologic history involving two major tectonothermal pulses. Much of our understanding of the metamorphic history throughout the MIT transect in the Scandinavian Caledonides has focused on the thermal conditions of the more recent Scandian phase of deformation and metamorphism (Tilke, 1986; Hodges and Royden, 1984; Crowley and Spear, 1987). The Seve rocks within the study area afford the opportunity to constrain the conditions of metamorphism for the earlier "Finnmarkian" event.

As discussed in the tectonostratigraphic section the Seve rocks of the Singis-Nikkaluokta region have been correlated with the Vaimok lens in the classification proposed by Zachrisson and Stephens (1984) for the Seve in the southern Norrbotten Caledonides. This classification splits the Seve into the uppermost Tsäkkok lens, the intermediate Sarek lens, and the lowermost Vaimok lens. Correlation of the Seve rocks from the study area with the Vaimok lens is based both on the presence of eclogites and the presence in both areas of underlying Seve rocks which consist predominantly of doleritic dyke complexes. In the southern Norrbotten Caledonides Zachrisson and Stephens (1984) term this overlying dyke bearing unit the Sarek lens. In the area studied by Svenningsen (1987) and Andréasson (1986a, 1987) within the Sarek National Park, nearly 80 km south of the study area, the overlying dyke complex rocks are termed the Sarektjåkka Nappe. The dolerite dyke rocks (for which Svenningsen (1989) obtained a Sm/Nd crystallization age of ca. 605 ma) have a rift related chemistry which indicate that portions of the Seve represent the outer portion of the Late Precambrian rifted margin of Baltica.

Several recent studies within the allochthonous Seve Nappes have focused on the recognition and tectonic significance of the few eclogite occurrences which have been documented to date (Stephens and van Roermund,1984; Santallier, 1988; van Roermund, 1985, 1989; Andréasson, 1985). These eclogites occur within both the Vaimok and the Tsäkkok lenses of the Seve Nappe Complex. Santallier (1988) obtained pressure and temperature estimates of 650-700°C and 18-20 kb using the Ellis and Green (1979) garnet-clinopyroxene geothermometer and the Holland (1980) albite-jadeite-quartz geobarometer for samples from both the Tsäkkok and Vaimok lenses, while Stephens and van Roermund (1984) obtained pressures and temperatures of 610°C and a minimum of 15kb using the garnet-clinopyroxene geothermometer (Ellis and Green) and the jadeite component in clinopyroxene based geobarometer of Gasparik and Lindsley (1980).

Mapping within the study area conducted by Tilke and Page during the summer of 1985 identified a new eclogite locality from within the Seve Nappe located in the Aurek Gabbro on the peaks Stuor and Unna Aurek in the western part of the study area (plate 1). Tilke (1986) examined the complex reaction textures present within the eclogitized portions of the Aurek Gabbro and obtained estimates for the temperature of 700-730°C and pressures greater than 12 kb. Recent Sm/Nd results presented by Mørk et. al. (1988) for the crystallization age of Seve eclogites from the Tsäkkok lens in the southern Norrbotten Caledonides indicate an age of 505±18 Ma for the eclogite facies metamorphism. This age is compatible with $^{40}Ar/^{39}Ar$ thermochronology (Dallmeyer and Gee, 1986; Page, this study) which indicate that Seve amphibolites surrounding eclogites cooled below Ar retention temperatures for hornblende of 500°C at ca 490 Ma.

Recent studies in the Seve Nappe of the Norrbotten Caledonides have focused primarily on: 1) Identifying and describing the different tectonostratigraphic elements comprising the Seve (Andreasson, 1987, 1986b; Svenningsen, 1989, 1987; Stølen, 1988;

Stephens and Zachrisson, 1984); 2) deciphering the deformational history; and 3) obtaining geochronologic age constraints (Dallmeyer and Gee, 1986; Dallmeyer et al., in prep; Svenningsen, 1988; Mørk, 1989). Excepting the studies of the eclogite grade rocks discussed previously, there has been very little work done towards quantifying the temperatures and pressures of metamorphism within the different tectonostratigraphic elements of the Seve. In trying to decipher the thermal and barometric history of a metamorphic terrane there are several techniques which are particularly useful. Rim thermobarometry constrains the temperatures and pressures of latest equilibrium. It is often possible in many metamorphic samples to obtain pressure-temperature trends using either inclusion thermobarometry (e.g., St. Onge, 1987) and/or the Gibbs' Method (Spear et al., 1982; Spear and Selverstone, 1983). Unfortunately the samples in this study do not contain the necessary inclusions to perform either the Gibbs' method or inclusion suite thermobarometry.

Quantitative Rim Thermobarometry

Sample Descriptions

The nature and mineralogy of the different tectonostratigraphic elements of the Singis-Nikkaluokta region have been discussed previously in the tectonostratigraphy chapter. Except for the rocks of the Seve Nappe, all other units in the study area are greenschist grade or less and contain no assemblages suitable for geothermobarometry.

Figure 4-1 shows a typical example of a quartzofeldspathic gneiss from the Seve which contains a biotite+muscovite+plagioclase+quartz subassemblage suitable for geothermobarometry. Minor amounts of kyanite are also found within the Seve quartzofeldspathic gneiss (Fig. 4-2), but only rarely is kyanite found associated with appropriate phases for geothermobarometry.

Figure 4-1 Typical example of the Savopakte Assemblage quartzofeldspathic gneiss. Sample contains garnet+biotite+muscovite+plagioclase assemblage suitable for geothermobarometry. Field of view approximately 4 cm.

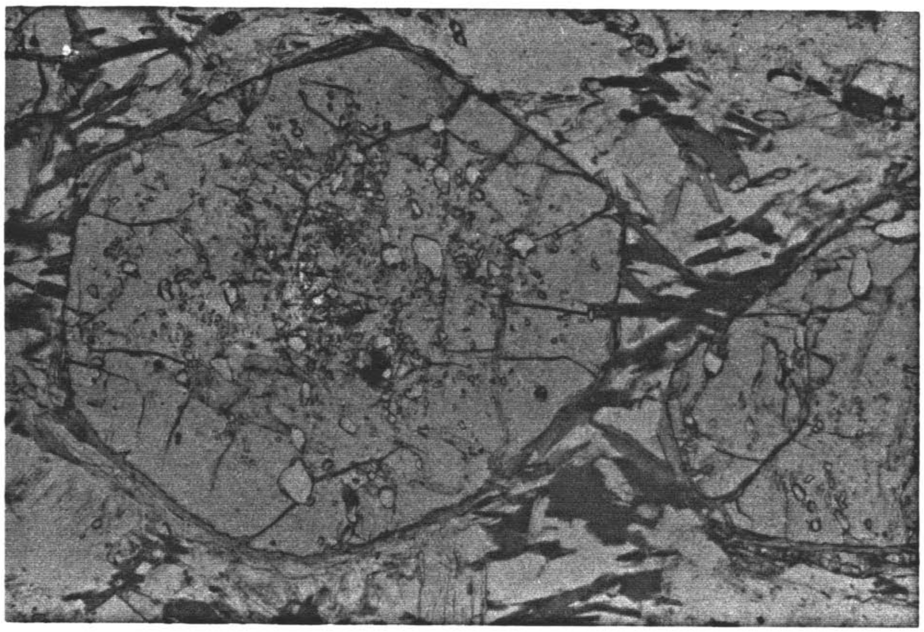
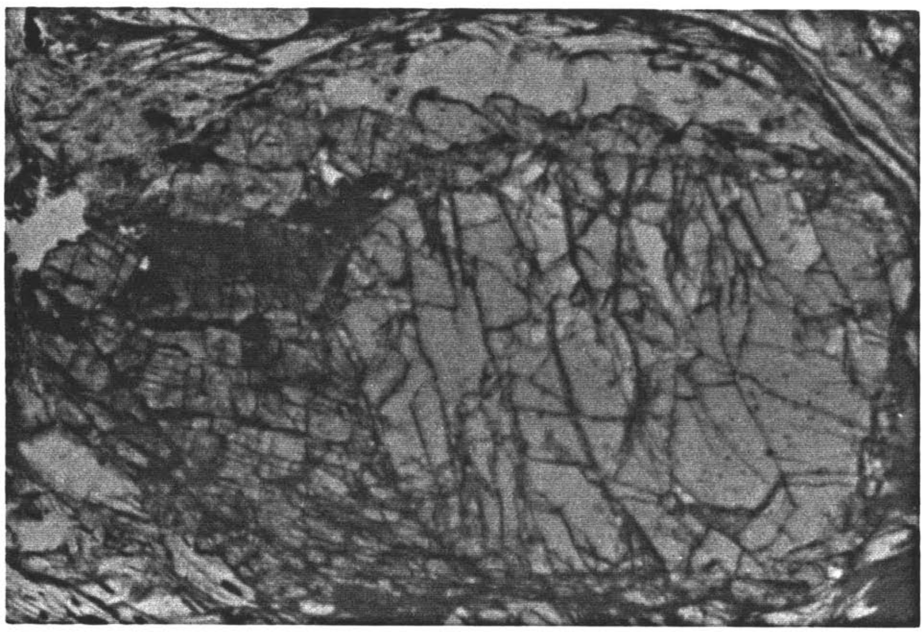


Figure 4-2: Kyanite bearing sample 87-D7 from the Vidja Assemblage. Field of view approximately 4 cm.



Analytical Techniques

Several samples from the units within the Seve Nappe of the Singis-Nikkaluokta region contain assemblages which allow the application of well-calibrated quantitative thermobarometers. For the quartzofeldspathic gneisses the thermobarometers that were chosen for this study (Table 4-1) include the garnet-biotite (GARB) geothermometer (Ferry and Spear, 1978), the garnet-biotite-muscovite-plagioclase (GBMP) geobarometer (Ghent and Stout, 1981; Hodges and Crowley, 1985), and the garnet-aluminum silicate-plagioclase-quartz (GASP) geobarometer (Ghent, 1976; Newton and Haselton, 1981). Impure phases were analyzed using a JEOL 733 Superprobe at the Massachusetts Institute of Technology. Synthetic and natural silicate standards were used and Bence and Albee (1968) corrections were applied by an on-line data reduction system. In each sample the analyzed phases were either adjacent or within close proximity to each other. In order to establish the conditions of latest equilibrium all rim analyses were performed within 3-5 microns of the grain boundary. Within each sample garnet rims were analyzed in contact with the relevant phases, in cases where the garnet composition adjacent to biotite varied with respect to the typical garnet rim composition the analyses from the points near biotite were excluded from the determination of the average rim composition for the sample. The standard deviations of the measured compositions for each phase in the thermometer and barometer were propagated through a simultaneous solution of the thermobarometers using a Monte Carlo technique (Hodges and McKenna, 1987) in order to determine the precision of the calculated pressures and temperatures.

Assuming the activity composition relationships shown in Table 4-2, pressures and temperatures were obtained for the Seve samples by simultaneously solving GARB with GASP (on 87-D7) or GBMP (all samples). The average and standard deviations of the

TABLE 4-1. GEOTHERMOBAROMETERS

1) GB

$$\underset{\text{garnet}}{Mg_3Al_2Si_3O_{12}} + \underset{\text{biotite}}{KFe_3AlSi_3O_{10}(OH)_2} = \underset{\text{garnet}}{Fe_3Al_2Si_3O_{12}} + \underset{\text{biotite}}{KMg_3AlSi_3O_{10}(OH)_2}$$

2) GBMP

$$\underset{\text{garnet}}{Fe_3Al_2Si_3O_{12}} + \underset{\text{garnet}}{Ca_3Fe_3Al_2Si_3O_{12}} + \underset{\text{muscovite}}{KAl_3Si_3O_{10}(OH)_2} = \underset{\text{plagioclase}}{3CaAl_2Si_2O_8} + \underset{\text{biotite}}{KFe_3AlSi_3O_{10}(OH)_2}$$

3) GASP

$$\underset{\text{garnet}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{kyanite}}{Al_2SiO_5} + \underset{\text{quartz}}{SiO_2} = \underset{\text{plagioclase}}{3CaAl_2Si_2O_8}$$

$K_1 = [(A_{py})(A_{ann})]/[(A_{ph})(A_{al})]$
$K_2 = [(A_{an})^3(A_{ann})]/[(A_{mu})(A_{gr})(A_{al})]$
$K_3 = (A_{an})^3/[(A_{gr})$

Calibrations

1) Ferry and Spear (1978)

2) Hodges and Crowley (1985)

3) Newton and Haselton (1981)

Table 4-2: Activity-Composition Relationships

(From Hodges and Royden, 1984)

$A_{al} = [X_{al} * \exp[((1.5T(°K) - 3300) * (X_{py}X_{gr})) / RT(°K))]^3$

$A_{py} = [X_{py} * \exp[((3300-1.5T(°K)) * (X_{gr}^2 + X_{al}X_{gr} + X_{gr}X_{sp})) / RT(°K))]^3$

$A_{gr} = [X_{gr} * \exp[((3300-1.5T(°K)) * (X_{py}^2 + X_{al}X_{py}+ X_{py}X_{sp})) / RT(°K))]^3$

$A_{an}(HC) = X_{an} * \exp(610.34 / T(°K) - .3837)$

$A_{an}(NH) = (X_{an} (1+X_{an})^2 / 4) * \exp(X_{ab}^2(2025 + 9442 Xan)) / RT(°K)$

$A_{mu} = (X_{kmu}X_{almu}^2) * \exp[((X_{namu}X_{almu}^2)^2 * (W_{mu} + 2X_{kmu}X_{almu}^2(W_{pa} - W_{mu}))) /$

$RT(°K)]$

$A_{ann} = (X_{ann})^3$

$A_{ph} = (X_{ph})^3$

X_{al} = Fe/Fe+Mg+Ca+Mn in garnet

X_{py} = Mg/Fe+Mg+Ca+Mn in garnet

X_{gr} = Ca/Fe+Mg+Ca+Mn in garnet

X_{sp} = Mn/Fe+Mg+Ca+Mn in garnet

X_{an} = Ca/Ca+Na+K in plagioclase

X_{ab} = Na/Ca+Na+K in plagioclase

X_{kmu} = K/Ca+Na+K in muscovite

X_{namu} = Na/Ca+Na+K in muscovite

X_{almu} = AlVI/Fe+Mg+Mn+Ti+AlVI in muscovite

X_{ann} = Fe/Fe+Mg+Ti+AlVI in biotite

X_{ph} = Mg/Fe+Mg+Ti+AlVI in biotite

$W_{pa} = 2923.1 + 0.1590\ P(bars) + 0.1698T(°K)$

$W_{mu} = 4650.1 + 0.1090\ P(bars) + 0.3954T(°K)$

compositions for minerals used in thermobarometry for each sample are given in the appendix at the end of this chapter.

Results

Pressure and temperature estimates were obtained for eight samples from the Seve Nappe by simultaneously solving GARB-GBMP, one of the eight samples (87-D7) also contained kyanite (Fig. 4-3) allowing the simultaneous solution of GB-GASP as well as GB-GBMP. Table 4-3 lists the pressures and temperatures obtained for the Seve samples from the Singis-Nikkaluokta region. Two-sigma error ellipses of propagated microprobe errors for the eight Seve samples are plotted on Figure 4-3. All analyzed samples come from the Savopakte Assemblage except for 87-D7, which comes from the Vidja Assemblage. The seven samples of the Savopakte Assemblage all give very high pressures (>8.9 kb) and temperatures which range from 571-766° C. Vidja Assemblage sample 87-D7 records a lower pressure of 7.3±1.7 kb and a temperature of 616±60° C.

Discussion

Although some of these samples have moderately large errors associated with their calculated temperatures and pressures, the fact that the samples were collected from a large area and they are all consistent with each other strengthens the interpretation that the Seve Nappe underwent regional metamorphism under these conditions. These pressures indicate that large portions of the Seve Nappe experienced burial depths of 27-40 Km during the Finnmarkian orogenic event.

Sample 87-D7 contains kyanite which allows for the simultaneous solution of GARB with either GASP or GBMP. The pressures and temperatures obtained using either of the geobarometers are statistically indiscernible (GARB with GASP yields 615±60° and

Figure 4-3: Seve P-T Diagram

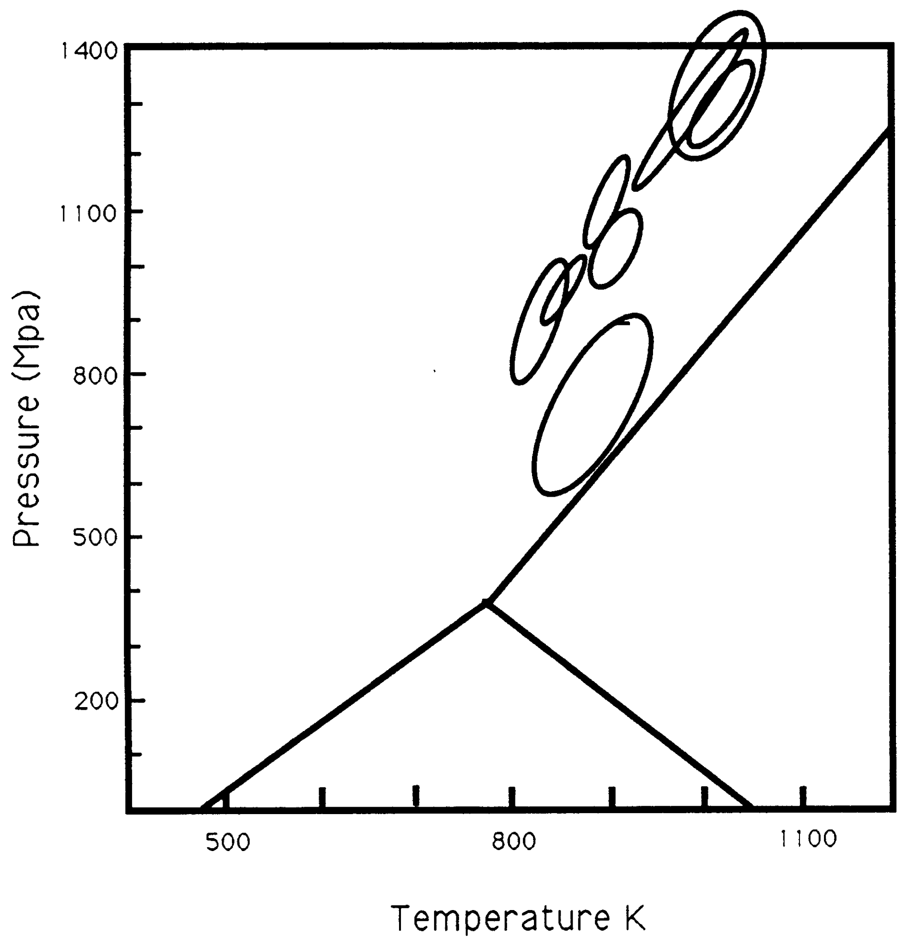


Table 4-3: Seve Pressure-Temperature Data

Sample	Temperature (°C)	Pressure (Kb)
85-F8	655±33	10.2±1.1
85 F17	762±49	12.5±1.3
85-F25	627±22	11.2±.87
86-12B	766±75	13.6±2.0
86-14B	584±34	9.4±.9
86-22B	571±51	8.9±1.5
87-C10	723±68	13.2±1.8
87-D7	616±60	7.3±1.7

7.30±2.0 kb while GARB with GBMP yields 616±60° and 7.3±1.7kb). The results obtained from 87-D7 have several possible interpretations:

1) The sample rims attained equilibrium and the pressures and temperature obtained records a portion of the Vidja Assemblages P-T history. It is conceivable that these conditions were obtained during development of a late stage Finnmarkian (450 Ma) shear zone (discussed in Chapter 5) separating the Aurek Assemblage and the overlying Vidja Assemblage. The regional age for cooling through the muscovite closure temperature (350° C) for the Seve is approximately 440-450 Ma. If a typical regional geothermal gradient of 15° C/km may be assumed (which would seem very reasonable for cooling from peak metamorphic ages of 40-50 Ma previous) a depth of 20-25 km could reasonably be expected. This depth, although recording a slightly younger time, coincides well with the pressure of 7.3 kb obtained for the Vidja Assemblage.

2) All minerals used in thermobarometry for sample 87-D7 may not be in equilibrium. This sample was selected for barometric analysis because it appeared to be an equilibrium assemblage in thin section.

3) Another possibility is that Sample 87-D7 is an assemblage that obtained equilibrium during the Scandian event (D4) which juxtaposed the Seve and Köli Nappes and thus records conditions of burial during the amalgamation of the Seve-Köli Nappe complex. This scenario seems unlikely given that the grade of metamorphism exhibited by both the Lower Köli Salka Group and the rocks in the Seve-Köli shear zone is of greenschist grade. This possibility however should be considered in light of the late stage west-

vergent motion associated with the Seve-Köli contact and the possibility, first proposed in this area by Tilke (1986), of a late stage normal fault associated with gravitational collapse of the Caledonian Orogen during the late Scandian. If the normal fault hypothesis is correct then rocks of lower grade juxtaposed against similarly aged rocks of higher grade would be expected.

Of the three possibilities examined here, observed data most strongly support the first, whereby the pressures and temperatures recorded by 87-D7 record the conditions associated with late stage Finnmarkian juxtaposition of the Vidja and Aurek Assemblages. Clearly however, more work throughout the Caledonian Orogen within the different Seve units and along the Seve-Köli contact is needed to fully constrain the problem.

Garnet Zoning

The implications of garnet zoning have been the basis of many metamorphic studies (e.g. Loomis, 1983; Tracy 1976; Hollister, 1966). Garnet zoning profiles were obtained for several samples (85-F25, 86-14B, and 87-D7, Figs. 4-4 through 4-6) from the Savopakte and Vidja Assemblages. In all of these samples a well-defined bell-shaped profile for the spessartine component in garnet is observed. Bell-shaped spessartine profiles are thought to be indicative of Mn depletion occuring during garnet growth (e.g., Hollister, 1966). The element distribution patterns within these garnets may therefore give information concerning the prograde or retrograde reaction history (if it may be assumed the reactions are continuous). Several other samples used in rim thermobarometry were analyzed for garnet zoning and were found not to be significantly zoned. Several studies suggest that complete homogenization of millimeter scale garnets may be likely at temperatures greater than 925 K (652° C) (Yardley, 1977; Tracy, 1982). If this is true it is

Figure 4-4: F25-85 Garnet Zoning

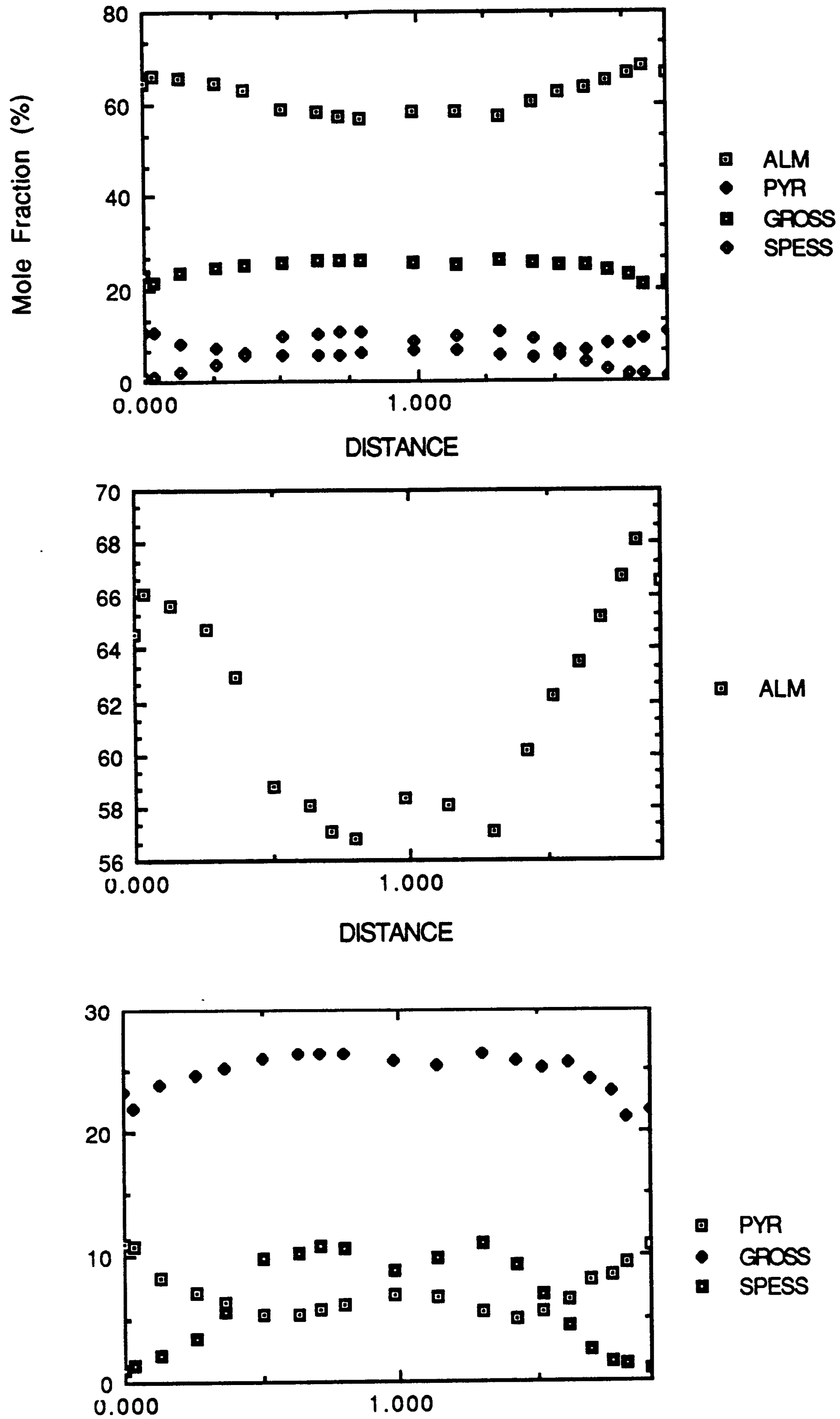


Figure 4-5: 14B-86 Garnet Zoning

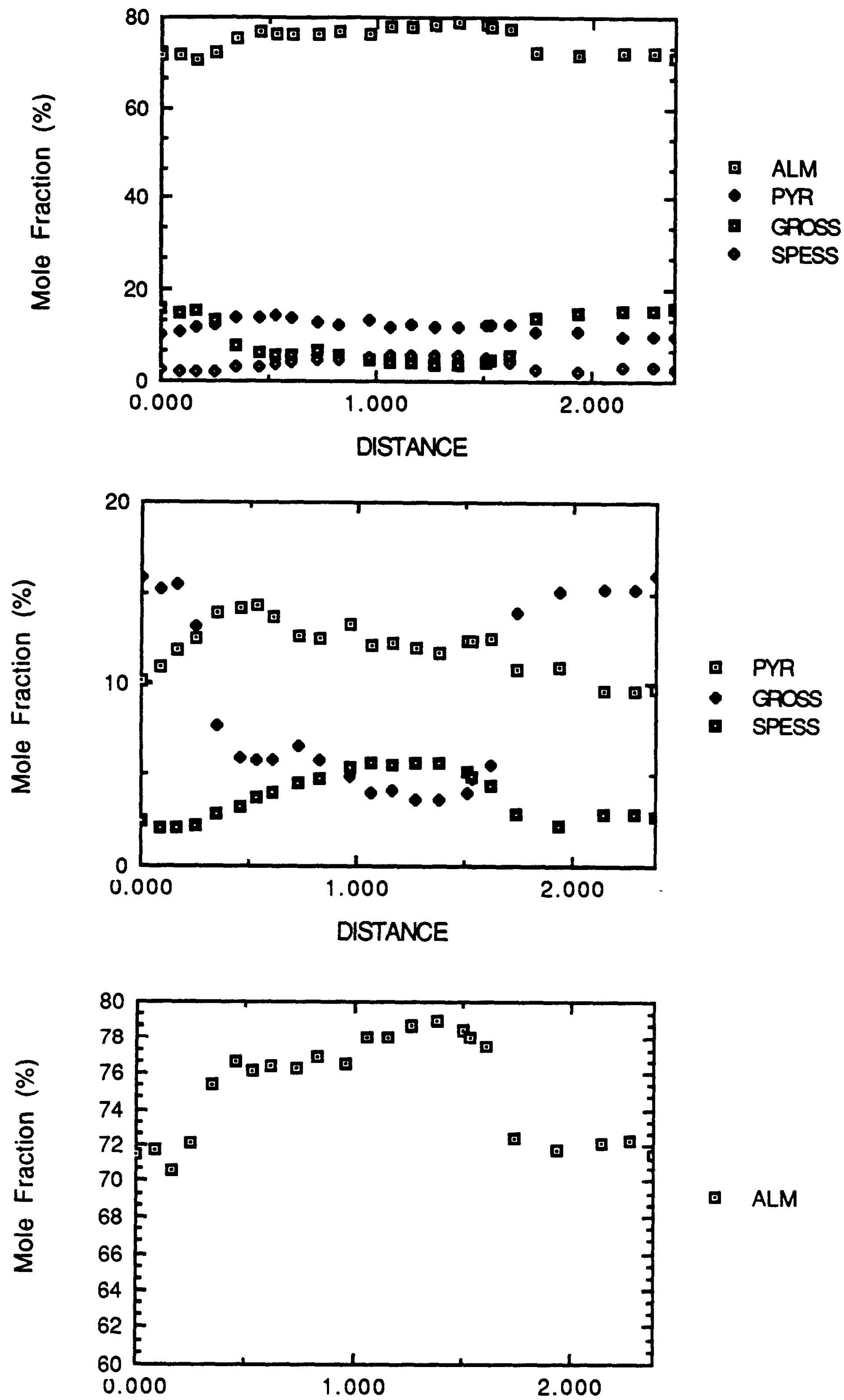
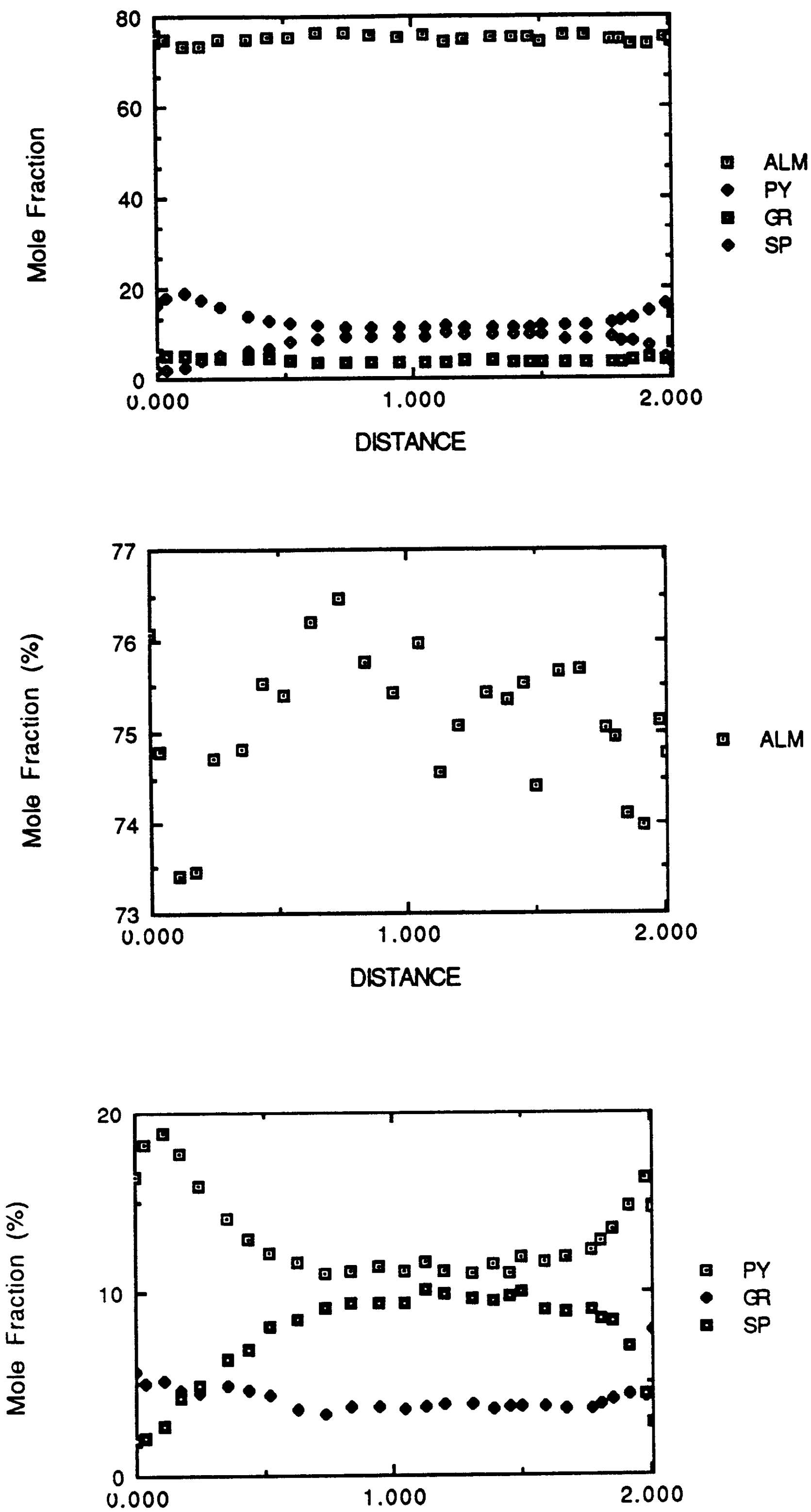


Figure 4-6: 87-D7 Garnet Zoning



interesting to note that all other samples in this study that do not contain zoned garnets all have rim equilibration temperatures in excess of 650° C. It is likely, therefore, that these high temperature samples experienced homogenization of any original growth zonation.

The samples which do show garnet zoning give some indication of their metamorphic history during growth. The garnet zoning profile for sample 86-14B (Fig. 4-4) exhibits a large increase from core to rim for the grossular component, and corresponding decreases in the almandine and pyrope components. Garnet-plagioclase barometers are based on the fact that Ca-partitioning between the two phases is strongly pressure dependent; as pressure increases, the anorthite component of plagioclase decreases with a corresponding increase in the grossular component of garnet. As plagioclase and garnet are the only two calcic phases in 86-14B, the garnet zoning exhibited in this sample is therefore consistent with an interpretation of growth during increasing pressure. Many geothermometers are established on the Fe-Mg exchange between phases. In garnets an increase in pyrope with an associated decrease in almandine is indicative of growth during increasing temperature. The garnet zoning profile for Vidja Assemblage sample 87-D7 (Fig. 4-5) exhibits a bell-shaped spessartine component profile, a relatively flat grossular component, a general decrease in the almandine component from core to rim and a corresponding increase in the pyrope component. The interpretation of garnet zoning within 87-D7 is consistent with growth during increasing temperature. The garnet zoning profile for sample 85-F25 (Fig. 4-6) shows a bell-shaped spessartine profile, a slight decrease in core to rim for the grossular component, a large (>10 wt%) increase in almandine, and a moderate increase in pyrope. Except for the evidence of growth zoning provided by the spessartine component, no conclusions may be drawn from the zoning pattern for sample 85-F25. Clearly more garnet zoning analyses are needed within the Seve Nappe (preferably from assemblages with lower variance so the Gibbs' method may also be employed), and will be a goal of future study in the northern Scandinavian Caledonides.

Conclusions

Quantitative thermobarometry and garnet zoning profiles for Seve quartzofeldspathic gneiss samples with appropriate assemblages yields important constraints on the "Finnmarkian" history of the Seve Nappe of the Singis-Nikkaluokta region. The metamorphic results from this study area include:

1) Eclogite grade rocks of the Aurek Assemblage yield temperatures and pressures in excess of 12 kb and 730° C.

2) The temperatures and pressures obtained in this study for seven samples from the Savopakte Assemblage of the Seve Nappe range from 571-766° C and 8.9-13.6 kb. These data imply, with $^{40}Ar/^{39}Ar$ data, burial depths of approximately 30-40 km during the Finnmarkian (490 Ma) for the outer margin of Baltica.

3) Sample 87-D7 from the Vidja Assemblage gives a lower pressure of 7.3±1.7 kb and a temperature of 616° C. If this sample records an equilibrium assemblage in the Finnmarkian, then this pressure is consistent with the interpretation of a late Finnmarkian intra-Seve juxtaposition of the Vidja and Aurek Assemblages (dated by an hornblende plateau age of 450 Ma., chapter 5) after approximately 40 km of slow (0.5 mm/yr) uplift.from the pressures recorded in the early Finnmarkian.

4) Garnet zoning occurs in samples whose rim equilibrium temperature are less than 650° C. Samples used in thermobarometry whose rim temperatures

exceed 650° C do not exhibit zoning. This is consistent with several studies (Yardley,1977; Tracy, 1982) which indicate that homogenization of garnet growth zoning by intragranular volume diffusion is possible. Three samples have bell-shaped spessartine profiles which are indicative of Raleigh fractionation (Hollister, 1966) during garnet growth. Sample 86-14B from the Savopakte Assemblage has a zoning profile which is consistent with growth during increasing pressure. Sample 87-D7 demonstrates growth during increasing temperature.

Rim equilibria, inclusion suite thermobarometry, and the Gibbs' method are all powerful quantitative techniques that may be applied to the study of metamorphic rocks. More detailed work throughout the Scandinavian Caledonides is needed to better constrain the different metamorphic histories for the different tectonostratigraphic elements between and within the major nappes. Future studies by this author plan to focus on applying the different quantitative metamorphic techniques in combination with $^{40}Ar/^{39}Ar$ geochronology to the Seve Nappe to the south of the study area.

Microprobe Data

	F25-85 BIO AVG 27283940	627±22 ST DEV	11.2±.87	F25-85 GNT AVG 24254142	STDEV	F25-85 MUSC AVG 22-23,35	STDEV
MGO	11.5965	0.2579		2.8823	0.0415	1.4070	0.0476
AL2O3	16.4800	0.3161		20.8008	0.1644	31.1197	0.3015
SIO2	36.7303	0.4833		37.7115	0.1251	46.0897	0.2280
CAO	0.0628	0.0283		8.1943	0.2870	0.0127	0.0112
TIO2	1.4985	0.1705		0.0330	0.0062	0.6307	0.1366
MNO	0.0720	0.0407		0.4270	0.1275	0.0060	0.0104
FEO	17.8253	0.5317		29.8605	0.2145	2.7357	0.1657
NA2O	0.0560	0.0721				1.1197	0.1008
K2O	9.4183	0.3297				9.2283	0.1577
CR2O3				0.0143	0.0176		
TOTAL	93.7400	0.7080		99.9225	0.3111	92.3467	0.2892
MG	1.3276	0.0188		0.3423	0.0042	0.1447	0.0047
AL	1.4915	0.0154		1.9523	0.0101	2.5290	0.0284
SI	2.8207	0.0223		3.0035	0.0069	3.1782	0.0115
CA	0.0052	0.0023		0.6991	0.0225	0.0009	0.0008
TI	0.0866	0.0103		0.0020	0.0004	0.0327	0.0070
MN	0.0047	0.0027		0.0288	0.0087	0.0003	0.0006
FE	1.1449	0.0429		1.9886	0.0192	0.1578	0.0093
NA	0.0083	0.0107				0.1497	0.0137
K	0.9225	0.0261				0.8117	0.0128
CR				0.0009	0.0011		
CAT TOTAL	7.8119	0.0068		8.0174	0.0048	7.0049	0.0017
AL				65.0125	0.5074		
PY				11.1875	0.1144		
GR				22.8600	0.7768		
SP				0.9400	0.2801		

F25-85		22B-86	571±51	8.9±1.5	22B-86	
PLAG AVG	STDEV	MUSC AVG	MUSC STDEV		BIO AVG	BIO STDEV
29-31,36-38						
0.0000	0.0000	1.5401	0.0577		9.9985	0.2539
22.3712	0.4961	31.1148	0.3132		17.3735	0.4249
62.9318	0.7519	46.9191	0.5298		36.7243	0.2094
3.9987	0.5136	0.0366	0.0132		0.0265	0.0327
		0.6594	0.1117		2.0113	0.1267
		0.0000	0.0000		0.0385	0.0206
0.1337	0.0752	2.5258	0.4338		20.3890	0.4630
9.0490	0.3761	0.6971	0.0685		0.0855	0.0257
0.0713	0.0112	9.9068	0.1703		8.6823	0.1613
98.5567	0.1922	93.4000	0.3982		95.3275	0.4399
0.0000	0.0000	0.1566	0.0067		1.1321	0.0229
1.1808	0.0285	2.5009	0.0133		1.5550	0.0297
2.8184	0.0275	3.2000	0.0190		2.7893	0.0118
0.1919	0.0250	0.0027	0.0009		0.0022	0.0027
		0.0339	0.0060		0.1149	0.0078
		0.0000	0.0000		0.0025	0.0013
0.0050	0.0028	0.1442	0.0255		1.2951	0.0355
0.7857	0.0311	0.0922	0.0092		0.0126	0.0038
0.0041	0.0007	0.8619	0.0137		0.8411	0.0120
4.9857	0.0068	6.9923	0.0176		7.7447	0.0045

22B-86 GNT AVG	GNT STDEV	22B-86 PLAG AVG	PLAG STDEV	14B-86 GNT 63-65,73-75	584±34 ST DEV
2.2647	0.1577	0.0075	0.0112	2.3070	0.1228
20.5558	0.2266	22.9115	0.4445	21.5132	0.0780
37.9028	0.1282	63.3245	0.5974	37.7107	0.1877
5.4815	0.4454	4.3386	0.4448	6.9095	0.4063
0.0633	0.0259			0.0125	0.0115
1.3140	0.1203			1.5760	0.2347
33.4243	0.5333	0.0993	0.0994	31.1868	0.2810
		9.5443	0.2713		
		0.1015	0.0171		
0.0683	0.0123			0.0375	0.0183
101.0750	0.4942	100.3288	0.3950	101.2517	0.1011
0.2689	0.0177	0.0005	0.0007	0.2719	0.0149
1.9298	0.0155	1.1921	0.0239	2.0046	0.0071
3.0195	0.0082	2.7955	0.0218	2.9816	0.0107
0.4679	0.0396	0.2052	0.0213	0.5852	0.0337
0.0038	0.0015			0.0008	0.0007
0.0887	0.0082			0.1055	0.0158
2.2265	0.0301	0.0037	0.0037	2.0619	0.0206
		0.8168	0.0216		
		0.0057	0.0010		
0.0043	0.0008			0.0024	0.0011
8.0092	0.0049	5.0194	0.0040	8.0137	0.0095
72.9517	0.7803			68.1700	0.4472
8.8100	0.5805			8.9900	0.4553
15.3350	1.3158			19.3533	1.1762
2.9050	0.2660			3.4867	0.5113

9.4±.9

14B-86 MUSC AVG69,70,83-86	STDEV	14B-86 BIO AVG 66-68,78,80-82	ST DEV	14B-86 AVG PLAG76,77	STDEV
1.2428	0.1769	10.2830	0.2652	0.0365	0.0021
32.9545	0.4092	17.4630	0.1405	23.3950	0.0849
46.6603	0.2202	36.7790	0.3894	62.6890	0.1598
0.0113	0.0157	0.0583	0.0447	4.8385	0.0785
0.7642	0.1338	2.3743	0.1969		
0.0257	0.0251	0.0277	0.0299		
1.6912	0.2026	19.0234	0.3015	0.1100	0.0311
0.7662	0.1118	0.1154	0.0346	9.0910	0.0127
10.0423	0.1362	8.6840	0.2559	0.0800	0.0156
94.1600	0.3889	94.8071	1.0293	100.2400	0.1697
0.1249	0.0178	1.1630	0.0200	0.0024	0.0001
2.6180	0.0298	1.5616	0.0153	1.2191	0.0019
3.1454	0.0135	2.7905	0.0089	2.7718	0.0011
0.0008	0.0011	0.0047	0.0036	0.2292	0.0042
0.0387	0.0068	0.1355	0.0119		
0.0015	0.0014	0.0018	0.0019		
0.0954	0.0114	1.2069	0.0123	0.0041	0.0011
0.1001	0.0145	0.0169	0.0050	0.7793	0.0028
0.8635	0.0107	0.8404	0.0193	0.0045	0.0008
6.9882	0.0087	7.7213	0.0236	5.0103	0.0039

F8-85	655±33	10.2±1.1	F8-85		F8-85	
GNT AVG	GNT STDEV		BIO AVG	BIO STDEV	MUSC AVG	MUSC STDEV
4.2638	0.1019		12.3645	0.5452	1.3202	0.0560
20.5843	0.1153		17.1851	0.2336	32.1694	0.3298
38.1298	0.1161		37.0347	0.4325	46.8610	0.2291
3.8163	0.3006		0.0572	0.0396	0.0064	0.0143
0.0678	0.0090		1.4525	0.1829	0.6878	0.0918
1.4010	0.1976		0.1120	0.0378	0.0000	0.0000
32.4353	0.3797		17.4504	0.6653	1.2422	0.0612
			0.1180	0.0353	1.2932	0.0554
			8.6095	0.3925	9.3542	0.0865
0.0465	0.0242					
100.7450	0.6688		94.3836	0.7535	92.9340	0.4751
0.5033	0.0112		1.3942	0.0568	0.1338	0.0061
1.9207	0.0012		1.5319	0.0147	2.5764	0.0144
3.0190	0.0103		2.8013	0.0115	3.1846	0.0046
0.3237	0.0252		0.0046	0.0032	0.0005	0.0010
0.0041	0.0006		0.0826	0.0099	0.0352	0.0047
0.0939	0.0130		0.0072	0.0025	0.0000	0.0000
2.1473	0.0187		1.1040	0.0487	0.0706	0.0032
			0.0173	0.0051	0.1704	0.0070
			0.8306	0.0362	0.8110	0.0116
0.0029	0.0015					
8.0147	0.0095		7.7737	0.0227	6.9822	0.0087
69.9875	0.7471					
16.4025	0.3689					
10.5475	0.8043					
3.0575	0.4073					

F8-85		F17-85	762±49	12.5±1.3	F17-85	
PLAG AVG	PLAG STDEV	GNT AVG	GNT ST DEV		BIO AVG	STDEV
0.0215	0.0214	4.1300	0.0970		10.8400	0.5800
22.9170	0.2796	21.3100	0.0590		17.1600	0.4500
63.0853	0.8218	37.9800	0.1580		36.2000	0.7300
4.4018	0.2919	4.7300	0.3580		0.0982	0.0300
		0.4500	0.0579		0.1748	0.0162
		0.0200	0.0221		1.2930	0.4370
0.0505	0.0199	32.0500	0.5073		19.4646	0.6826
9.6250	0.1633	0.0000	0.0000		0.0662	0.0227
0.0565	0.0187	0.0000	0.0000		8.3170	0.9826
100.1575	0.6991	100.6800	0.4460		93.6134	1.2270
0.0014	0.0014	0.4848	0.0111		1.2520	0.0764
1.1948	0.0176	1.9784	0.0078		1.5669	0.0448
2.7907	0.0185	2.9910	0.0092		2.8039	0.0371
0.2087	0.0143	0.3993	0.0299		0.0082	0.0021
		0.0269	0.0035		0.0102	0.0009
		0.0015	0.0015		0.0847	0.0283
0.0019	0.0008	2.1111	0.0311		1.2610	0.0464
0.8255	0.0146	0.0000	0.0000		0.0100	0.0034
0.0032	0.0010	0.0000	0.0000		0.8215	0.0929
5.0260	0.0090	7.9929	0.0093		7.8182	0.0320
		0.7045				
		0.1618				
		0.1332				
		0.0005				

F17-85		F17-85		12B-86	766±75
MUSC AVG	STDEV	PLAG AVG	STDEV	GNT AVG	STDEV
				13-14,30	
1.0302	0.0396	0.0550	0.0092	1.4063	0.0709
33.8830	0.5944	24.1325	0.1641	20.8663	0.2145
46.3067	0.4045	60.9993	0.4035	37.6467	0.0964
0.0110	0.0132	5.4200	0.0560	10.7450	1.2681
0.0200	0.0176	0.0000	0.0000	0.1217	0.0492
0.5035	0.1255	0.0000	0.0000	2.3527	1.0549
1.0623	0.1499	0.0803	0.0528	27.3917	0.2014
1.6355	0.0659	8.6893	0.1490	0.0000	0.0000
8.8790	0.1240	0.0515	0.0211	0.0000	0.0000
				0.0000	0.0000
93.3320	0.8349	99.4278	0.4509	100.5267	0.6363
0.1039	0.0048	0.0037	0.0006	0.1668	0.0091
2.7000	0.0218	1.2700	0.0097	1.9559	0.0062
3.1316	0.0089	2.7250	0.0073	2.9944	0.0139
0.0008	0.0010	0.2594	0.0032	0.9151	0.1011
0.0010	0.0009	0.0000	0.0000	0.0073	0.0030
0.0289	0.0075	0.0000	0.0000	0.1588	0.0719
0.0602	0.0091	0.0030	0.0020	1.8217	0.0061
0.2151	0.0072	0.7549	0.0103	0.0000	0.0000
0.7660	0.0093	0.0029	0.0012	0.0000	0.0000
				0.0000	0.0000
7.0078	0.0051	5.0190	0.0049	8.0199	0.0129

13.6±2	12B-86		12B-86		12B-86	
	PLAG AVG	STDEV	BIO AVG	STDEV	MUSC AVG	STDEV
	15-16,19,20,40,41		17,24,31-32		35-36,21,22	
	0.0000	0.0000	6.1243	0.0509	1.4113	0.1536
	23.0180	1.0941	16.6968	0.1285	30.4818	0.2738
	63.2148	1.9460	35.2755	0.3120	46.4828	0.1808
	4.3775	0.6740	0.0295	0.0199	0.0000	0.0000
	0.0000		3.7353	0.3280	1.2390	0.0654
	0.0000		0.1748	0.0363	0.0000	0.0000
	0.1128	0.0547	23.8003	0.7251	2.9633	0.1042
	8.9118	0.3520	0.1013	0.0934	0.2968	0.0455
	0.1310	0.0541	9.3778	0.3231	10.8985	0.0312
	99.7667	0.3026	95.3175	0.9344	93.7750	0.2198
	0.0000	0.0000	0.7125	0.0048	0.1442	0.0157
	1.2018	0.0649	1.5353	0.0077	2.4614	0.0209
	2.7994	0.0658	2.7524	0.0075	3.1850	0.0113
	0.2079	0.0333	0.0025	0.0017	0.0000	0.0000
			0.2192	0.0203	0.0638	0.0033
			0.0116	0.0025	0.0000	0.0000
	0.0042	0.0020	1.5527	0.0389	0.1698	0.0060
	0.7652	0.0291	0.0154	0.0142	0.0394	0.0060
	0.0074	0.0031	0.9333	0.0293	0.9526	0.0036
	4.9857	0.0385	7.7346	0.0242	7.0160	0.0041

87-C10 GNTAVG PTS5-9,12	723±68	13.2±1.8	87-C10 BIOAVG EX GR4		87-C10 MUSCAVG ALL	
2.53683333	0.31512246		10.9491667	0.18034569	1.50183333	0.14650927
20.3076667	0.2458444		16.7591667	0.03114108	31.3398333	0.41841005
37.8838333	0.13504728		36.5308333	0.30802235	46.6958333	0.46381523
8.01333333	0.35488458		0.03833333	0.01336663	0.023	0.01335665
0.04966667	0.02872397		1.99533333	0.13693746	0.98283333	0.17425661
1.41166667	0.21186379		0.026	0.02175316	0.0155	0.01950128
28.9405	0.61682696		19.3985	0.36898062	1.60616667	0.07914902
			0.08316667	0.0489915	0.74266667	0.0619602
			8.99916667	0.24828888	10.0421667	0.13393493
0.09166667	0.01853285					
99.2366667	0.54624781		94.7766667	0.57881488	92.95	0.37094474
0.3032	0.03674812		1.24581667	0.01633725	0.15293333	0.01456745
1.91961667	0.01913493		1.50746667	0.00605365	2.52323333	0.04013167
3.0384	0.01248855		2.7882	0.01796975	3.18993333	0.02190823
0.68863333	0.03296821		0.00311667	0.00109803	0.00168333	0.0009786
0.003	0.00174814		0.1145	0.00783837	0.05046667	0.00889644
0.0959	0.01449869		0.00168333	0.00141056	0.00091667	0.00113915
1.94081667	0.03620284		1.2381	0.02569685	0.09176667	0.00429216
			0.0113	0.0076115	0.09835	0.00843914
			0.8761	0.02140252	0.87508333	0.01153732
0.00583333	0.00120277					
7.99536667	0.00959847		7.78725	0.02731188	6.98426667	0.00739531
64.08	0.84156996					
10.0116667	1.20385077					
22.7416667	1.16580301					
3.16666667	0.48006944					

87-C10 PLAG 1,3,4R,5		87-D7 GNT AVG	616±60 GNT STDEV	7.3±1.7	87-D7 BIO AVG	BIOSTDEV
0	0	4.32573333	0.26766196		11.6609167	0.64878732
24.1474286	0.33109156	21.3378667	0.14402424		18.8855	0.41972491
61.0894286	0.59173019	38.0553333	0.22332477		36.6810833	0.42536304
5.52671429	0.15324459	2.1172	0.39952118		0.003	0.00712231
		0.07746667	0.22724118		2.52375	0.16207357
		0.8772	0.15244306		0.02766667	0.01715879
0.04914286	0.04262796	34.3852	0.38260446		16.6934167	0.85009149
8.562	0.19089875				0.1255	0.04193827
0.04185714	0.01439246				9.17991667	0.20799933
		0.01213333	0.01250638			
99.4157143	0.65390767	101.19	0.43177375		95.7825	0.41257782
0	0	0.5085	0.03060577		1.29279167	0.06776414
1.27075714	0.01961469	1.98286667	0.00966338		1.65455833	0.03731291
2.72777143	0.0139902	3.00076	0.01182194		2.72825	0.0277268
0.26442857	0.00782447	0.17884667	0.03373057		0.00023333	0.00055158
		0.0046	0.01347575		0.14115	0.00934778
		0.05857333	0.01009565		0.00175833	0.0010681
0.00185714	0.0015831	2.26724667	0.02806154		1.03840833	0.0565441
0.74115714	0.01367892				0.0178	0.00661816
0.0024	0.00082865				0.87090833	0.01751703
		0.00090667	0.00083364			
5.0083	0.00541849	8.00224	0.00736214		7.74690833	0.03085369
		75.246	0.92208459			
		16.874	1.00214627			
		5.936	1.11877356			
		1.944	0.33185195			

87-D7 MUSC AVG	MUSC STDEV	87-D7 PLAG AVG	PLAG STDEV
1.37383333	0.05447354	0.002875	0.00813173
32.505	0.37811109	23.375	0.14041876
46.8938333	0.28616178	63.3525	0.62348926
0.018	0.01048809	4.521625	0.15746196
1.28933333	0.08407061		
0	0		
1.22916667	0.10475002	0.05575	0.03286227
0.60616667	0.06000139	9.055125	0.17205932
10.2658333	0.10100182	0.095	0.03636325
94.18	0.19401031	100.45875	0.61261588
0.13786667	0.00567685	0.0001875	0.00053033
2.57846667	0.02895864	1.2124875	0.00981143
3.1564	0.01739356	2.788275	0.01226595
0.00131667	0.00076004	0.2132375	0.00837546
0.06526667	0.00429682		
0	0		
0.0692	0.00593801	0.00205	0.00119403
0.07908333	0.00771425	0.772625	0.01328186
0.88141667	0.00910899	0.0053375	0.00206808
6.96888333	0.00738686	4.99415	0.01306478

Chapter 5

A New Empirical Garnet-Hornblende Thermometer

ABSTRACT

A new geothermometer based on the Fe-Mg exchange between garnet and hornblende has been empirically calibrated on a data set of 21 samples containing coexisting garnet, hornblende and biotite. Temperatures were calculated using the garnet-biotite thermometer (Ferry and Spear, 1978) with garnet activities calculated as described in Hodges and Spear (1982). Hornblende activities were modeled as ideal mixing on the M3 site such that Xfe-hbl = Fe2/(Fe2+Fe3+Mg+Mn+Ti) and Xmg-hbl = Mg/(Fe2+Fe3+Mg+Mn+Ti). Ferric iron composition was estimated using the average of maximum and minimum acceptable stoichiometric values as described in Spear and Kimball (1984). Preliminary results of a Mossbauer study of metamorphic hornblendes indicate that this is a more realistic assumption than assigning all Fe as Fe2, as was done in the garnet-hornblende thermometer calibrated by Graham and Powell (1984). A simple regression of the data set with $\Delta V = -0.0196$ cal/bar to fit the equation:

$$LnK+(P-1)\Delta V/RT = -\Delta H/RT+\Delta S/R \quad \text{(equ. 1)}$$

gives values of $\Delta H = -3524.0 +/- 578.6$ cal/mol and $\Delta S = -1.639+/-.67$ cal/mol-k for 90% confidence intervals with an r-squared = .812. Testing of this thermometer gives values similar to those predicted by other geothermometers.

Introduction

The goal of many recent studies within metamorphic petrology has been the establishment of well calibrated empirical geothermometers and geobarometers (Kohn and Spear, 1989; Hoisch, 1989; Hammerstrom and Zen, 1988; Hodges and Crowley, 1985).

Geothermobarometers may be calibrated either experimentally, thermochemically or empirically. Experimental calibrations are generally considered to be the best method to constrain a particular reaction. However, the technique is limited by several drawbacks. First, the experimental reactions usually involve pure end member phases that are often difficult to make and are not representative of natural systems. Second, experimental calibrations are relatively time consuming because the reactions take a long time and have to be done under a variety of conditions. Last, because the reactions are sluggish, experiments are usually done at elavated temperatures thus necessitating the extrapolation of the results to temperatures more typical of metamorphic conditions.

Thermochemical calibrations are in many ways the easiest to do because $\Delta H^\circ rx$ and $\Delta S^\circ rx$ may be solved for directly. Unfortunately, strict thermochemical calibrations have only a limited use because entropy and enthalpy data is of variable quality, and for many important phases is non-existent.

Another approach is to calibrate the reaction empirically using pressures and temperatures obtained by some other method with the compositions of the pertinent phases. In the empirical method the "fundamental" thermodynamic equation is set in the form:

$$LnK+(P-1)\Delta V/RT = -\Delta H/RT+\Delta S/R$$

Therefore, by plotting the data on a $LnK+(P-1)\Delta V/RT$ vs. $1/T$ diagram, ΔS and ΔH may be obtained from the slope and the y-intercept, respectively, of a line obtained from regressing a line through the data points. Empirical calibrations are relatively straight forward, however the results are limited by the reliabilities of the pressures and temperatures used in calibrating the system. Other caveats which should be observed in any calibration scheme include: 1) the system should be calibrated within conditions as near as possible to those of intended use; 2) the equilibrium constant must be known or modeled accurately; and 3) the reactions of interest should generally be fluid independent, otherwise, K becomes dependent on the fugacity of the fluid phase.

There are at present very few useful quantitative thermobarometric techniques that may be applied to mafic metamorphic rocks. This study focuses on the calibration of a garnet-hornblende thermometer. An empirical garnet-hornblende thermometer was calibrated by Graham and Powell (1984). The Graham and Powell thermometer was calibrated from temperature constraints calculated using the garnet-clinopyroxene thermometer of Ellis and Green (1979) in samples with coexisting garnet, hornblende, and pyroxene. The new calibration presented here uses different garnet solution models and will be calibrated on samples with coexisting garnet, hornblende, and biotite. Temperatures for this calibration are calibrated using the garnet-biotite thermometer of Ferry and Spear (1978) with garnet activities presented in Hodges and Spear (1982). The range of temperatures expected for coexisting garnet and hornblende may be as low as 400-450° C. The Graham and Powell thermometer was calibrated within a range of 600-920° C, whereas this new calibration was performed on samples ranging from 500° C to 754° C, thereby more closely approximating the temperature range for many amphibolite grade rocks.

Just as in every empirical calibration the Graham and Powell thermometer relies on particular assumptions. Two of the major assumptions include: 1) the assignment of all non-ideality in the garnet-hornblende system to a Ca-correction for garnet, which they obtain by regression of

$$\ln Kd = S' + H'(-1/T) + W'(-X_{ca,g}/T)$$

As Graham and Powell note, the value they obtained for the correction factor is very similar to the one used in the thermometer of Ellis and Green (1979). This should not be surprising as the temperatures calculated for the calibration are dependent on the correction for Ca used in the Ellis and Green thermometer; and 2) the assignment of all Fe in hornblende to Fe^{2+} which will result in significant temperature over-estimates for hornblendes with ferric contents significantly over the average of those used in the calibration data set. The new thermometer calibrated here uses different solution models which may more accurately model the system, and includes a correction for the ferric content of hornblendes. Becuase of these differences and the fact that the calibration is against a different mineral system it is hoped that this new calibration will give more consistent results than the previous garnet-hornblende thermometer.

Calibration

Activities

Garnet and hornblende activity models used in this study are listed in Table 5-1. Several activity models for hornblende were tested and the model which gives the best statistical fit asumes ideal mixing on the M3 site in hornblende. A possible reason for this may be that for within reasonable crystal chemical limits (Robinson et al, 1982) the M3 site is not affected by Ca or Na which reside on the M4 site or Al^{vi} which goes on the M2 site, therefore minimizing the effects of non-ideality of these cations. The non-ideality of garnet was modeled using the activity relationships described in Hodges and Spear (1982). The Fe-Mg exchange reaction for garnet and hornblende may be expressed as:

$$\underset{\text{ferro-pargasite}}{1/4NaCa_2Fe_4Al_3Si_6O_{22}(OH)_2} + \underset{\text{pyrope}}{1/3Mg_3Al_2Si_3O_{12}} = \underset{\text{pargasite}}{1/4NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2} + \underset{\text{almandine}}{1/3Fe_3Al_2Si_3O_{12}}$$

The equilibrium constant for this reaction is:

$$K = (Aalm/Apy)^{1/3}(Apar/Afe\text{-}par)^{1/4}$$

Table 5-1

The Fe-Mg exchange reaction for garnet and hornblende may be written as

$$1/4NaCa_2Fe_4Al_3Si_6O_{22}(OH)_2 + 1/3Mg_3Al_2Si_3O_{12}$$

$$=1/4NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2 + 1/3Fe_3Al_2Si_3O_{12}$$

The equilibrium constant for this reaction is

$$K=(Aalm/Apy)^{1/3}(Apar/Afepar)^{1/4}$$

Activities
(Aalm,Apy from Hodges and Spear(1982))
$Aalm = [Xalm*exp[((1.5T-3300)*(XpyXgr))/RT)]^3$
$Apy =[Xpy* exp[((3300-1.5T)*(Xgr^2 + XalXgr + XgrXsp))/RT)]^3$
(For ideal mixing on the M3 site)
Apar = Xmg-hbl
Afepar = Xfe-hbl

At equilibrium

$$LnK +(P-1V)\Delta V°/RT = -\Delta H°/RT + \Delta S°/R$$

This equation has been fit in order to find values of $\Delta H°$and $\Delta S°$ for the above reaction

Ferric Assignment

Ferric iron composition was estimated using the average of maximum and minimum acceptable stoichiometric values (Spear and Kimball, 1984). This estimation was considered necessary due to the rather large (100° C) possible temperature over-estimates inherent in assigning all iron as Fe^{2+} in the calculation of hornblende stoichiometries. A Mössbauer spectroscopy study of 16 metamorphic hornblende samples (Page, in progress) indicates that the estimated ferric values, although not perfect, are quite good (generally within 5% Fe^{3+}/Fe_{total}) and give a much more realistic value than assigning all iron as ferrous.

Calibration Data Set

Samples which contain coexisting garnet, hornblende, and biotite in equilibrium were chosen both from the literature and from unpublished data (kindly provided by Jane Selverstone, Alan Boyle, and Wendy Kirk). Table 5-2 lists the calibration data set and the sources for this data.

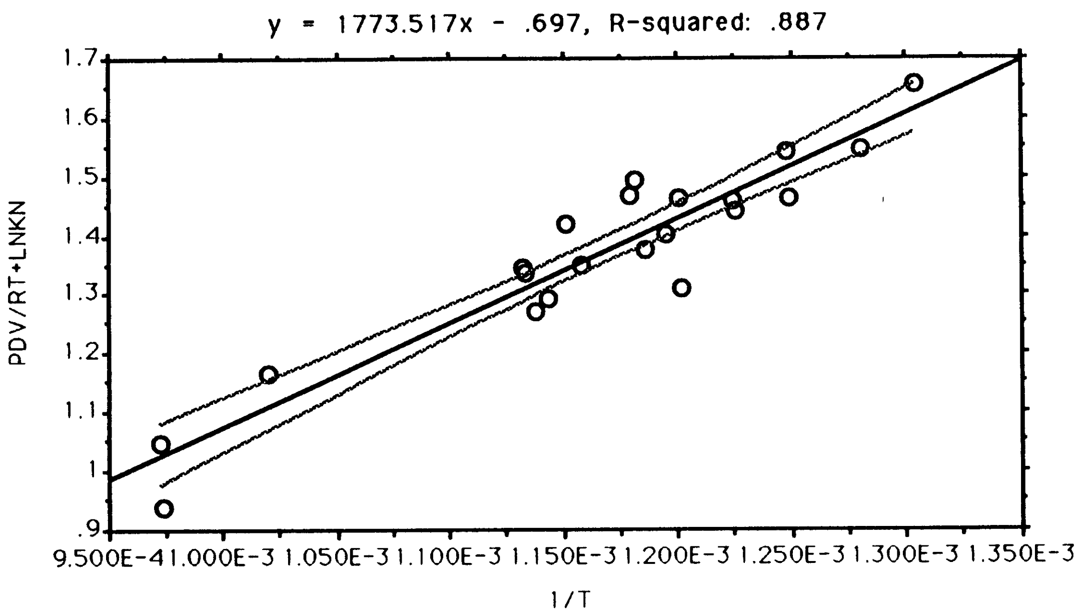
Results

The samples used in the calibration were regressed to fit equation 1 (Fig. 5-1). The results of this regression give values for ΔH and ΔS of -3524.0±289.3 and-1.385±.336 respectfully for 90% confidence intervals. Preliminary results using robust regression approaches to examine the possible effects of non-normality of the data set indicate that different regression techniques will not significantly effect the values of this calibration. Uses and comparison of different regression techniques for empirical calibrations is the focus of a paper in preparation.

Table 5-2: Calibration Data

	SAMPLE	XGR	XPY	XSP	XAL	XFEHBL	XMGHBL	TEMP	P	LNK	T gar-hbl	T diff
JS	Z3-D	0.1444	0.1533	0.0508	0.6514	0.2793	0.4849	883.7	7	1.4223	871	12.7
	Z3-N	0.1373	0.1601	0.1503	0.5523	0.3206	0.5355	980.3	7	1.2376	955.3	25
	Z3-Z	0.1357	0.1304	0.0209	0.713	0.4432	0.4743	816.9	7	1.5424	822.1	-5.2
	FH-1Q	0.113	0.1492	0.0595	0.6783	0.4063	0.4365	832	7	1.392	877.1	-45.1
	FH-2C	0.116	0.1625	0.01	0.7175	0.3324	0.5272	843.1	7	1.4586	853.6	-10.5
	PJ-8B	0.1856	0.1026	0.0408	0.672	0.5702	0.4188	846.6	7	1.5781	814.9	31.7
	PM-305D	0.147	0.188	0.029	0.636	0.3843	0.4716	1028.6	10	1.1436	1018.4	10.2
WK	268C	0.1641	0.111	0.086	0.6389	0.5022	0.4642	816	6.5	1.5204	827	-11
	979A	0.243	0.0643	0.2083	0.4843	0.4166	0.5376	767.2	6.5	1.7403	756.3	10.9
	12O1	0.1497	0.1143	0.0567	0.6797	0.5444	0.431	847.8	6.5	1.5441	823.1	24.7
	TA 160	0.1762	0.093	0.1052	0.6258	0.5206	0.426	801.3	6.5	1.6241	793	8.3
	64K180	0.2238	0.1244	0.0572	0.5944	0.4371	0.5038	879.3	6.5	1.3458	896	-16.7
AB	70888	0.2134	0.1168	0.0392	0.6306	0.4088	0.5071	868.8	6.5	1.4932	843.6	25.2
	7O893	0.1985	0.1341	0.06	0.6074	0.3788	0.5258	875	6.5	1.3657	888.4	-13.4
	7O895	0.2223	0.1033	0.0658	0.6085	0.4398	0.5243	832.7	6.5	1.5418	798.8	33.9
	7O899	0.1764	0.125	0.0709	0.6277	0.481	0.4683	882.3	6.5	1.4082	874.1	8.2
	7O901	0.1973	0.1011	0.0863	0.6153	0.4778	0.4759	800.9	6.5	1.5448	816.7	-15.8
	7O954	0.2112	0.0827	0.157	0.5491	0.4534	0.504	781.3	6.5	1.63	788.3	-7
SP	73-29D	0.077	0.16	0.0126	0.7496	0.4054	0.4325	836.5	5.5	1.4659	844 5	-8
	73-30N	0.0846	0.2527	0.025	0.637	0.3245	0.5721	1027.5	5.5	0.9935	1053.5	-26
	73-30S	0.075	0.1805	0.0331	0.711	0.3306	0.5513	863.7	5.5	1.4112	866.7	-3

Figure 5-1: Regression of calibration data



Test Samples

Samples from the literature were used for comparison with other geothermometers (Table 5-3). These samples include several which were tested by Graham and Powell (1984). The test samples come from a variety of metamorphic regions including amphibolites from the Post Pond Volcanics (Spear, 1982) and eclogitic garnet amphibolites (Morgan, 1970; Ernst & dal Piaz, 1978; Sorensen, 1988). Future work will focus on testing of this thermometer in regions where temperature constraints are known, and in simultaneously solving this garnet-hornblende thermometer with the Garnet-hornblende-plagioclase-quartz barometers of Kohn and Spear (1989).

Table 5-3: Test Samples

Sample	xalm	xpy	xgr	xsp	xfehbl	xmghbl	Pressure(Kb)	T G-Cpx	T GR+PO	T this CAL.
Spear 82										
73.25a	0.6949	0.0745	0.1881	0.0424	0.5052	0.3355	6		601	449
73.25c	0.7352	0.1565	0.0843	0.0241	0.4069	0.4463	6		561	573
73.20a	0.6977	0.1584	0.1017	0.0422	0.446	0.4213	6		614	620
73.28a	0.7139	0.1631	0.1015	0.0214	0.4895	0.4303	6		609	629
Ernst-Dal										
MRO857	0.6763	0.0765	0.2343	0.0129	0.2111	0.7399	10	454	370	398
MRO1609	0.6351	0.1198	0.2088	0.0363	0.1621	0.785	10	765	506	488
MRO1611	0.6448	0.1022	0.2267	0.0263	0.3707	0.6222	10	565	481	519
DBL379	0.6576	0.0791	0.2218	0.0415	0.4181	0.5235	10	579	507	464
DBL409	0.7099	0.0659	0.1978	0.0263	0.4928	0.4291	10	594	508	417
DBL497	0.6588	0.089	0.2236	0.0286	0.4053	0.5592	10	661	501	488
Morgan										
1058-1	0.5111	0.2402	0.2453	0.0034	0.0624	0.8719	12	620	445	728
1115	0.6084	0.1042	0.2706	0.0168	0.2505	0.6962	12	514	473	528
Sorensen 88										
HGB	0.58	0.16	0.24	0.02	0.2976	0.6105	9	645		691
9980SC2	0.48	0.15	0.35	0.01	0.3713	0.5872	9	745		817
91480SC2	0.51	0.15	0.33	0.01	0.2863	0.6666	9	671		739
7484SC5	0.58	0.15	0.26	0.02	0.3461	0.5998	9	611		690

Chapter 6

^{40}Ar-^{39}Ar Geochronology

Introduction

$^{40}Ar/^{39}Ar$ geothermochronology has become an indispensable tool in the analysis of complexly deformed and metamorphosed regions (e.g. Berger, 1975; Dallmeyer, 1975; Harrison and McDougall, 1980a,b; Sutter et al, 1985). This technique is especially useful within the Scandinavian Caledonides becuase it commonly allows for the correction of analyses for excess Ar components, which seem unusually common within the Caledonides, perhaps as a result of degassing of the Precambrian Baltic Shield. The age of metamorphism and deformation within the Caledonides ranges over much of the early and middle Paleozoic, but the various events have been grouped into two orogenic episodes. The earliest is a Late Cambrian to Early Ordovician event termed the Finnmarkian phase by Sturt et al (1978). Even though recent work by Krill and Zwaan (1987) has cast doubt on the original interpretation of the age of deformation for the type Finnmarkian in northern Scandinavia, an early Paleozoic tectonothermal event has been firmly documented within the allochthonous nappes of the Caledonides (Dallmeyer 1985, Dallmeyer and Gee 1986,Tilke 1986, Mørk 1988, this study). The second major event is termed the Scandian phase and is responsible for the final metamorphism of the nappe units and emplacement of the allochthonous nappes onto the Baltic shield. Previous studies (e.g. Dallmeyer 1985, Dallmeyer and Gee 1986,Tilke 1986) have yielded valuable information concerning the general polyphase nature of orogenesis within the Caledonides. With minor exceptions (Tilke, 1986; Dallmeyer et al., 1985) most of the rocks preserving the older tectonothermal event belong to the different tectonic units within the Seve Nappe. This study is the first within the MIT transect to examine the tectonothermal history within the Seve in detail, and thus affords the opportunity to examine the timing and conditions of early Paleozoic orogenesis and the subsequent effect the Scandian phase of metamorphism and deformation had on these rocks. The Singis-Nikkaluokta part of the transect also allows examination of the timing of tectonothermal activity within the lower Köli Nappe, the Seve-Köli shear zone, and the shear zone rocks of the Middle Allochthon, and thus to better understand the complex tectonic relationships between the different nappes. In this chapter the analytical and statistical techniques used in this study will be discussed, followed by a presentation and discussion of the results and their implications for the tectonic history of the Northern Scandinavian Caledonides.

ANALYTICAL TECHNIQUES

Samples for geochronologic analysis were collected from the different tectonostratigraphic units within the field area. Thin sections were examined from more than sixty potential samples and the best samples were chosen for analysis. Samples that were too fine grained, had chloritic or sericitic alteration or had abundant inclusions were not used. The hand samples were crushed and sieved to a 0.45 to 0.25 mm size fraction, and hornblende, muscovite, and biotite were separated using standard magnetic and heavy liquid techniques. Final purification of the separates was achieved by hand-picking. Four hundred milligrams of hornblende and 100 mg of mica splits were irradiated for 48 hours along with monitors (interlaboratory standard SB-51, 246.7 Ma) in the Ford reactor at the University of Michigan. Incremental step heating analyses were performed at the geochronology lab at the University of Maine at Orono under the supervision of Dr. Dan Lux. The argon extraction line at the University of Maine at Orono uses a molybdenum crucible with radio frequency induction heating followed by gettering using Cu-CuO and Zr-Al getters and a molecular sieve desiccant. A Nuclide 6-60-SGA 1.25 m mass spectrometer was used for the isotopic analyses. Six to eight steps were run on micas, while 11-17 steps were run on the hornblendes. Correction factors for interfering isotopes were measured on CaF_2 and K_2SO_4 salts for each of the two batches. For sample batch 1 (Sept. 1986) they are: Ar (40/39) K corr. factor =0.0391, Ar (36/37) Ca corr. factor = 0.000275, Ar (39/37) Ca corr. factor = 0.000753. For sample batch 2 (April 1989) they are: Ar (40/39) K corr. factor = 0.0347, Ar (36/37) Ca corr. factor = 0.0002572, Ar (39/37) Ca corr. factor = 0.0007494.

Statistical Methods

McDougall and Harrison (1988) discuss the generally accepted criteria for determination of a plateau in an age spectrum (cf. Dalrymple and Lanphere, 1974; Fleck et al., 1977; Lanphere and Dalrymple, 1978) which include a minimum of three contiguous steps representing a significant proportion of the the total ^{39}Ar released with concordant ages. Ages are concordant if they do not differ at the 95% confidence level. For reasons of consistency the statistical methods used in this study for the isotope correlation technique (Roddick et al, 1980) are the same as followed and discussed by Tilke (1986), and will be briefly summarized again here. The isotope correlation technique provides a test for the assumption that the non-radiogenic Ar component is of atmospheric composition ($^{40}Ar/^{36}Ar$=295.5). By plotting each heating increment on a $^{39}Ar/^{40}Ar$ vs $^{36}Ar/^{40}Ar$ isochron plot, the nonradiogenic component of the $^{36}Ar/^{40}Ar$ ratio and the radiogenic component (^{40}Ar) of the $^{39}Ar/^{40}Ar$ ratio (which corresponds to the true age of the sample, ie the intercept age) may be found by the x and y-intercepts respectively. Tilke (1986) determined the error associated with the calculated intercept age by applying the error regression techniques of York (1969). In order to account for the fact that there are no replicate analyses for each individual increment, a factor of 2.5 was multiplied by the analytical error associated with each data point used in the regression before the York regressions were applied.

^{40}Ar-^{39}Ar Results

Introduction

Thirty-one samples were analyzed and 19 gave interpretable spectra. Rocks from the Scandinavian Caledonides are notorious for having an excess argon problem and in this group of samples there were 8 excess hornblendes, 3 excess biotites and 1 failed run. Of the 19 good runs there are 4 hornblendes and 15 muscovites. Sample localities are shown on plate 1, and the heating schedules, release spectra, and isotope correlation diagrams are in appendices 6:1-3 respectively. Successful results are tabulated in table 6-1.

Upper Nappe Complex

Köli Nappe

Sample 87-D19 is from a muscovite-bearing, psammitic gneiss unit within the Salka Group of Tilke (1986) from the lower Köli nappe. This sample was collected from approximately 50 m above the contact between the Seve and Köli nappes. The release spectra for this sample gives a slightly saddle shaped profile with a minimum at 423.8±1.5 Ma for 23.9% of the gas released while the majority of the other increments give ages of about 430 M.

Seve-Köli Shear Zone

Two samples,87-D16 and 87-D17, from the Seve-Köli shear zone were collected near the stream Viddjajohka in the southwest part of the field area. Both samples give consistent ages within error. Sample 87-D16 has a plateau age defined by 59.5% of the gas of 430.1± 2.9 Ma, while 87-D17 has a slightly saddle-shaped spectrum with a minimum which contains 26.4% of the gas with an age of 428.8±1.0. The rest of this spectra is relatively flat and gives ages of around 432 Ma.

Table 6-1

SAMPLE	PHASE	unit	#	K/CA	AGE1	AGE2	AGE3	MSWD	EXCESS	#REG
C1-87	HBL	SEVE	7	0.083	504.8±3.5	508.0±9.2	495.3±7.5	5.7	834.1±231.3	13
C7-87	HBL	SEVE	3	0.119	485.8±1.4	485.9±2.6	470.0±15.8	5.4	943.6±409.9	11
D8-87	HBL	SEVE	5	0.11	448.6±1.0	451.3±5.6	449.1±3.3	2.8	384.6±59.3	11
16D-86	HBL	SEVE	1	0.04	543.0±5.7		531.5±20.8	3.6	601.1±302.3	10
D26-86	HBL	SEVE	1	0.077	542.3±13.4	559.5±9.8	545.5±6.8	2.6	828.9±115.5	12
F3-87	HBL	SEVE	4	0.043	439.7±1.8	439.9±2.8	436.5±8.8	2.1	309.7±126.8	12
87-A1	MUSC	MA	1		426.8±0.7					
28A-86	MUSC	SEVE	2		425.0±1.1	425.4±3.4				
B9-87	MUSC	SEVE	2		427****	427***				
B10-87	MUSC	SEVE	3		433.3±1.2	433.5±2.4	428.2±6.8	4.9	705.8±372.9	
C1-85	MUSC	MA	3		429.9±4.0	430.4±3.4	426.4±3.4		468.6±89.2	
10C-86	MUSC	MA	1		436.8±1.3					
C16-87	MUSC	MA	1		420.7±1.5		425.1±4.0	4.8	344.9±99.6	
D11-87	MUSC	SEVE	2		457.5±0.9	458.0±3.8				
87-D16	MUSC	S-K SH	3		429.7±1.1	430.1±2.9				
D17-87	MUSC	S-K SH	1		428.8±1.0					
D19A-85	MUSC	MA	3		431.0±0.9	431.8±3.9				
87-D19	MUSC	KOLI	1		423.8±1.5					
20D-86	MUSC	SEVE	1		428.0±0.7					
85-D23M	MUSC	MA	1		431.8±0.7					
F25-85	MUSC	SEVE	2		450.7±1.4	451.1±3.4				

Seve Nappe

There are 4 hornblende and 6 muscovite ages from the 3 tectonostratigraphic units within the Seve nappe.

Vidja Assemblage

Sample 87-D11 was collected from a garnet and mica bearing quartzofeldspathic gneiss within the Vidja assemblage near Sánjarvággi in the western part of the field area. The release spectrum for this sample is slightly saddle-shaped with a near plateau age accounting for 53.7% of the gas and giving an age of 458.0±3.0 Ma.

Aurek Assemblage

Many hornblende spectra from the Aurek assemblage were obtained. Unfortunately, most of these samples gave uninterpretable release spectra due to an extremely large excess argon component. Samples 86-D16, 86-D26 and 85-F12 are some examples of these excess spectra. Tilke (1986) also was unable to obtain any meaningful hornblende spectra from within the Aurek assemblage. The only meaningful age that was obtained from this unit is sample 87-D8 which comes from the amphibolitic black wall which surrounds the Aurek gabbro. This sample comes from near the contact with the structurally overlying Vidja gneiss unit and was collected nearly 1 km to the NW of Stuor Aurek. The release spectra for this sample defines an excellent plateau which accounts for 83.4% of the gas and gives an age of 451.1±5.9 Ma and a corresponding intercept age of 449.1±3.3 Ma.

Savotjåkka Assemblage

Three hornblende spectra were obtained from the Savotjåkka assemblage of the Seve. Sample C1-87 is a hornblende separate from a garnet-amphibolite collected near the peak of Tjålmetjåkka in the south-central part of the field area. This sample gives a near plateau age of 506.8±6.8 Ma for 95.2% of the gas. This sample yielded an intercept age from a 13 point regression using the isotope correlation technique of 495.3±7.5 Ma. Hornblende sample 87-C7 was collected nearly 3 km west of the previous sample near the peak of Läipetjäpetjåkka, and has a 3 increment plateau age of 486.8± 5.5 Ma, which accounts for 37.2% of the gas, and an intercept age of 470.0±15.8 Ma. The third hornblende spectrum was obtained for sample 87-F3, which was collected about 2 km NW along the ridge from peak Savotjåkka within a garnet-amphibolite. This sample shows a diffusive loss profile and gives a plateau age for 4 increments totalling 81.1% of the gas of 439.9±2.8 Ma and a corresponding intercept age of 436.5±8.8 Ma.

Five muscovite spectra were also obtained from within this unit. Sample 85-F25 was collected near lake Skartajaure in the central part of the study area from within a muscovite-bearing quartzofeldspathic gneiss about 20 m structurally above the Manak assemblage. Although this sample yielded a saddle-shaped spectra a good two increment near plateau accounting for 36% of the gas gave an age of 451.1±3.4 Ma. The rest of the Seve muscovite samples all came from micaceous quartzofeldspathic gneisses and gave ages of between 425-433 Ma. Sample 86-28A came from about 2 km NW of the small peak Skártavárdu in the central part of the study area and is approximately 120 m structurally above the Middle Allochthon mylonites. This sample has a slightly saddle-shaped spectra with a minima which represents 20.1% of the gas and an age of 425.0±1.1 Ma, and a near-plateau age of 425.4±3.4 Ma representing 37.7% of the gas. Sample 87-B10 was collected at Tjäpet-tjåkka in the eastern part of the study area, and is located approximately 160 m structurally above the mylonites of the Middle Allochthon. The release spectra for this sample shows an excess profile for the first few increments coming down in age to a plateau which makes up 62.9% of the total gas and gave an age of 433.5±2.4 Ma. Sample 86-20D came from about 3 km due south of peak Guodekjåkka in the NE region of the study area. The release spectrum shows a generally saddle-shaped spectrum with a minima giving a maximum interpreted age for the last thermal event responsible for significant Ar. loss of 428.0±0.7 Ma.

Manak Assemblage

Sample 86-10C from the Manak assemblage was collected just north of lake Urtejaure from within a micaceous gneiss surrounding pods of the Manak leucogabbro. The spectrum for this sample has an excess profile in the first few increments and comes down to a minimum age of 436.8±1.3 Ma.

Middle Allochthon Mylonites

Matert Shear Zone

The Matert shear zone rocks are located in the western part of the region above the basement rocks of the Singis window. Four samples from this unit yielded ages which range from 421-431 Ma. Sample 85-C1 came from the north side of the central Singis window from a muscovite-bearing, S-C granite mylonite. The release spectrum for this sample gave a plateau age of 430.4±3.4 Ma for three increments totalling 75.4% of the gas, while an intercept age for a 5 point regression gives an age of 426.4±3.4 Ma. Sample C16-87M was collected nearly 1 km NW of the southern tip of Lake Jertajaure in the west-central part of the study area from a muscovite bearing schist just below the contact with the overlying Seve amphibolites. This sample does not have a well defined plateau but has a minima which accounts for 23.3% of the gas with an age of 420.7±3.4 Ma, while an intercept age for the regression of seven points gives 425.1±4.0 Ma. Sample 85-D23 from a similar unit as the previous sample was collected about 1 km SE of lake Jertajaure. The release spectra for this sample also does not define a plateau but has a minima at 431.8±0.7 Ma for 21.9% of the gas, while the isotope correlation diagram defines an intercept age of 432.0±5.5 Ma for a regression through all release points. Sample 85-D19A is the last sample from the Matert shear zone rocks and is from a few 100 meters NE of the previous sample. This sample gives a good plateau age of 431.8±3.9 Ma which accounts for 71.4% of the total gas released.

Paltavare Shear Zone

Sample 87-A1 was collected nearly 2 km east of lake Paikejaurasj in the central part of the study area from a dark micaceous phyllonitic unit. The release spectrum for this sample does not form a plateau, but has a minimum which yields an age of 426.8±0.7 Ma.

Previous ^{40}Ar-^{39}Ar Geochronology

Tilke (1986) obtained ^{40}Ar-^{39}Ar results for 9 hornblendes, 3 muscovites and a biotite throughout the Efjord-Singis part of the MIT transect. He interpreted his data to fall within five major phases:

1) 500-440 Ma Finnmarkian retrograde metamorphism.
2) 430-420 Ma Scandian retrograde metamorphism and early thrusting onto the Baltic Shield.
3) 415-410 Ma imbrication of the upper nappe complex and thrusting onto the Baltic Shield.
4) 390-385 Ma final thrusting of the upper nappe complex onto the Baltic Shield.
5) 385-355 Ma post-thrusting uplift and cooling.

These results are from a relatively large portion of the transect (90 km) and therefore are of a more general nature. The relevant results and interpretations of Tilke (1986) will be discussed in the interpretation and discussion sections to follow.

Interpretation of ^{40}Ar-^{39}Ar Results

The "art" of interpreting ^{40}Ar-^{39}Ar release spectra has been a subject of much recent literature (re.McDougall and Harrison, 1988). Within this study there are several main types of spectra represented including: excellent plateaux, excess profiles, diffusive loss patterns, and saddle-shaped spectra. The data presented in the prior section support an interpretation which will be discussed further in this section that two deformational and metamorphic events occured in this part of the Caledonides.

Finnmarkian Phase

The Finnmarkian (late-Cambrian through Ordovician) event is documented within rocks of the Seve nappe in the Singis-Nikkaluokta portion of the MIT transect. Hornblende samples 87-C7 and 87-C1 from the Savotjåkka assemblage give ages of 485 and 495 Ma respectively for Finnmarkian retrograde cooling below the nominal closure temperature for hornblende (Harrison, 1981) of ≈ 500° C. Muscovite sample 85-F25 also from the Savotjåkka assemblage gives an age of 450 Ma for retrograde cooling below the closure temperature for muscovite (Harrison et al., 1985) of ≈350°C. Muscovite sample 87-D11 from the Vidja assemblage cooled below 350° C at 458 Ma. Tilke (1986) reported muscovite ages of 450 and 448 Ma. for samples T85-4E and T85-13B from within the same unit. Hornblende sample 87-D8 gives an excellent plateau age of 451 Ma. This sample is from within the amphibolitic black wall surrounding the Stuor Aurek meta-gabbro and is interpreted to be the age of a late stage Finnmarkian shear zone which juxtaposed the Vidja assemblage quartzofeldspathic gneisses with the gabbroic body. It is clear from these ages that the high grade metamorphism and associated fabrics within the Seve nappe are older than 490 Ma.. Regionally this is also substantiated by Mørk (1988) who obtained a Sm-Nd age on an eclogite boudin of 505 Ma.

Scandian phase

The Scandian phase of deformation variably metamorphosed deformed and juxtaposed all of the allochthonous nappes and emplaced this complex package onto rocks of the Baltic shield (Gee, 1975; Dallmeyer and Gee, 1985). Within the study area, all units were effected by the Scandian phase of deformation. Sample 87-D19 from the Salka unit of the Köli nappe gives a maximum age of 424 Ma. Samples 87-D16 and 87-D17 from the Seve-Köli shear zone give ages of ≈ 430 and 429 Ma. respectively. Four of the six muscovite samples from the Seve give good Scandian ages of between 425-433 Ma. which indicate that the majority of the Seve rocks underwent metamorphism with temperatures in excess of 350° C during this event. The spectrum of hornblende sample F3-87 shows a diffusive loss profile with a plateau of 440 Ma. This is interpreted to be a result of partial Ar loss during the Scandian . Because the other two Seve hornblende samples still retain their Finnmarkian ages the rocks of the Seve probably did not exceed the ≈ 500° C closure temperature for a significant length of time during the Scandian; however, the partially reset sample indicates the temperature experienced by the previously deformed and metamorphosed Seve rocks may have been near 500° for a length of time sufficient to cause some Ar loss. Another possible interpretation is that this sample was involved in a Scandian dynamic recrystallization event which occured below the hornblende closure temperature.

All five samples from the Middle Allochthon shear zone give Scandian ages of between 421-431 Ma. Most of the spectra for these samples have slightly saddle shaped profiles with minima which indicate the maximum age for the samples. These ages represent the age of cooling below the muscovite closure temperature and in some cases may be crystallization ages dating the mylonitization.

Discussion

The results presented here compliment other recent geochronologic studies within the northern Scandinavian Caledonides. Mørk et al. (1988) obtained 2 Sm-Nd mineral whole-rock isochrons from eclogites within the Tsäkkok and Vaimok lenses (Zachrisson and Stephens, 1984) of the Seve Nappe in southern Norrbotten approximately 150 km south of the present study area. The ages of these eclogites are 505±18 Ma. and 503±14 Ma. Also in Norrbotten, Dallmeyer and Gee (1986) obtained a ^{40}Ar-^{39}Ar hornblende age of 491 Ma. for retrograde amphiboles within eclogites and 2 phengitic muscovite ages of 436 and 444 Ma..The closure temperature for Sm/Nd varies significantly with garnet composition from 700-480° C (Humphries and Cliff, 1982); therefore, the eclogite ages reported by Mørk are reasonably interpreted as cooling ages from peak Finnmarkian metamorphism or as crystallization ages. The data from the Singis-Nikkaluokta transect for the older tectonothermal event give hornblende cooling ages of 485-495 Ma. and muscovite cooling ages of 451-458 Ma. For closure temperatures of 500° and 350° C for hornblende and muscovite respectively give cooling rates of between 3.3-5.6° C / Ma.

The Scandian ages recorded for samples within the Köli, Seve-Köli shear zone, Seve, and the Middle Allochthon mylonites all overlap and fall within the range 421-431 Ma. This suggests that all of these units were juxtaposed while the temperatures were above the blocking temperature for Ar retention of muscovite. Fortunately the structural relationships discussed in chapter 2 allow for an understanding of the relative timing of the deformation and metamorphism of the different tectonic units within the area. The stratigraphic relationships discussed in chapter 1 indicate that the Salka Group of the lower Köli nappe may be correlated with equivalent rocks ≈ 300 km to the south in the Bjorkvattnet area (Stephens, pers. comm.; Stephens, 1982) which contain fossils and have a late Ordovician to early Silurian age, thus constraining the age of metamorphism and deformation for the lower Köli into a narrow (as little as a few to 8 million years) time period. The younger events discussed by Tilke (1986) are not recorded in the mapped area and may be absent from this region because the rocks were in a more eastern or shallower part of the Scandian nappe wedge and therefore cooled earlier than rocks further west.

Conclusions

The results of a detailed ^{40}Ar-^{39}Ar geochronologic study of rocks from the Singis-Nikkaluokta region of the northern Scandinavian Caledonides indicate:

1) The high grade metamorphism and associated deformation of the Seve units was a late Cambrian to early Ordovician event (Finnmarkian) in which the rocks cooled below the respective closure temperatures for hornblende at ≈ 490 Ma and muscovite at ≈ 454 Ma.

2) Assuming a simple linear cooling model a cooling rate of 3-6° C/Ma. was obtained for the older tectonothermal event.

3) There is evidence for a late stage Finnmarkian (450 Ma.) relatively high grade shear zone separating the Vidja Assemblage and the Stuor Aurek meta-gabbros.

4) The Scandian phase of deformation and metamorphism partially reset some of the Seve hornblendes and a majority of the muscovites which indicate that the rocks effected by the Finnmarkian event felt a second tectonothermal pulse of more than 350° C beginning at ≈ 430 Ma.

5) During the Scandian event all of the far travelled allochthonous tectonic units were juxtaposed and the Middle Allochthon mylonites were formed as these nappes were emplaced above the Baltic Shield. The tectonic units of the Singis-Nikkaluokta transect were assembled prior to regional cooling through the closure temperature of muscovite. No evidence obtained from the rocks of the Singis-Nikkaluokta region corroborate the younger tectonic events discussed by Tilke (1986) having occurred for the rocks of this region.

Appendix 6:1

Heating Schedules

87-C1

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
C1-87H	J=.004083			(E-14)				
800	758.3	3.004	0.7992	0.8	0.4	68.9	0.1627	2062.8±23.6
850	443.3	3.1064	0.4706	0.8	0.4	68.7	0.1574	1459.7±51.0
900	242.42	2.774	0.1849	1	0.5	77.5	0.1763	1029.1±29.5
945	140.91	3.6717	0.0962	1.1	0.5	80	0.1331	684.7±24.7
985	88.66	4.8059	0.0236	2.4	1.1	92.5	0.1016	522.7±13.4
1025	82.71	5.1983	0.0196	4.4	2.1	93.4	0.0939	496.5±9.1
1065	81.26	5.5827	0.0098	7.6	3.6	96.9	0.0874	504.8±3.5
1100	80.36	5.8053	0.0067	15.8	7.5	98	0.084	505.0±2.0
1135	80.7	5.8894	0.0058	16.1	7.6	98.4	0.0828	508.5±1.8
1165	80.89	5.8793	0.0063	18.6	8.8	98.2	0.083	508.8±3.1
1195	81.42	5.8898	0.0053	17.6	8.3	98.6	0.0828	513.4±2.2
1235	80.5	5.9126	0.0037	22.3	10.5	99.2	0.0825	510.9±1.2
1430	79.46	5.9624	0.0039	103.9	48.9	99.1	0.0818	504.9±.8
TOTAL				212.6	100			520.12
PLAT AGE	508±9.2							

87-C7

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
B7-87H	J=.004076			(E-14)				
635	729.41	6.0801	0.5891	0.5	0.2	76.2	0.0802	2140.6±107.6
730	482.05	7.2524	0.4877	0.6	0.2	70.2	0.0672	1569.7±53.9
800	377.01	5.157	0.3684	0.8	0.3	71.2	0.0946	1337.4±125.5
850	247.86	3.3644	0.2212	1.2	0.4	73.7	0.1453	1006.1±20.4
900	154	3.4118	0.0944	2.7	0.9	82	0.1433	751±13.5
945	108.99	3.8095	0.0404	6.9	2.3	89.3	0.1283	604.1±12.2
985	90.97	4.0764	0.016	14.6	4.9	95.1	0.1198	546.4±2.2
1025	83.65	4.1584	0.0101	27.6	9.2	96.8	0.1175	515.7±2.1
1070	80.45	4.1611	0.0085	44.9	15	97.2	0.1174	500.7±1.9
1115	78.98	4.1573	0.0066	53.7	18	97.9	0.1175	495.5±1.5
1155	77.91	4.135	0.0072	49	16.4	97.6	0.1181	488.6±1.5
1195	77.9	4.097	0.0088	39.8	13.3	97	0.1192	485.8±1.4
1235	78.95	3.9985	0.0122	22.3	7.5	95.8	0.1222	486±2
1430	78.04	3.7519	0.0131	34.2	11.5	95.4	0.1302	479.2±1.7
TOTAL				298.7	100			509.57

86-16D

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
16D-86H	J=.004090			(E-14)				
730	2081.88	6.4604	1.891	0.2	0.2	73.2	0.0755	3576.8±749.7
850	1207.95	9.6237	1.1794	0.3	0.4	71.2	0.0505	2730.8±165.5
900	175.49	16.5556	0.1423	1.8	2	76.7	0.0292	799.6±25.5
945	114.72	16.7142	0.0542	3.9	4.4	87.1	0.0289	625.0±5.6
985	121.02	16.9824	0.0862	3.8	4.3	80	0.0285	608.4±12.7
1025	103.23	16.9517	0.0466	7.4	8.3	87.9	0.0285	575.5±28.9
1070	95.64	16.7588	0.0215	16	18	94.7	0.0289	574.5±2.4
1115	95.63	16.6703	0.0232	12.5	14.1	94.1	0.029	571.6±4.9
1155	95.08	16.7024	0.0237	12.3	13.8	93.9	0.029	567.8±3.0
1195	95	16.76	0.0312	10.2	11.4	91.6	0.0289	555.4±7.9
1235	97.88	16.3654	0.0327	9.3	10.5	91.4	0.0296	568.3±4.0
1430	90.84	12.2963	0.0225	11.2	12.6	93.7	0.0395	543.0±5.7
TOTAL				88.9	100			587.83

87-D8

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
D8-87H	J=.004083			(E-14)				
830	442.24	3.279	1.0123	0.9	0.3	32.4	0.1491	832.7±61.7
900	253.11	3.7187	0.506	1	0.3	41	0.1314	639.1±73.2
965	98.71	4.0512	0.0749	3.2	1.1	77.9	0.1206	493.7±5.9
1025	74.69	4.3966	0.0153	10.4	3.5	94.4	0.1111	457.5±3.7
1070	72.08	4.3263	0.0066	15.5	5.2	97.7	0.1129	457.2±2.0
1115	71.13	4.344	0.0035	18.4	6.2	99	0.1124	457.1±2.8
1155	70.8	4.363	0.0062	23.7	8	97.8	0.1119	450.6±2.8
1190	70.78	4.327	0.005	25.9	8.7	98.3	0.1129	452.5±2.1
1220	70.7	4.3421	0.0048	33.2	11.1	98.4	0.1125	452.4±.9
1280	69.85	4.304	0.0041	104 5	35.1	98.7	0.1135	448.6±1
1430	70.48	4.2914	0.0041	61.2	20.5	98.7	0.1138	452.3±.9
TOTAL				297.8	100			453.86
PLAT AGE	451.3±5 6							

87-F3

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
F3-87H	J=.004083			(E-14)				
730	964.41	5.6063	2.6588	0.2	0.2	18.6	0.087	993.5±834.4
800	463.45	6.4663	1.3513	0.4	0.3	13.9	0.0754	424.1±323.3
900	118.24	6.0226	0.1598	0.2	0.2	60.4	0.081	463.6±153.0
945	82.63	7.3436	0.1146	0.4	0.3	59.7	0.0664	332.5±79.8
985	65.46	10.4965	0.0621	0.5	0.4	73.1	0.0463	324.4±39.2
1025	72.11	11.7473	0.0475	1.2	1.1	81.7	0.0413	392.1±17.0
1070	73.46	11.3913	0.0293	5.6	5	89.3	0.0426	431.6±11.9
1115	73.12	11.4264	0.0187	12.5	11.3	93.6	0.0425	447.9±3.1
1155	73.68	11.4532	0.0237	16.1	14.5	91.6	0.0424	442.6±1.7
1195	71.78	11.396	0.0189	24	21.7	93.4	0.0426	439.7±1.8
1235	71.32	11.3265	0.0171	29.1	26.3	94.1	0.0429	440.2±1.7
1430	75.24	11.3592	0.0306	20.6	18.6	89.1	0.0428	439.7±2.9
TOTAL				110.9	100			440.63
PLAT AGE	439.9±2.8							

86-D26

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
D26-86H	J=.004090			(E-14)				
830	592.45	1.863	0.6202	1.4	1.3	69.1	0.2626	1776.0±49.2
900	314.77	1.713	0.2741	2.3	2.1	74.3	0.2857	1212.0±17.6
965	122.89	2.154	0.0432	1.2	1.1	89.7	0.2271	672.4±24.4
1025	99.88	2.805	0.0306	1.6	1.5	91 1	0.1743	572.0±16.1
1070	95.09	3.4644	0 023	2.1	2	93.1	0.1411	558.6±12.9
1115	92.15	3.7616	0.0234	2.6	2.4	92.8	0.1299	542.3±13.4
1155	92.14	4.6528	0.0181	3.2	3	94.5	0.1049	551.4±10.5
1190	91.98	5.5944	0.0062	5.4	4.9	98.4	0.0872	570.4±2.8
1220	90.59	6.5032	0.0067	13.1	12.1	98.3	0.075	562.8±3.6
1250	89.94	6.4827	0.0052	12.9	11.9	98.8	0.0752	561.7±3.3
1280	89.8	6.0742	0.0066	10.1	9.3	98.3	0.0803	558.3±2.9
1430	88.54	7 194	0.0049	52.8	48.6	98.9	0.0677	555.0±1.9
TOTAL				108.7	100			588.29
PLAT AGE	559.5±9.8							

87-B10

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
B10-87M	J=.004230			(E-14)				
730	97.99	0.0815	0.1342	3	0.6	59.5	6.009	397.7±10.8
840	77.72	0.01	0.0309	10.7	2.1	88.2	48.9996	459.3±4.8
910	71.89	0.0125	0.0114	23	4.5	95.3	39.1058	459.0±1.5
975	67.82	0.0101	0.0062	43.4	8.5	97.2	48.3708	443.8±1.0
1055	65.26	0.0106	0.0035	101.8	19.8	98.3	46.226	433.3±1.2
1135	65.27	0.0078	0.0034	94.9	18.5	98.4	62.925	433.5±1.1
1235	64.89	0.0063	0.0021	126.3	24.6	99	77.6911	433.5±.7
1430	65.51	0.014	0.0029	110.7	21.5	98.6	35.0247	436.0±.7
TOTAL				513.9	100			436.36
PLAT AGE	433.5±2.4							

85-C1

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
C1-85M	J=.006060			(E-14)				
905	49.75	0.0235	0.0127	47.8	10.3	92.4	20.851	443.3±4.8
930	45.34	0.0107	0.003	153.6	32.9	97 9	45.901	429.9±4.0
975	45.22	0.0039	0.0026	102.9	22.1	98.2	126.943	430.1±4.0
1000	45.78	0.0479	0.0041	95	20.4	97.3	10.229	431.1±4.3
1025	46.94	0.0348	0.0048	47.5	10.2	96 9	14.08	439.2±4.8
1050	52.78	0.2435	0.0025	15.4	3.3	98.5	2.012	494.4±5.5
1180	97.37	3.085	0.0388	4	0.9	88.4	0.158	759.0±12.4
TOTAL				466.3	100			437.51
PLAT AGE	430.4±3.4							

86-28A

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
28A-86M	J=.004157			(E-14)				
730	87.98	0.01	0.0674	7.6	1	77.3	48.9996	449.4±5.8
840	69.22	0.0055	0.0113	30.9	3.9	95.1	88.6714	436.6±1.9
910	64.98	0.0051	0.0019	144	18.3	99.1	96.6275	427.8±1.2
975	64.78	0.0107	0.0016	130.1	16.5	99.2	45.8369	427.2±1.6
1055	64.22	0.007	0.001	158.2	20.1	99.5	70.2505	425.0±1.1
1135	64.28	0.0071	0.0007	138.9	17 6	99.6	68.7831	425.9±0.8
1235	64.8	0.0063	0.0006	87.6	11.1	99.7	77.5804	429.1±0.8
1430	66.01	0.018	0.003	91	11.5	98.6	27.2521	432.0±1.1
TOTAL				788.4	100			427.98
PLAT AGE	425.4±3.4							

87-C16

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
C16-87M	J=.004199			(E-14)				
730	81.23	0.003	0.0609	7.6	1	77.8	163.333	424.7±8.4
840	66.69	0.0087	0.0092	57	7.7	95.9	56.4447	429.1±3.0
910	64.64	0.0083	0.0034	81	10.9	98.4	59.207	427.1±.8
975	63.87	0.006	0.0023	133.7	18	98.9	81.422	424.4±1.0
1055	63.15	0.0053	0.0019	173.6	23.3	99.1	92.7149	420.7±1.5
1135	64.16	0.0129	0.0024	108.7	14.6	98.8	37.9547	425.9±1.0
1235	64.13	0.0186	0.0018	126	16.9	99.1	26.3296	426.8±1.1
1430	69.94	0.0376	0.0196	56.3	7.6	91.7	13.035	430.2±1.1
TOTAL				743.9	100			425.25

87-D11

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
D11-87M	J=.004162			(E-14)				
730	111.24	0.1485	0.202	2.6	0.6	46.3	3.2993	350.5±46.7
840	85.2	0.0638	0.0471	2.5	0.6	83.6	7.6775	468.5±22.7
910	87.99	0.1057	0.0096	4.8	1.1	96.7	4.6354	547.1±5.1
975	87.34	0.0467	0.004	12.7	2.9	98.6	10.4989	552.7±1.7
1055	75.28	0.0475	0.0034	41.4	9.3	98.6	10.3154	485.8±1.4
1135	70.33	0.0348	0.0026	115.2	25.9	98.9	14.0882	458.6±0.8
1235	69.95	0.0386	0.0019	123.5	27.8	99.1	12.6939	457.5±0.9
1430	71.66	0.3354	0.0016	141.4	31.8	99.3	1.4606	468.2±1.0
TOTAL				444.1	100			466.96
PLAT AGE	458.0±3.8							

87-D16

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
87-D16M	J=.004217			(E-14)				
730	90.45	0.0402	0.077	5.1	0.9	74 8	12.1887	452.9±9.0
840	74.31	0.0175	0.0219	20.2	3.6	91.3	27.9996	453.8±9.5
910	67.8	0.0205	0.0067	36.2	6.5	97.1	23.9021	441.8±1.3
975	64.56	0.0081	0.0022	114	20.4	98.9	60.5233	430.3±0.9
1055	64.49	0.0163	0.0023	118.6	21.2	98.9	30.0628	429.7±1.1
1135	64.76	0.0095	0.0028	99.9	17.9	98.7	51.8076	430.4±1.0
1235	64.73	0.0027	0.0011	86.4	15.5	99.5	181.0118	433.4±1.3
1430	64.78	0.0142	0.0026	77.8	13.9	98.8	34.6286	431.0±1.2
TOTAL				558.3	100			432.56

87-D17

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
D1787M	J=.004212			(E-14)				
730	98.66	0.0122	0.1029	19.4	3.5	69.2	40.0978	455.7±3.6
840	75.55	0.0052	0.0155	18.2	3.2	939	94.0748	471.5±1.8
945	64.88	0.0069	0.0023	129.6	23.1	93.9	71.4803	431.7±1.1
1015	64.24	0.0072	0.0017	148.1	26.4	98.9	68.2448	428.8±1.0
1090	65.19	0.006	0.0019	81.7	14.6	99.2	81.6663	434.1±1.0
1160	65.82	0.0083	0.0036	50.2	9	99.1	59.1941	434.9±0.9
1275	65.27	0.0068	0.0034	24.7	4.4	98.3	72.5707	432.1±0.9
1430	68.52	0.0132	0.0136	89	15.9	98.4	37.1377	433.5±1.1
TOTAL				560.9	100	94.1		433.98

85-D19A

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
D19A85M	J=.006112			(E-14)				
880	47.75	0.0767	0.0106	34	8.9	93.3	6.3865	434.6±3.3
930	45.58	0.025	0.0041	100.5	26.4	97.3	19.5996	432.7±1.2
975	44.91	0.0489	0.0022	56.3	14.8	98.5	10.0221	431.8±2.3
1000	44.69	0.037	0.0017	115	30.2	98.8	13.2465	431.0±0.9
1025	45.36	0.0357	0.0022	55.9	14.7	98.5	13.7082	435.5±1.6
1050	46.42	0.1437	0.0012	13.7	3.6	99.2	3.4095	447.4±2.4
1075	67.25	0.75	0.0518	3.9	1	77.3	0.653	497.9±15.2
1180	67.03	1.665	0.0049	1.7	0.5	98	0.2939	609.5±8.3
TOTAL				381	100			434.61
PLAT AGE	431.8±3.9							

87-D19

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
87D19M	J=.004229			(E-14)				
730	100.23	0.0932	0.1464	3.8	0.7	56.8	5.2555	389.2±5.8
840	74.68	0.0271	0.0355	17.7	3.3	85.9	18.0675	433.0±2.8
945	75.87	0.0206	0.0414	61.6	11.4	83.8	23.7399	429.7±2.5
1015	87.86	0.0166	0.083	82.9	15.3	72.1	29.4645	428.0±1.0
1090	72.92	0.0837	0.0348	128.9	23.9	85.9	5.8567	423.8±1.5
1160	72.2	0.0109	0.0295	62.5	11.6	87.9	44.9331	428.9±1.2
1240	73.93	0.0169	0.0348	59.6	11	86	28.9594	429.8±1.1
1430	80.3	0.1294	0.0559	123.2	22.8	79.4	3.7863	430.7±1.0
TOTAL				540.1	100			428.01

86-20D

TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
20D-86M	J=.004231			(E-14)				
730	76.92	0.0294	0.0522	7.3	1.1	79.9	16.655	417.0±7.4
840	67.91	0.0308	0.0097	21.3	3.3	95.7	15.8984	438.4±2.0
910	65.5	0.02761	0.0032	49.3	7.7	98.8	17.71	437.5±2.5
975	64.91	0.0152	0.0026	66.8	10.4	98.8	32.2577	433.0±1.0
1055	64.15	0.0111	0.0017	129	20	99.2	44.1438	430.0±0.7
1135	64.02	0.0087	0.0015	134.9	20.9	99.2	56.4317	429.5±0.7
1235	63.72	0.008	0.0014	153.8	23.9	99.3	61.1045	428.0±0.7
1430	64.65	0.0318	0.0017	81.7	12.7	99.2	15.3988	432.9±0.9
TOTAL				644.1	100			430.8

85-D23

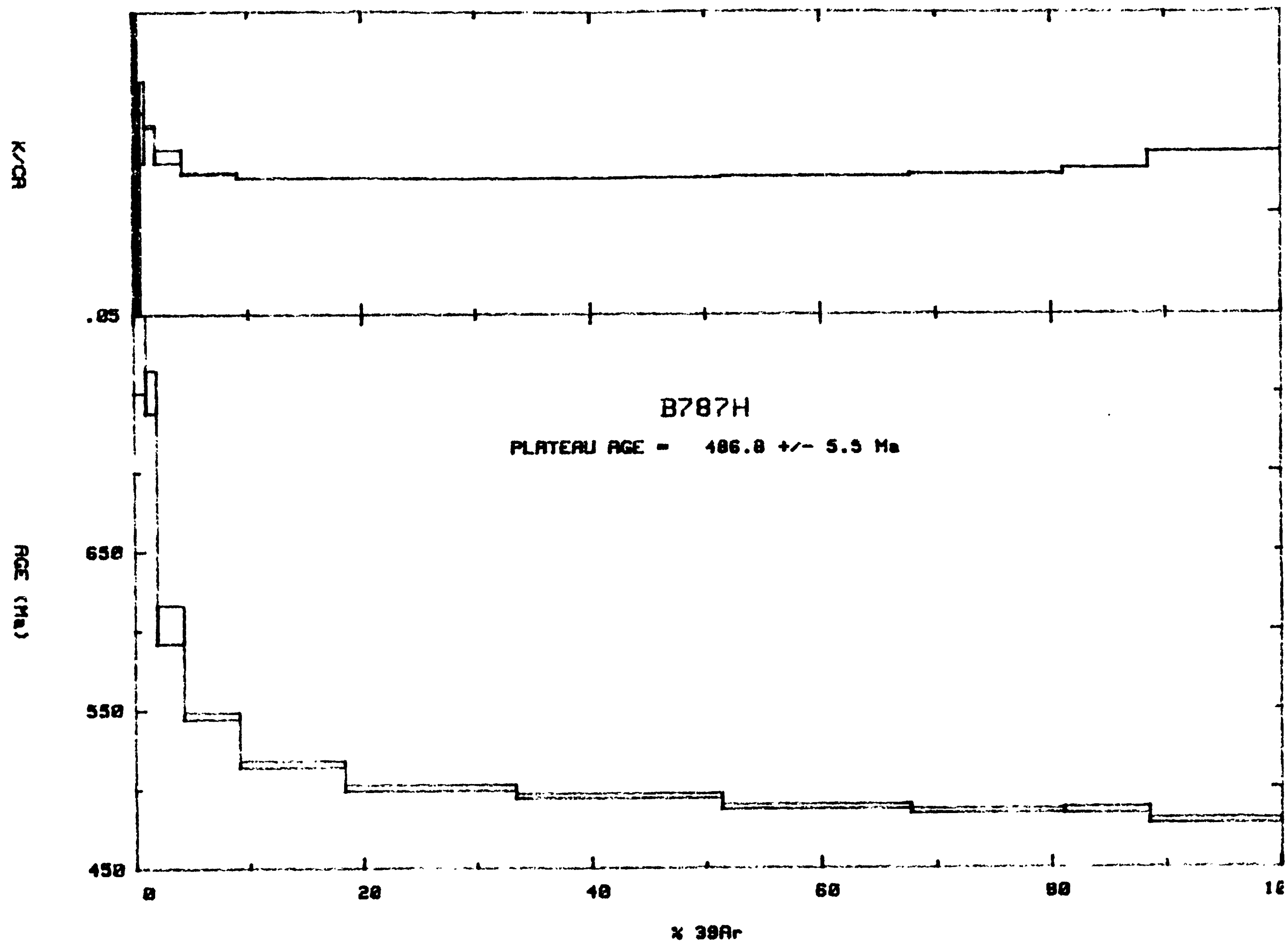
TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
85D23M	J=.0042116			(E-14)				
730	86.75	0.01	0.0662	5	1	77.4	48.9996	449.3±9.6
840	72.77	0.0452	0.0185	16.7	3.3	92.4	10.8403	450.0±2.0
910	67.96	0.0023	0.0064	23.9	4.7	97.1	216.8138	442.6±1.9
975	65.52	0.0067	0.0026	89	17.5	98.8	73.134	434.8±0.8
1055	65.24	0.01	0.0023	103.1	20.3	98.9	48.9996	433.7±1.0
1135	65.31	0.01	0.0023	91.6	18	98.9	48.9996	434.1±0.7
1235	64.85	0.01	0.0021	111.4	21.9	99	48.9996	431.8±0.7
1430	66.46	0.025	0.0057	68.2	13.4	97.4	19.6389	434.9±1.1
TOTAL				508.9	100			434.82
PLAT AGE	434.2±3.3							

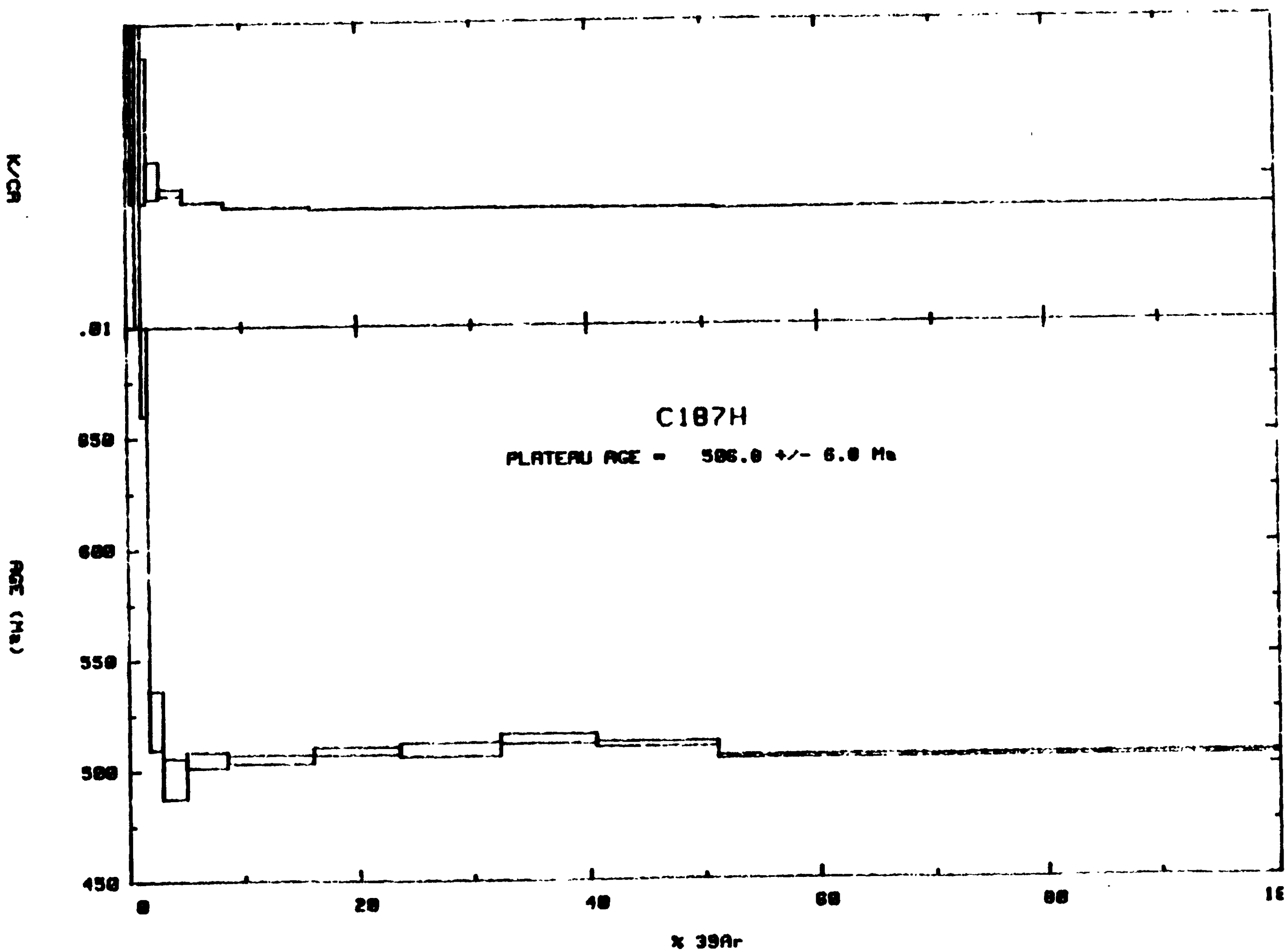
85-F25

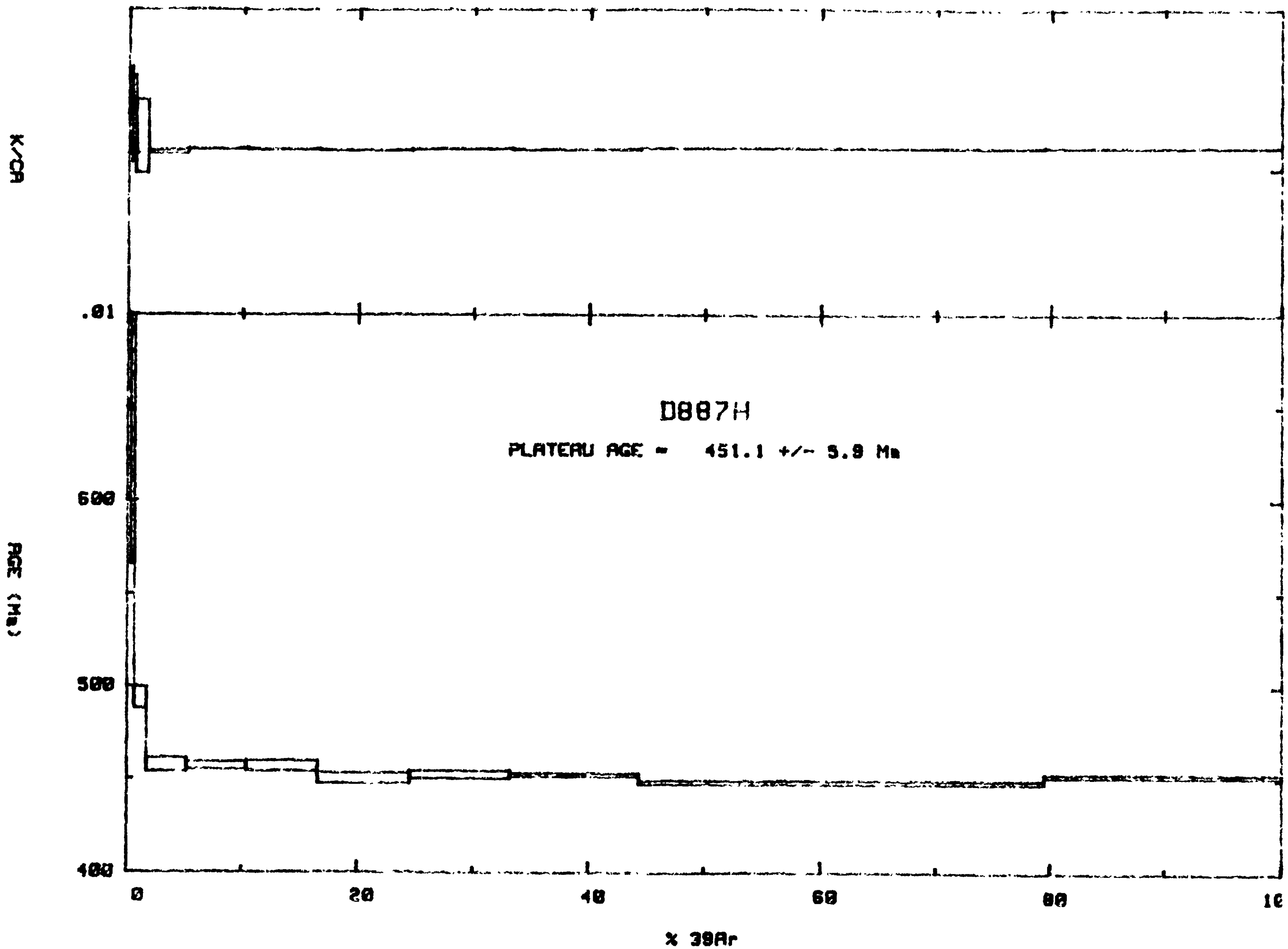
TEMP C	40AR/ 39AR	37AR/ 39AR	36AR/ 39AR	MOLES 39AR	39AR %TOTAL	%40AR RAD	K/ CA	APPARENT AGE MA
F25-85M	J=.004151			(E-14)				
730	88.28	0.0159	0.0306	6.6	1.2	89.7	30.7592	512.8±10.9
840	79.67	0.0281	0.0098	23.8	4.4	96.3	17 4374	499.0±2.0
910	71.3	0.029	0.0035	76.6	14	98.5	16.8787	461.5±1.0
975	69.19	0.0164	0.0022	96.2	17 6	99	29.8777	451.5±1.5
1055	68.94	0.0154	0.0018	100.6	18.4	99.2	31.8385	450.7±1.4
1135	70.93	0.0358	0.0021	79.1	14.5	99.1	13.6944	461.7±1.1
1235	69.8	0.0187	0.0015	103.8	19	99.3	26.2169	456.2±1.1
1430	70.9	0.0276	0.003	59.4	10.9	98.7	17.7276	460.0±1.7
TOTAL				546.1	100			458.89
PLAT AGE	451.1±3.4							

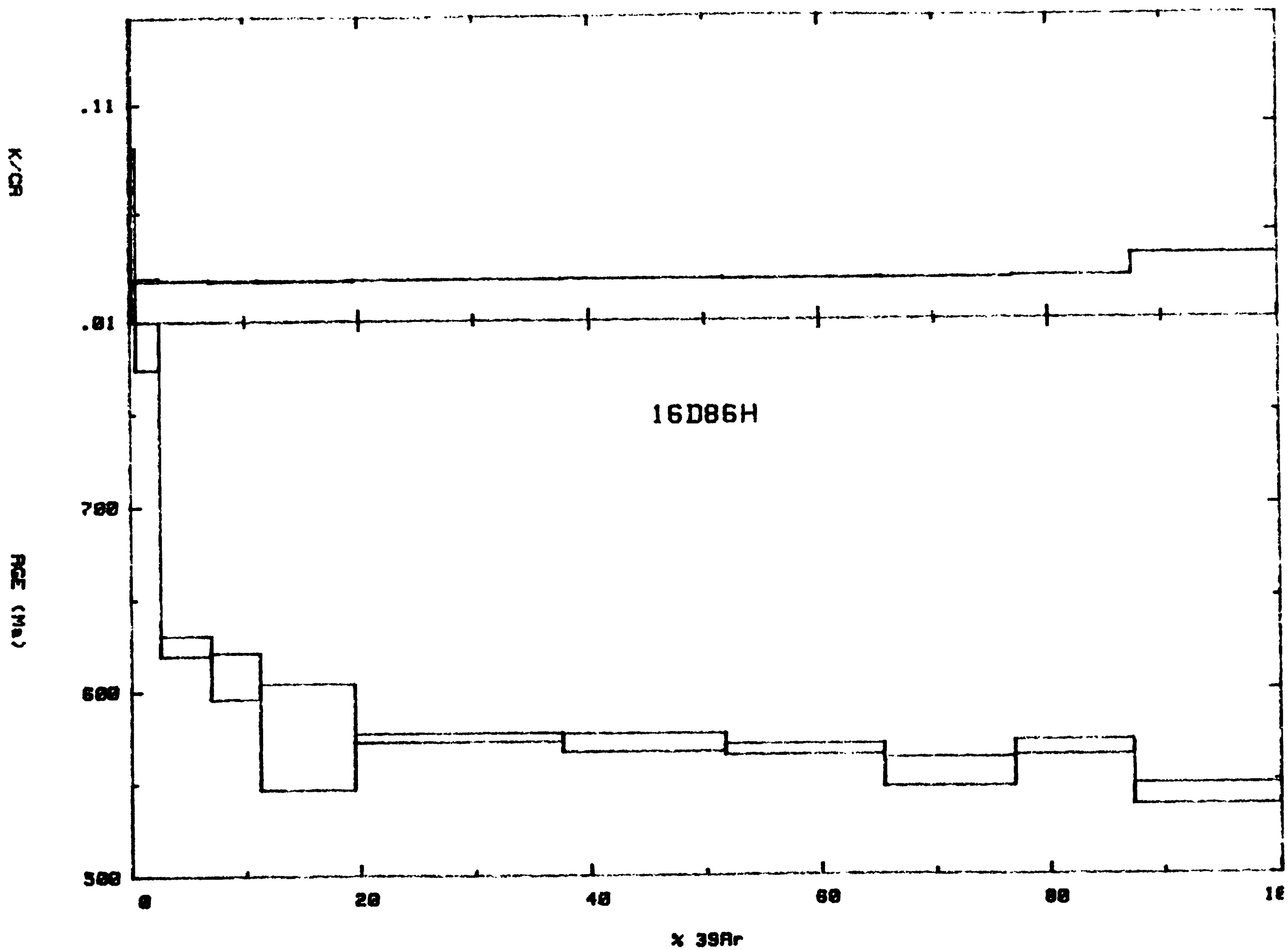
Appendix 6:2

Release Spectra

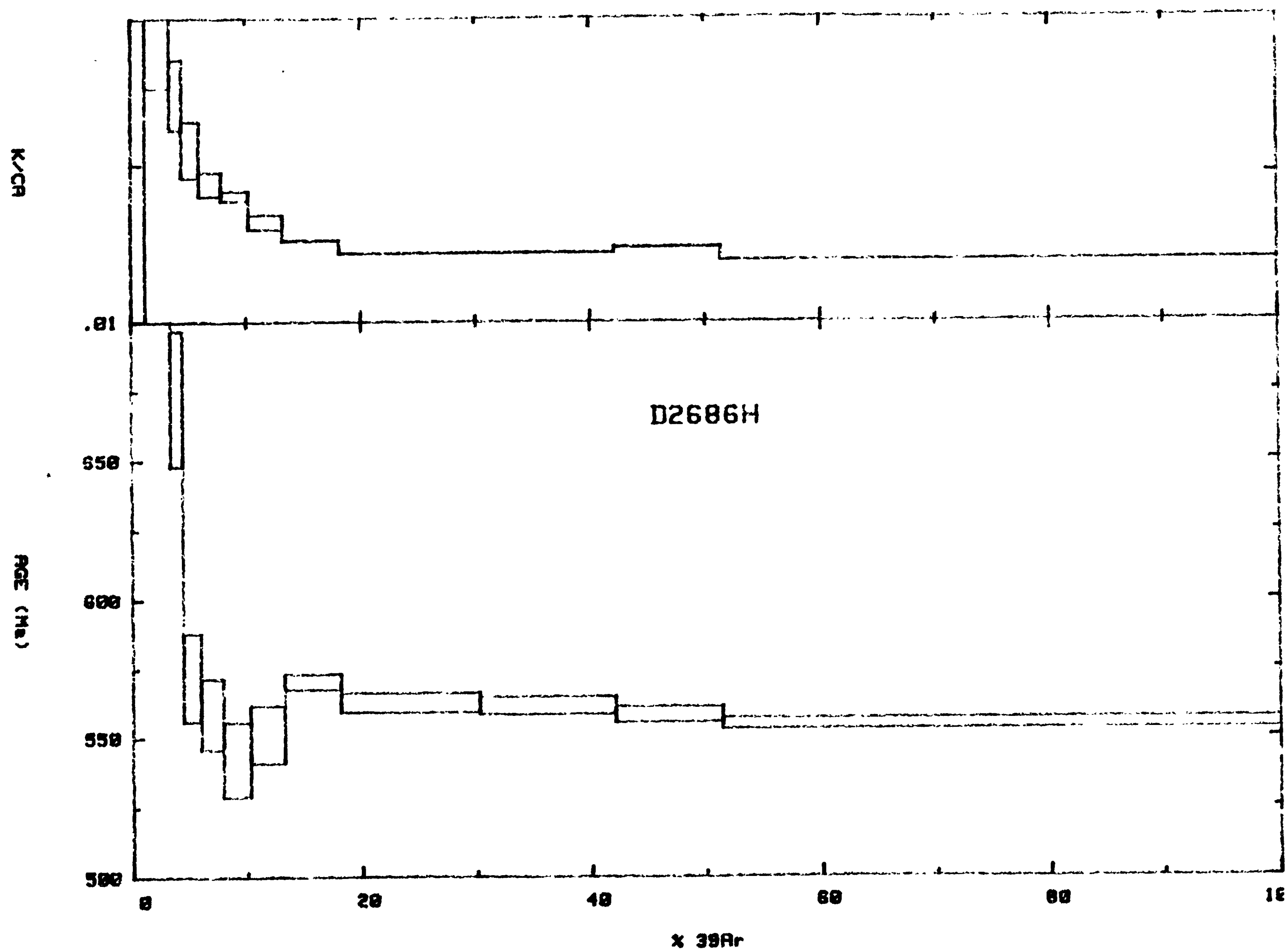

K/CA
.05
B787H
PLATEAU AGE = 486.8 +/- 5.5 Ma
AGE (Ma)
650
550
450
0
20
40
60
80
% 39Ar


K/CA
.01
650
600
550
500
450
AGE (Ma)
C187H
PLATEAU AGE = 506.0 +/- 6.0 Ma
0
20
40
60
80
% 39Ar

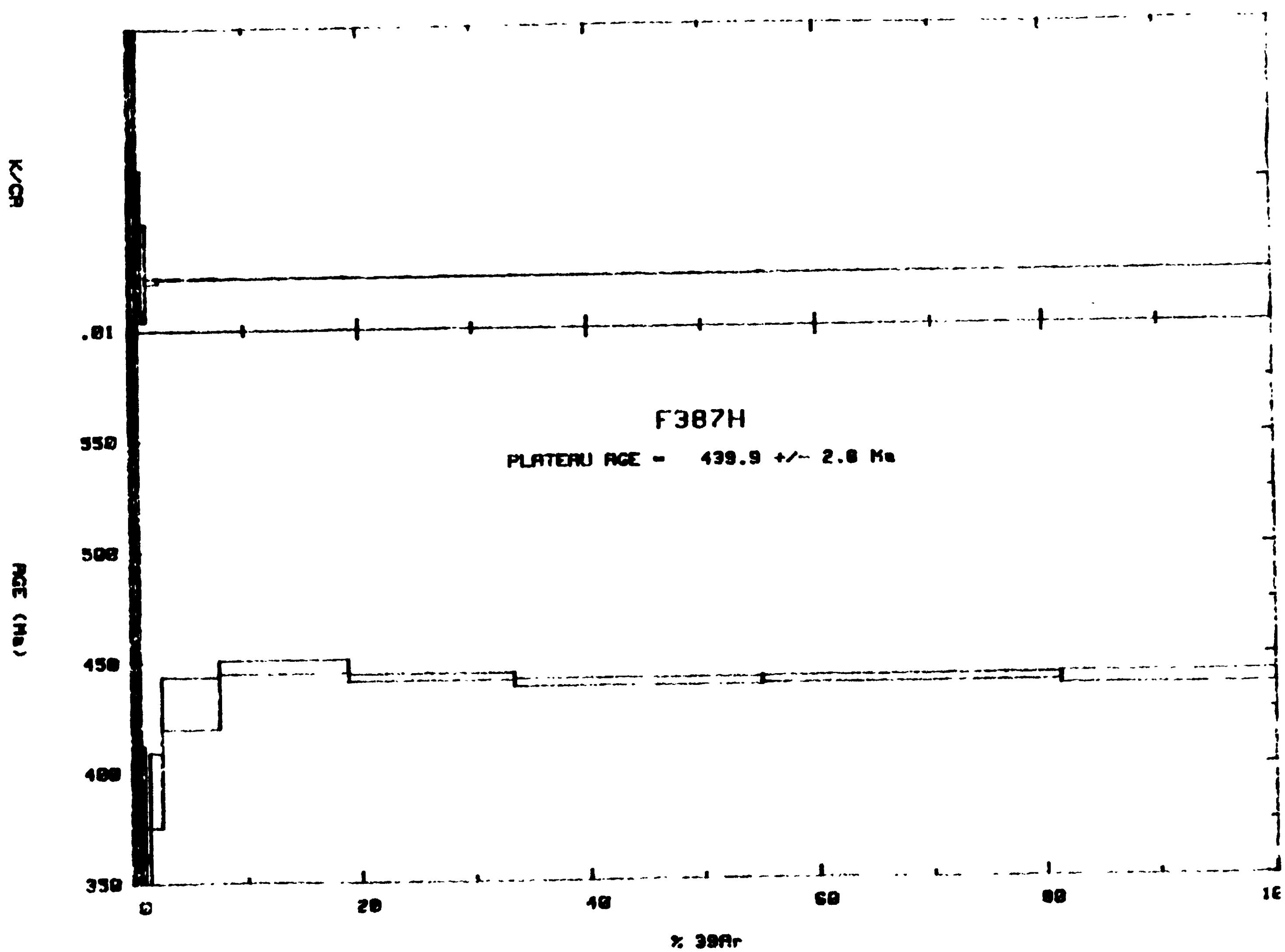

D887H
PLATEAU AGE = 451.1 +/- 5.9 Ma
K/CA
.01
600
500
400
AGE (Ma)
0
20
40
60
80
10
% 39Ar

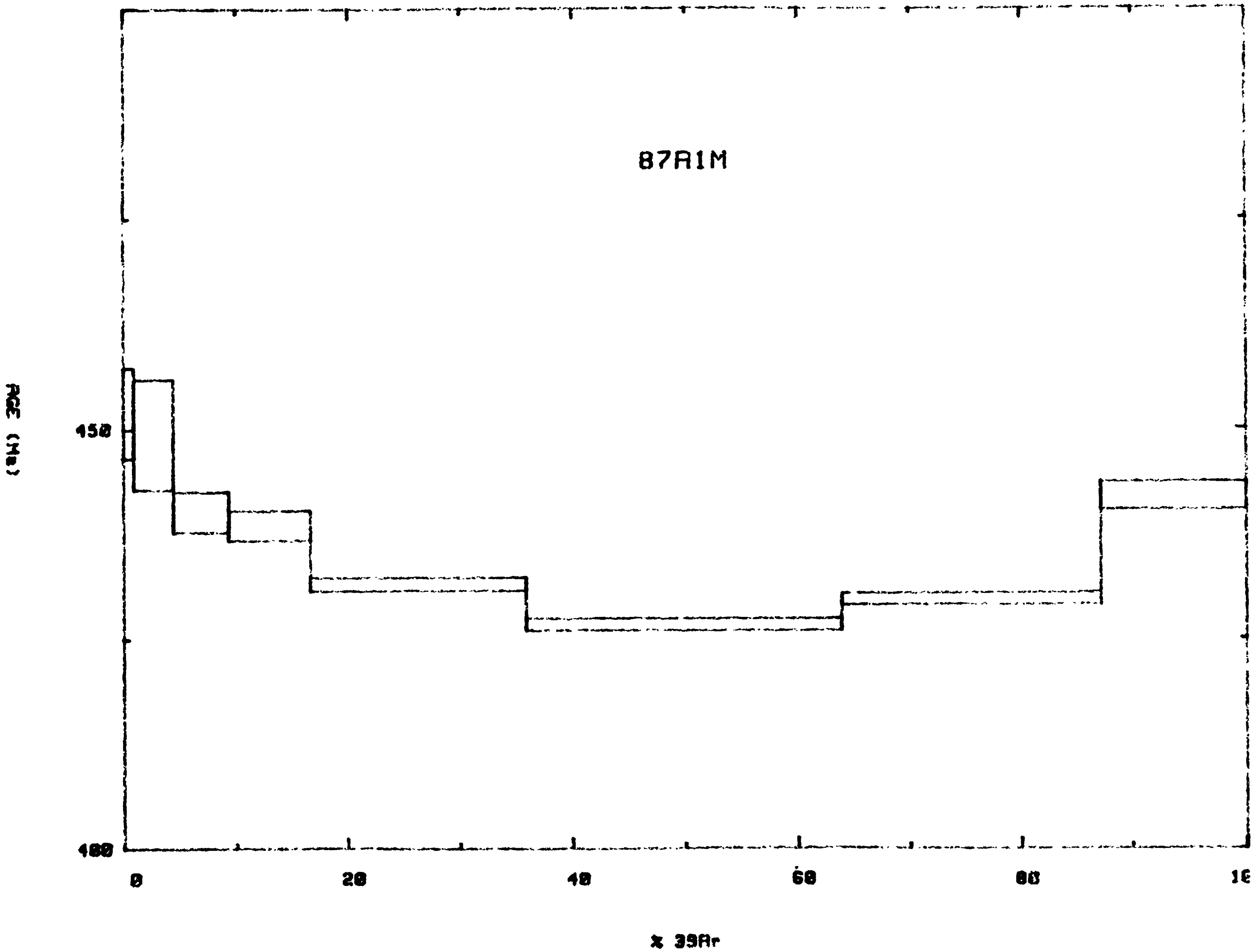


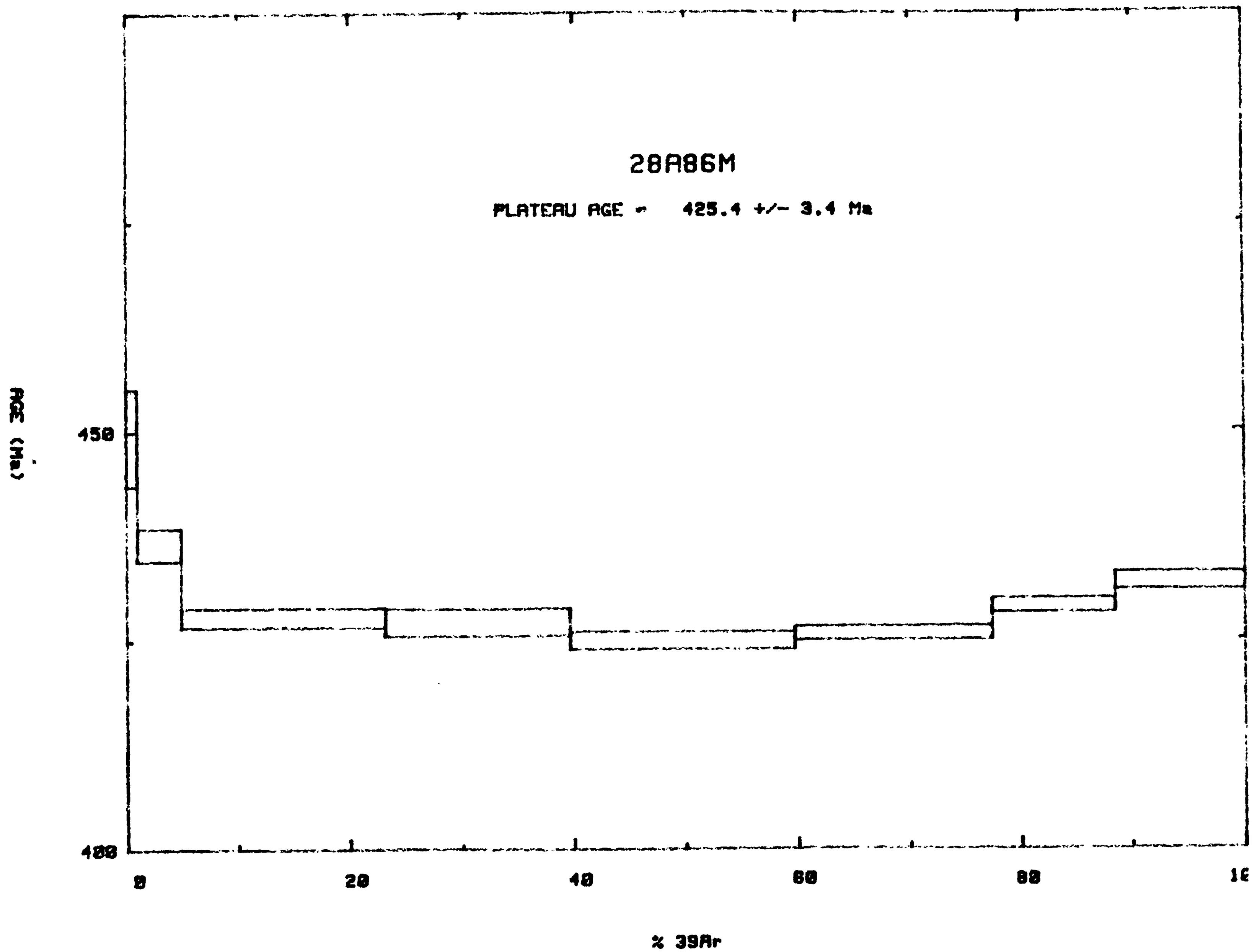
.11
K/CA
.01
16D86H
700
AGE (Ma)
600
500
0
20
40
60
80
% 39Ar

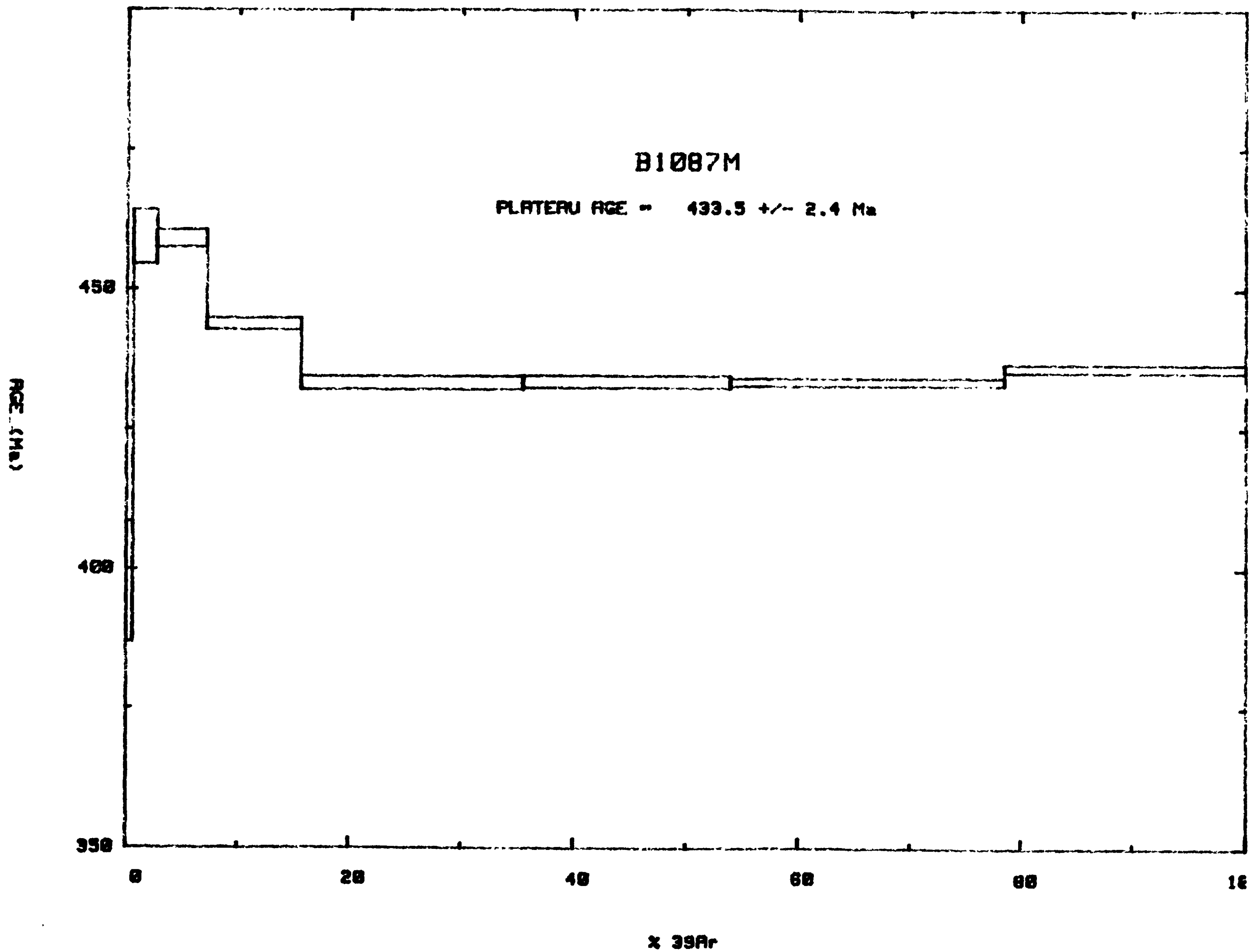


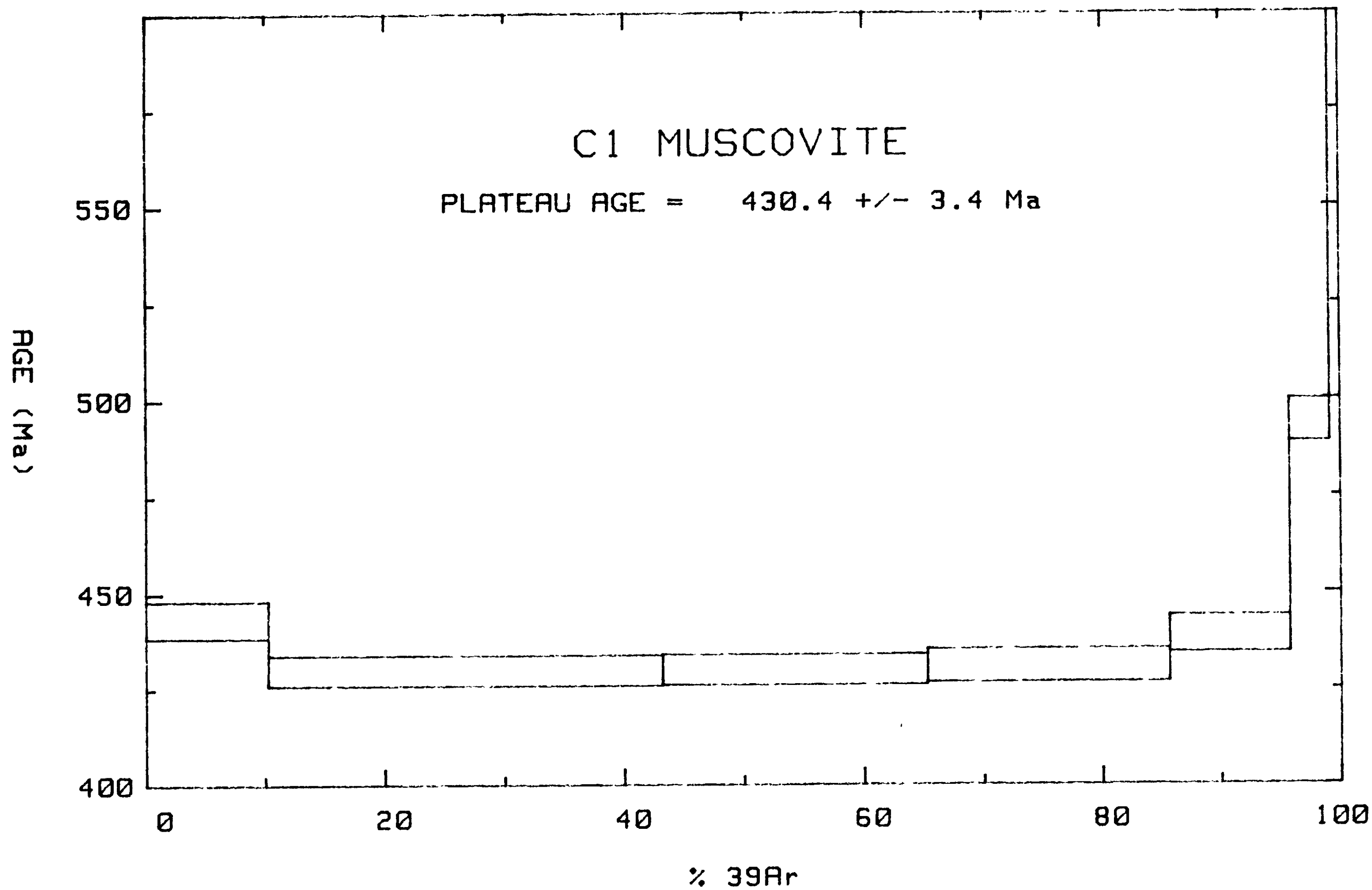
K/CA
.01
650
600
550
500
AGE (Ma)
D2686H
0
20
40
60
80
% 39Ar

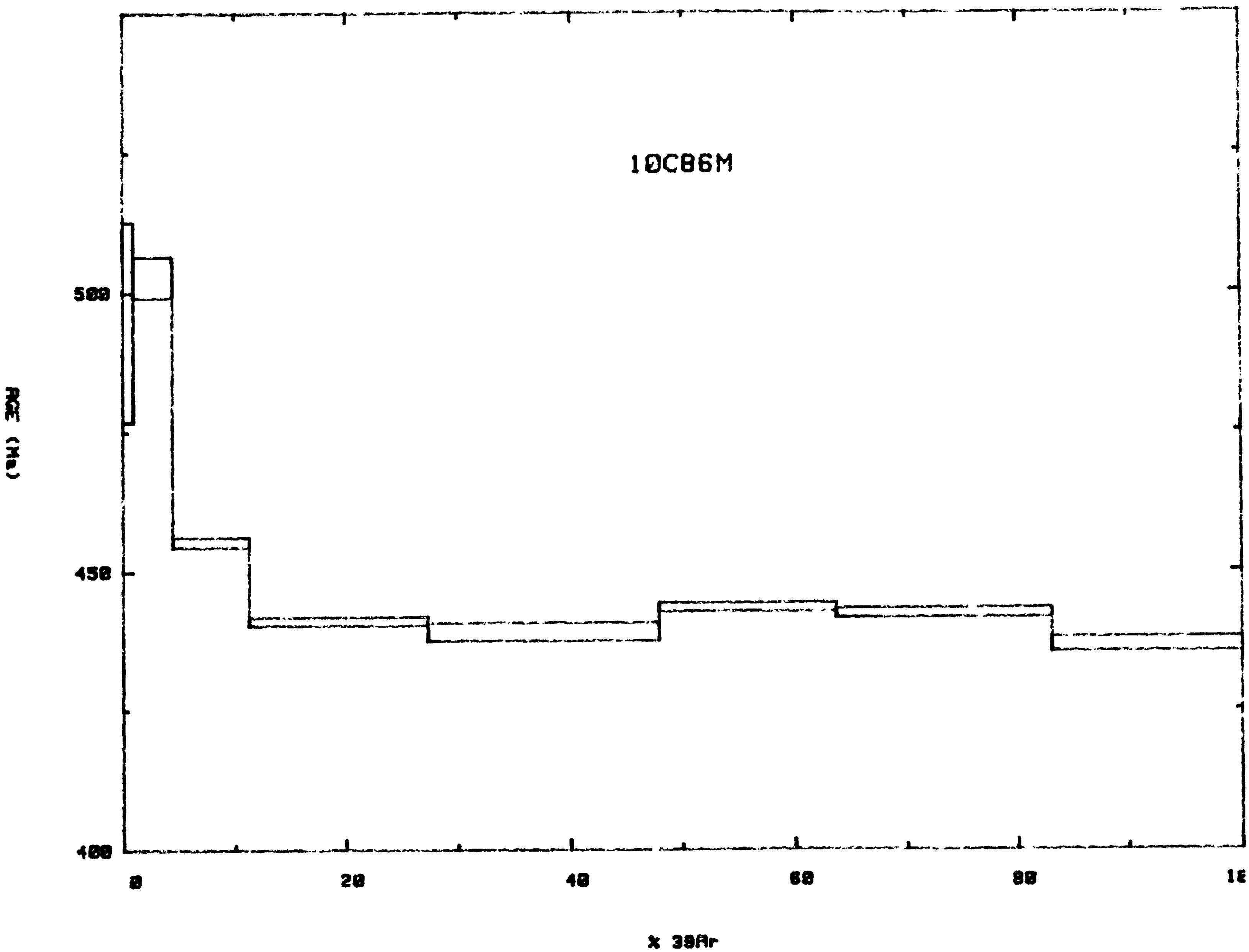

K/CA
.01
F387H
PLATEAU AGE = 439.9 +/- 2.8 Ma
550
500
450
400
350
AGE (Ma)
0
20
40
60
80
% 39Ar

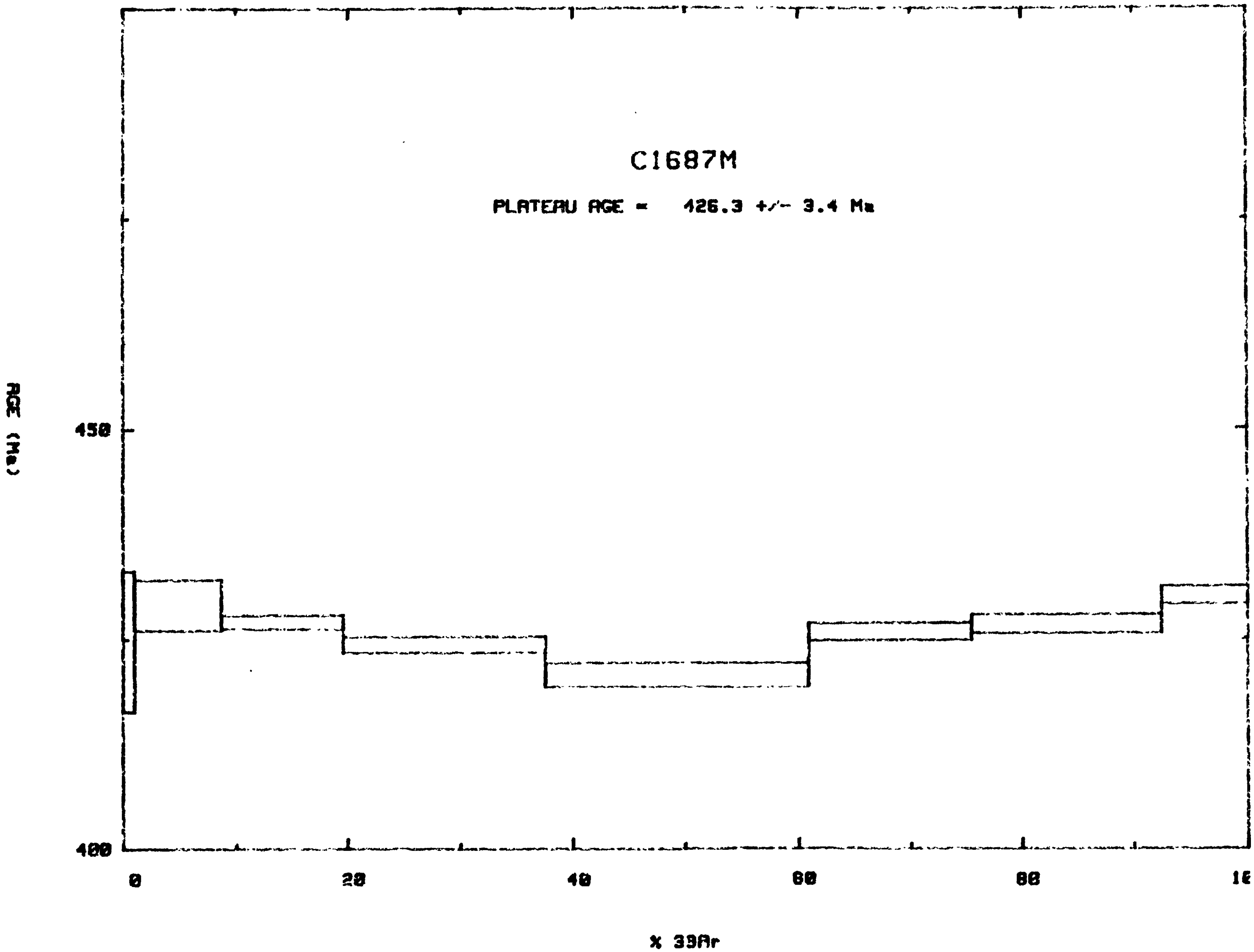

87A1M
AGE (Ma)
450
400
0
20
40
60
80
1E
% 39Ar

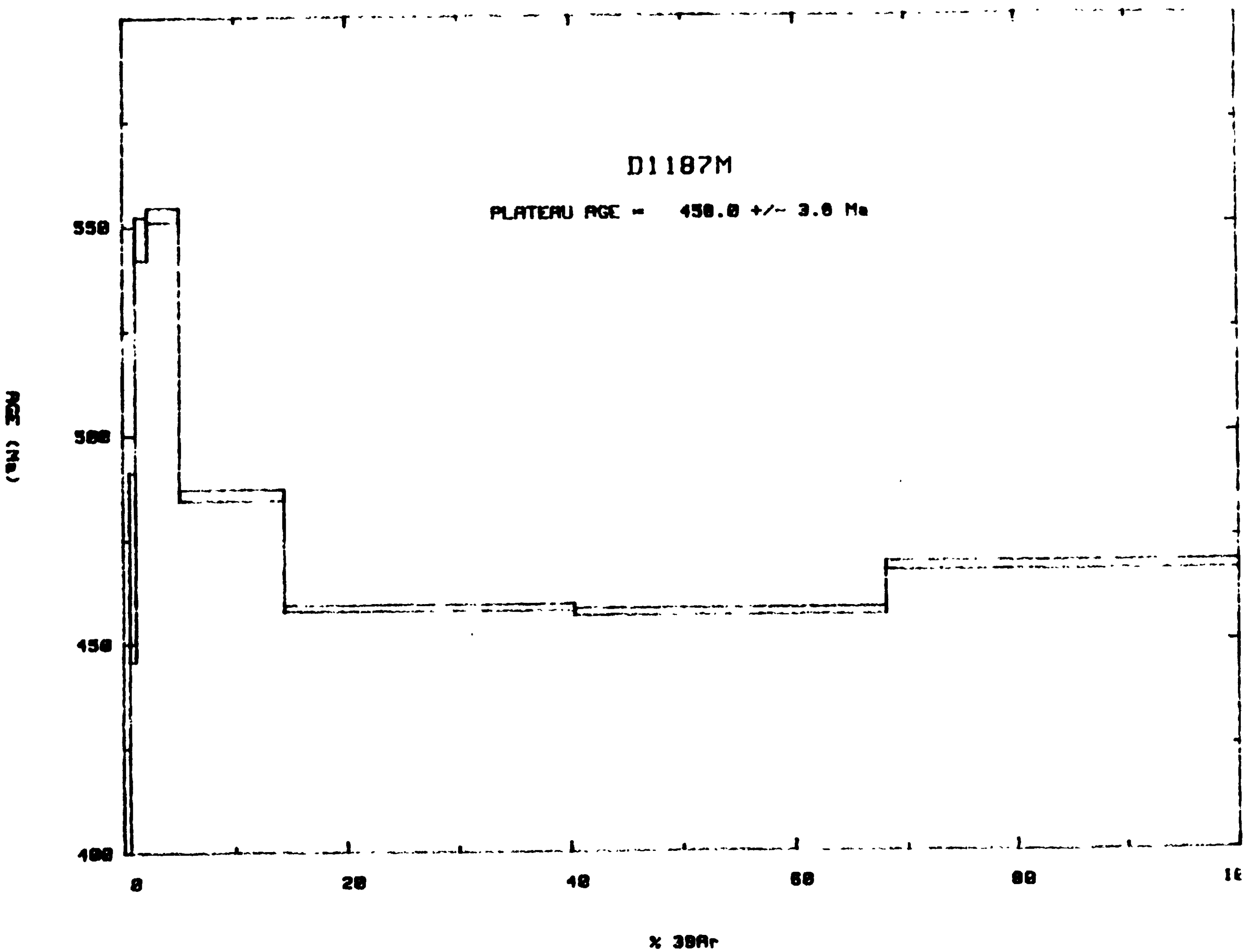

28A86M
PLATEAU AGE = 425.4 +/- 3.4 Ma
AGE (Ma)
450
400
0
20
40
60
80
10
% 39Ar

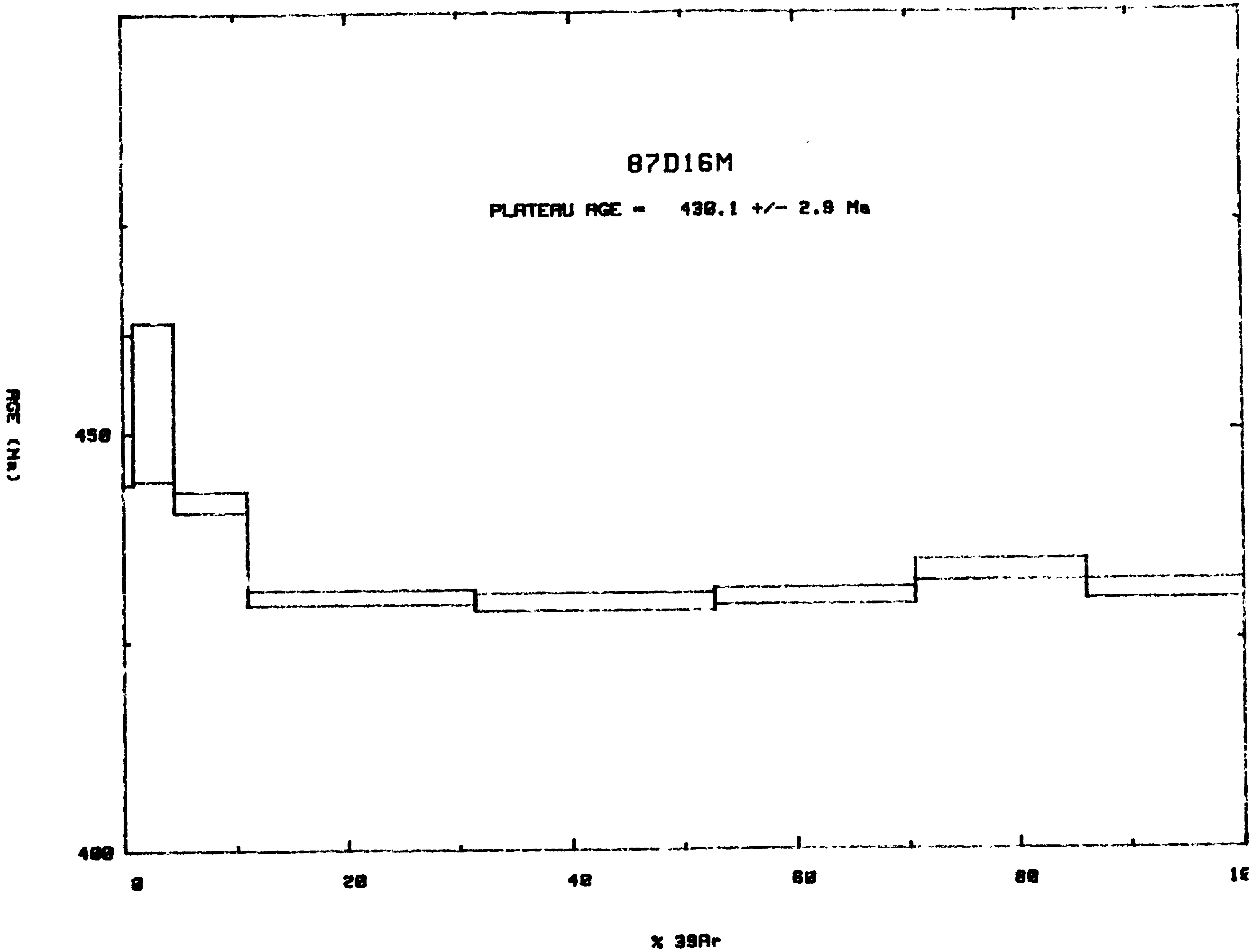

B1087M
PLATEAU AGE = 433.5 +/- 2.4 Ma
AGE (Ma)
450
400
350
0
20
40
60
80
% 39Ar

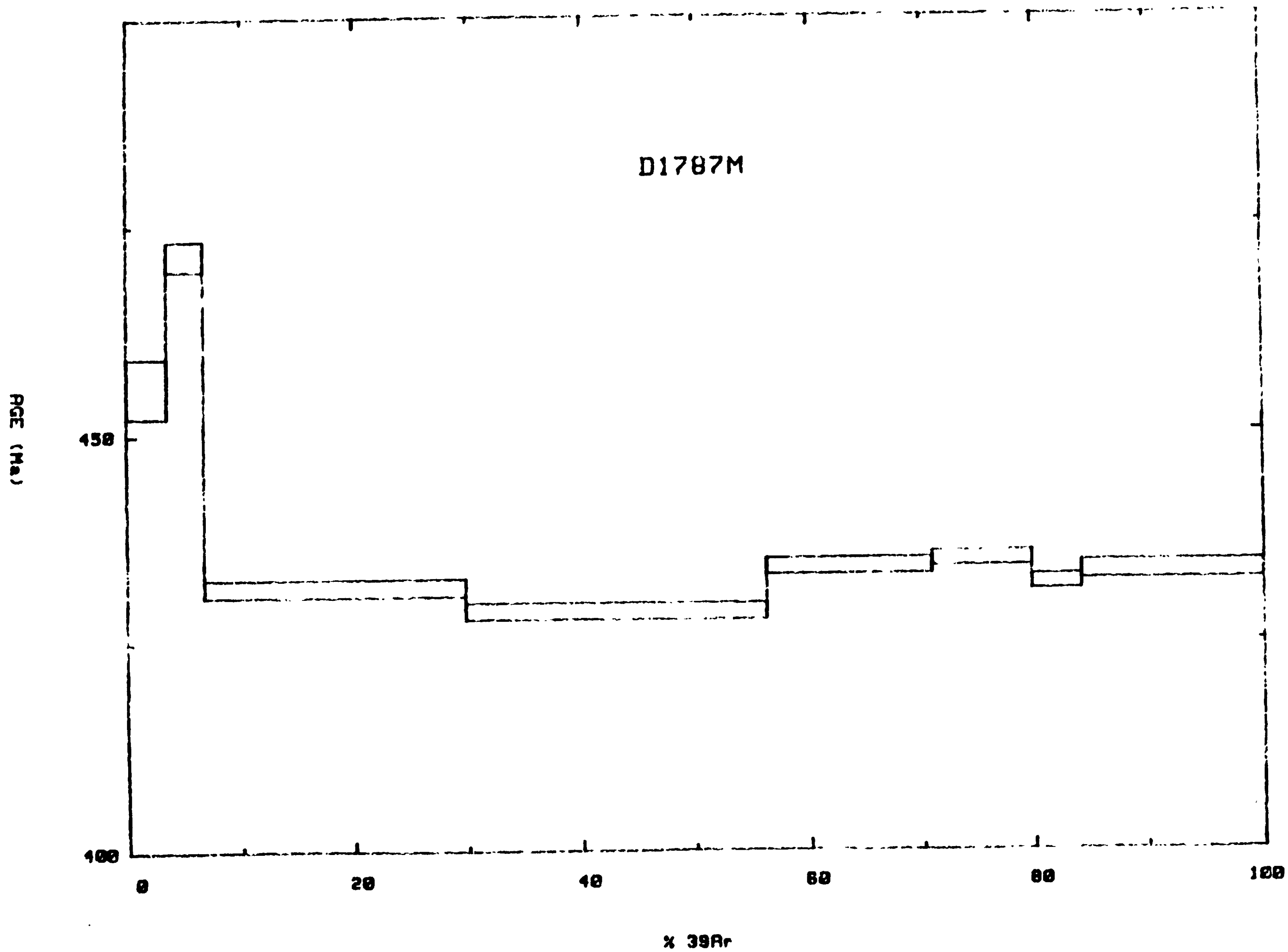

C1 MUSCOVITE
PLATEAU AGE = 430.4 +/- 3.4 Ma
AGE (Ma)
550
500
450
400
0
20
40
60
80
100
% 39Ar


10C86M
AGE (Ma)
500
450
400
0
20
40
60
80
% 39Ar

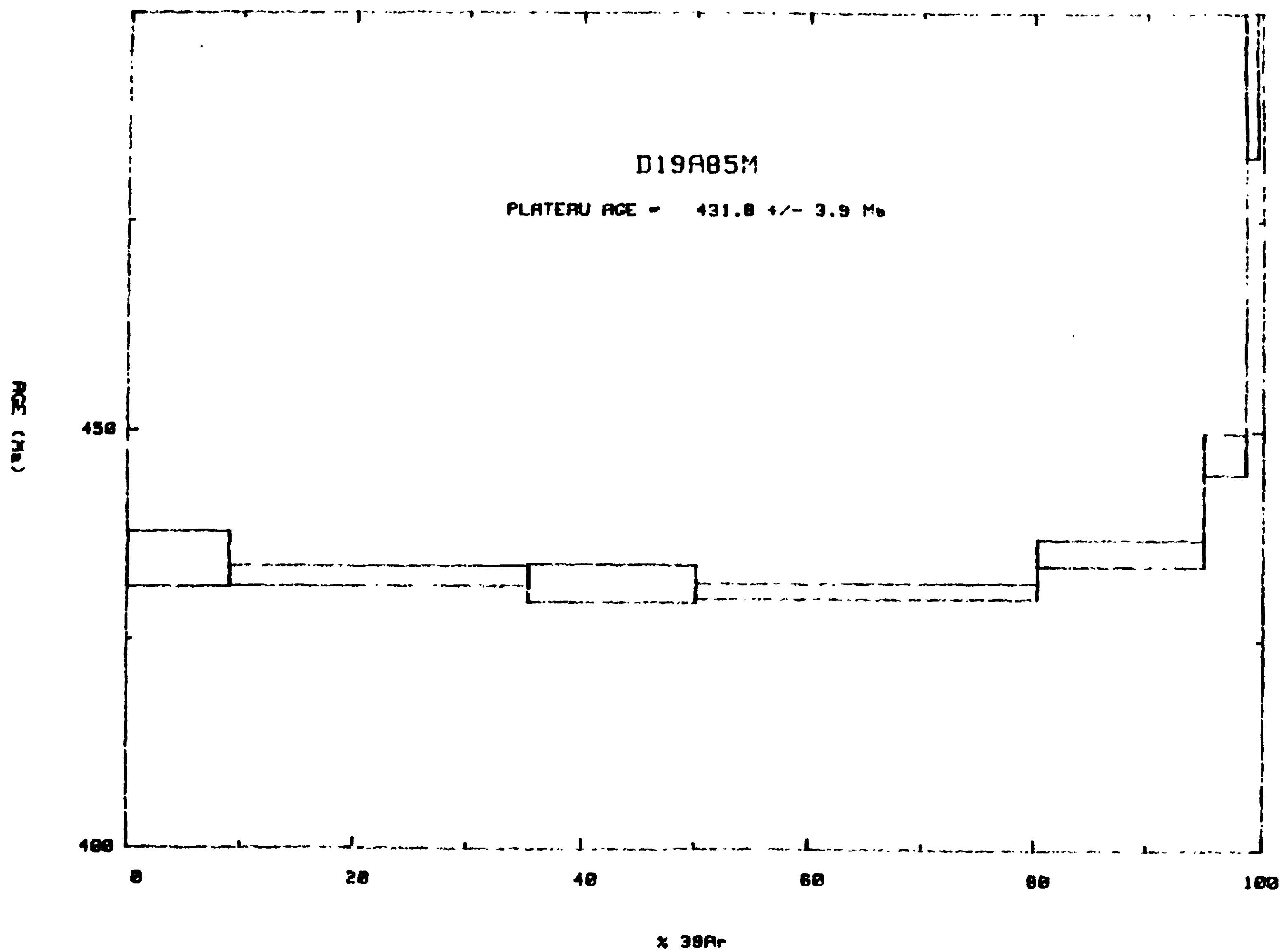

C1687M
PLATEAU AGE = 426.3 +/- 3.4 Ma
AGE (Ma)
450
400
0
20
40
60
80
1E
% 39Ar


D1187M
PLATEAU AGE = 450.0 +/- 3.0 Ma
550
500
450
400
AGE (Ma)
0
20
40
60
80
% 39Ar

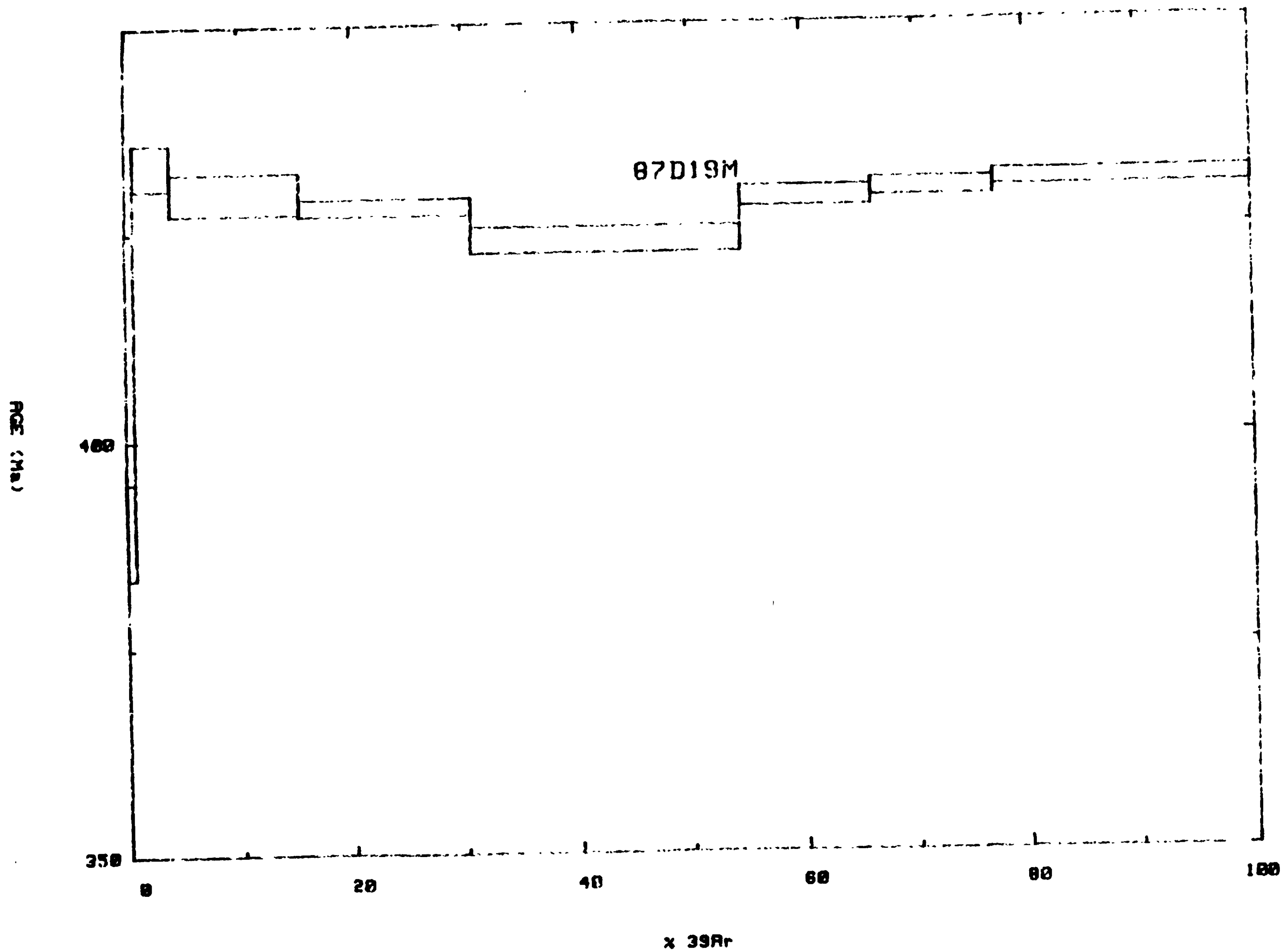

87D16M
PLATEAU AGE = 430.1 +/- 2.9 Ma
AGE (Ma)
450
400
0
20
40
60
80
% 39Ar

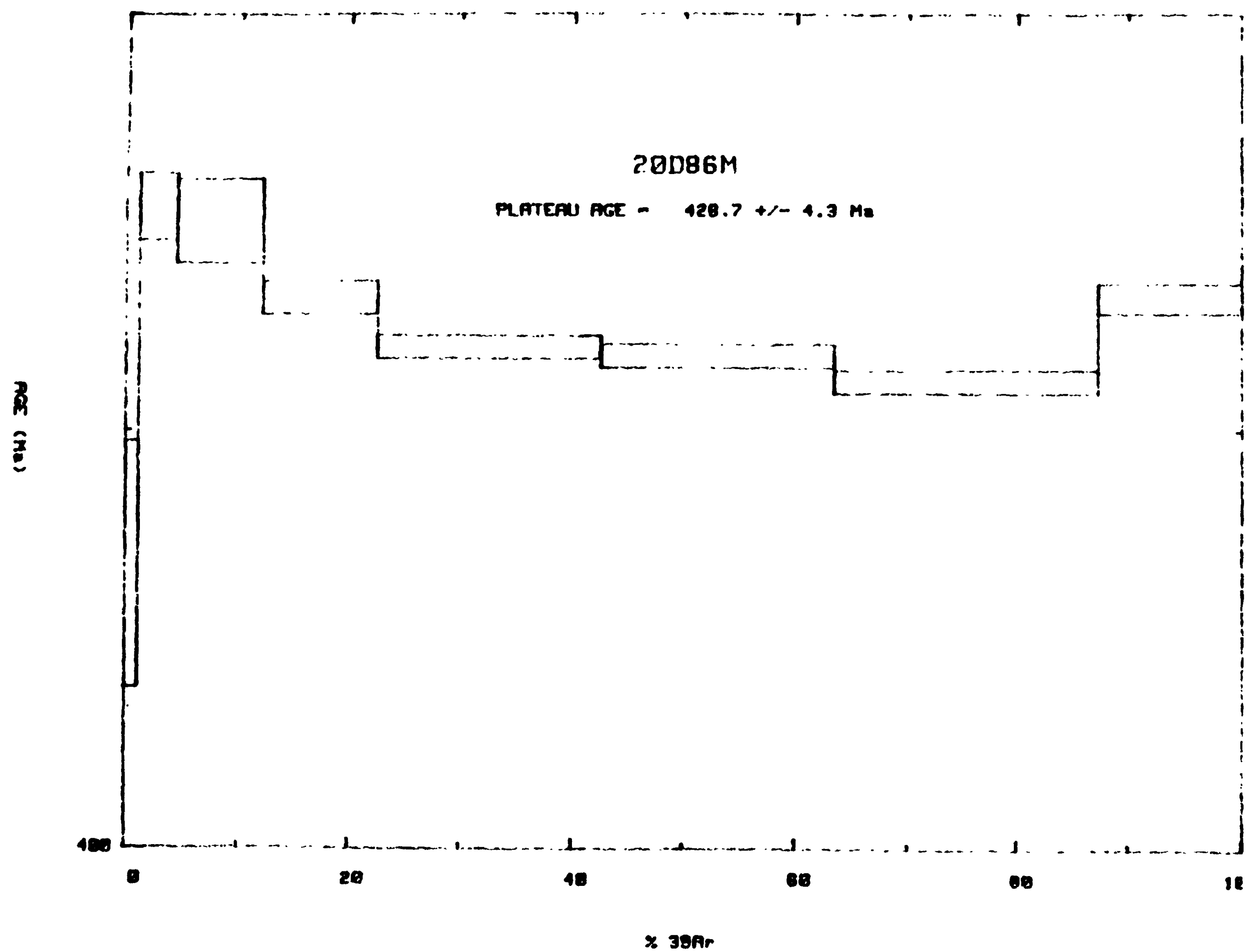


D1787M
AGE (Ma)
450
400
0
20
40
60
80
100
% 39Ar

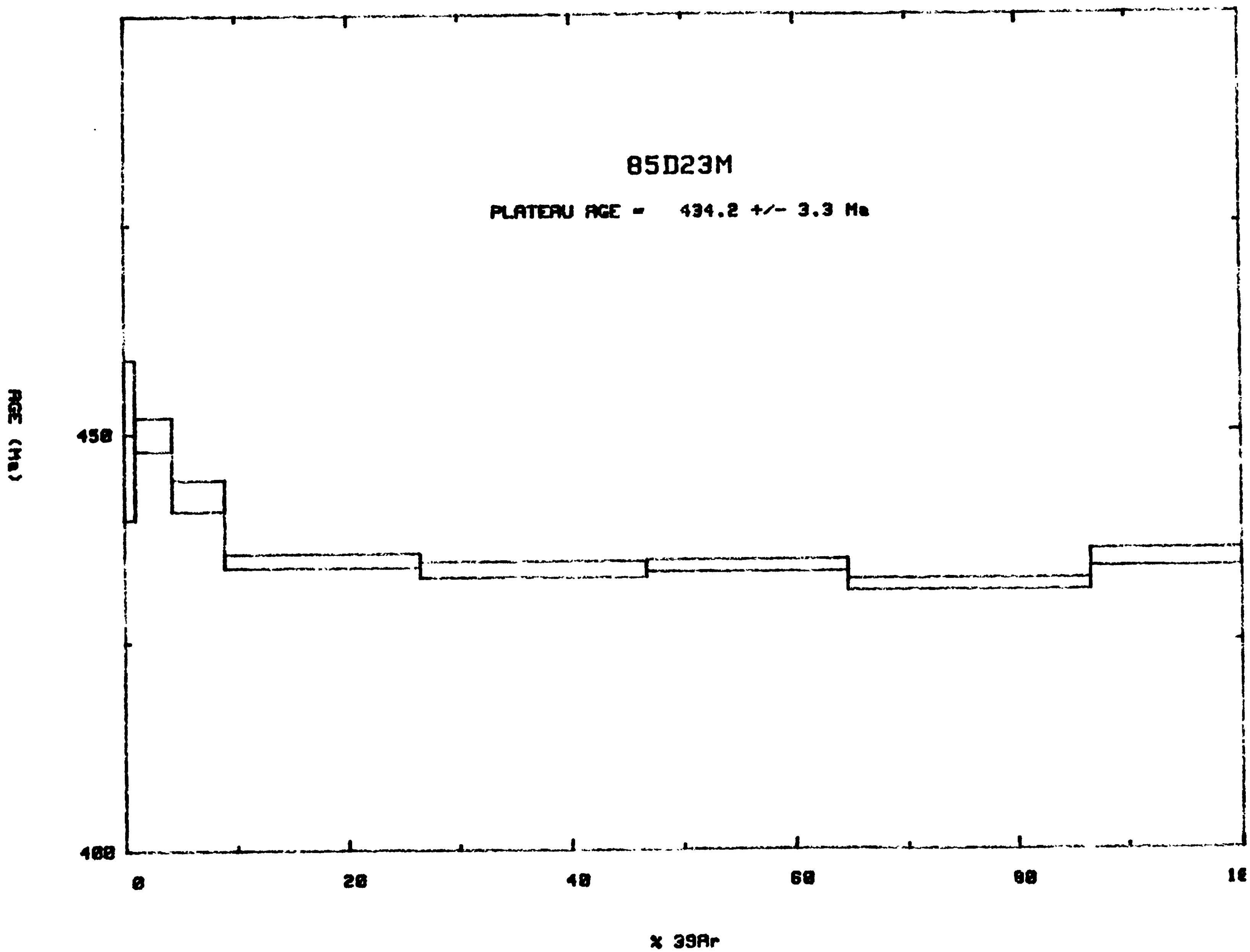


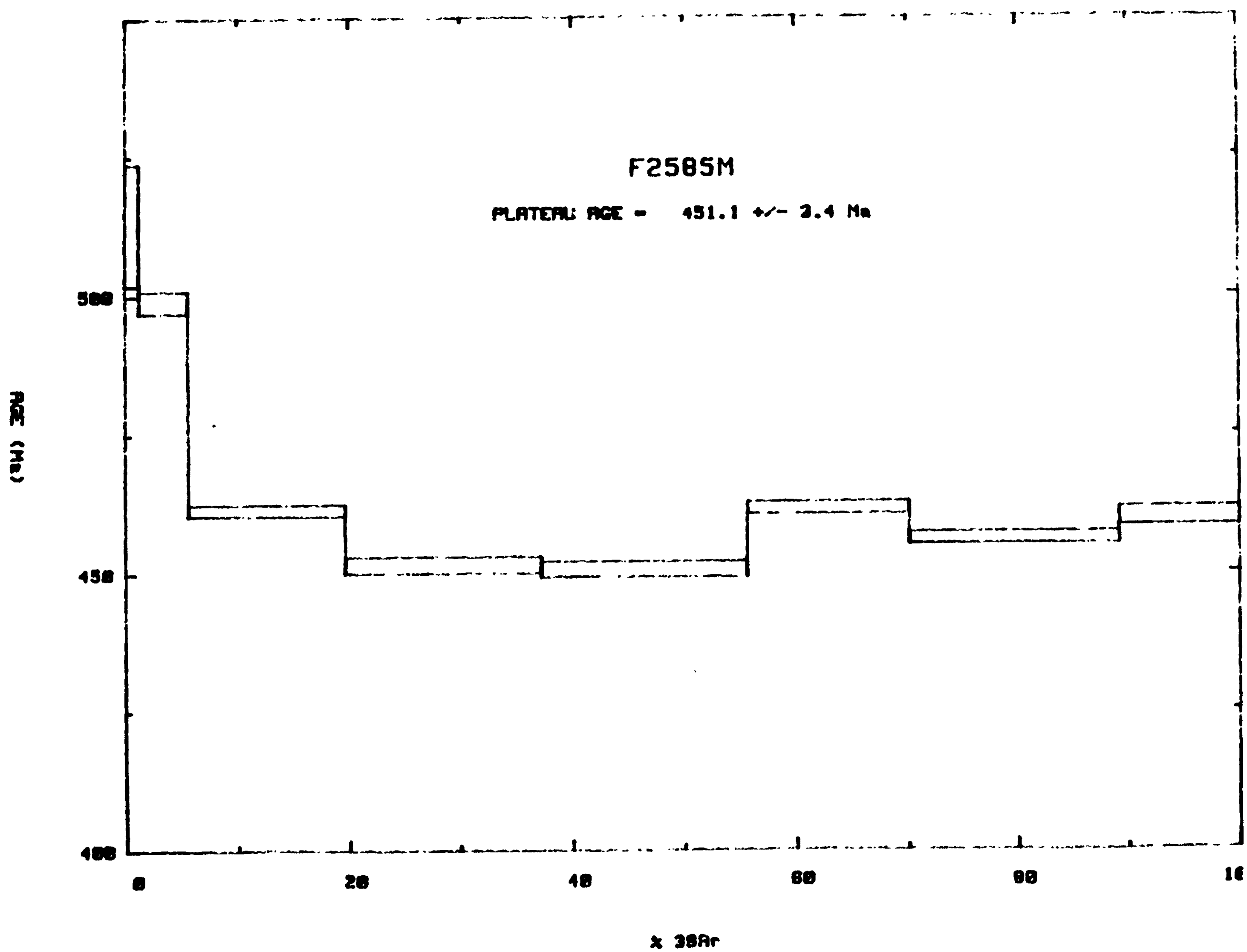
D19A85M
PLATEAU AGE = 431.8 +/- 3.9 Ma
AGE (Ma)
450
400
0
20
40
60
80
100
% 39Ar


87D19M
AGE (Ma)
400
350
0
20
40
60
80
100
x 39Ar



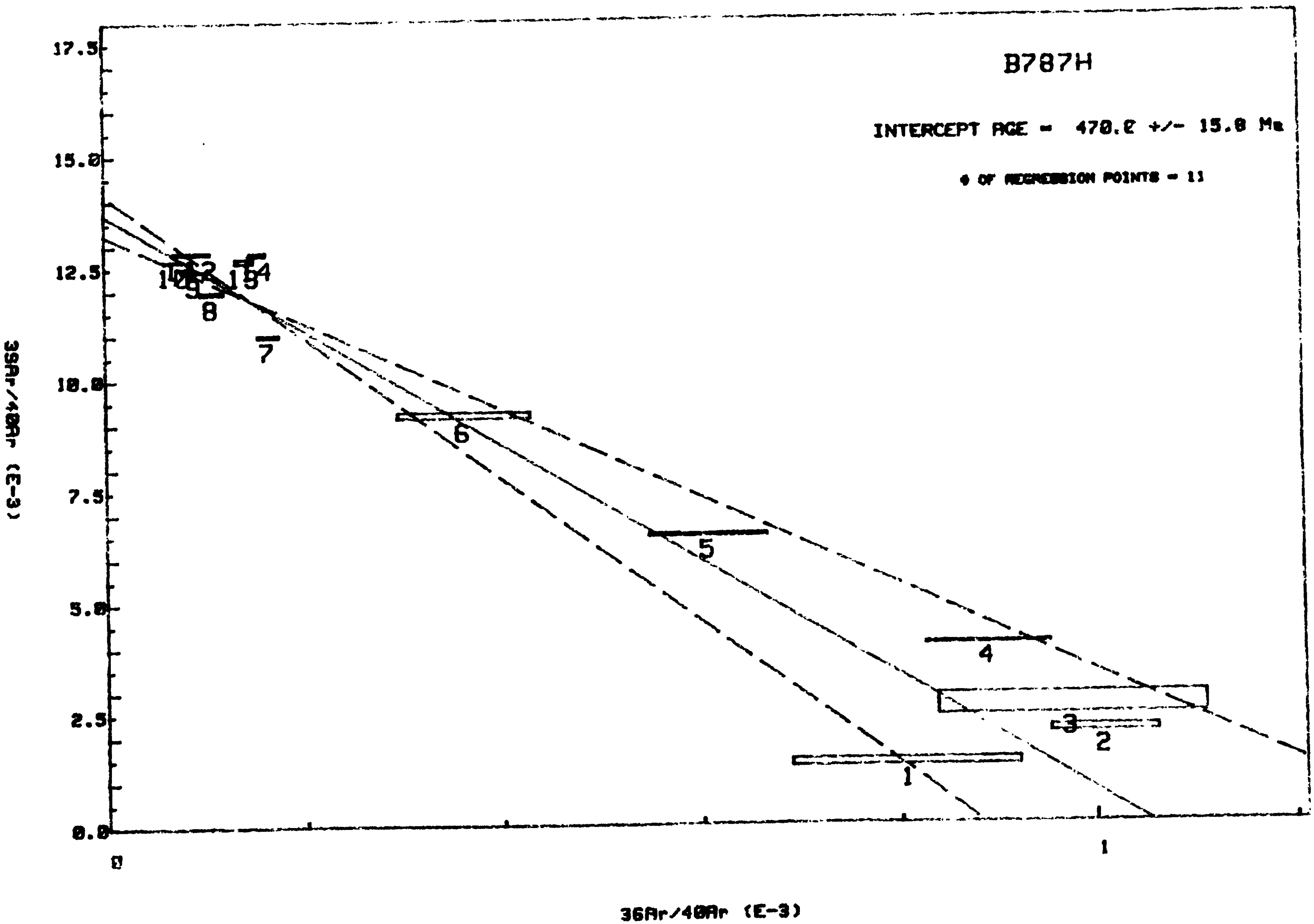
20D86M
PLATEAU AGE = 420.7 +/- 4.3 Ma
AGE (Ma)
400
0
20
40
60
80
10
% 39Ar

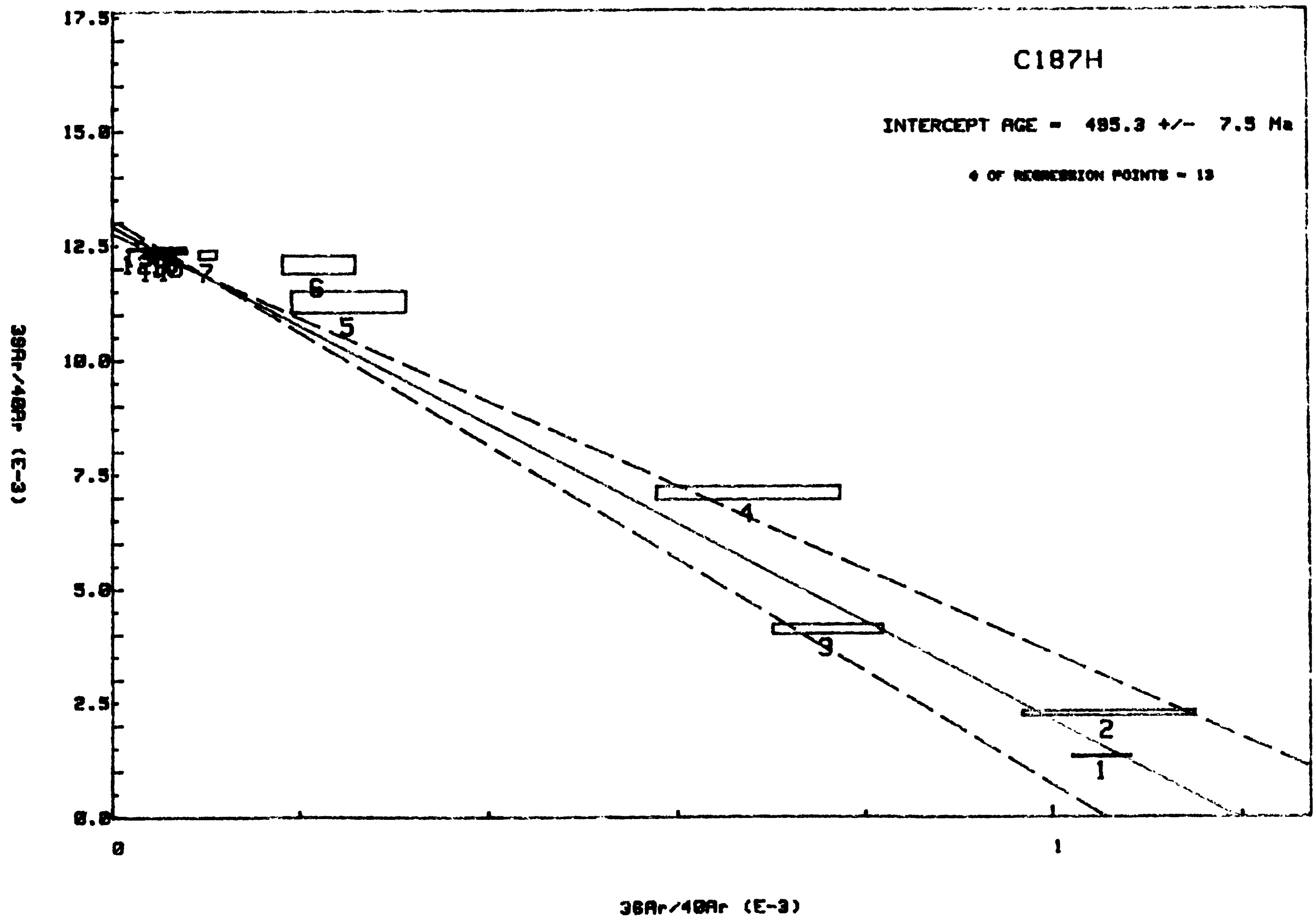

85D23M
PLATEAU AGE = 434.2 +/- 3.3 Ma
AGE (Ma)
450
400
0
20
40
60
80
% 39Ar

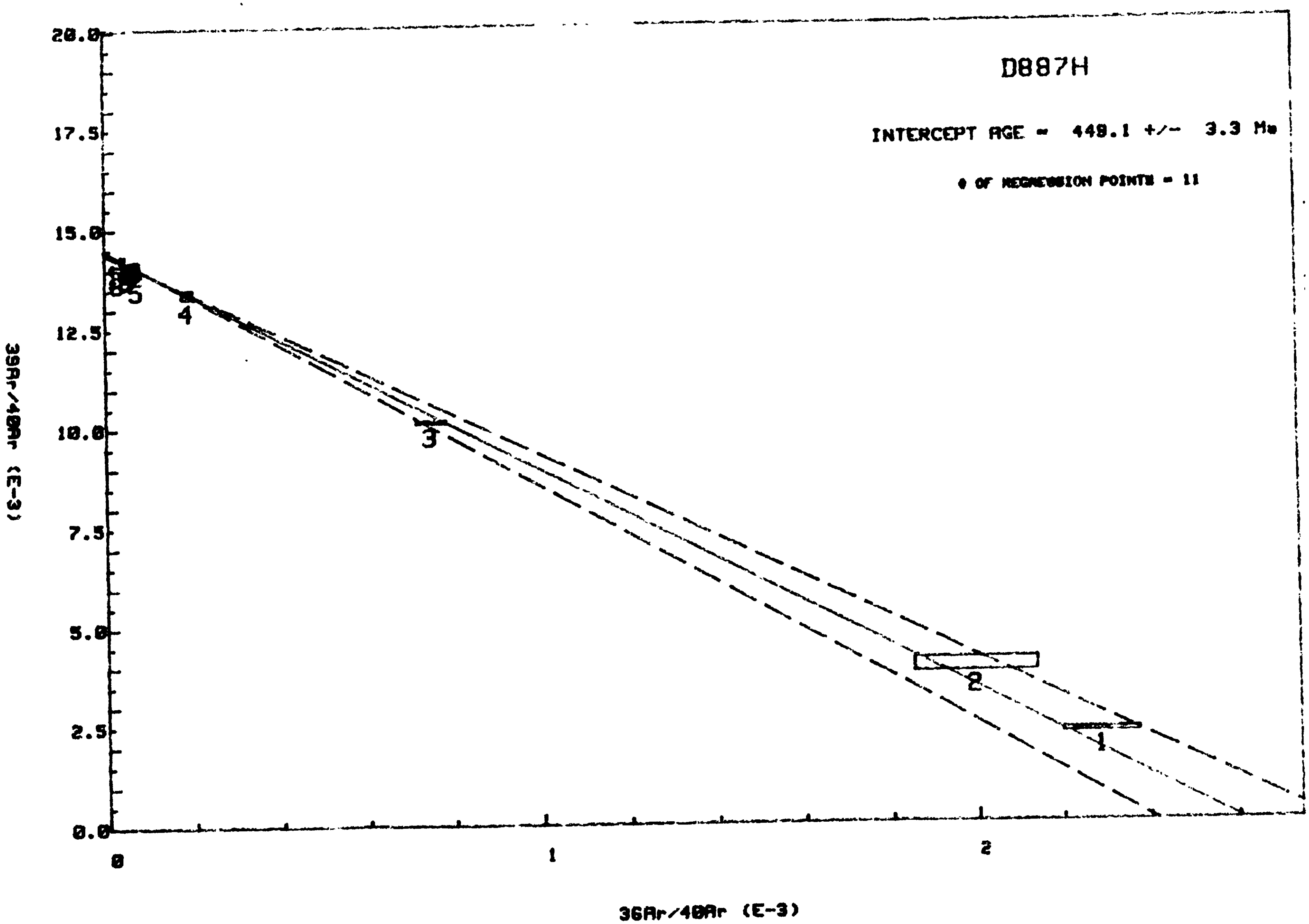

F2585M
PLATEAU AGE = 451.1 +/- 3.4 Ma
AGE (Ma)
500
450
400
0
20
40
60
80
10
% 39Ar

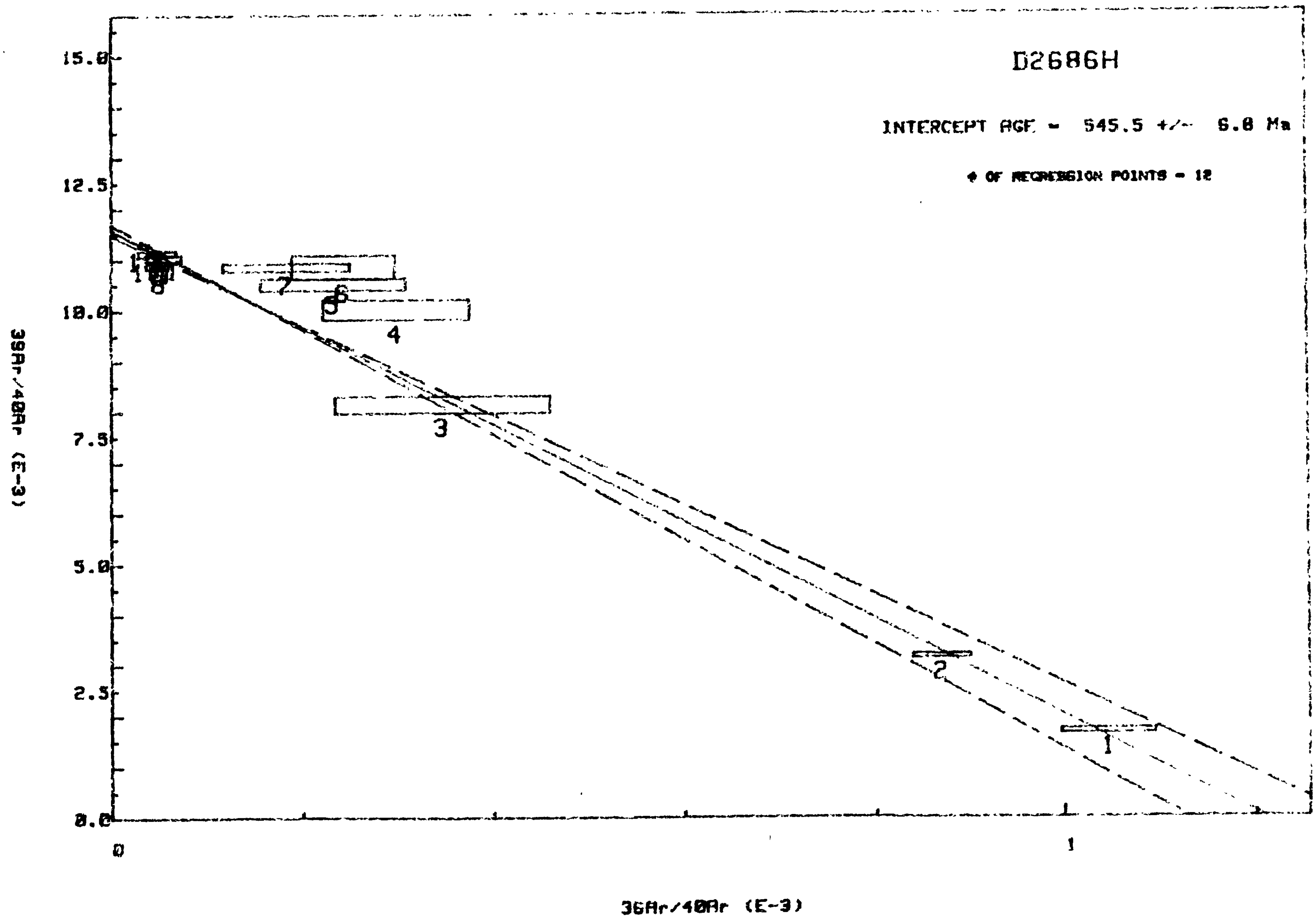
Appendix 6:3

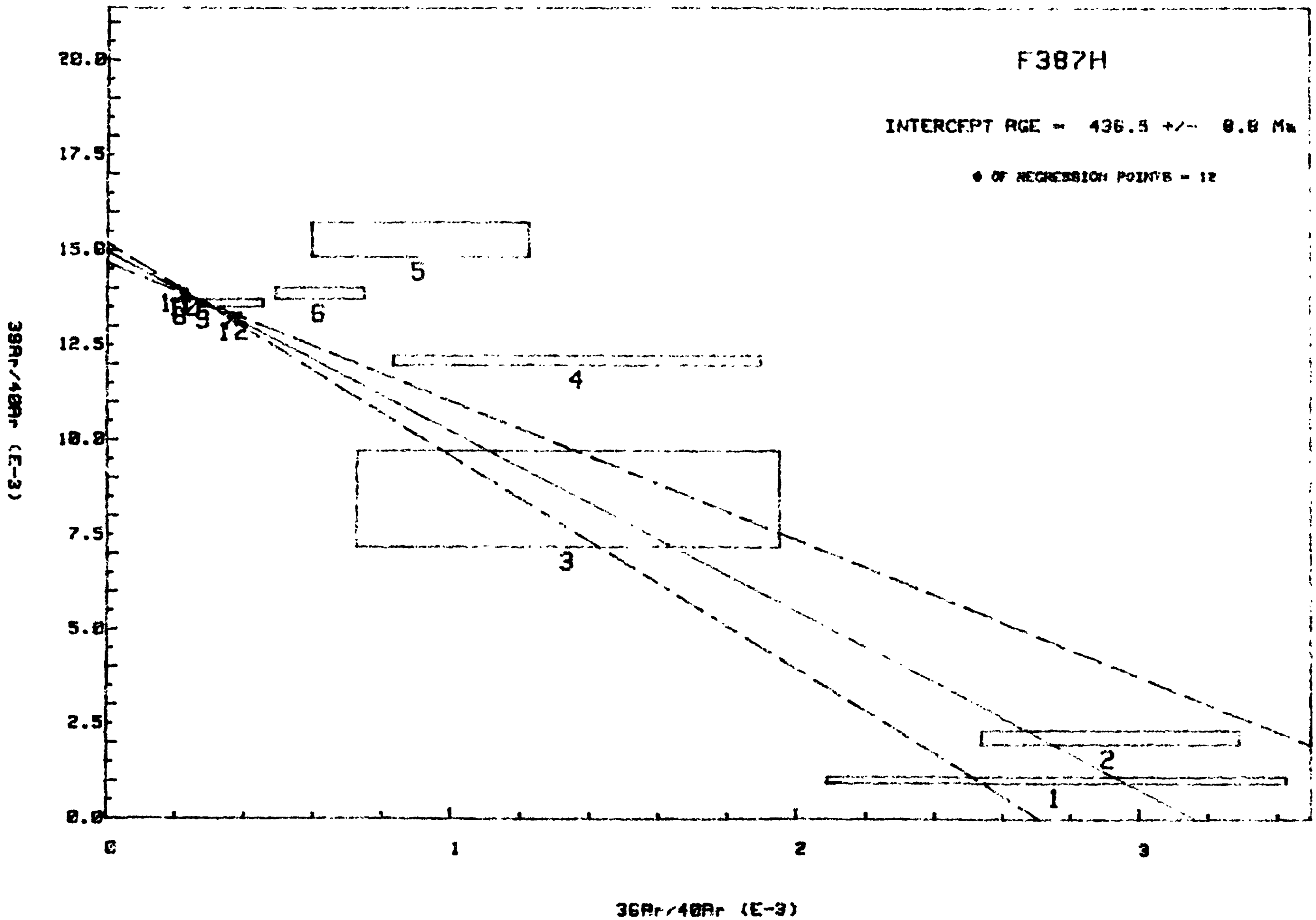
Isotope Correlation Diagrams

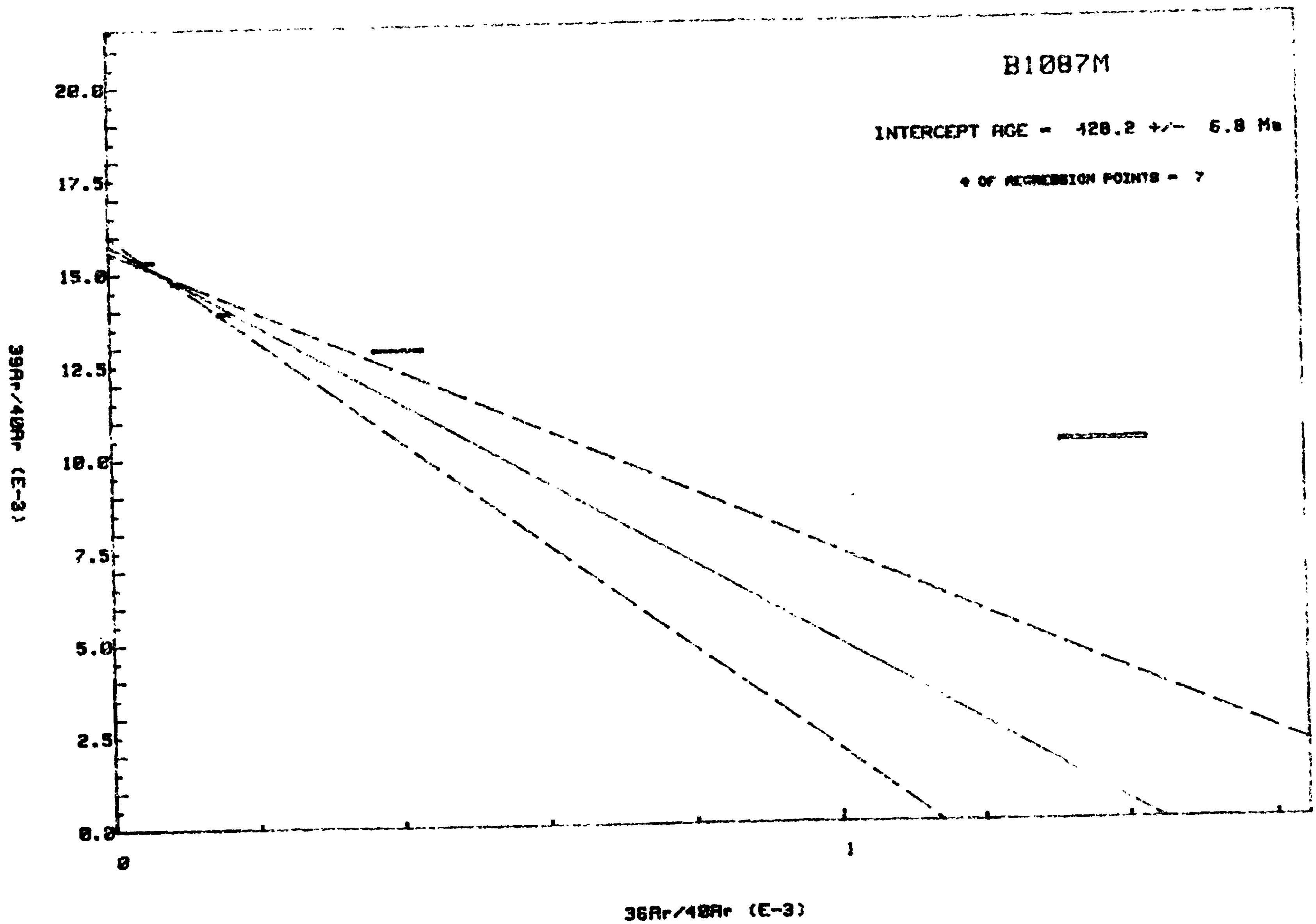

B787H
INTERCEPT AGE = 470.2 +/- 15.8 Ma
OF REGRESSION POINTS = 11
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
39Ar/40Ar (E-3)
0
1
36Ar/40Ar (E-3)
1
2
3
4
5
6
7
8
9
10
13
14

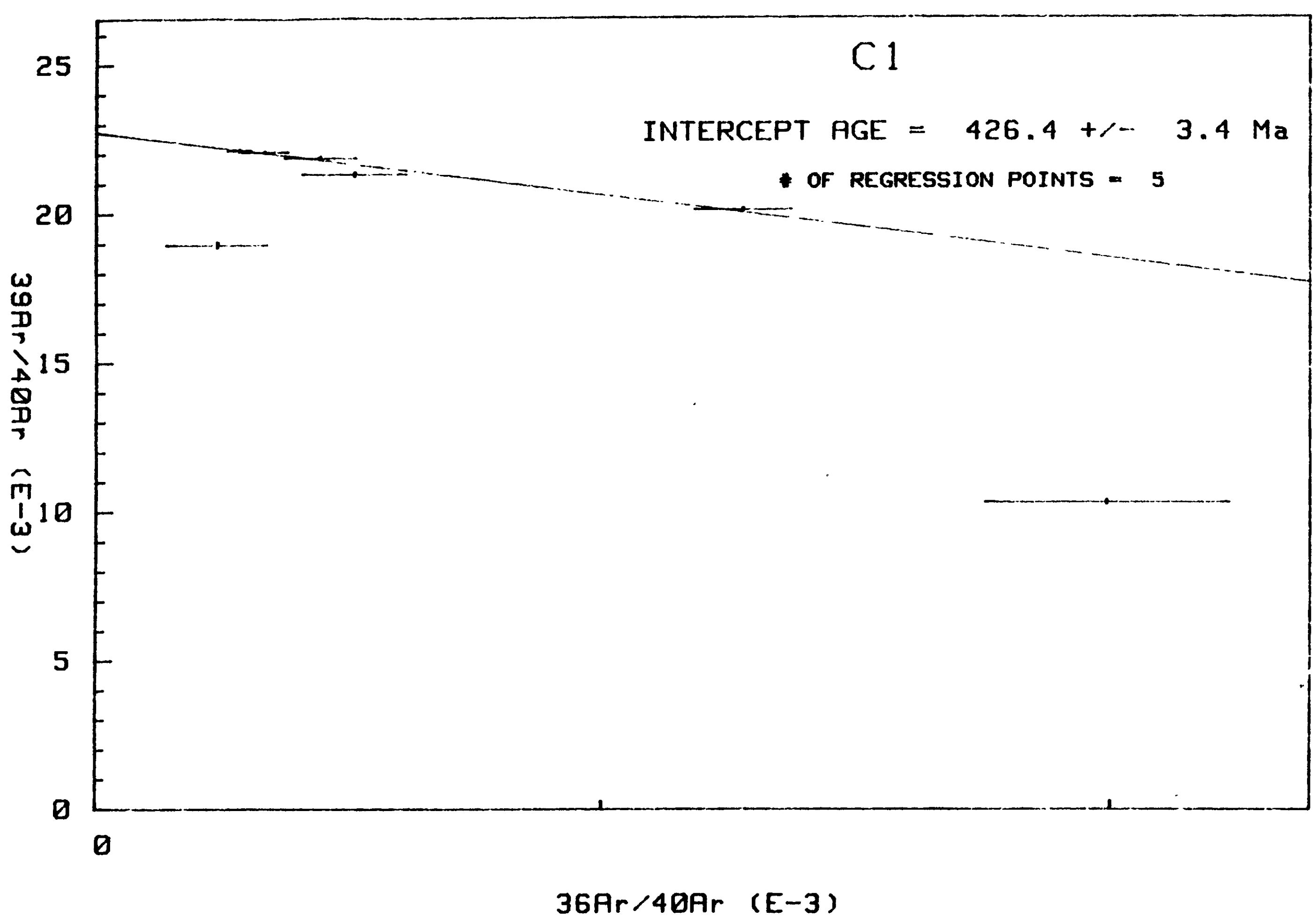

C187H
INTERCEPT AGE = 495.3 +/- 7.5 Ma
OF REGRESSION POINTS = 13
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
39Ar/40Ar (E-3)
0
1
36Ar/40Ar (E-3)
1
2
3
4
5
6
7


D887H
INTERCEPT AGE = 449.1 +/- 3.3 Ma
OF REGRESSION POINTS = 11
39Ar/40Ar (E-3)
36Ar/40Ar (E-3)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
1
2
1
2
3
4
5


D2686H
INTERCEPT AGE = 545.5 +/- 6.8 Ma
OF REGRESSION POINTS = 12
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
1
39Ar/40Ar (E-3)
36Ar/40Ar (E-3)
1
2
3
4
5
6
7
8


F387H
INTERCEPT AGE = 436.5 +/- 0.8 Ma
OF REGRESSION POINTS = 12
39Ar/40Ar (E-3)
36Ar/40Ar (E-3)


B1087M
INTERCEPT AGE = 420.2 +/- 6.8 Ma
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
1
39Ar/40Ar (E-3)
36Ar/40Ar (E-3)


C1
INTERCEPT AGE = 426.4 +/- 3.4 Ma
OF REGRESSION POINTS = 5
25
20
15
10
5
0
0
39Ar/40Ar (E-3)
36Ar/40Ar (E-3)

175

Chapter 7

Conclusions

The purpose of this study has been both to complete the MIT geologic transect of the Scandinavian Caledonides through to the present day erosional front, and to apply an integrated multidisciplinary approach to better constrain the complex geologic history of the continent-continent collision which produced the orogen. In this chapter the results and conclusions presented in the previous chapters will be briefly reviewed, followed by a discussion of the tectonic history of the Singis-Nikkaluokta region. Constraints provided by this study will then be examined and incorporated into new models and those proposed by previous workers.

Tectonostratigraphy

The general tectonostratigraphy of the Singis-Nikkaluokta region consists of: 1) autochthonous-parautochthonous Precambrian crystalline basement and its sedimentary cover; 2) the Middle Allochthon shear zone which consists of a heterogeneous tectonic assemblage of variably mylonitized sedimentary and crystalline rocks of the Baltic Shield; and 3) The Upper Allochthon, which in the Singis-Nikkaluokta region is comprised of the Seve and structurally overlying Köli Nappe sequences.

The sedimentary cover rocks overlying the Precambrian basement in both the foreland and within tectonic windows through the Caledonides may be correlated throughout the Norrbotten Caledonides with the Vendian-Cambrian aged Group sediments (Thelander, 1982). The Middle Allochthon is present throughout the Scandinavian Caledonides and represents the shear zone formed between Baltica and the overlying Allochthonous Nappes. The Seve Nappe in the Singis-Nikkaluokta region has been correlated with the Vaimok lens described by Zachrisson and Stephens (1984), on the basis of 1) regional tectonostratigraphic position in both areas below units containing sheeted dikes, and 2) the occurrence in both units of eclogites. Evidence, discussed in detail within the tectonostratigraphy chapter, indicates that parts of the Seve Nappe represent the outermost portions of the Baltoscandian Margin. Structurally overlying the Seve Nappe in the study area are the greenschist grade psammitic gneisses of the Salka Group of the Lower Köli Nappe. The Salka Group may be correlated with the Lower Köli in the central to northern Scandinavian Caledonides (Stephens, pers. comm; Stephens and Gee, 1989). Stephens and Gee (1985) group these Lower Köli rocks into the Virisen terrane which contain volcanic, and high level intrusive rocks (ca. 490 Ma, Claesson et al, 1983) that are thought to be related to ensimatic rifted-arc development. The Virisen terrane includes Early Llanvirn age (478-468 Ma) fossils of both North American and Baltoscandian affinities that are present within detrital serpentinites. The volcano-sedimentary sequence is overlain by turbidites and conglomerates whose detritus indicates erosion from a continental margin with local influx of material from a mafic volcanic and ultramafic source. These rocks regress upwards into shallow marine quartzites and limestones which contain Ashgillian brachiopods and corals similar to those on the Baltoscandian Platform (Stephens and Gee, 1989). Models proposed by Dallmeyer and Gee (1986) and discussed in Stephens and Gee (1985, 1989) associate the Early Ordovician arc volcanism of the Virisen terrane with possible subduction of the outer margin of Baltica during arc-continent collision; however at present there is no geologic evidence relating the Virisen Complex to the Baltoscandian Margin during the Early Ordovician. There is evidence based on the nature of post-arc clastic material and on the occurrence of typical Baltoscandian platformal faunal assemblages, of proximity of the Virisen complex with Baltica during the Middle Ordovician (Stephens and Gee, 1989).

Structure

The structural history of the Singis-Nikkaluokta region has been subdivided into eight deformational events (Fig. 7-1, Table 3-1). The first two events are associated respectively with the eclogite grade and upper-amphibolite grade metamorphic events evidenced within the Seve. D2 kinematic indicators are consistent with S60E transport within the Seve Nappe. The third deformation is associated with the post-Ashgillian metamorphism of the Lower Köli Nappe. Juxtaposition of the Köli and Seve Nappes along the Rusjka Fault zone produced D4 fabrics. The emplacement of the Upper Allochthon onto the Baltic shield produced D5, D6, and D7. D5 kinematic indicators; such as asymmetric augen, S-C fabrics, oriented quartz C-axis, and mineral lineations, within the Middle Allochthon granite mylonites are consistant with S60E shearing. The final deformation (D8) is associated with late, west-vergent motion along the Seve-Köli contact.

Metamorphism

Evidence for two major tectonothermal events are exhibited by the rocks of the Singis-Nikkaluokta region. The earliest event (Finnmarkian) affected the rocks of the Seve Nappe. The conditions of metamorphism experienced by the Seve Nappe during the Finnmarkian were obtained by rim thermobarometry performed on the Paltavare and Vidja Assemblages of the Seve Nappe. Pressure-temperature conditions of the Paltavare Assemblage range from 8.9-13.6 kb and 571-766° C, while the Vidja Assemblage yields a pressure and temperature of 7.3±1.7 kb and 616°±60° C. These results are among the first quantitative results for non-eclogitized portions of the Seve, and thus provide important new constraints for the Finnmarkian tectonic evolution. The second event, termed the Scandian, was responsible for: 1) metamorphism in the Köli Nappe; 2) juxtaposition of the Seve and Köli Nappe with concomittant retrogression of the Seve; and 3) emplacement of the Seve-Köli Complex onto the Baltic Shield with associated development of the Middle Allochthon shear zone. Metamorphic conditions exhibited during the Scandian were Greenschist Facies for the Lower Köli and retrogressed portions of the Seve Nappe, and a very low grade development of a weak schistosity in the sedimentary rocks of the Singis window and foreland.

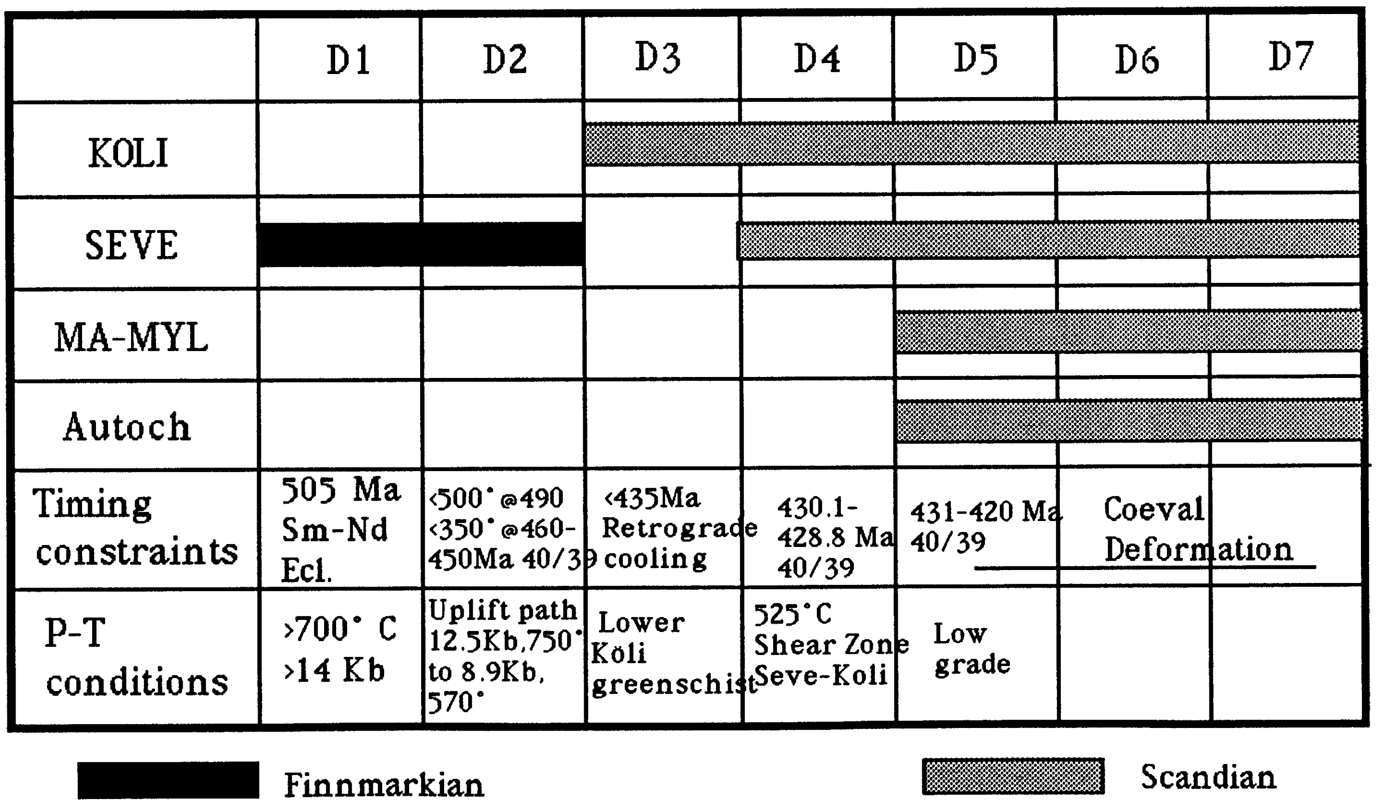
$^{40}Ar/^{39}Ar$ Geochronology

Results of a detailed $^{40}Ar/^{39}Ar$ geochronologic study of the Singis-Nikkaluokta region indicate: 1) High grade metamorphism and associated deformation of the Seve was a Late Cambrian to Early Ordovician event (Finnmarkian) in which rocks cooled below the closure temperatures of hornblende and muscovite at ~ 490 and 454 Ma respectively; 2) A simple linear cooling model gives a cooling rate of 3-6° C/Ma for the older tectonothermal event; 3) a hornblende plateau of 450 Ma provides evidence for a late stage, intra-Seve shear zone between the Vidja and Aurek Assemblages; 4) The Scandian phase of deformation partially reset some hornblendes and most of the muscovites from the Seve, indicating that the rocks originally metamorphosed during the Finnmarkian were affected by a second tectonothermal pulse in excess of 350° at ~ 430 Ma; and 5) it is likely that the tectonic units of the Singis-Nikkaluokta transect were assembled prior to regional cooling through the closure temperature of muscovite, because all tectonostratigraphic elements sampled give overlapping Scandian ages.

Integrated Geologic History

The results presented previously can be integrated to constrain the tectonic history of the Singis-Nikkaluokta region. Figure 7-1 visually represents the relationships between deformational and thermal events in the tectonostratigraphic elements of the area. Rocks of

Figure 7:1 Tectonothermal History of the Singis-Nikkaluokta Area



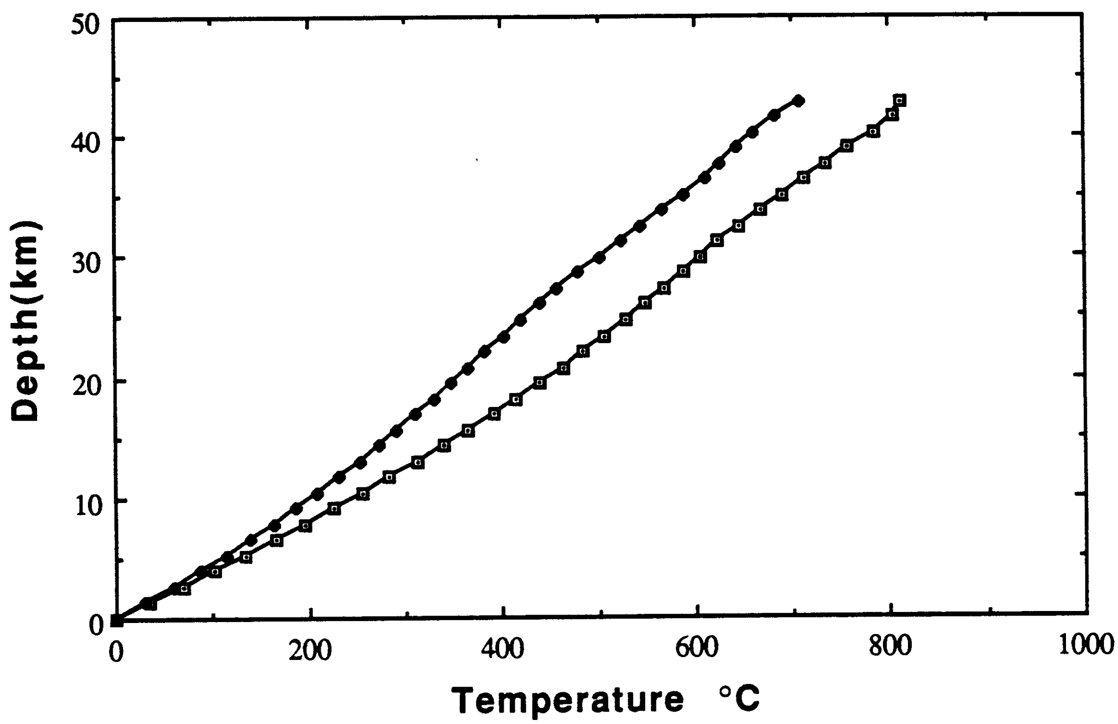
the study area have been affected by two major tectonothermal events. The earliest event termed the Finnmarkian phase is associated with deformation and metamorphism of the Seve Nappe. The younger event (Scandian Phase) was experienced by all tectonostratigraphic elements in the study area, and resulted in the emplacement of the Upper Allochthon onto rocks of the Baltic Shield.

Portions of the Seve Nappe are interpreted to represent the Late Precambrian outermost portion of Baltica (Gee, 1975). Svenningsen (1989) obtained a Sm/Nd crystallization age of ca. 605 Ma for dolerite dyke rocks of the Sarektjåkka Nappe, approximately 100 km south of the study area, which have a rift related chemistry and are associated with the development of Iapetus. The oldest deformational event (D1) observed within the study area includes the development of a weak foliation produced during eclogite grade metamorphism of the Aurek Assemblage in the Seve Nappe. Temperature and pressure conditions of 730° C and >12 kb for the eclogite metamorphism in the study area were obtained by Tilke (1986). These conditions are consistent with the pressures and temperatures obtained for other Seve eclogites throughout the Scandinavian Caledonides (eg. Santallier, in press, 1985; van Roermund, 1985, 1989). A Sm/Nd age of 505 ±18 Ma was obtained for Seve eclogite metamorphism from the Tsäkkok lens in the southern Norrbotten Caledonides (Mørk, 1988). The second deformation in the study area also occurs only within the Seve Nappe. D2 deformation is associated with high grade metamorphism, the development of intrafolial isoclinal folds with a well developed axial planar (N10-30°E 25° W) foliation with axes whose trend is ~N50-60°W (parallel to the infered transport direction), and mineral and intersection lineations parallel to the fold axis direction. Rim thermobarometry constrains the pressures and temperatures of the Savopakte Assemblage of the Seve Nappe to range from 8.9-13.6 kb and 571-766° C. Timing constraints for the Seve metamorphism are provided by $^{40}Ar/^{39}Ar$ geothermochronology, which indicate that hornblendes from the garnet-amphibolites cooled below the 500° C closure temperature for Ar retention at ~490 Ma and muscovites cooled below their Ar retention temperature of 350° C at between 450-460 Ma. These ages coincide with the results of other $^{40}Ar/^{39}Ar$ studies of the Seve from the Scandinavian Caledonides (Dallmeyer 1985; Dallmeyer and Gee, 1986). The ages presented in this study are also consistent with an interpretation of Finnmarkian cooling from the 505 Ma formation of Seve eclogites.

Interesting insights into the Finnmarkian history of the Scandinavian Caledonides are provided by combining geochronologic and thermobarometric results obtained from the Seve. The Seve cooled the 150° C difference in Ar retention temperatures of hornblende and muscovite within approximately 30-50 Ma, this corresponds to a simple linear cooling rate of 3-5° C/Ma. This cooling rate is consistent with cooling during slow uplift. An important problem in deciphering the Finnmarkian geologic history is; what were, and what happened to the 30-40 km of rock that were overlying the high pressure rocks of the Seve? Thermobarometry indicates that portions of the Seve Nappe (marginal Baltica) were buried at depths of 30-45 km before 490 Ma. If it is assumed that by 440-450 Ma when the majority of the Seve rocks, both within the study area and throughout the Scandinavian Caledonides, cooled below 350° C that there was a typical geothermal gradient of ~ 15-20° C/km, then this temperature corresponds to a depth of ~17-23 km. Therefore from 490 to 440 Ma there was uplift of at most 15-20 km. This corresponds to an uplift rate on the order of .4 mm/yr. It is important to note that this simple model does not equate cooling rate with uplift rate; it simply assumes that after 30-50 Ma any thermal perturbation associated with Finnmarkian thrusting would have relaxed and a typical geotherm may be expected. In order to more realistically model the uplift path for the Seve, the method developed by Royden and Hodges (1984) was utilized. In this technique the complete uplift trajectory can be calculated by knowing the temperatures and pressures for a few points along the the uplift path. Three points from the P-T trend obtained for the Savopakte Assemblage (Fig. 4-3) were used in the model. In order to use the Royden and Hodges technique the P-T points used in the model must correspond to points along a segment of the uplift path. The trend established by the Savopakte Assemblage P-T points is thought to represent retrograde reequilibration at different points during Finnmarkian uplift and cooling; however, as the trend of these points parallels the slope of the Kd line for the geobarometer the possibility that the trend is an artifact of the different closure temperatures of the geothermometer and geobarometer can not be precluded. Figure 7-2 shows the maximum and minimum uplift paths obtained from the Royden and Hodges model for the data from the Savopakte Assemblage. This uplift path may be used in combination with the $^{40}Ar/^{39}Ar$ geochronologic data obtained for the Seve which yielded cooling ages for 500° C and 350° C of 490 Ma and 440-450 Ma respectively to obtain cooling rates of .21-.26 mm/yr. While not precluding uplift due to tectonic denudation, this magnitude of uplift may easily be accounted for solely by erosion. Evidence for erosion of a Finnmarkian thickened crust include (Stephens and Gee, 1989): 1) the Middle Ordovician influx of detritus from a continental margin found in the Virisen Terrane (Lower Köli); which require, in part, a mafic or ultramafic source area, and 2) the development, beginning in the Early Ordovician, of a clastic wedge in the foreland basin which has been interpreted to be related to orogenic activity along the Baltoscandian margin.

The Scandian orogenic phase was responsible for deformations 3 through 8 observed in the study area. The Lower Köli greenschist metamorphism and associated isoclinal folds, axial planar foliations, and lineations formed during D3. $^{40}Ar/^{39}Ar$ geochronolgy (Tilke, 1986; Page, this study) yield muscovite ages which range from 435-424 Ma. D4 includes juxtaposition of the Köli and Seve Nappes along the Rusjka fault. Synkinematic garnets preserve sygmoidal inclusion trails which indicate SE directed shear Tilke (1986) obtained a garnet-biotite temperature of 525° C for rocks within the Seve-Köli shear zone. This event was also responsible for retrogression and transposition of the F2 foliation of the Seve Nappe near the contact with the Rusjka fault. D5 includes emplacement of the Upper Allochthon onto the Autochthon-Parautochthon. During emplacement the Middle Allochthon was formed by the detachment of thin variably

Figure 7-2: Modeled Seve Uplift Path

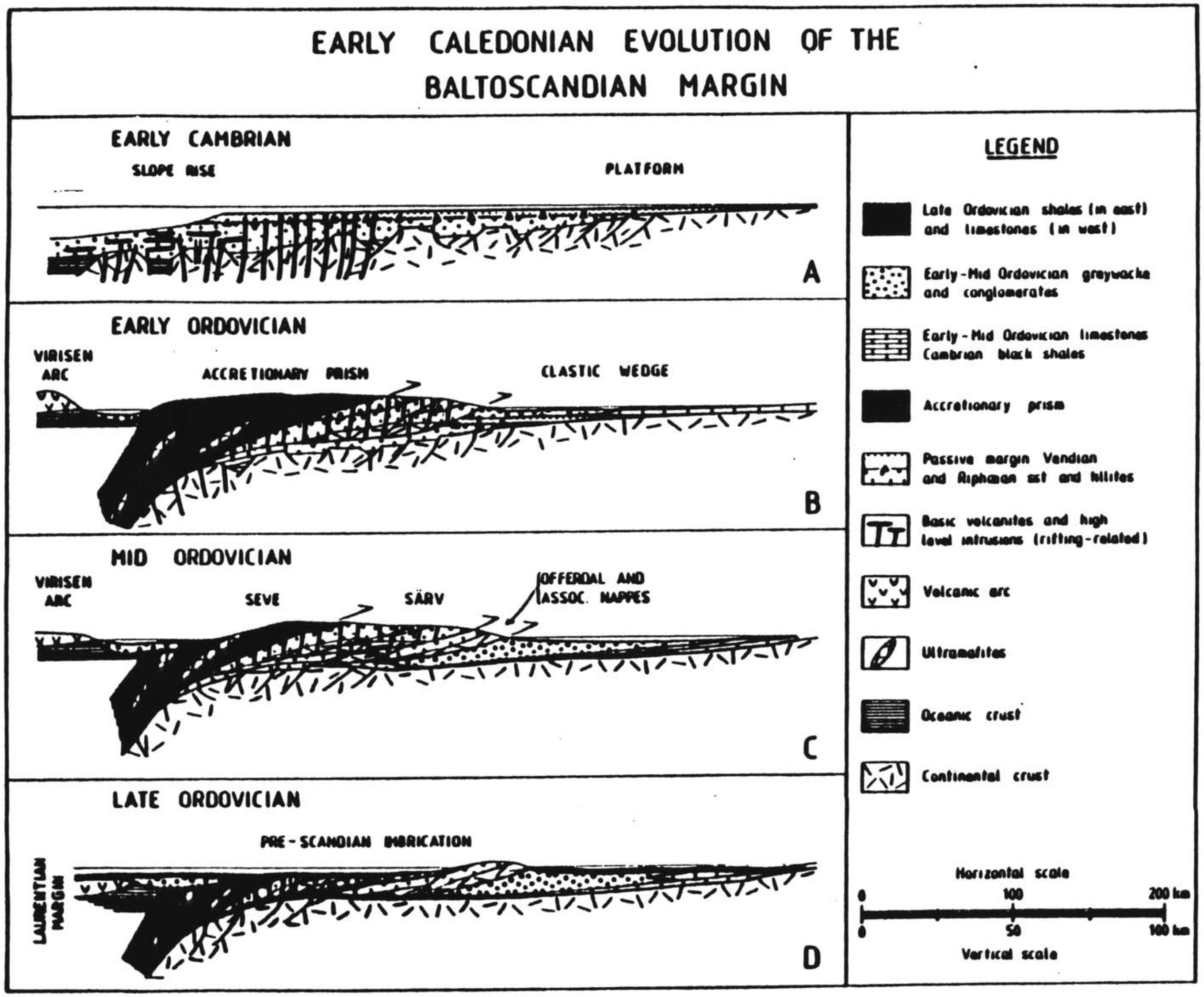


mylonitized slivers of Baltic crystallines and sedimentary cover. Kinematic indicators provided by S-C fabrics, mineral lineations, quartz c-axes, and isoclinal fold axes within the Middle Allochthon consistently demonstrate S60E transport during D5. $^{40}Ar/^{39}Ar$ geochronology yields Middle Allochthon muscovite ages of 431-421 Ma. The overlap in muscovite ages from different tectonostratigraphic elements probably indicates that these units were assembled prior to regional cooling below the muscovite closure temperature. D6 and D7 are represented by late gentle warps along N60W and N30E respectively. D5 was the first event which affected the Autochthonous sediments within the Singis window and in the foreland. These sedimentary rocks have developed only a slight schistosity at very low metamorphic grade. The final deformational event (D8) was associated with late west-vergent motion along the Seve-Köli contact. Tilke (1986) proposed that this motion may have been the result of normal faulting during gravitational collapse of the Scandian orogen, however much more work throughout the Scandinavian Caledonides is needed to confirm or deny this hypothesis.

Discussion

The data presented within this study are consistent with the tectonic models proposed by Dallmeyer and Gee (1986) for the early Caledonian (Finnmarkian) evolution of the Baltoscandian Margin. In this model (Fig 7-3) the Baltoscandian margin was subducted westward beneath an inferred volcanic arc (documented by the presence of arc-related volcanics found within the lower Köli Nappe) beginning in Late Cambrian time. During the Early Ordovician an accretionary wedge developed and high grade metamorphism occured within the Seve units. Uplift occured during the Late-Middle Ordovician and provided a source for the westerly derived turbidites which are preserved within the foreland and also for the Middle Ordovician turbidites preserved within the Lower Köli Virisen Terrane. The Scandian event resulted in the complete closure of

Figure 7-3: Tectonic model for the Baltoscandian margin (Dallmeyer and Gee, 1986).



Iapetus with associated emplacement of a complex Nappe package (containing elements of Laurentian, Baltic and unknown affinities) onto the Baltic Shield. Stephens and Gee (1989) use the terrane concept (Coney et al., 1980) to better constrain the polyphase accretionary history of the Scandinavian Caledonides and demonstrate that several terranes had a complex tectonic history prior to coming into proximity with Baltica during the Scandian. Within the Singis-Nikkaluokta region the rocks of the Lower Köli are correlated with the Virisen Terrane; which has been interpreted to be proximal to Baltica during the Middle Ordovician and contain fossils of Ashgillian age (Stephens and Gee, 1985). $^{40}Ar/^{39}Ar$ geochronology of the study area indicates that the Köli, Seve and Middle Allochthon, although demonstrating cross cutting structural relationships, yield overlapping ages of ~431-421 Ma, indicating that the units were probably juxtaposed prior to regional cooling through 350° C.

This study provides some of the first integrated P-T-t constraints for the evolution of the Finnmarkian tectonothermal event within the northern Scandinavian Caledonides. While these constraints are consistent with the models proposed by Dallmeyer and Gee (1986) and Stephens and Gee (1989) discussed above, the results obtained in this study provide some additional constraints which need to be considered in future tectonic models. These constraints include: 1) The metamorphic conditions obtained for the Savopakte Assemblage of the Seve Nappe record high pressures and high temperatures during the Finnmarkian. Therefore, tectonic models need to be considered which elevate the geotherms and account for 40-60 km of overlying material. 2) Constraints provided by this study indicate that Finnmarkian uplift rates of .2-.4 mm/yr were likely for marginal Baltica after peak metamorphism. Rates of this magnitude may be accounted for solely by slow erosion and do not require (but do not preclude) more complex tectonic interpretations. and 3) The juxtaposition throughout the Seve Nappe of eclogites with rocks of lower grade indicates these rocks were tectonically juxtaposed during the Finnmarkian.

A tectonic model provided by the Late Cenozoic thrust belts of the Apennine (Fig.7-4), Carpathian, and Hellenic systems of the mediterranean region, may lead to new insights into the Early Paleozoic evolution of the Scandinavian Caledonides. The tectonic setting for these systems have developed within convergent systems in which thrusting, associated with arc-type volcanism, occurred behind a zone of trench retreat (slab rollback); causing synchronous extension in the overriding plate (Royden, 1988; Royden and Burchfiel, 1989, in press). This model is attractive for the evolution of the Caledonides because it helps explain several salient points: 1) The overriding plate is a zone of extension allowing for the elevation of geotherms; therefore explaining the high temperatures at high pressures recorded within the Seve. 2) Although evidence for arc-related volcanic rocks has been documented (Stephens and Gee, 1985), there exists no evidence within the Scandinavian Caledonides of the volcanic arc. The Apennine model while containing arc-type volcanism in the overlying plate, does not require the presence of a massive volcanic-arc. The arc region is extended during its development and may be disrupted and spread across a broad region of extension. 3) Within the Mediterranian systems the extended area is often a zone of subsidence, thus a topographic high with associated rapid erosion rates are not necessary. The low (.2-.4 mm/yr) uplift rates obtained in this study may be consistent with this interpretation.

Clearly further integrated, multidisciplinary studies throughout the Scandinavian Caledonides are needed to better constrain and to distinguish between the arc-continent collision versus the Apennine model for the evolution of the Early Paleozoic Finnmarkian event. However, the new results presented in this study provide new constraints which require incorporation into tectonic models for the tectonic evolution of the Scandinavian Caledonides.

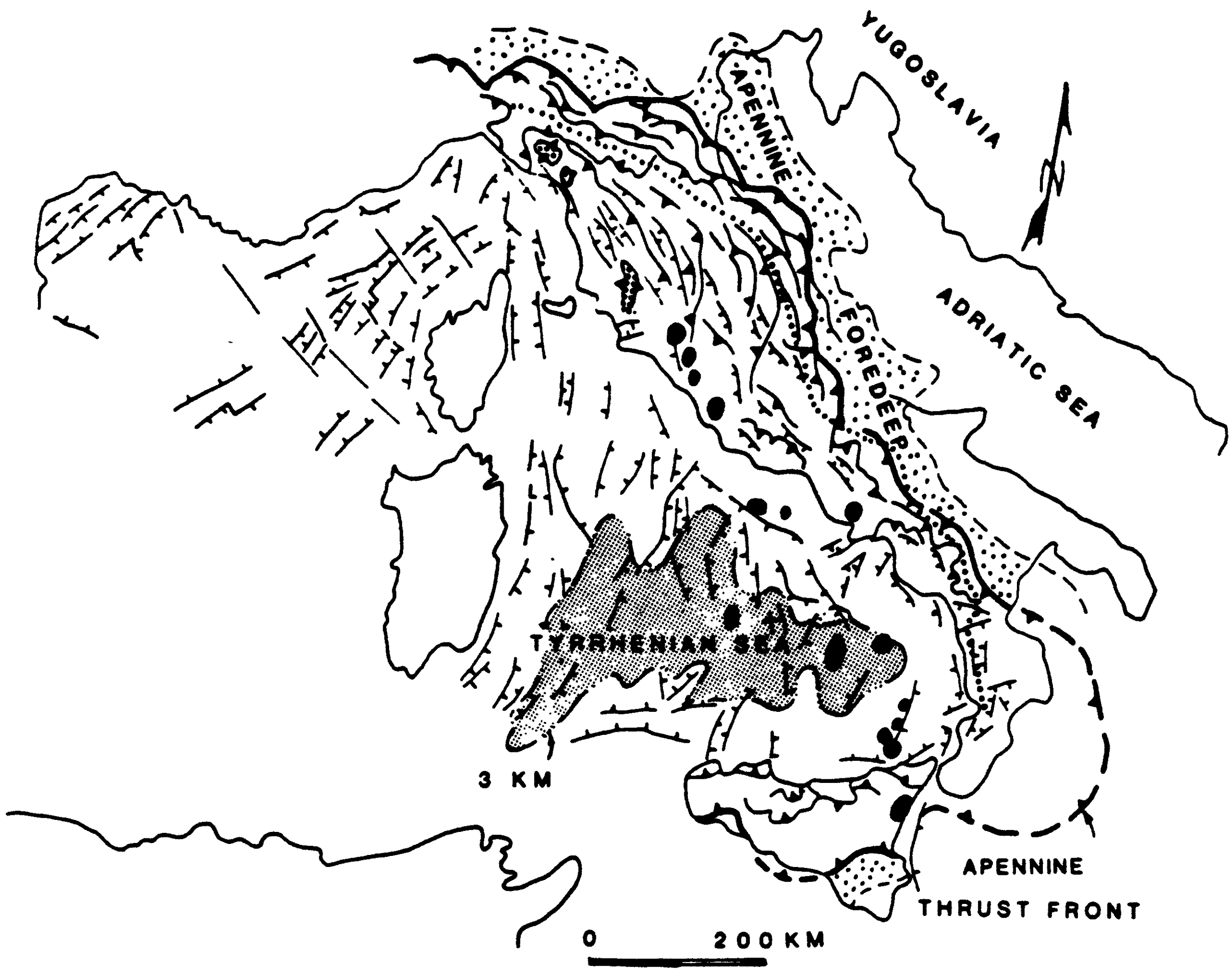


Figure 7:4: Tectonic map of the Apennines from Burchfiel and Royden (in Press)

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Plate 1: Simplified Geologic Map of the Singis - Nikkaluokta Area, Sweden with Sample Localities

Symbols

Argon Sample Locality

P-T Sample Locality

Strike and Dip of Foliation

Tectonostratigraphy

		Qal	Cover
Köli	Salka Group	Kpq	Patta Quartzite
		Krg	Rusjka Graphitic Schist
		Krc	Rusjka Calcareous Schist
Seve	Vidja Assemblage	Sva	Vidja Amphibolite
		Svm	Vidja Muscovite Gneiss
		Svq	Vidja Quartzofeldspathic Gneiss
	Aurek Assemblage	Sag	Aurek Gabbro
		Saa	Aurek Amphibolite
	Savotjåkka Assemblage	Ssa	Savotjåkka Amphibolite
		Ssq	Savotjåkka Quartzofeldspathic Gneiss
	Manak Assemblage	Mag	Manak Gabbro
		Mgn	Manak Mylonite Gneiss
Middle Allochthon	Matert Shear Zone	Msz	Matert Shear Zone
	Paltavare Shear Zone	MPP	Paltavare Phyllonite
		Mpm	Paltavare Mylonite
Autochthon-Parautochthon	Dividal Group	Dtg	Torneträsk Formation
	Grunfjell Group	Pcg	Precambrian Basement

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