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Acadian Orogeny: An Abrupt and Brief Event

Abstract. *Rubidium-strontium dating indicates the Barre-type granites in eastern Vermont were emplaced at least 380 × 10⁶ years ago. This result suggests the Acadian orogeny was more abrupt than previously suspected, and is consistent with the hypothesis that the orogeny involves a collision between two sialic plates.*

The Devonian Acadian orogeny has long been recognized as encompassing the most intense period of deformation, regional metamorphism, and granite intrusion affecting the northern Appalachian Mountains. Throughout much of the region the relative sequence of events was as follows: (i) deposition of geosynclinal sediments as young as Early Devonian, (ii) deformation and regional metamorphism, and (iii) emplacement of granitic plutons. Many radiometric ages have been measured on the metamorphic rocks and the granites, but the values show a wide spread indicating some combination of slow cooling and younger thermal disturbances. This report presents a refinement of the measurement of the age of a series of granites in eastern Vermont, which results in a minimum age older than previously suspected. In conjunction with other data this result indicates that the Acadian orogeny was a very abrupt event. The data permit a span of not more than 30×10^6 years for a sequence of orogenic events which included the formation of large-scale nappes and the burial of rocks initially at the surface to a depth of 12 to 15 km prior to the emplacement of the granites.

A series of some 20 discordant granite plutons ranging from 0.5 to 10 km in diameter crop out in a 200-km belt along the eastern border of Vermont (*1*). The well-known monument stone quarried at Barre, Vermont, is typical of the granites, hence the application of the term, Barre-type granites, to the series. Medium-grained, equigranular, slightly foliated quartz-monzonite is the dominant and characteristic rock type, although some of the plutons contain minor amounts of rocks ranging from ultramafic and mafic to granitic in the strict sense. Primary muscovite coexisting with biotite and abundant quartz are characteristic of the granitic rocks. As will be demonstrated later, these granites were intruded late in the sequence of Acadian events, hence, dating the granites should give a reliable minimum age for the major Acadian events.

A K/Ar age of 349×10^6 years was previously reported for the Adamant granite northwest of Barre (*2*). This is recognized as a minimum age inasmuch as the same authors demonstrated that the region has been affected by later disturbances. Attempts to refine this age measurement have been frustrating. Within each pluton the granitic rocks are too homogeneous in their Rb and Sr content to yield whole-rock isochrons with adequately defined slopes, and the Rb/Sr ratios are too low to yield reliable "single-point" ages. There is no basis for assuming that the separate plutons are comagmatic or even that they formed at the same time, so there are no grounds for constructing an isochron for the series as a whole. Samples weighing 50 kg have yielded only a few milligrams of very fine-grained zircon, hence dating by this technique has not been attempted.

An attempt to see through these later disturbances has been made by studying the systematics of the mineral ages. Consistent with previous experience, coarse muscovite seems to retain most successfully its accumulated radiogenic strontium (Table 1). Coarse muscovite from the northernmost pluton yields an Rb/Sr age of 380×10^6 years, and samples of coarse muscovite handpicked from the southernmost pluton yield apparent ages of 383×10^6 and 377×10^6 years (*3*). These are regarded as reliable minimum ages for the plutons.

The biotite ages decrease systematically from north to south, which suggests a southward increase in the intensity of subsequent disturbance. Fine-grained muscovite fractions from the granites are also disturbed. Two of the granites yielded only the fine-grained muscovite, with apparent ages very close to those of the biotites. At first glance these might appear to be concordant-mica ages indicating these two plutons are younger than the others. Data on plagioclase and microcline, however, demonstrate that these rocks have also been disturbed. The apparent concordance is not significant.

The granites intrude country rock which was already intensely deformed and regionally metamorphosed. Large recumbent folds are indicated by the complex map pattern of the Standing Pond Amphibolite marker horizon (*4, 5*). Rotated garnet porphyroblasts and the orientation of other porphyroblasts in planes parallel to the axial surfaces of the recumbent folds indicate that medium- to relatively high-temperature regional metamorphism accompanied this phase of the deformation (*6*). In most of eastern Vermont this metamorphism was of biotite to garnet grade, but there are several areas where the intensity reached kyanite-staurolite grade.

The contact aureoles (sillimanite- or andalusite-grade) surrounding the granite bodies are superposed on this earlier regional metamorphism, the pattern of whose isograds shows little correlation with the distribution of the granites. The granite bodies are only weakly foliated. They are sharply discordant and, although slightly elongated parallel to the regional trend, are much less deformed than the country rock. Locally (for example, around the Black Mountain granite at the southern end of the belt) the country rock adjacent to the granite is invaded by thin aplite dikes and sills which clearly postdate most of the deformation. The main phase of Acadian deformation is therefore older than the measured age of the granite bodies.

A maximum age for the Acadian deformation is given by the age of the youngest strata affected. In general the youngest strata are as intensely deformed and metamorphosed as older units. In other words, there is no indication that the onset of deformation was a gradual process significantly overlapping in time with the deposition of the sediments. Of the units affected, the Waits River Formation may span the Silurian-Devonian boundary (*7*) or may be wholly of Early Devonian age (*5*). Most workers in the area believe that the Gile Mountain Formation is somewhat younger and thus wholly of Devonian age. The uppermost part of the Gile Mountain Formation may be equivalent to the Mountainhouse Wharf Limestone of earliest Middle Devonian age (*8*). On the same time scale as used for the dating of the granites the Silurian-Devonian boundary is about 410×10^6 years. Some of the metasedimentary rocks are considerably younger.

Table 1. Rubidium-strontium data for granites. The Sr data are normalized to $^{86}Sr/^{88}Sr = 0.1194$; $\lambda = 1.39 \times 10^{-11}$ year^{-1}. Mineral ages are calculated from slope of line through whole-rock datum. Sample locations: Derby Pluton VND-2, Willey Quarry (44°57.86′N; 72°8.82′W); Echo Pond Pluton VEP-1 (44°54.5′N; 72°00′W); Barre Pluton VBA-1, Rock of Ages Quarry (44°9.59′N; 72°28.58′W); Black Mountain Pluton DGQ-1, Dummerston Quarry (42°55.51′N; 72°36.66′W).

Sample	^{86}Sr ($\times$ 10^{-9} mole/g)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age (10^6 yr)
		Derby Pluton VND-2		
Coarse muscovite	17.7	126.2	1.381	380
Biotite	31.8	109.7	1.267	363
Whole rock I	228	2.50	0.725	
Whole rock II	228	2.47	0.726	
		Echo Pond Pluton VEP-1		
Fine muscovite	63.6	21.97	0.816	357
Biotite	19.6	116.5	1.281	354
Whole rock	449	0.83	0.711	
		Barre Pluton VBA-1		
Fine muscovite	187	7.09	0.741	344
Biotite	37.0	61.21	0.998	340
Whole rock	630	0.828	0.711	
		Black Mountain Pluton DGQ-1		
Coarse muscovite I	17.6	93.4	1.203	383
Coarse muscovite II	18.3	91.3	1.185	377
Fine muscovite	56.5	30.8	0.851	337
Biotite	11.3	280.0	1.941	316
Whole rock	197	2.96	0.720	

These limits leave a maximum span of 30×10^6 years for the recumbent folding and regional metamorphism and also for the burial of rocks at the sediment-water interface in Early Devonian time to depths sufficient for the formation of the kyanite-staurolite assemblage. The actual span was probably considerably shorter. At least in some areas pressure probably exceeded that of the kyanite-sillimanite-andalusite triple-point. Andalusite is absent in the aureoles of most of the plutons intruded into kyanite-bearing rocks, which indicates a direct transition to sillimanite with increasing temperature. The high degree of plastic deformation in the rocks suggests that they were incapable of supporting significant tectonic overpressures, hence the pressure must be due to burial. This indicates rapid burial of the rocks to depths exceeding 12 km if the triple-point is associated with pressures exceeding 4 kb. From the late Precambrian through Early Devonian (about 200×10^6 years) a maximum of 20 km of strata accumulated in the geosyncline, corresponding to a mean sedimentation rate of 10^{-7} km/year. It seems very unlikely that an additional 12 km could have been deposited in the next 30×10^6 years; hence, the rapid burial must be tectonic and is probably the result of a piling up of nappes, the lower members of which are still preserved.

Similar time constraints are indicated in central Massachusetts where granites of the Prescott Complex south of Athol cut through the root-zone of the Skitchewaug Nappe (*9*). A preliminary Rb/Sr whole-rock isochron indicates an age of 385×10^6 years for the Prescott granite (*10*).

The Acadian orogeny has been recognized as an abrupt and brief event in northern Maine where deformation and low-grade metamorphism of Lower Devonian strata was completed prior to deposition of the upper Middle Devonian Mapleton Formation (*11*). The new data extend this inference to the highly metamorphosed and deformed terrane of southeastern New England. The term Acadian apparently characterizes a sequence of events of deformation, plutonism, metamorphism, and uplift which occurred over a large area in approximate synchronization. This may be contrasted with earlier periods in the history of the geosyncline in which a probable continuum of orogenic activity has been rather arbitrarily subdivided into named orogenic events (such as Penobscot, Taconic, Salinic).

The data are consistent with a hypothesis that the Acadian orogeny involves the closing of a former ocean basin in which the geosynclinal strata had accumulated (*12*). In southern New England there could have been near collision of the sialic plates bounding the former basin. The early Acadian period of recumbent folding and the abrupt increase in cover thickness noted above could have been caused by westward sliding of part of the sediments piled up between these two blocks. Heat from magmas emplaced during the sliding (tabular plutons such as the Bethlehem and Kinsman bodies) and the blanketing effect of the thickening cover resulted in prograde regional metamorphism. The deep-seated Barre-type granites were emplaced after cessation of the sliding. Erosion, which eventually removed as much as 10 to 15 km of cover from this region, probably began immediately. Further north the closure was not so complete, the blocks having stopped as much as 250 km short of each other. The sediments in between are strongly crumpled, but the folds are upright. There was minimum uplift or piling up, and probably less than 5 km of cover have been stripped from this northern region since Devonian time. The plate-tectonic hypothesis is only one of many which have been proposed to explain the history of the geosyncline. Although its proof remains for the future, the collision hypothesis is attractive in its suitability in explaining the abruptness of the Acadian orogeny.

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Land Clearance in the Irish Neolithic: New Evidence and Interpretation

Abstract. *Time scales are derived, from radiocarbon dating of pollen diagrams, for Neolithic land clearance at three Irish sites. Three stages are distinguished beginning in the 4th millennium B.C.: stage A, clearance and farming (possibly arable), 100 to 400 years; stage B, farming (possibly pastoral), 150 to 200 years; and stage C, forest regeneration, 50 to 100 years.*

Three radiocarbon-dated pollen diagrams from the north of Ireland are shown in Fig. 1. The sites studied were as follows: site I, Ballynagilly (*1*), and site II, Beaghmore (*2*), in County Tyrone; and site III, Ballyscullion, in County Antrim. The elevations of the sites above sea level are 640, 650, and 60 feet (195, 198, and 18 m). At sites I and II excavation has revealed evidence of Neolithic occupation adjacent to the deposits sampled: both sites are valley bogs. Site III, however, is a raised bog: it lies within a few miles of the diatomite flats of the Lower Bann Valley, intensively occupied in Neolithic and other periods (*3*). Radiocarbon dates for these sites, and for five others (*4, 5*) in Ireland, show that the beginning of the land-clearance phase, or the decline of elm pollen that usually accompanies it, falls between 5400 and 5000 radiocarbon years before the present, as in northwestern Europe in general.

The land-clearance phase at each site has been divided into three stages as follows: Stage A begins with a fall of forest tree pollen, usually elm and pine, or total tree pollen (as at site III), and is characterized by increased amounts of grass pollen and occasional plantain pollen. The overall amounts of grass pollen at site III are very low, but when the whole pollen diagram is inspected, rather than the section presented in Fig. 1, a definite increase is seen at the beginning of stage A. Stage A ends with a marked increase of plantain pollen. At sites I and II cereal-type pollen is present. Stage B begins with a marked increase of plantain pollen, which at sites I and III is accompanied by an increase of hazel pollen and a further decrease in the amount of elm pollen. Stage B ends when there is a relative increase of forest-tree pollen. This is taken as the beginning of stage C, which ends when the increase in the amount of tree pollen is complete.

The radiocarbon dates (*5, 6*) are plotted in Fig. 1 as Gaussian curves (truncated at three standard deviations) (*7*) against the same depth scale used for the pollen diagrams. The curves give a visual indication of the probability distribution of the date measurements. Deposition rates shown by these graphs are: ~40 (±10) year/cm at site I, ~35 (±15) year/cm at site II, and ~15 (±3) year/cm at site III. The precisions given are estimates only, derived by inspection. On the basis of these figures, the land-clearance phases appear to have lasted some 400 to 700 years.

A summary of the approximate age and duration of the three stages at each of the sites is given in Fig. 2. There are inherent difficulties in establishing an exact deposition rate and in dating the boundaries between the stages, because of the limited precision of the ^{14}C dates and the de Vries effect (*8*). The boundaries must not, therefore, be taken as fixed points in time. The time scale in Fig. 2 is in radiocarbon years: 1950 years have been subtracted for approximate conversion to the Christian calendar. In true calendar years, the beginnings of the land-clearance phases are likely to have occurred some 600 to 800 years before the time scale indicates (*9*). Although we show (in Fig. 2) stage A starting at different times for the three sites, the dates are derived only from the deposition rate curves and, within the limits of the method, could be contemporaneous. Unless there have been short-term fluctuations in the deposition rates, the durations shown for the stages are likely to be more precise than the dates for the individual stage boundaries.

Stage A apparently lasted 100 to 400 years. At site II cereal-sized grass pollen is present in nearly all samples. At site I also this stage has some cereal pollen. Plantain pollen is present, although sparse, at all three sites. On the basis of the presence of these cultural indicators, it seems that stage A was a farming period and that cereals were being grown. No cereal pollen was found at site III but, because of the poor dispersal of cereal pollen, the absence of crops in the vicinity need not be assumed. As has been shown in the experiments on primitive agriculture at Draved, in Jutland (*10*), even in the second year of crop growing the yields fall markedly. In view of the length of stage A, at least 100 years, we should perhaps envisage the continual opening of new ground.

Stage B appears to have lasted some 150 to 200 years. Cereal pollen is absent at sites I and II (it was present in stage A at both sites). Plantain pollen, which is generally accepted as an indication of prehistoric farming, is consistently present at all three sites. The differences between stages A and B, particularly at sites I and II, appear to represent some change of farming method. Plantain pollen is often regarded as evidence of pastoralism (*11*), and it appears possible, although it cannot be stated with certainty, that the emphasis changed from arable to pastoral agriculture. At sites I and III, and at Fallahogy, County Londonderry (*12*), the curve for hazel pollen rises sharply at the beginning of stage B. It