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# 4. AR/AR DATING OF WHITE MICA CLASTS IN EARLY TO LATE POSTRIFT SEDIMENTS SAMPLED DURING ODP LEG 210 OFF NEWFOUNDLAND[1]

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## ABSTRACT

Fifty-seven white mica clasts were separated from five samples taken from near the bases of turbidites ranging in age from early Albian to middle Eocene. Twenty two (39%) of the micas have ages between 260 and 340 Ma and five (9%) have older ages (~400–600 Ma). The former age range is characteristic of the North American Alleghenian orogeny and the Iberian Variscan orogeny. The latter range is characteristic of the North American Acadian orogeny and older basement rocks in the Grand Banks and Newfoundland areas. Both age ranges are present in the middle Eocene sample, but only the younger range occurs in the middle Albian sample. This difference could be a sampling artifact. If this is not the case, then the most likely explanation is that the Acadian-aged micas within the Meguma Zone underlying the Grand Banks were totally reset by Alleghenian reactivation of the zone, a feature which occurs extensively in Nova Scotia. The addition of Acadian-aged micas in the middle Eocene sample may reflect a change in sediment provenance as drainage systems unrelated to rift topography developed. With the exception of one clast dated at 186 Ma, the 12 other micas obtained from the upper Paleocene sample yielded ages between 55 and 74 Ma, with 7 falling within ±2 m.y. of the 57-Ma age of the sample indicated by the biostratigraphic age-depth plot for Site 1276. This, together with the volcaniclastic content of the sample, indicates an input from near-contemporaneous volcanism. The nearest known occurrences of near-contemporaneous late Paleocene volcanism that could

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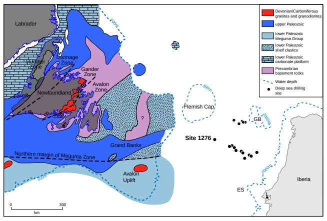
have produced white micas are in Greenland and Portugal, some 2000 and 1500 km distant, respectively, from Site 1276 during the Paleocene. However, ages of volcanism in these areas indicate that they could probably not be sources of micas younger than 60 m.y., which suggests some as-yet unknown volcanic source in the North Atlantic area. Accumulation in the Grand Banks area of airborne-transported volcaniclastic material from eruptions of slightly different ages, followed by a single resedimentation event, could account for the spread of dates obtained from the sample. White micas from the lowermost Albian sample show a spread of ages between 37 and 284 Ma that is completely different from the age distribution pattern of the middle Albian and middle Eocene samples. The sample location is between, and at least 25 m above and below, two igneous sills dated at 98 and 105 Ma. The sills have narrow thermal aureoles and ages older than the youngest detrital micas in the sample. It is unlikely, therefore, that the spread of mica ages in the sample is due to partial resetting of ages caused by thermal effects associated with the intrusion of the sills. The resetting may have been associated with a longer lived thermal event.

## INTRODUCTION

Detrital mineral dating using the $^{40}$Ar/$^{39}$Ar method is an established tool for determining the provenance of clastic sediments and for discriminating source regions of different ages (Sherlock et al., 2000). The objective of this study was to determine the sources of detrital white micas contained in sediments deposited at Site 1276.

Site 1276 is situated east of the Grand Banks and south of Flemish Cap (Fig. F1) at a water depth of 4550 m. Between 800 and 1739 meters below seafloor (mbsf) a succession of lower Oligocene to lowermost Albian mudrocks and interbedded sandstones and siltstones were cored with an overall recovery rate of 85% (Shipboard Scientific Party, 2004). The sediments were deposited from gravity flows (debris flows, low-density turbidity currents, and viscous gravity flows) with some mudstones having a hemipelagic origin.

**F1.** Conjugate margins, p. 11.



## METHODS

During the cruise one or two samples of micaceous siltstone per core were taken from the basal parts of turbidites. Subsequent to the cruise, United Kingdom Ocean Drilling Program funding was obtained to irradiate and analyze white mica clasts from five core samples selected for a preliminary study of the early postrift (Albian) to late postrift (Eocene) succession drilled at Site 1276.

Samples were gently disaggregated and cleaned, after which as many as 18 detrital white mica clasts per sample were hand picked and irradiated. White micas are rare in the Turonian sample, resulting in only three suitable clasts being selected. The clasts were analyzed using the infrared laser probe total fusion method, yielding a single age for each mica (Sherlock, 2001). This age may indicate the time of formation of the mineral grain or a combination of an original age and later thermal overprints that occurred before or after the clast was last deposited.

# RESULTS

The results obtained are presented in Table **T1** and Figure **F2.** The ages of the samples from which white mica clasts were obtained are based on information contained in the Leg 210 *Initial Report* volume for ODP Leg 210, in particular the biostratigraphic age-depth plot (see fig. F33 in Shipboard Scientific Party, 2004).

Fifty-seven detrital white micas were separated from five turbidite samples. Three clusters of ages are apparent in the plot of all the dates obtained (Fig. **F2A**):

1. Four micas (9% of all dates) have ages between 400 and 430 Ma. This cluster is produced solely by dates obtained from the middle Eocene sample (Fig. **F2B**).
2. Twenty-six micas (46% of all dates) have ages between 250 and 340 Ma. This range dominates the ages obtained from the middle Eocene and middle Albian samples (Fig. **F2B, F2E**).
3. Fourteen micas (25% of all dates) have ages between 50 and 90 Ma. All but three of the dates in this cluster are from the upper Paleocene sample (Fig. **F2C**), in which only one date is older than 74 Ma (Table **T1**).

The lower Albian sample shows no clustering of ages (Fig. **F2F**).

The possible significance of these results is discussed below, commencing with Clusters 1 and 2 and a review of the geology of the pre-Mesozoic basement of the Grand Banks, Newfoundland, and Iberia.

# CLUSTERS 1 (400–430 MA) AND 2 (250–340 MA)

## Possible Sources of White Micas

The age ranges of these clusters are broadly typical of the ages of pre-Mesozoic basement rocks that occur beneath the conjugate margins of eastern Canada and Iberia (Fig. **F1**). The history of the pre-Mesozoic basement of these margins is reviewed briefly below, commencing with the onshore areas.

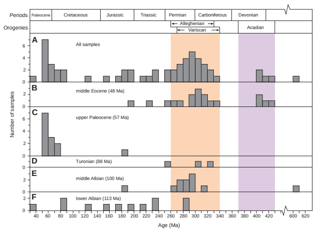
Onshore in Newfoundland the tectonic zones shown on Figure **F1** are terranes accreted onto the Canadian margin of the early Paleozoic Iapetus Ocean. They were deformed by the Acadian (370–430 Ma) and earlier orogenic events, so they are possible source areas for the white micas in Cluster 1.

In eastern Newfoundland, Devonian–Carboniferous granites occur along the boundary between the Avalon and Gander tectonic zones (Fig. **F1**). These granites generally range in age from 320 to 400 Ma (Mandeville, 1989) and are situated some 900 km west-northwest of Site 1276. They could be possible sources for the micas aged between 320 and 340 Ma in Cluster 2.

The Iberian margin was strongly affected by the Variscan orogeny. The mica-rich metamorphic rocks and associated granites of this orogeny were formed largely between 270 and 340 Ma (Capdevila and Mougenot, 1988; Pinheiro et al., 1996) and so could be possible sources of all but the very youngest micas in Cluster 2, especially because Galicia Bank, located only ~200 km east-northeast of Site 1276 prior to ocean

**T1.** Ages of white mica clasts, p. 13.

**F2.** Ages of white mica clasts, p. 12.



opening, is known to be underlain by Variscan basement (Capdevila and Mougenot, 1988).

Offshore, the pre-Mesozoic basement subcrop beneath the Grand Banks (Fig. **F1**) was described by Bell and Howie (1990). The Meguma Group (metamorphosed early Paleozoic sediments) occurs in the southeastern part of the Grand Banks (the Avalon Uplift). It is intruded by at least one late Middle Devonian granite (376 ±17 Ma). To the north, early Paleozoic shelf clastics dominate, and some late Paleozoic sediments (possibly containing some volcanic rocks) and possibly Precambrian metamorphic rocks are present.

The Meguma Group or Zone forms the most outboard terrane of the Appalachian orogen (Culshaw and Liesa, 1997) and is exposed in much of southwestern Nova Scotia some 1000 km west-southwest of the southeast Grand Banks. In Nova Scotia the Meguma Zone was deformed and metamorphosed between 375 and 415 Ma during the Acadian orogeny and later intruded by granitic batholiths dated at ~370 Ma (Culshaw and Liesa, 1997). If the Meguma Zone beneath the southeast Grand Banks is similar to its lateral equivalent in Nova Scotia, then it could be a possible additional source for the Acadian-aged micas in Cluster 1.

The Meguma Zone in Nova Scotia was reactivated during the Alleghenian orogeny. Resetting of mica ages there was caused by magmatic events (Dallmeyer and Keppie 1987; White, 2002) or movement and/or mineralization along shear zones (Culshaw and Reynolds, 1997; Culshaw and Liesa, 1997; Pe-Piper, 2004). If similar reactivation of the Meguma Zone occurred in the Grand Banks area, then it is a possible source for the micas in Cluster 2.

In summary, Cluster 1 micas (400–430 Ma) could have been sourced from the Meguma Zone or the terranes exposed today in Newfoundland, and those in Cluster 2 (250–340 Ma) could have originated from an Alleghenian-reactivated Meguma Zone or from Variscan basement in Iberia. The next section examines other evidence that helps constrain the likely sources.

## Discussion

**Hiscott** (this volume) deduced, using current-ripple foreset dips and sand-grain fabric determinations, that Cretaceous turbidity currents transported sediment to Site 1276 from the west-southwest. He concluded from this result that the Avalon Uplift (situated in the southeast part of the Grand Banks; Fig. **F1**) was the likely source of the sediments. This conclusion is supported by petrographic studies undertaken on Site 1276 sandstones by **Marsaglia et al.** (this volume).

The distribution of white mica ages in the middle Albian sample from Site 1276 is consistent with **Hiscott's** (this volume) conclusion that the Avalon Uplift was the source of Cretaceous sediments if a Meguma source was reset during the Alleghenian orogeny. There are no Acadian-aged clasts present, although there is one much older clast (608 Ma). The absence of Acadian ages might be due to the smaller number of clasts analyzed (only 11, compared to 18 from the middle Eocene sample). If this is not the case, then the absence could be due to Alleghenian reactivation of the Meguma Zone beneath the southeast Grand Banks that totally reset the mica ages. This seems unlikely to have occurred everywhere because the granite drilled in this area yielded an Acadian age of 376 Ma (Bell and Howie, 1990). Another possibility is that the Site 1276 sediments were sourced from early Paleozoic shelf clastics (Fig. F1); however, these clastics probably contain Acadian-aged micas. Finally, the absence of Acadian ages might also be explained if the sediments were supplied directly from Variscan rocks in the adjacent Iberian margin to the east. This is very unlikely for three reasons:

1. The paleoflow direction reported by Hiscott (this volume) is from the south-southwest. In addition, the dip direction of Albian seismic reflectors is to the east. As this dip direction is unlikely to have changed since deposition of Albian sediments, it indicates progradation of a slope system oceanward from the Grand Banks.
2. The presence of a mid-ocean ridge between Iberia and Site 1276 during the Albian would have been a barrier to westward sediment transport.
3. Marsaglia et al. (this volume) rule out an Iberian source for the Site 1276 sandstones because, unlike their time equivalents drilled at ODP sites off the Iberian margin, they have a low K-feldspar content.

The possibility cannot be ruled out that Variscan clasts originally derived from Iberia during the late Carboniferous, Permian, or early Mesozoic were deposited in prerift sandstones in the Grand Banks area and then recycled. This could account for the low feldspar content noted by Marsaglia et al. (this volume), if most feldspars were altered during recycling, as well as the absence of Acadian-aged white micas in the middle Albian sample. The single mica clast dated at 608 Ma from this sample could have been derived from the Newfoundland area.

Unlike the middle Albian sample, the middle Eocene sample contains clusters of ages representative of both the Alleghenian and Acadian orogenies (Fig. F2B). These could have been derived from the Meguma Zone in the vicinity of the Avalon Uplift, providing that Alleghenian reactivation had not totally reset Acadian-age micas in the source area being eroded at that time. If complete resetting had occurred, then the Acadian-age micas could have been sourced from the region that is today Newfoundland.

The absence of Acadian-aged clasts in the middle Albian sample and their appearance in the middle Eocene sample are broadly comparable to changes in the ages of clasts in Mesozoic early to late postrift sediments drilled off Nova Scotia and described by Grist et al. (1992). They suggested that the early postrift deposits were derived from local sources inferred to be rift-related highs, whereas younger postrift sediments containing older clasts were derived from the interior of eastern Canada as drainage systems developed that were unrelated to rift topography. A similar interpretation may be applicable to the Site 1276 data.

## CLUSTER 3 (50–90 MA)

As stated earlier, all but three of the dates in this cluster are from the upper Paleocene sample (Fig. F2C), in which there is only one date older than 74 Ma (Table T1). Seven of the thirteen dates obtained from the upper Paleocene sample fall within ±2 m.y. of the 57-Ma age of the sample indicated by the biostratigraphic age-depth plot for Site 1276 (see fig. F33 in Shipboard Scientific Party, 2004). As reported by Marsaglia et al. (this volume), shipboard petrographic observations found felsic and mafic epiclastic volcanic debris in this interval, so it seems likely that the mica clasts with ages of 74 Ma and younger are volcanic in origin.

The nearest known occurrences of near-contemporaneous late Paleocene volcanism that could have produced white micas are in Greenland and Portugal. Larsen and Saunders (1998) reported a very brief bimodal volcanic episode with dacitic and basaltic end-members at Site 917 off southeast Greenland. This episode dates to 60–61 Ma, when the site was some 2000 km north of Site 1276 (Ziegler, 1989). This volcanic episode preceded the 56- to 53-Ma intrusion of thick basaltic lavas at Site 917. Storey et al. (2007) report a $^{40}$Ar/$^{39}$Ar age of 55 Ma from sanidines obtained in Danish Ash 17 from DSDP Site 550 some 300 km southwest of Ireland. This ash is widespread in the North Atlantic and North Sea. Storey et al. (2007) correlate this pyroclastic deposit with a similar sanidine-bearing tuff that occurs near the top of the East Greenland lava series, which is believed to have originated from a melanephelite-carbonatite volcanic complex on the East Greenland margin.

Pinheiro et al. (1996) reviewed the occurrence of alkaline volcanism dated between 60 and 80 Ma onshore and offshore Portugal (Estremadura Spur [Fig. F1] and Gorringe Bank, ~300 km southeast of Lisbon). These locations were situated ~1500 km east of Site 1276 during the Paleocene (Ziegler, 1989). This volcanism could have been the source of volcaniclastic material reported by **Marsaglia et al.** (this volume) from ODP sites off Iberia. Of the Portuguese occurrences, the three onshore subvolcanic massifs that dated to between 70 and 80 Ma (Sintra, ~20 km west of Lisbon; Sines, ~70 km south-southeast of Lisbon; Monchique, ~150 km south-southeast of Lisbon) are the most likely to have erupted white micas.

In light of the above information, it is possible that the micas older than 60 Ma in the upper Paleocene sample could have been sourced from Portugal and/or possibly Greenland. Subaqueous transport from Greenland or Portugal seems most unlikely given the distances involved and likely seafloor topographic barriers. It is more likely, therefore, that airborne transport to the Grand Banks area was involved. Accumulation in the Grand Banks area of volcaniclastic material from eruptions of slightly different ages, followed by downslope resedimentation, could account for the spread of dates obtained from the sample. Because Paleocene sedimentation rates were low at Site 1276 (~4.3 m/m.y.; see fig. F27 in Shipboard Scientific Party, 2004), this resedimentation is likely to have occurred in a single subaqueous gravity flow.

Given the ages of 55 Ma reported by Storey et al. (2007) from sanidine-bearing ash layers correlated with the final phase of basalt eruption in East Greenland, it seems likely that the micas dated between 55 and 58 Ma were sourced from Greenland although other as-yet unknown volcanic centers in the North Atlantic area cannot be ruled out.

## MIXED AGES (LOWER ALBIAN SAMPLE)

The interval from which this sample was obtained is situated between two alkaline diabase sills: 25 m below an upper, 10-m-thick sill and 71 m above a lower sill, 18 m of which was drilled before Hole 1276A was abandoned. Hart and Blusztajn (2006) reported $^{40}$Ar/$^{39}$Ar plateau ages of 97.8 Ma for the upper sill and 105.3 Ma for the lower sill. These ages are ~14 and ~7 m.y. younger than the age of our lower Albian sample, as determined from the biostratigraphic age-depth plot for Site 1276 (see fig. F33 in Shipboard Scientific Party, 2004).

Clasts analyzed from the lower Albian sample show a spread of ages between 37 and 284 Ma. This age distribution pattern is completely different from those observed in the middle Albian and middle Eocene samples. Intuitively it would be reasonable to interpret this spread to have resulted from thermal overprinting and partial resetting of ages by the intrusion of the diabase sills. For example, Thomas Pletsch (pers. comm., 2006) reports that Rock-Eval $T_{max}$ and vitrinite reflectance data obtained from a sample 2 m above our sample indicates temperatures between 95° and 120°C. He believes that such temperatures would have been sufficient to partially reset the ages of white micas, and he observes a significant and abrupt change from abundant ordered smectite to poorly ordered (R0) illite-smectite layers 90 m above the upper sill that could be a thermal effect. However, thermal aureoles around the sills as defined by vitrinite reflectance data are very narrow; the aureole is 1–2 m around the upper sill and ~10 m above the lower sill (T. Pletsch, pers. comm., 2006), and Pross at al. (2007) report a 4-m aureole above the upper sill. It may be unlikely, therefore, that short-lived, sill-related thermal events would have significantly reset mica ages farther away from the sills. T. Pletsch (pers. comm., 2006) postulates that a much longer-lived thermal event may account for changes in clay mineralogy and the resetting of mica ages.

## CONCLUSIONS

We conclude that the Meguma Zone beneath the southeastern Grand Banks is the most likely source of the white mica clasts dated between 250 and 340 Ma in our middle Albian and middle Eocene samples. This conclusion is based on paleocurrent data (**Hiscott,** this volume) and the assumption that the Meguma Zone beneath the Grand Banks experienced a tectonic history similar to that part of the zone exposed today in southwest Nova Scotia. The Meguma Zone in the latter region was deformed and metamorphosed between 375 and 415 Ma during the Acadian orogeny and later reactivated during the Alleghenian orogeny. The latter orogeny reset mica ages in some areas of Nova Scotia to between 260 and 350 Ma. The absence of Acadian-aged clasts in the Cretaceous to Middle Paleocene samples could be a sampling artifact or it could indicate that the entire Meguma Zone in the Grand Banks area was reactivated during the Alleghenian orogeny. If this occurred, then the presence of Acadian-aged clasts only in the middle Eocene sample could reflect a change in sediment transport pathways. The early postrift deposits (e.g., the lower Albian sample) could have been derived from local sources related to remaining rift-related topography, whereas later postrift sediments that contain older Acadian-aged clasts could have been derived from the interior of eastern Canada as drainage systems unrelated to rift topography developed. We cannot rule out the possibility of an Iberian provenance for some mica clasts aged between 270 and 340 Ma. They could have been transported westward and deposited in the Grand Banks area during the late Carboniferous, Permian, or early Mesozoic and later recycled into the sediments drilled at Site 1276.

The Paleocene sample contains abundant volcaniclastic material. Seven out of the thirteen dates fall within ±2 m.y. of the 57-Ma biostratigraphic age of the sample determined at Site 1276, which indicates a near-contemporaneous volcanic source. The nearest known occurrences of near-contemporaneous late Paleocene volcanism that could have produced ~60-Ma white micas are in Greenland and Portugal, some 2000 and 1500 km distant, respectively, from Site 1276 during the Paleocene. The dating of an extensive sanidine-bearing ash layer in the North Atlantic suggest that the younger (55–58 Ma) micas at Site 1276 were probably sourced from an alkaline volcanic center on the East Greenland margin. Accumulation in the Grand Banks area of volcaniclastic material from eruptions of slightly different ages, followed by a single resedimentation event, could account for the spread of dates obtained from the sample.

White micas from the lower Albian sample show a wide spread of ages between 37 and 284 Ma that is completely different from the age distribution patterns in the younger samples. Because the sample location is between two igneous sills dated at 98 and 105 Ma, partial resetting of mica ages due to heating is a possible explanation for these results. However, thermal aureoles around the sills are narrow, and some micas have ages younger than the sills. Based on changes in clay mineralogy observed beginning 90 m above the upper sill, T. Pletsch (pers. comm., 2006) suggests that a longer lived thermal anomaly may have affected the sediments.

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**Figure F1.** Reconstruction of the conjugate margins of eastern Canada and Iberia to early Aptian time showing the location of ODP Site 1276. Features of pre-Mesozoic basement on the Canadian margin are shown (offshore geology from Bell and Howie, 1990; onshore geology from Colman-Sadd et al., 1990). Variscan basement (270–340 Ma) underlies onshore Iberia and extends offshore beneath Galicia Bank (GB) and out to the two most inboard deep sea drilling sites. All but one of the deep-sea drilling sites shown are ODP sites (the northern cluster completed during Leg 103 and the southern cluster during Legs 149 and 173; the most eastern site is DSDP Site 398). ES = Estremadura Spur, L = Lisbon.

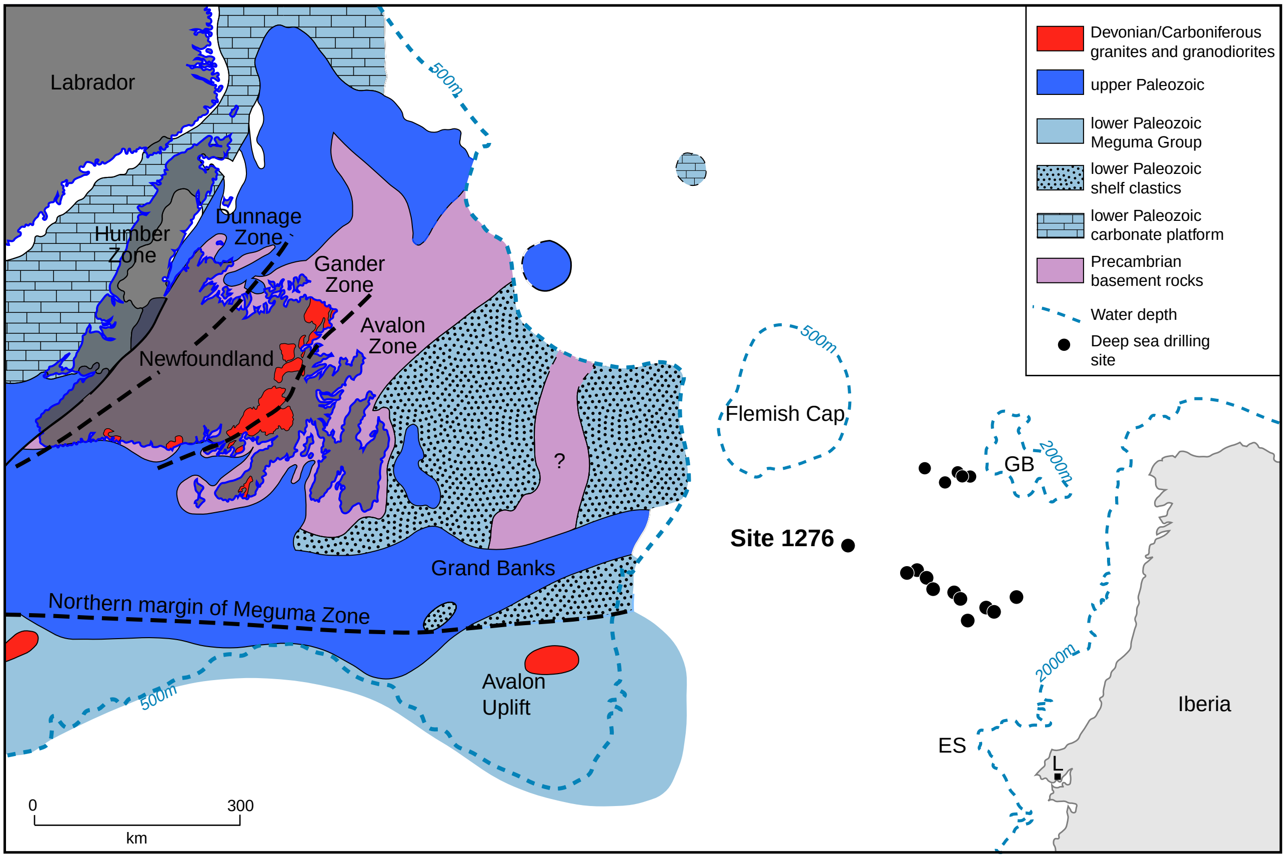

**Figure F2. A–F.** Histograms of white mica clast ages reported in this paper. Age ranges of the North American Alleghenian and Acadian orogenies are taken from fig. 6 in Roden-Tice and Wintsch (2002) and those for the Iberian Variscan orogeny are from Capdevila and Mougenot (1988) and Pinheiro et al. (1996). Geologic timescale is from Gradstein et al. (2004).

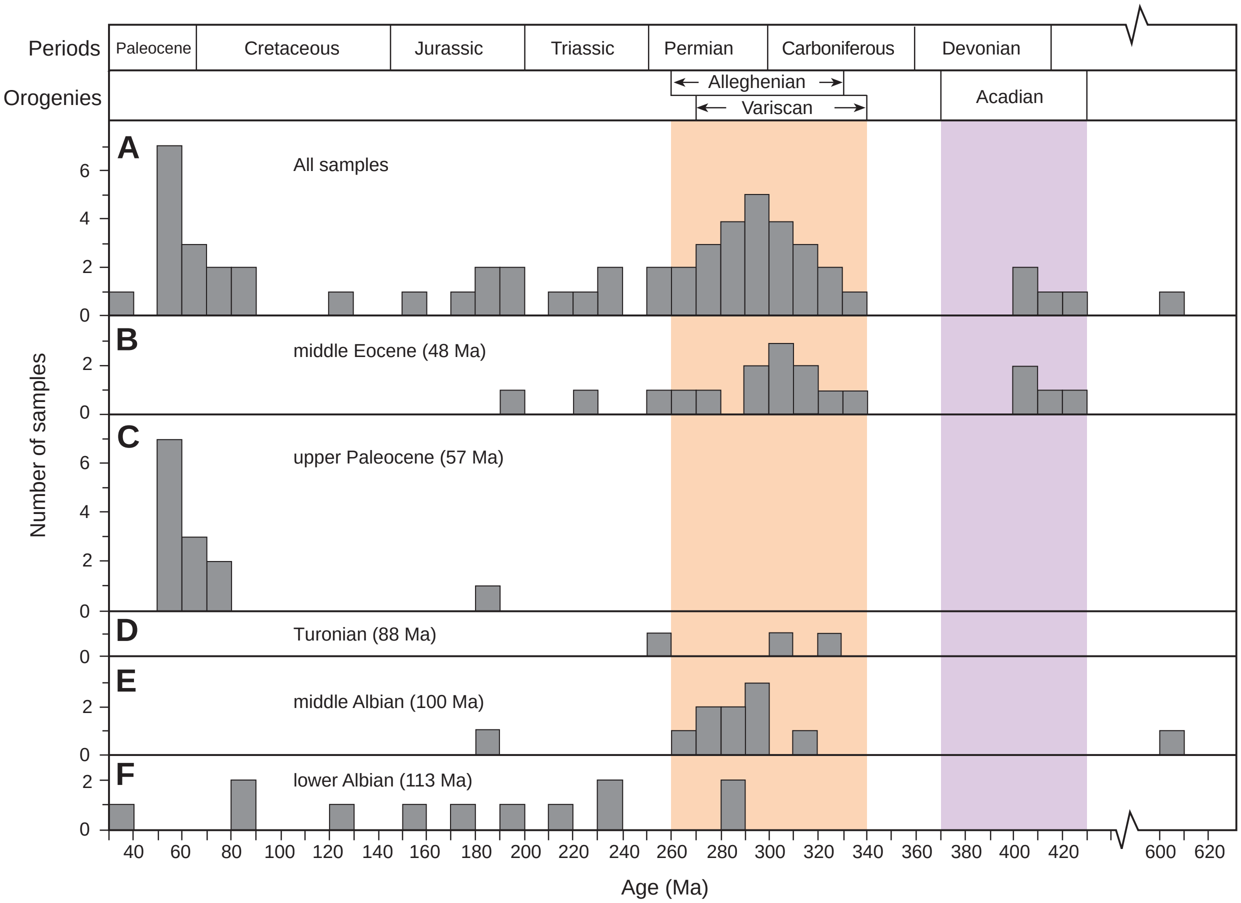

**Table T1.** Ages of white mica clasts in core samples, Hole 1276A.

| Core, section, interval (cm) | Depth (mbsf) | Age of sample | | Age of clast | |
|---|---|---|---|---|---|
| | | From biostratigraphy | From age-depth plot (Ma) | Ma | ± |
| 210-1276A- | | | | | |
| 9R-2, 67–71 | 869.4 | middle Eocene | 48 | 193 | 10 |
| | | | | 225 | 7 |
| | | | | 253 | 3 |
| | | | | 267 | 3 |
| | | | | 274 | 3 |
| | | | | 297 | 3 |
| | | | | 298 | 3 |
| | | | | 300 | 4 |
| | | | | 302 | 4 |
| | | | | 308 | 18 |
| | | | | 311 | 9 |
| | | | | 312 | 5 |
| | | | | 325 | 2 |
| | | | | 337 | 7 |
| | | | | 402 | 17 |
| | | | | 409 | 25 |
| | | | | 412 | 18 |
| | | | | 428 | 5 |
| 15R-3, 108–110 | 929.1 | upper Paleocene | 57 | 55 | 1 |
| | | | | 56 | 1 |
| | | | | 56 | 1 |
| | | | | 57 | 3 |
| | | | | 57 | 1 |
| | | | | 58 | 0 |
| | | | | 58 | 2 |
| | | | | 61 | 1 |
| | | | | 65 | 1 |
| | | | | 68 | 1 |
| | | | | 72 | 3 |
| | | | | 74 | 2 |
| | | | | 186 | 4 |
| 31R-5, 6–9 | 1085 | Turonian | 88 | 259 | 10 |
| | | | | 308 | 14 |
| | | | | 323 | 13 |
| 56R-3, 52–54 | 1322.3 | middle Albian | 100 | 182 | 3 |
| | | | | 262 | 5 |
| | | | | 278 | 10 |
| | | | | 279 | 6 |
| | | | | 284 | 8 |
| | | | | 286 | 5 |
| | | | | 290 | 5 |
| | | | | 293 | 3 |
| | | | | 295 | 6 |
| | | | | 314 | 19 |
| | | | | 608 | 11 |
| 91R-4, 100–103 | 1648.3 | lower Albian | 113 | 37 | 18 |
| | | | | 85 | 22 |
| | | | | 89 | 6 |
| | | | | 128 | 9 |
| | | | | 157 | 8 |
| | | | | 174 | 14 |
| | | | | 192 | 8 |
| | | | | 216 | 13 |
| | | | | 233 | 4 |
| | | | | 235 | 5 |
| | | | | 284 | 5 |
| | | | | 284 | 6 |