Continental Drainage in North America During the Phanerozoic from Nd Isotopes

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Neodymium (Nd) isotopic data show consistent patterns in the sources of sedimentary rocks in North America at a continental scale. Between 600 and 450 million years ago (Ma), ancient continental shield sources dominated. Around 450 Ma, detritus from the Caledonian-Appalachian mountains overwhelmed sediment from all older sources, and is documented over large areas of the southern, western, and northern margins of North America. This material continued to dominate the sediment supply until about 150 Ma, probably due to cannibalistic recycling of sedimentary rocks formed earlier. Around 150 Ma, the rising western Cordillera delivered new and different detritus to the sedimentary system.

Radiogenic isotopic data for the rare earth element Nd have been applied for the past 15 years to study the provenance of clastic sedimentary rocks (*1*, *2*). The utility of this isotopic system is twofold: the parent Sm and daughter Nd are largely unfractionated by clastic sedimentary processes, and the measured isotopic compositions are an integrated average of the isotopic composition and crust formation age of the source area. Fine-grained clastic sedimentary rocks (shales) are preferred, as they represent a more finely comminuted average sediment. Crustal provenances with different average ages can be distinguished because the parameter ε_{Nd} (*3*) is more negative in older crust (for example, for Archean crust, $\varepsilon_{Nd} < -20$) and is less negative, or even positive, in younger crust (for example, for recent island arc volcanic rocks, $\varepsilon_{Nd} > 2$). Here we use extensive Nd isotopic data from clastic sedimentary sequences around North America, from the southern United States to western Canada and the Arctic margin of Canada, to assess sediment sources and dispersal paths through the Phanerozoic.

An extensive Nd isotopic database has been developed (*4*–*8*) for sedimentary rocks in cratonic and syn-orogenic sequences around North America (Fig. 1; most locations are shown in Fig. 2). We age-corrected the data to reflect the Nd isotopic values of the rocks at their approximate time of deposition. Samples of sediments older than 450 Ma, namely Late Proterozoic, Cambrian, and Early Ordovician in age, define ε_{Nd} values that mostly lie below –12 (Fig. 1). These values reflect the isotopic composition of Archean and Proterozoic basement rocks in North America. Such cratonic domains were the main available sediment sources before the existence of the Caledonian-Appalachian mountains.

The Nd data show regional variations in these cratonic signatures (Fig. 1). Sedimentary rocks in regions of North America where the continental crust is older show more negative ε_{Nd} values. For example, Cambrian and Lower Ordovician samples from the Innuitian Province in the Arctic Islands, where the neighboring shield areas are dominated by Archean [2.5 billion years ago (Ga) and older] crust, have ε_{Nd} values ranging from –17 to –26. On the other hand, in the southern United States, where the craton consists of Proterozoic rocks (1.9 to 1.3 Ga), the pre-Appalachian sediments have less negative ε_{Nd} values, ranging from –12 to –17. In the eastern United States, the local cratonic basement belongs to the Grenville orogenic belt (1.4 to 1.0 Ga). As a result, Cambrian to Lower Ordovician sedimentary rocks have even less negative ε_{Nd} values, between –3 and –13 at the time of sedimentation (*7*).

This regional pattern of ε_{Nd} values in sediments seems to disappear around 450 Ma, coincident with the onset of the Caledonian-Appalachian orogeny. In all areas, post–450 Ma sedimentary rocks have ε_{Nd} values of –5 to –13 (Fig. 1). Thus, sedimentary rocks in all areas except the eastern United States show a jump in ε_{Nd} of about eight units. The ε_{Nd} values in the range –5 to –13 would correspond to continental crust with Nd model ages of 1.0 to 1.6 Ga. This is the range of model ages usually shown by rocks of the Grenville Orogenic Belt (*4*, *5*, *9*). The actual source of the sediment lies in Paleozoic fold belts, not in the Grenville Province proper [for example, see (*4*)]. The Grenville signature predominates because it appears that the sedimentary formations that make up most of the Appalachian orogen inherited the average Nd signature of Grenville-belt crust. The

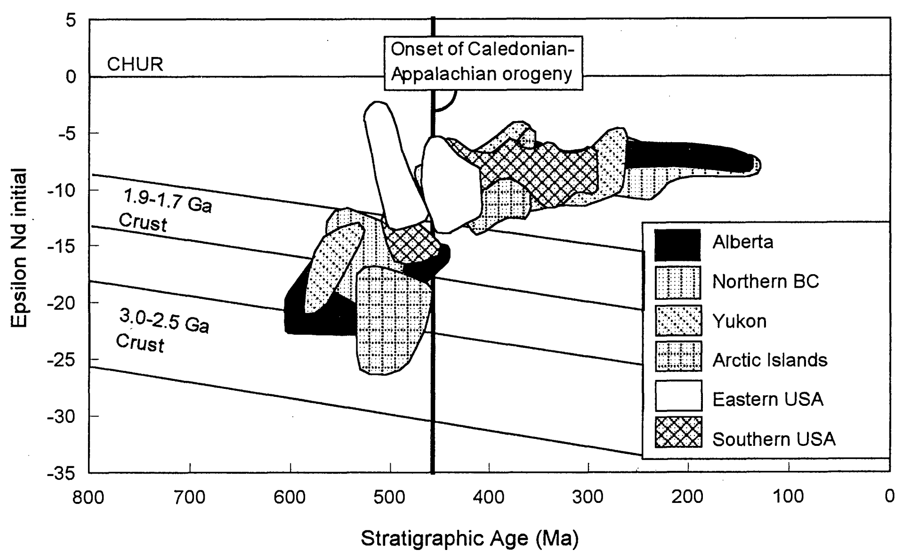

Fig. 1. Values of ε_{Nd} at the time of sedimentation for clastic samples (shales and fine- to medium-grained sandstones) from North America. There are two fields of Nd isotopic data for each region, representing signatures before and after the onset of Caledonian-Appalachian mountain building. Before 450 Ma, all clastic samples seem to have been derived from the erosion of cratonic rocks, and there are regional variations due to the ages of cratonic hinterlands (ε_{Nd} evolution for cratonic crustal regions of two prevalent ages is shown). Around 450 Ma, there was a jump in ε_{Nd} in all areas except the eastern United States. This jump corresponds in timing with the earliest tectonic phases of Caledonian-Appalachian orogenesis. The new values of ε_{Nd}, averaging –8, persisted through the remainder of Paleozoic time and up to the Late Jurassic in Alberta and British Columbia (BC).

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Grenville orogeny was the most recent orogenic event preceding formation of the Early Paleozoic Iapetus Ocean, and Grenvillian terrain bordered the ocean all along its western, and part of its eastern, margin. Thus there is no substantial change in ε_{Nd} values at 450 Ma in the eastern United States, where the local basement as well as both pre–450 Ma and post–450 Ma sedimentary rocks all have the Grenville Nd signature (*4, 7, 8*).

The fact that the Devonian-to-Pennsylvanian sequences of the central and southern United States ultimately derive from Appalachian sources is well established (*10–12*). The Nd results (*4*) show that the Appalachian detritus overwhelmed cratonic sources as soon as it appeared. The Nd data also show that sources lying ultimately in the Caledonian orogen of northeast Greenland and other Arctic regions fed a dynamic sedimentary system that carried clastic material all the way across the Canadian Shield into the Cordilleran margin of Canada (Fig. 2). Large amounts of sediment were transported into the Early and mid-Paleozoic deep-water trough of northern Greenland and the Canadian Arctic Islands, after the onset of orogenesis in the Caledonian belt at or shortly before 450 Ma [see references in (*6*)]. This component of the Innuitian Province, first a deep-water trough, later a mountain belt (Fig. 2), is called the Franklinian orogen. Paleocurrents were firmly toward the southwest [see (*6*) and references therein]. As soon as the Franklinian sequence itself began to be deformed and uplifted, a very thick shallow-marine–to–subaerial foreland sequence was deposited in the present-day region of the southern Arctic Islands. It is of mid- to Late Devonian age, approximately 8 km thick, with a further 4 km having probably been removed by erosion (*13*). Paleocurrent data show that sediment was transported southwest toward the Cordilleran miogeocline (Fig. 2). The Imperial Assemblage, 2000 m of clastic sediment in the northern Yukon that lies in the Cordilleran miogeocline and is known to have been derived from the direction of the Franklinian orogen, has ε_{Nd} values that correspond closely to those of the Devonian Arctic foreland wedge (*5*). From that region, facies relationships and inferred transport directions (*14*) indicate that detritus was carried south toward Alberta. There may have been direct across-craton transport (Fig. 2). Thus, the signature of the Caledonian orogen in the Arctic was carried to the Canadian Cordilleran margin, where it immediately dominated the clastic sediment budget, in exactly the same way as in the eastern and southern United States.

Age constraints on the timing of the jump in ε_{Nd} values vary in precision. In Alberta, latest Ordovician through mid-Devonian rocks are missing from the studied sequence, so there the constraint is poor. In the Arctic Islands, the jump is constrained by graptolite index fossils to Late Ordovician time, but the number of mid-Ordovician to Early Silurian Nd samples is small. In the southern United States, better constraints are available. The Caledonian-Appalachian signature was already established in the southern Appalachians by about 460 Ma, corresponding to the arrival of clastic sediments deposited during the onset of Appalachian orogenic events (*8, 15*). In the Ouachita region, sediment with an Appalachian signature is first detected at 457 Ma, and a section within the *Climacograptus bicornis* zone oscillates between ε_{Nd} values of −13 and −6 (*15*), indicating that a complete shift to the Appalachian signature may have taken several million years.

In both the Canadian Arctic and the southern United States, the provenance of clastic sediment changed during deposition of deep-water shale sequences when sedimentation rate was low (*4, 6*). Large amounts of clastic sediment, in the form of turbidites, arrived only some 20 to 30 million years after the change in provenance.

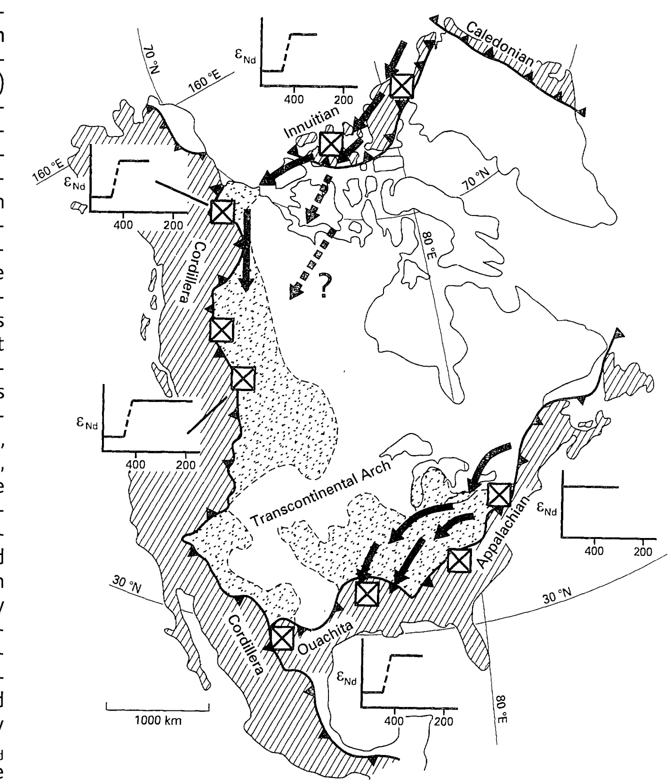

Fig. 2. The regions studied for Nd evolution in sediments in North America (boxed squares) (*4–8*) and the large-scale features of sediment movement inferred. The transport of sedimentary material from Caledonian mountains into the Franklinian orogen of the Innuitian Province took place in Silurian time, but otherwise the diagram shows geography and sediment transport in Late Devonian time. Transport systems on the western miogeocline were still active, with the same directions, during Mississippian time and persisted into Pennsylvanian time in the eastern and southern United States. The dotted region represents the present-day occurrence of Late Devonian clastic sedimentary rocks; real depositional edges probably extended beyond the present-day zero edges. No jump in ε_{Nd} values occurred in the eastern United States because the presence of Grenville-age cratonic basement there caused the pre–450 Ma sedimentary rocks to carry the same Nd values as the post–450 Ma samples.

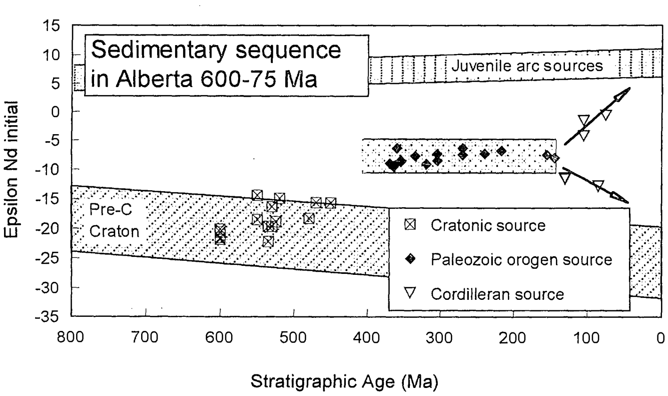

Fig. 3. Evolution of ε_{Nd} in sedimentary rocks in the Cordilleran miogeocline and foreland in Alberta (*5*). Pre-C, Precambrian. The signature of Paleozoic fold belts, with average ε_{Nd} of −8, persists until Late Jurassic time. Its persistence is terminated by the arrival of detritus from the uplifting Cordillera. This material is more heterogeneous, showing evidence of at least two discrete contributions: ε_{Nd} around zero, corresponding to juvenile igneous sources, and $\varepsilon_{Nd} = -12$ or lower, corresponding to sources in Cordilleran terranes with older continental components. The western Cordillera has not yet evolved sufficiently to produce a single range of average ε_{Nd} values in its erosion products.

Thus far-traveled hemipelagic mud, derived from erosion of the Caledonian-Appalachian mountains, reached deep-water depositional sites long before the arrival of prograding abyssal turbidite fans.

In the southern and eastern United States, the westerly dispersal of Appalachian detritus was impeded by the Transcontinental Arch (Fig. 2). No such topographic barrier was present between the Canadian Arctic and regions to the south and west. Transport may have been associated with a south and southwesterly slope away from the Innuitian Province (Fig. 2), similar to the modern Amazon transcontinental drainage. An additional component of tilt may have been added by dynamic topography in the craton created as a consequence of convection in the mantle (*16*) or the subduction of cold lithosphere (*17*).

The data show that detritus from the Caledonian-Appalachian mountains overwhelmed cratonic sources on a continent-wide scale as soon as it was available after the first tectonic pulses around 450 Ma. This can only have occurred if the detritus from the Paleozoic fold belts was far greater in volume than cratonic sediment. Models of rates of erosion and transport from mountainous regions are consistent with domination of the sediment supply by mountain belts (*18–22*). According to the equations of Pinet and Souriau (*21*), an orogenic belt younger than 250 Ma at an average elevation of 2000 m would be eroded down at a rate of 0.6 m per 1000 years, whereas a crustal region older than 250 Ma at an average elevation of 300 m would be denuded 30 times more slowly. These elevation differences correspond roughly to those that exist between the present-day Cordillera and the craton, and the same would be expected in Late Paleozoic time between Caledonian, Appalachian, or Franklinian mountains and the craton. Under these circumstances, sediment derived from young mountains, which is 30 times greater in production rate than any sediment from the craton, has no trouble dominating the clastic budget.

In Alberta, data are available for the entire miogeoclinal sequence, up to and including a partial sampling of Late Jurassic–to-Cretaceous sequences representing foreland deposition from the Cordilleran orogen (Fig. 3). Here the clastic material that arrived around 450 Ma from the Franklinian and Caledonian belts continued to dominate the sedimentary system until it was overwhelmed by Cordilleran detritus around 140 Ma. Pennsylvanian through Jurassic clastic sediments of Alberta were probably derived from the east [for example, see (*23*)]. The fact that the present-day zero edge of Devonian strata lies only 400 km east of the Cordilleran deformation front may imply that a reservoir of sedimentary rocks with the post–450 Ma ε_{Nd} signature covered the Canadian interior far more extensively than it does today. This cover would have been removed slowly through Late Paleozoic and Mesozoic time. Devonian limestone xenoliths in Jurassic kimberlite pipes of the Slave province have been taken to indicate that the northern Canadian Shield was covered by 800 m of sedimentary rocks in the Jurassic (*24*). The presence of this thickness in one region is consistent with our Nd isotopic data and has implications for long-term models of continental freeboard and cratonic sedimentation (*25*).

Our Nd isotopic results therefore show that provenance can be expected to be dominated by mountain belts and the sediments derived from them for extended periods following orogenic events, up to 300 million years in the present case. The production of a substantial sedimentary cover on the craton causes dominance of the sedimentary budget by material originally sourced in orogenic highlands to continue long after those highlands have been eroded down and until the next major mountain-building event affects the continent.

Cordilleran detritus would be distinguished by more juvenile isotopic parameters such as ε_{Nd}, as compared even to Caledonian-Appalachian sediment, because it contains juvenile arc volcanic components (Fig. 3). More outboard portions of the Cordillera that did not contribute to the foreland sequence in Alberta contain large terranes with positive ε_{Nd} (*26*). A clear Cordilleran influence over the whole continent has not yet been achieved because (i) Cordilleran tectonic events are far from complete, and the maximum supply of sediment has not yet been delivered onto the North American craton; and (ii) the heterogeneous ε_{Nd} values delivered from different terranes (Fig. 3) have not yet been homogenized into a single average. In the geologic future, North American sediment will probably be dominated by a distinctive average Cordilleran clastic signature, perhaps with an ε_{Nd} value as high as zero (*26*).

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3. ε_{Nd} represents the deviation, in parts in 10,000, of the isotopic ratio $^{143}Nd/^{144}Nd$ above (positive ε_{Nd}) or below (negative ε_{Nd}) a reference undifferentiated Earth [chondritic uniform reservoir (CHUR)] evolution of $^{143}Nd/^{144}Nd$ through time. The formula is ε_{Nd} = [$^{143}Nd/^{144}Nd$(rock at time *t*)/ $^{143}Nd/^{144}Nd$(CHUR at *t*)] – 1, where $^{143}Nd/^{144}Nd$(CHUR at *t*) = $0.512638 - 0.1966(e^{\lambda t} - 1)$; radioactive decay constant, $\lambda^{147}Sm = 6.54.10^{-12}$.
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