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# $^{40}Ar/^{39}Ar$ age pattern associated with differential uplift along the Eastern Highlands shear zone, Cape Breton Island, Canadian Appalachians

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**Abstract**

The Eastern Highlands shear zone in Cape Breton Island is a crustal scale thrust. It is characterized by an amphibolite-facies deformation zone ~5 km wide formed deep in the crust that is overprinted by a greenschist-facies mylonite zone ~1 km wide that formed at a more shallow level. Hornblende $^{40}Ar/^{39}Ar$ plateau ages on the hanging wall decrease towards the centre of the shear zone. In the older zone (over 7.8 km from the centre), the ages are between ~565 and ~545 Ma; in the younger zone (within 4.5 km of the centre), they are between ~425 and ~415 Ma; and in the transitional zone in between, they decrease abruptly from ~545 to ~425 Ma. Pressures of crystallization of plutons in the hanging wall, based on the Al-in-hornblende barometer and corresponding to depth of emplacement, increase towards the centre of the shear zone and indicate a differential uplift of up to ~28 km associated with movement along the shear zone. The age pattern is interpreted to have resulted from the differential uplift. The pressure data show that rocks exposed in the younger zone were buried deep in the crust and did not cool through the hornblende Ar blocking temperature (~500°C) until differential uplift occurred. The $^{40}Ar/^{39}Ar$ ages in the zone (~425–415 Ma) thus date shear zone movement or the last stage of it. In contrast, rocks in the older zone were more shallowly buried before differential uplift and cooled through the blocking temperature soon after the emplacement of ~565–555 Ma plutons in the area, long before shear zone movement. The transitional zone corresponds to the Ar partial retention zone before differential uplift. The $^{40}Ar/^{39}Ar$ age pattern thus reflects a Neoproterozoic to Silurian cooling profile that was exposed as a result of differential uplift related to movement along the shear zone. A similar K–Ar age pattern has been reported for the Alpine fault in New Zealand. It is suggested that such isotopic age patterns can be used to help constrain the ages, kinematics, displacements and depth of penetration of shear zones. 

## 1. Introduction

Shear zones are common structures in deformed terranes and elucidation of the tectonic evolution of these terranes to a large degree depends on understanding the kinematic history of the shear zones. Most terranes experienced multiple episodes of deformation and shear zones that formed at different times may have different kinematics. For shear zone studies to be most useful for tectonic analysis, both the kinematics and the timing of deformation need to be documented.

Shear zone deformation can potentially be directly dated using syn-kinematic intrusions or metamorphic minerals that formed/cooled during shearing, or bracketed in age using both pre- and post-kinematic intrusions. A potential complication for these methods is that it is not always easy to determine unambiguously whether intrusions concerned are pre-, syn- or post-kinematic (see, e.g. Paterson and Tobisch, 1988), and whether minerals that grew syn-kinematically cooled through their respective blocking temperatures during or after deformation. The cooling ages of such minerals can potentially be much younger than the host shear zone.

It is common for isotopic ages to gradually decrease towards the centre of shear zones (e.g. Adams and Gabities, 1985; Percival and Peterman, 1994), and it is tempting to use the age pattern to help determine the ages of shear zones. However, the interpretation of such age patterns has been controversial (see later discussion on the Alpine fault in New Zealand, for example). A better understanding of this age pattern cannot only help constrain the ages of the shear zones concerned, it can also place constraints on the structural and tectonic interpretation of the shear zones. In this paper, the hornblende $^{40}Ar/^{39}Ar$ age pattern associated with the Eastern Highlands shear zone in Cape

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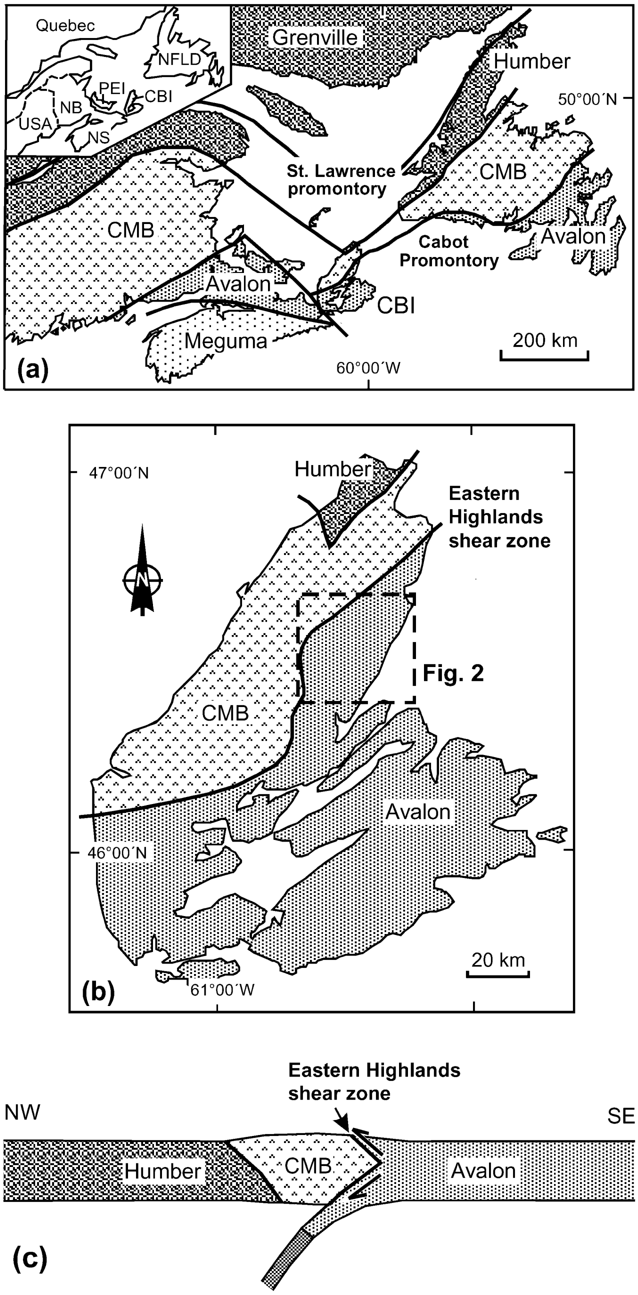


Fig. 1. (a) Tectonostratigraphic zones of the northern Appalachians showing the regional geological setting of Cape Breton Island (CBI) (simplified after Williams, 1979; Lin et al., 1994). CMB: Central Mobile Belt. (b) A simplified map of Cape Breton Island showing the tectonic setting of the Eastern Highlands shear zone (simplified from Barr and Raeside, 1989). (c) Schematic diagram showing a tectonic interpretation for the Eastern Highlands shear zone. The movement along the shear zone is antithetic to the westward subduction and is interpreted to be related to tectonic wedging (based on Lin et al., 1994; Lin, 1995).

Breton Island in the Canadian Appalachians (Fig. 1a, b) is described. Based on the kinematics of the shear zone and the variation in pressures (corresponding to depth) of pluton crystallization, it is concluded that the age pattern is a result of differential uplift associated with the movement along the shear zone.

## 2. Geological setting

### 2.1. Regional geological setting

The Canadian Appalachians contain the remnants of the Iapetus Ocean (the Dunnage Zone) and its eastern and western continental margins (the Gander and the Humber zones; Williams, 1979; Williams et al., 1988). The Dunnage and the Gander zones together are traditionally termed the Central Mobile Belt (CMB; Fig. 1a). The collision between Laurentia and Avalon and the closure of the Iapetus Ocean took place in the Late Ordovician to Silurian (e.g. van Staal, 1994). The subduction leading to the collision had a westward polarity (e.g. van der Pluijm et al., 1990; van Staal, 1994).

Cape Breton Island and southwestern Newfoundland have been interpreted as the location of a Silurian collision between the St. Lawrence promontory on the Laurentian margin and the Cabot promontory on the Avalon margin (Fig. 1a; Lin et al., 1994). The CMB in this area is different from that in other parts of the Canadian Appalachians in that it is narrower, Silurian deformation is stronger and syntectonic metamorphism records higher pressure. Here, orogen-parallel Silurian thrusts are west vergent, antithetic to the westward subduction. The Eastern Highlands shear zone (EHSZ) of this study (Fig. 1b) is one of these west-vergent, antithetic Silurian thrusts. In contrast, orogen-parallel Silurian thrusts in other parts of the Canadian Appalachians are mostly east-vergent, synthetic to the westward subduction. The antithetic thrusting has been interpreted to be related to tectonic wedging at the location of promontory–promontory collision (Fig. 1c; Lin et al., 1994).

### 2.2. Local geology

The pre-Carboniferous supracrustal rocks in the study area in northeastern Cape Breton Island (Fig. 2) are composed of Ordovician–Silurian metasedimentary and metavolcanic rocks in the west and Late Precambrian metasedimentary and metavolcanic rocks in the east, separated by the EHSZ. Intrusive rocks in the area include: (1) Late Precambrian dioritic–tonalitic–granodioritic–granitic plutons (~555–565 Ma; U–Pb zircon or titanite, Dunning et al., 1990), exposed to the east of the EHSZ, (2) Early Ordovician granitic plutons (~493 Ma; U–Pb zircon, Dunning et al., 1990), also exposed to the east of the EHSZ, and (3) Devonian granitic plutons (U–Pb zircon and monazite ages, Dunning et al., 1990), exposed mainly to the west of or near the EHSZ. All of these rocks are unconformably overlain by unmetamorphosed Carboniferous sedimentary rocks.

Detailed structural analysis in northeastern Cape Breton Island (Lin, 1992, 1995) reveals two major episodes of pre-Carboniferous ductile shearing: $D_1$ and $D_2$. $D_1$ deformation took place in Late Silurian to Early Devonian time, after the emplacement of Lower Silurian volcanic rocks and before

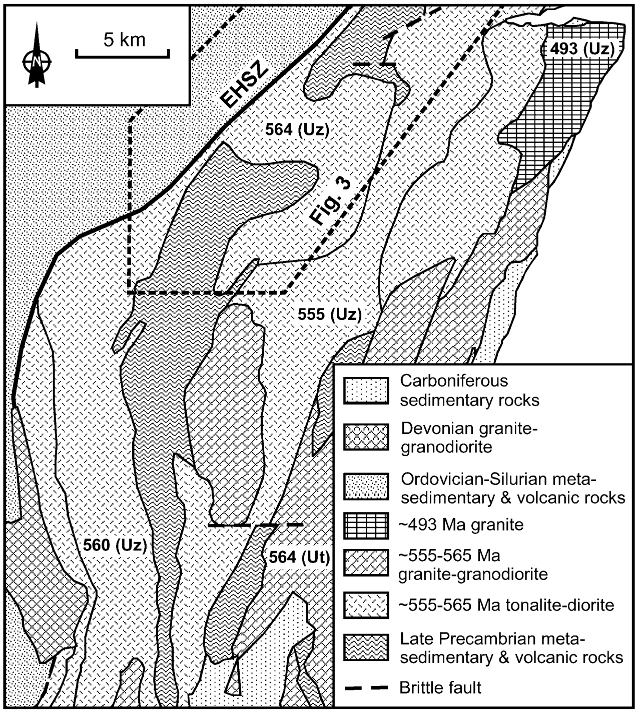


Fig. 2. A simplified geological map of part of northeastern Cape Breton Island (compiled from Lin, 1992,1993; Barr et al., 1992; Raeside and Barr, 1990). See Fig. 1(b) for location. The numbers are U–Pb zircon (Uz) and titanite (Ut) ages (Ma) from Dunning et al. (1990). EHSZ: Eastern Highlands shear zone.

the intrusion of Middle Devonian granitoids. It is concentrated in, but not confined to, the EHSZ. In the area of Fig. 2, Ordovician–Silurian supracrustal rocks to the west of the EHSZ are generally metamorphosed to greenschist facies. Late Precambrian supracrustal rocks to the east of the EHSZ are metamorphosed to amphibolite facies near the shear zone centre, with the grade decreasing gradually towards the east to greenschist facies and lower (Raeside and Barr, 1992). North of Fig. 2, Ordovician–Silurian supracrustal rocks west of the EHSZ are also of amphibolite facies, due to movement along $D_2$ shear zones.

$D_2$ deformation took place in Late Devonian to Early Carboniferous time, after the intrusion of Middle Devonian granitic plutons and before the deposition of a Carboniferous conglomerate. It occurred under greenschist-facies conditions and was concentrated in several north-northeast-striking shear zones along lithological contacts, mainly to the north of the area of Fig. 2. In the area of Fig. 2 and further south, $D_2$ deformation is very weak and is only manifested by locally developed small-scale shear zones. $D_2$ shear zones strike north-northeasterly and dip steeply to the southeast. Movement along the shear zones is oblique, with a dextral horizontal component and a west-side-up dip–slip component (Lin, 1992; Lin et al., 1998).

The main features of the EHSZ are summarized below based on Lin (1995). Note that Lin's (1995) structural analysis of the shear zone was mainly based on data collected in the area of Fig. 3, where $D_2$ overprinting is minimal.

## 3. Kinematics of the Eastern Highlands shear zone

The EHSZ is characterized by an amphibolite-facies deformation zone ~5 km wide with late-stage greenschist-facies deformation localized in a zone ~1 km wide at the western margin (Fig. 3). The greenschist- and amphibolite-facies deformation zones are gradational and have the same kinematic framework, and deformation in both zones is constrained to have occurred in the same time interval. Lin (1995) concluded that deformation in the two zones represents two stages of a single episode of deformation ($D_1$).

In most parts of the EHSZ, rocks have amphibolite-facies mineral assemblages. These rocks are strongly deformed, and a foliation ($S_1$), a lineation ($L_1$) and folds ($F_1$) are well developed. The foliation is defined by a preferred orientation of mafic minerals (biotite and hornblende) and inequant conglomerate pebbles, by migmatite veins, and by compositional layering with layers rich in biotite and/or hornblende alternating with those rich in quartz and feldspar. The lineation is defined by a preferred orientation of biotite and/or hornblende crystals in the foliation, by elongate conglomerate pebbles, and by elongate feldspar augen. The folds are tight to isoclinal. They are very noncylindrical with fold hinges varying from shallowly to steeply plunging (Fig. 3), even within a single outcrop. Locally, sheath folds are developed.

In a zone ~1 km wide at the western margin of the shear zone, the rocks have a greenschist-facies mineral assemblage. They are classical mylonites or phyllonites with widespread dynamic recrystallization structures. The mylonitic foliation is defined by platy aggregates, and the stretching lineation by elongate aggregates, of fine-grained, dynamically recrystallized minerals. Folds intrafolial to the mylonitic foliation are locally recognized in these rocks. Most of them are tight folds of the mylonitic foliation. Their hinges plunge shallowly to the northeast and are highly oblique to the stretching lineation (Fig. 3).

The foliation in the shear zone strikes northeasterly and dips steeply (Fig. 3). The lineation pitches steeply on the foliation. In the greenschist-facies deformation zone, it pitches steeply to the southwest. Although the orientation of fold hinges varies significantly as a result of hinge rotation during progressive shearing, hinges of sheath folds consistently plunge steeply to the south. The plot of the fold hinges defines a great circle girdle (Fig. 3). The girdle is interpreted to be subparallel to the shear plane (as explained by, e.g. Suppe, 1985, pp. 342–343). These structural data indicate that the shear zone dips steeply to the southeast, and the movement direction plunges steeply south, or pitches steeply to the southwest on the shear plane

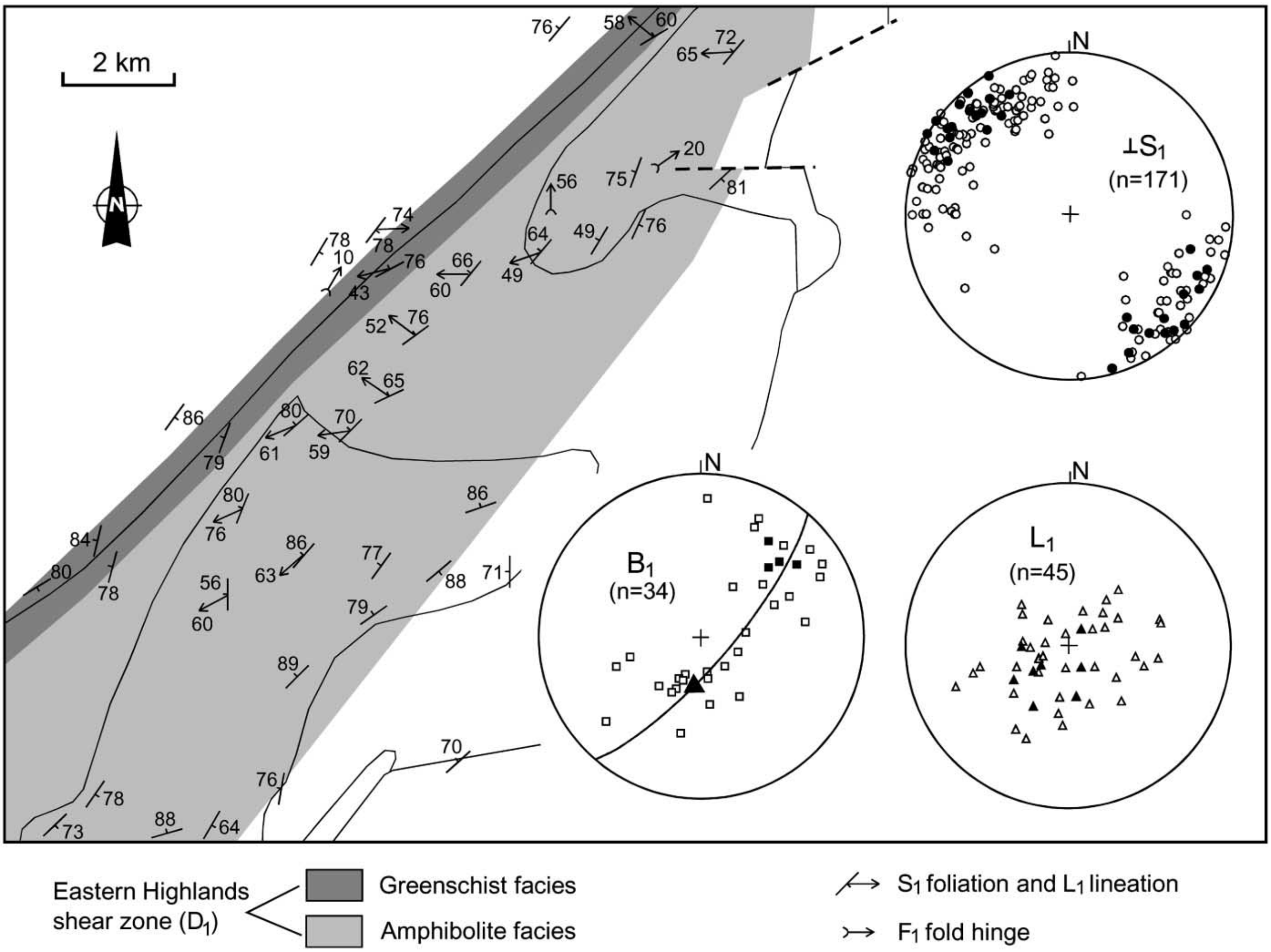


Fig. 3. A simplified structural geology map of part of northeastern Cape Breton Island, showing structures related to the Eastern Highlands shear zone (modified from Lin, 1995). See Fig. 2 for location. The unit contacts shown are the same as those in Fig. 2. The equal-area lower-hemisphere projections show poles to foliation ($S_1$), lineations ($L_1$) and fold hinges ($B_1$) from the shear zone. Data from the amphibolite-facies deformation zone are shown by open symbols (□, △, ○) and those from the greenschist-facies deformation zone by filled symbols (■, ▲, ●). The interpreted attitude and shear direction of the shear zone are indicated in the $B_1$ diagram by a great circle and a filled triangle, respectively.

(Fig. 3). Shear sense indicators such as small-scale shear zones, drag folds and shear bands, indicate a dominant east-over-west dip–slip movement with a minor sinistral horizontal component (Fig. 4).

## 4. Differential uplift based on Al-in-hornblende barometer

Since Hammarstrom and Zen (1986) presented evidence that the aluminium (Al) content of hornblende can be used as a barometer for granitoid crystallization, a lot of additional work (both experimental and field-based) has been done to test the validity of or to improve the Al-in-hornblende barometer (e.g. Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992; Anderson and Smith, 1995; Ague, 1997). These studies indicate that the barometer is at least qualitatively valid and regional pressure gradients delineated by the barometer are geologically meaningful, although the barometer is yet to be precisely calibrated and the influences of temperature, magma composition and fluid composition remain incompletely understood.

Farrow and Barr (1992) calculated the pressures of crystallization of the Late Precambrian dioritic–tonalitic–granodioritic plutons exposed to the east, or on the hanging wall, of the EHSZ based on the Al-in-hornblende barometer, using equations of Hammarstrom and Zen (1986), Hollister et al. (1987), and Johnson and Rutherford (1989). Individual samples yield somewhat different pressures depending on the equations used, reflecting the imprecise nature of the barometer. By comparing the pressure values with the grade of metamorphism in the country rocks, Farrow and Barr (1992) concluded that the pressures calculated using the equation of Johnson and Rutherford (1989) are most realistic. For this reason, the following discussion is


Fig. 4. Photomicrograph of a mylonite from the Eastern Highlands shear zone. *S*–*C* and *S*–*C*′ structures indicate SE-over-NW shear sense. *C*-surfaces are parallel to the longer edge of the photo and are best developed near its right margin, and *C*′-surfaces are indicated by an arrow. The section is cut parallel to the lineation and perpendicular to the foliation.

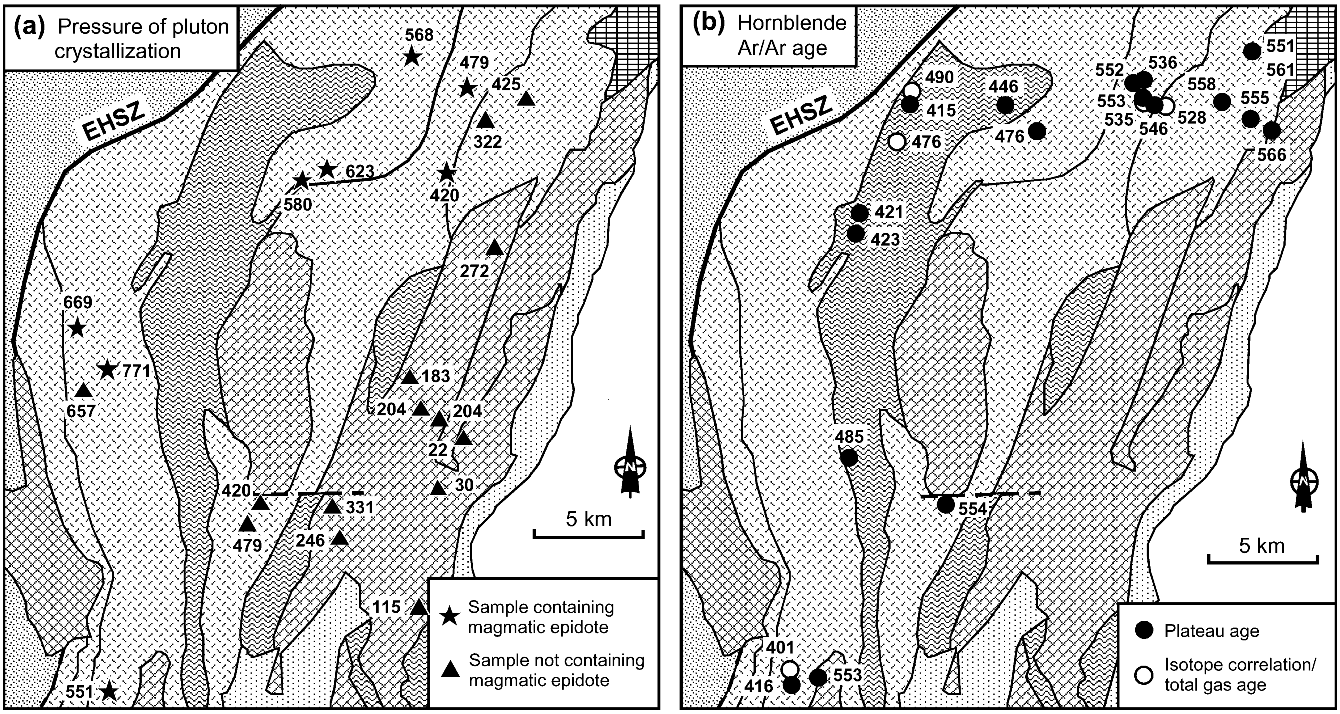


Fig. 5. Simplified geological map of part of northeastern Cape Breton Island showing (a) pressures of pluton crystallization (MPa) and (b) hornblende $^{40}Ar/^{39}Ar$ ages (Ma). Legend same as Fig. 2. The pressures of pluton crystallization are from Farrow and Barr (1992) and the $^{40}Ar/^{39}Ar$ ages are from Reynolds et al. (1989); Dallmeyer and Keppie (1993).

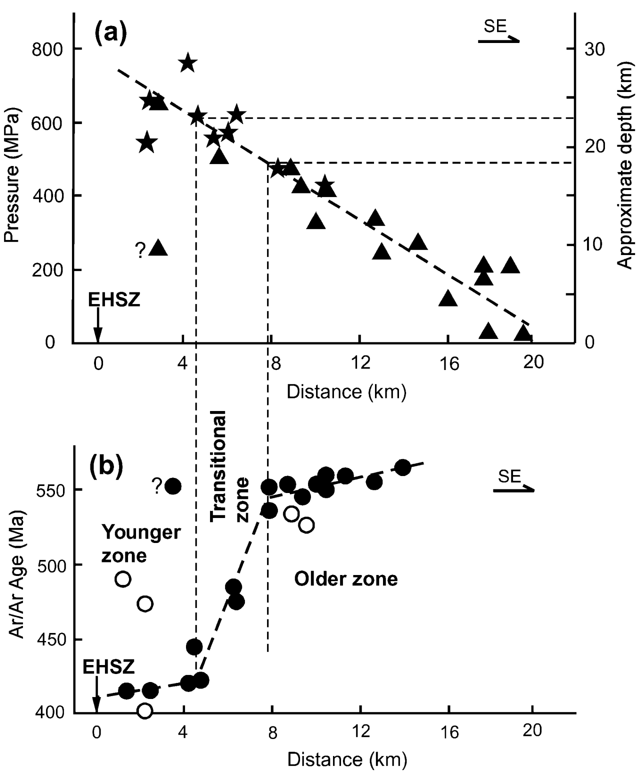


Fig. 6. (a) and (b) Plots of pressures of pluton crystallization and hornblende $^{40}Ar/^{39}Ar$ ages relative to surface distance from the centre of the Eastern Highlands shear zone (EHSZ or distance 0). The corresponding depths of pluton crystallization in (a) are calculated based on an average crustal density of 2.7 g $cm^{-3}$. Data outside the area of Fig. 5 are also included. Data sources and symbols same as Fig. 5.

only based on pressures calculated using this equation. It should be noted that the pressure pattern discussed below and the general conclusions of the paper are the same irrespective of the equations used.

The pressure data of Farrow and Barr (1992) are summarized in Fig. 5(a). They are plotted against the surface distance from the centre of the EHSZ in Fig. 6(a). These data clearly show that the pressure of pluton crystallization increases towards the centre of the shear zone. This is consistent with the observed increase in metamorphic grade in the country rocks in the same direction. It is also consistent with the presence of magmatic epidote in the plutons in the west, and the absence of magmatic epidote in the east (Figs. 5a and 6a; Farrow and Barr, 1992; Raeside and Barr, 1992). The presence of magmatic epidote in rocks of tonalitic and granodioritic composition has been interpreted to indicate deep emplacement and high pressures (over ~600 MPa) (Zen and Hammarstrom, 1984, 1988; Zen, 1985).

Farrow and Barr (1992) also calculated the temperatures of pluton crystallization based on the amphibole–plagioclase thermometer of Blundy and Holland (1990), using the pressures based on the Al-in-hornblende barometer. Although the pressures of pluton crystallization can vary significantly within a single pluton, their results show that the temperatures are uniform within error for an individual pluton. This further supports the validity of the Al-in-hornblende barometer.

The pressure data presented above show a significant increase in depth of pluton emplacement westwards towards the centre of the EHSZ, i.e. a significant uplift of the hanging wall rocks near the centre relative to those away from the centre. In contrast, rocks on the footwall to the west of the EHSZ show no evidence of significant uplift. The close spatial association between the differential uplift and the EHSZ indicates that the differential uplift resulted from the east-over-west movement along the EHSZ.

## 5. $^{40}Ar/^{39}Ar$ age pattern and interpretation

Available hornblende $^{40}Ar/^{39}Ar$ plateau ages from northeastern Cape Breton Island (Reynolds et al., 1989; Dallmeyer and Keppie, 1993) are summarized in Fig. 5(b).[1] They are plotted against distance from the centre of the EHSZ in Fig. 6(b). The data show a clear trend of decreasing plateau ages westwards towards the centre of the shear zone. Based on the age pattern shown in Fig. 6(b), the area is divided into three zones. Over 7.8 km away from the centre of the EHSZ (the older zone in Fig. 6b), the ages are between ~565 and ~545 Ma and decrease slightly westwards. These ages are very close to the crystallization ages (~565–555 Ma) of Late Precambrian plutons in the area. Within 4.5 km of the centre of the shear zone (the younger zone in Fig. 6b), the ages are between ~425 and ~415 Ma and also decrease slightly westwards. In the transitional zone in between (Fig. 6b), the ages decrease abruptly westwards from ~545 to ~425 Ma.

The close correlation between the $^{40}Ar/^{39}Ar$ ages and the amount of uplift as shown in Fig. 6 indicates that the $^{40}Ar/^{39}Ar$ age pattern is a result of differential uplift associated with the movement along the EHSZ. The proposed interpretation is illustrated in Fig. 7 and is summarized below.

Assuming a crustal density of 2.7 g cm$^{-3}$ and a thermal gradient of 25°C km$^{-1}$, the pressure data indicate that before the differential uplift, rocks exposed in the older zone were buried less than ~18 km below the surface and their temperatures were less than ~450°C, lower than the geologically most likely range of hornblende Ar blocking temperature ($T_b$, ~450–575°C; Harrison, 1981; Brodie et al., 1989) (Figs. 6 and 7a). Therefore, these rocks must have had cooled through $T_b$ before differential uplift. Their hornblende $^{40}Ar/^{39}Ar$ ages (~565–545 Ma) indicate that they cooled through $T_b$ soon after crystallization of the ~565–555 Ma plutons in the area and long before the differential uplift (see below for the age of the uplift), which supports the above assumption on the thermal gradient. The slight westward decrease in age now observed in the older zone (Fig. 6b) reflects that the upper parts of the plutons cooled earlier.

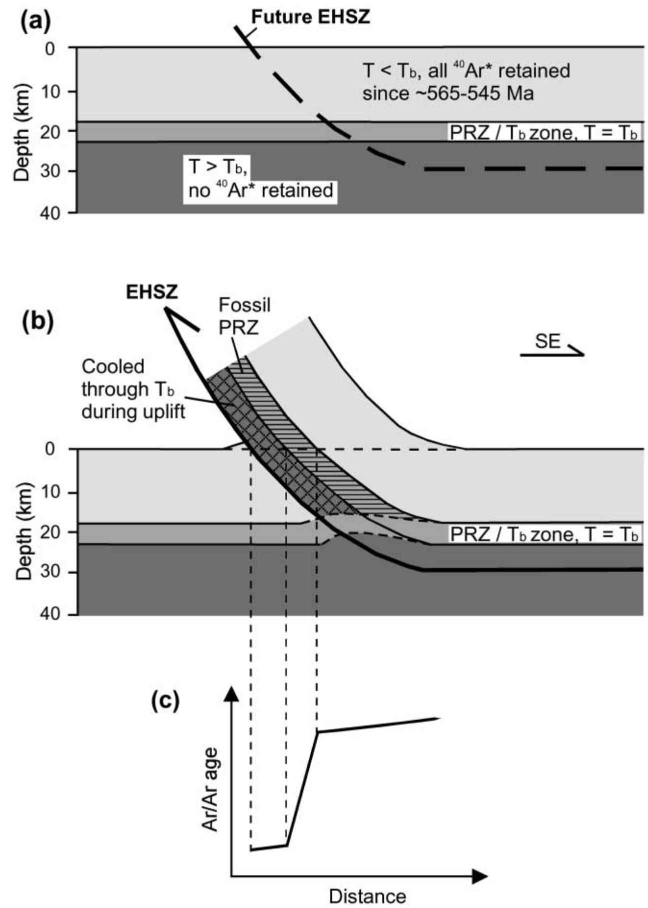


Fig. 7. Schematic diagram showing the proposed interpretation for the $^{40}Ar/^{39}Ar$ age pattern associated with the Eastern Highlands shear zone (EHSZ). (a) Situation immediately before movement along the EHSZ. Rocks above the partial retention zone (PRZ), exposed in the older zone, had cooled through the hornblende Ar blocking temperature ($T_b$, ~500°C) at ~565–545 Ma. Rocks below the PRZ, exposed in the younger zone, had not yet cooled through the blocking temperature. (b) Situation during movement along the EHSZ. The movement resulted in differential uplift and rocks exposed in the younger zone cooled quickly through the blocking temperature ($T_b$) during the differential uplift at ~425–415 Ma. The transitional zone is the exposed (fossil) PRZ. (c) Predicted age pattern as a result of the differential uplift. See text for further discussion.

Assuming the same crustal density and thermal gradient, the pressure data also indicate that before the differential uplift, rocks exposed in the younger zone were buried over ~23 km below the surface and their temperatures were above ~575°C, higher than $T_b$ (Figs. 6 and 7a). Therefore, these rocks did not cool through $T_b$ until the uplift (Fig. 7b) and their hornblende $^{40}Ar/^{39}Ar$ ages of ~425–415 Ma record the time of the uplift. The gradual westward decrease in age in the zone reflects that rocks exposed closer to the shear zone centre passed through $T_b$ later (see later discussion).

Rocks exposed in the transitional zone were buried between ~18 and ~23 km below the surface before the differential uplift (Fig. 6). They occupied a zone transitional between the zone where the temperature was low enough for

[1] For samples that do not show clear plateaux on $^{40}Ar/^{39}Ar$ age spectra, Dallmeyer and Keppie (1993) report total gas or isotope correlation ages. These ages are also shown in Figs. 5(b) and 6(b). Because their geological significance is not clear, they are not considered here.

all radiogenic Ar to be retained, and the zone where the temperature was high enough that no radiogenic Ar was retained (Fig. 7a). The transitional zone therefore corresponds to a zone before differential uplift in which the ambient temperature fell within the range of $T_b$ and radiogenic Ar was only partially retained. Such a zone before differential uplift is hereafter referred to either as the Ar partial retention zone (PRZ) where the emphasis is on Ar partial retention, or as the $T_b$ zone where the emphasis is on the range of the Ar blocking temperature. The transitional zone is therefore the exposed PRZ (fossil PRZ in Fig. 7b). From the eastern to the western boundary of the transitional zone, i.e. from the upper to the lower boundary of the PRZ, the percentage of radiogenic Ar retained decreases sharply. This explains the abrupt decrease in $^{40}Ar/^{39}Ar$ ages westwards (downwards). Therefore, the ages in the transitional zone do not have precise age significance.

As discussed by Harrison (1981), Brodie et al. (1989), and Goodwin and Renne (1991), the precise value of $T_b$ for a given mineral varies with the diffusion radius (or the 'effective' grain size, which may be smaller than the true grain size) and the cooling rate (as well as composition); the larger the effective grain size and the higher the cooling rate, the higher the $T_b$. The depth of the $T_b$ zone depends on both the $T_b$ and the thermal gradient. For these reasons, the depth of the $T_b$ zone in the shear zone during the uplift might have been different from that outside the shear zone. Thrusting of higher temperature hanging wall rocks over the cooler foot wall (and shear heating, if any) must have elevated the local isotherm, and the deformation in the shear zone might have reduced the effective grain size of hornblende and thus decreased its $T_b$. Both of these processes have the effect of elevating the $T_b$ zone. On the other hand, the uplift of the hanging wall rocks along the shear zone must have increased the cooling rate for these rocks and thus increased the $T_b$ of hornblende in them, which has the effect of lowering the $T_b$ zone. The increase in cooling rate may also have reduced the blocking temperature range and thus the width of the $T_b$ zone. It is possible that the combined effect of these competing processes is a slightly elevated $T_b$ zone near the centre of the shear zone, which explains the observation that the $^{40}Ar/^{39}Ar$ ages in the younger zone decrease slightly towards the centre of the shear zone (Fig. 7b, c). Whether this has contributed to the overall age difference between the younger zone and the older zone is difficult to determine. Such an effect, if any, is considered to be secondary. The pressure data presented above clearly shows that the differential uplift is the dominant, if not the only cause for the age pattern. In this context, it should be noted that none of the dated samples are from within 1 km of the centre of the shear zone where deformation-induced grain-size reduction is most evident; the rocks here have a greenschist-facies mineral assemblage and do not contain hornblende.

Before the differential uplift, the upper part of the crust as a whole may have cooled slowly (Percival and Peterman, 1994). As a result, the isotherm and thus the PRZ or the $T_b$ zone may have slowly moved downwards, and the rocks exposed in the transitional zone may not have been located in the PRZ at the same time. Rocks in the upper part of the transitional zone were in the PRZ early (at or soon after ~545 Ma) and would be out of it if the PRZ moved down, and rocks in the lower part of the transitional zone would not be included in the PRZ until very late in the process (at or soon before ~425 Ma; Fig. 8). Therefore, the real thickness of the PRZ at any specific point of time should be thinner than the thickness of the transitional zone (~5 km). At the time when the rocks in the transitional zone were uplifted, the lower limit of the PRZ should have coincided with the lower limit of the transitional zone, but the upper limit should lie somewhere in the transitional zone (Fig. 8). Therefore, the real temperature range in which the radiogenic Ar was only partially retained (i.e. the range of $T_b$) should be smaller than the ~125°C (~450–575°C) documented here. The upper limit should be at ~575°C, but the lower limit should be higher than ~450°C. The precision of the temperature values depends on the precision of the Al-in-hornblende barometer of Johnson and Rutherford (1989) and the validity of the estimates of crustal density and thermal gradient.

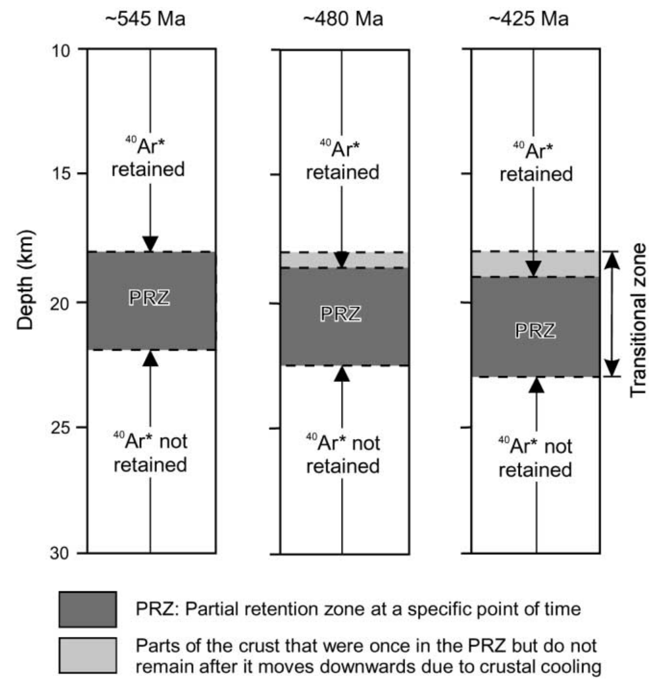


Fig. 8. Schematic diagram showing a possible relationship between the partial retention zone (PRZ) at any specific time and the transitional zone of Fig. 6(b). Because the upper part of the crust as a whole cooled slowly downwards, the isotherm and thus the PRZ moved slowly downwards. The rocks now exposed in the transitional zone include all those that had been in the PRZ before the differential uplift.

The above interpretation means that the $^{40}Ar/^{39}Ar$ age pattern reflects a Neoproterozoic to Silurian cooling profile that was exposed as a result of differential uplift related to the movement along the EHSZ (Fig. 7). A similar

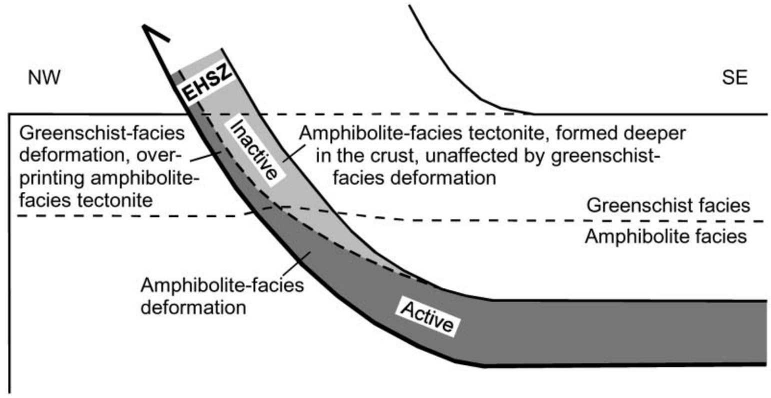


Fig. 9. Schematic diagram explaining the observation at the present level of exposure in the Eastern Highlands shear zone (EHSZ) that an amphibolite-facies deformation zone ~5 km wide is overprinted by a greenschist-facies deformation zone ~1 km wide. See text for discussion.

interpretation has been proposed by Kamp et al. (1989) to explain a similar K–Ar age pattern associated with the Alpine fault in New Zealand (see below), and by Percival and Peterman (1994) to explain Rb–Sr mineral ages associated with a major thrust in the Kapuskasing uplift in the Superior Province of the Canadian Shield.

The above interpretation of the $^{40}Ar/^{39}Ar$ age pattern requires that the EHSZ cut the crust to below the PRZ or the $T_b$ zone (Fig. 7). The pressure data indicate that it cut to a depth of at least ~28 km. If the shear zone flattens at a depth of ~28 km as shown in Fig. 7, the total displacement can potentially be much larger than the total uplift, because the amount of displacement before the exposed rocks were uplifted is unknown.

The above interpretation also implies that rocks exposed in the younger zone started to be uplifted through the $T_b$ zone at ~425 Ma and that movement along the EHSZ stopped some time after ~415 Ma during which the rocks were uplifted from the $T_b$ zone to their 'final' position. The movement along the shear zone may thus have started earlier than ~425 Ma, but before these rocks were uplifted through the $T_b$ zone, their history is not recorded by the hornblende $^{40}Ar/^{39}Ar$ system.

## 6. Relationship between amphibolite- and greenschist-facies deformation

As demonstrated above, the EHSZ is a crustal-scale thrust. It is suggested that deep in the crust, deformation occurred under amphibolite-facies conditions and the shear zone was ~5 km wide, whereas shallower in the crust, deformation occurred under greenschist-facies conditions and was localized into a zone about 1 km wide (Fig. 9). During movement along the shear zone, the amphibolite-facies tectonites that formed deep in the crust were lifted to shallower levels in the crust where they were overprinted by greenschist-facies deformation within the narrow zone, remaining unaffected outside (Fig. 9). This readily explains the observation of Lin (1995) that the narrow greenschist-facies deformation zone overprints the wider amphibolite-facies deformation zone at the present level of exposure (Fig. 3). It is also consistent with the conclusion of Lin (1995) that deformation in the two conditions represents two stages of a single episode of deformation.

## 7. Comparison with the K–Ar age pattern associated with the Alpine fault, New Zealand

As stated earlier, it is common that isotopic ages (e.g. $^{40}Ar/^{39}Ar$ or K–Ar, Rb–Sr and U–Pb fission track ages) decrease towards the centres of shear zones. However, such an age pattern has not been fully understood. The K–Ar age pattern associated with the Alpine fault in the South Island of New Zealand is probably the best established, but its interpretation is still controversial.

K–Ar ages were reported by Mason (1961), Harper and Landis (1967), Sheppard et al. (1975), and Adams and Gabities (1985). The results show a clear decrease in age towards the Alpine fault. From ~170 to ~27 km east of the fault (the older zone), mica and whole-rock ages decrease gradually from ~170 to ~120 Ma. Between ~27 and ~12 km from the fault (the transitional zone), the ages decrease sharply from 120 to 20 Ma. Within a zone ~12 km wide immediately to the southeast of the fault (the younger zone), the mica and whole-rock ages are generally below 20 Ma, with hornblende and feldspar ages being higher due to the effects of excess Ar. This age pattern is best shown by Adams and Gabities (1985) who reported results of the most detailed study, and is very similar to the $^{40}Ar/^{39}Ar$ age pattern associated with the EHSZ. It is interesting to note that movement along both the EHSZ and the Alpine fault are antithetic to subduction, and both shear zones are related to tectonic wedging and are thus retroshears of Willett et al. (1993; compare Fig. 1c with fig. 2 of Waschbusch et al., 1998).

The K–Ar ages of ~170–120 Ma in the older zone away from the Alpine fault have generally been interpreted to be related to a Jurassic to Cretaceous uplift and cooling event. The decrease in ages from ~120 to <20 Ma towards the Alpine fault has been interpreted in two different ways. The first interpretation (e.g. Mason, 1961; Harper and Landis, 1967; Wellman, 1979) is similar to the one proposed in this paper. It attributes the age decrease to a recent differential uplift associated with the movement along the Alpine fault and suggests that rocks exposed in the younger zone did not cool through the Ar blocking temperature until the differential uplift. This interpretation explains the K–Ar ages in the younger zone as cooling/uplift ages. However, it does not address the origin or the significance of the K–Ar ages in the transitional zone. The second interpretation (Sheppard et al., 1975; Scholz et al., 1979; Adams, 1981; Adams and Gabities, 1985) suggests that the most significant uplift in the area occurred at ~170–120 Ma (K–Ar ages in the older zone) and all the rocks had cooled through the Ar blocking temperature during the uplift. The ages in the younger zone are interpreted to result from late Cenozoic complete degassing, and those in the transitional zone to result from partial degassing of the 170–120 Ma ages caused by frictional heating associated with movement along the Alpine fault. The proponents of the second interpretation (e.g. Sheppard et al., 1975; Scholz et al., 1979) suggest that, to explain the ages in the transitional zone, the first interpretation requires the unlikely scenario that interpreted differential uplift was active for ~100 m.y., the age range of the transitional zone. However, Kamp et al. (1989) argue that such a scenario is not necessary. By analogy with an apatite fission track partial annealing zone, they interpret the transitional zone as an exhumed Ar partial retention zone. Because both interpretations predict a transitional zone, it is difficult to determine which of the two interpretations are more realistic based on the age pattern alone. By analogy with the EHSZ where the interpretation is supported by independent evidence for differential uplift, the author prefers the first interpretation for the Alpine fault as explained by Kamp et al. (1989).

## 8. Summary and discussion

The EHSZ is a large-scale shear zone with east-over-west shear. It dips steeply to the southeast near the surface and is interpreted as a ramp in a crustal-scale northwest-vergent thrust that shallows with depth in the crust. Movement along the shear zone resulted in a differential uplift of up to ~28 km.

Hornblende $^{40}Ar/^{39}Ar$ plateau ages decrease towards the centre of the shear zone, from ~565–545 Ma in the older zone (over 7.8 km from the shear zone centre), through a transitional zone, to ~425–415 Ma in the younger zone (within 4.5 km from the centre). The age pattern reflects a Neoproterozoic to Silurian cooling profile that was exposed as a result of the differential uplift. Before the differential uplift, the rocks now exposed in the older zone and the younger zone were buried respectively above and below the hornblende Ar partial retention zone (PRZ) or the $T_b$ zone. The former had cooled quickly through the hornblende Ar blocking temperature ($T_b$) at ~565–545 Ma, soon after the emplacement of the ~565–555 Ma plutons in the area and long before the movement along the shear zone. The latter did not cool through $T_b$ until the shear zone-related differential uplift brought them to above the $T_b$ zone at ~425–415 Ma. The transitional zone is the exposed PRZ.

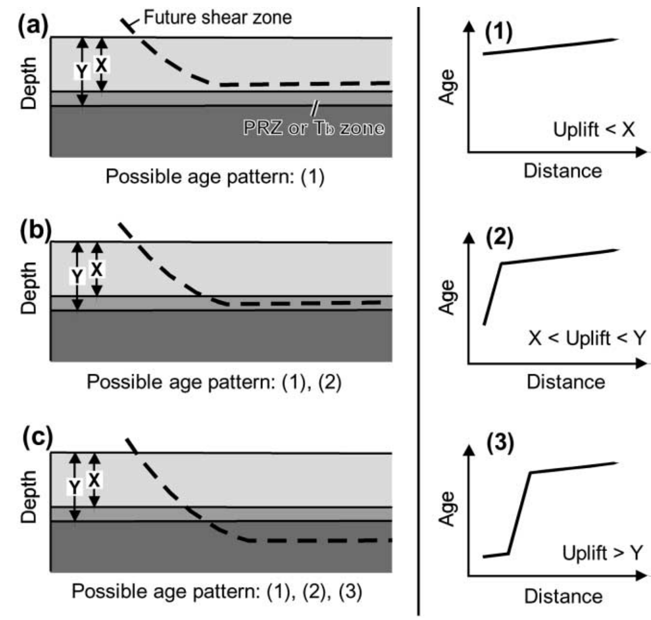


Fig. 10. Schematic diagrams showing possible age patterns (right) for different depths of penetration of shear zones relative to the partial retention zone (PRZ) or the $T_b$ zone (left), the depths of which vary from mineral to mineral. See text for discussion.

The above interpretation means that age patterns associated with shear zones can potentially be used to constrain not only the ages but also the kinematics, amount of resulting uplift, displacements and penetration depths of the shear zones. This is applicable not only to $^{40}Ar/^{39}Ar$ (or K–Ar) ages of hornblende, but also to ages of other minerals with known blocking temperatures (e.g. biotite, muscovite, titanite) and other isotopic dating methods (e.g. Rb–Sr; Percival and Peterman, 1994). Possible age patterns for different penetration depths and displacements of shear zones are schematically shown in Fig. 10. For example, if the younger zone is well defined, as in the case of the EHSZ, the shear zone must have cut down to below the PRZ or the $T_b$ zone of the mineral concerned, and the uplift and displacement along the shear zone must be large enough to bring the rocks up from below the PRZ (Fig. 10c, case 3). In this case, the age of the younger zone is a reliable age of the shear zone. The younger zone can be absent because the shear zone did not cut deep enough (Fig. 10a, b). It can also be absent if the shear zone cuts deep enough but the displacement was not large enough to bring the rocks up from below the PRZ (Fig. 10c, cases 1 and 2). Where the transitional zone is present but the younger zone is absent, either in the case of Fig. 10b or c, the amount of uplift must be just large enough to bring the rocks up from the PRZ, although in the case of Fig. 10(b), the displacement can be much larger. Where the younger zone is absent, the youngest age in the age pattern is only a maximum age of the shear zone, which can potentially be much younger. In any case, the ages, amount of associated uplift and displacements of shear zones can be better constrained by considering age patterns of minerals with different blocking temperatures.

As mentioned above with respect to the Alpine fault, New Zealand, age patterns similar to those discussed above could also result from complete and partial resetting by reheating of rocks that had already cooled through the blocking temperature of the mineral concerned, a process similar to what happens in the thermal aureole of a pluton. $^{40}Ar/^{39}Ar$ or K–Ar ages may also decrease towards the centre of a shear zone due to deformation-induced reduction in effective grain size. Therefore, caution is needed in interpreting such age decreases. Work on the potential differences among age patterns caused by these different processes can be very helpful. For example, Baldwin and Lister (1998) have shown that in the case of reheating the ages in the partial resetting/retention zone can be very irregular. Before more progress is made in this regard, independent evidence, like the pressure data summarized in this paper, should be sought to determine whether the age pattern is due to differential uplift.

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