

# Ordovician paleogeography and the evolution of the Iapetus ocean

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## ABSTRACT

**Paleomagnetic data from northern Appalachian terranes identify several arcs within the Iapetus ocean in the Early to Middle Ordovician, including a peri-Laurentian arc at ~10°–20°S, a peri-Avalonian arc at ~50°–60°S, and an intra-oceanic arc (called the Exploits arc) at ~30°S. The peri-Avalonian and Exploits arcs are characterized by Arenigian to Llanvirnian Celtic fauna that are distinct from similarly aged Toquima–Table Head fauna of the Laurentian margin, and peri-Laurentian arc. The Precordillera terrane of Argentina is also characterized by an increasing proportion of Celtic fauna from Arenig to Llanvirn time, which implies (1) that it was in reproductive communication with the peri-Avalonian and Exploits arcs, and (2) that it must have been separate from Laurentia and the peri-Laurentian arc well before it collided with Gondwana. Collectively, the paleomagnetic and faunal data require an open Ordovician ocean adjacent to the Appalachian margin and argue against a Taconic-Famatinian collision between North and South America.**

## INTRODUCTION

Since J. Tuzo Wilson's (1966) classic demonstration of a proto-Atlantic (Iapetus) ocean, the Caledonian-Appalachian orogen has been a key area in the construction of Ordovician paleogeographic models. Until recently, the Early Ordovician Iapetus has been viewed as being an open ocean, bounded by Laurentia to the north, Baltica to the south and later the east, and Gondwana to the south (including peri-Gondwanide elements such as Avalonia and Armorica; e.g., Cocks and Fortey, 1982; Van der Voo, 1993) (Fig. 1, A and B). Recent models (Dalla-Salda et al., 1992a, 1992b; Dalziel et al., 1994) challenged this view and proposed an alternative paleogeographic model. Expanding on a southwestern North America–East Antarctic (SWEAT) connection in the Late Proterozoic (Moores, 1991) and the Rodinia reconstruction of Hoffman (1991), these alternative models depict a complex series of Laurentia–Gondwana collisions throughout the Paleozoic, culminating in the eventual formation of Pangea. As such, the Taconic orogeny, previously ascribed to arc-continent collision associated with subduction at the Laurentian margin of Iapetus (e.g., Bird and Dewey, 1970; Hatcher, 1987; Drake et al., 1989; van der Pluijm et al., 1990; McKerrow et al., 1991), is regarded as a continent-continent collision (Fig. 1C). Both the more traditional and alternative paleogeographic models are permissible within the confines of the paleomagnetic data available from the major Iapetus-bordering continents, given that paleolongitudes cannot be determined directly from paleomagnetic data.

The expanding dataset of paleomagnetic observations from accreted terranes in the Appalachian-Caledonian orogen, however, has been underutilized in the recent global plate models. In addition, the increased use of statistical analyses in looking at faunal signatures and provinces (e.g., Fortey and Mellish, 1992; Neuman and Harper, 1992; Harper et al., 1996) has indicated that patterns of faunal distribution and migration cannot be explained simply in terms of continent-continent interactions. We contend here that the paleomagnetic data and faunal distributions from the various accreted terranes of the Appalachian-Caledonian orogen point to a much more dynamic evolution of the Iapetus ocean than the classic three-plate model, with several arcs and subduction zones present in the ocean. Fur-

thermore, we contend that the combined paleomagnetic and faunal data argue against a shared Taconic history between North and South America.

## PALEOMAGNETIC DATA FROM IAPETAN TERRANES

Displaced terranes occur along the extent of the Appalachian-Caledonian orogen, although reliable Ordovician paleomagnetic data from Iapetan terranes have only been obtained from the Central Mobile belt of the northern Appalachians (Table 1). The Central Mobile belt separates the Laurentian and Avalonian margins of Iapetus and preserves remnants of the ocean, including arcs, ocean islands, and ophiolite slivers (e.g., Keppie, 1989). Paleomagnetic results from Arenigian and Llanvirnian volcanic units of the Moreton's Harbour Group and the Lawrence Head Formation in central Newfoundland indicate paleolatitudes of 11°S (Table 1), placing them near the Laurentian margin. Similarly, results from Llanvirnian to Llandeilian Winterville and Llandeilian to Caradocian Stacyville and Bluffer Pond formations of north-central Maine have also yielded near-Laurentian paleolatitudes of 11°S, 20°S, and 18°S, respectively (Table 1). Taken together, these results indicate that an extensive arc system was located near the Laurentian margin in Early to Middle Ordovician time. Conversely, results from Llanvirnian to Llandeilian volcanic rocks of the Tetagouche Group, in the Miramichi terrane of northern New Brunswick, indicate an original paleolatitude of 53°S (Table 1), placing them on the southern (Avalonian) margin of Iapetus in the Middle Ordovician. Results from the Llanvirnian Robert's Arm, Summerford, and Chanceport groups of the Exploits subzone of the Central Mobile belt yield paleolatitudes intermediate to the Laurentian and Avalonian margins, at about 30°S.

Thus, the paleomagnetic data from the northern Appalachians indicate the presence of at least three major arc systems within the Iapetus ocean in the Early to Middle Ordovician: a peri-Laurentian arc (at about 10°–20°S), an intra-Iapetan arc-system, the Exploits arc (at about 30°S), and a peri-Avalonian arc (at about 50°S).

## FAUNAL CONSTRAINTS FROM IAPETAN TERRANES

Early attempts to assign shelfal brachiopod assemblages from several of the accreted terranes in the Appalachian-Caledonian collage to continental platform provinces proved problematic, and therefore the Toquima–Table Head faunal realm (Ross and Ingham, 1970) and Celtic brachiopod biogeographic province (Williams, 1973) were erected in addition to the classic Laurentian, Baltic, and Mediterranean provinces. The Early to Middle Ordovician Toquima–Table Head fauna typify low-latitude, warm-water environments surrounding equatorial Laurentia (Neuman and Harper, 1992; Cocks and McKerrow, 1993; Harper et al., 1996). In contrast, the Early to Middle Ordovician Celtic brachiopod province was postulated by Neuman (1984) to have originated around islands within the Iapetus ocean, away from the Laurentian margin. Although the paleogeographic utility of the Celtic brachiopod province has been the subject of considerable debate, recent statistical analyses of brachiopod fauna from Maine, New Brunswick, Newfoundland, Britain, Ireland, and Scandinavia have shown that the Celtic brachiopod fauna differ significantly from the Toquima–Table Head realm of the Laurentian margin in the Early to Middle Ordovician, with less pronounced differences in the Late Ordovician (Harper et al., 1996). It is significant that the only two published paleomagnetic results of units associated with the Toquima–Table Head fauna have yielded low paleolatitudes; these are the type Table Head Group of western Newfoundland (19°S; Hall and Evans, 1988) and the Mweelrea Formation (Llanvirn) in western Ireland (16°S; Morris et al., 1973). It is equally important that the two published paleomagnetic

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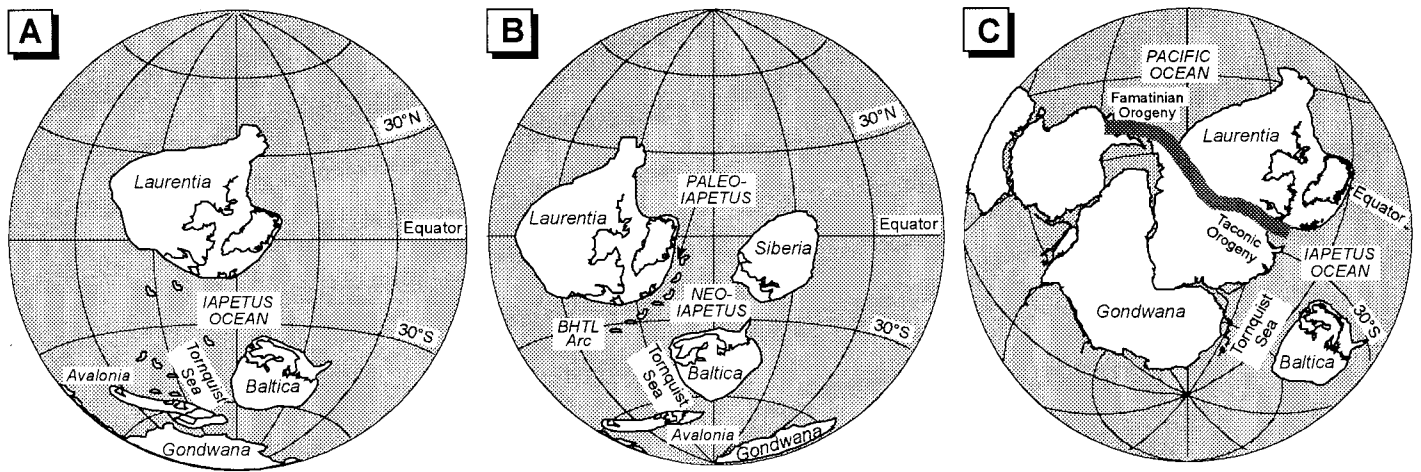


Figure 1. Selected views of Early and Middle Ordovician paleogeography. A: Classic three-plate model with possible ocean islands added (Neuman, 1984). B: Reconstruction of Cocks and McKerrow (1993) with accreted terranes represented as single arc; Bronson Hill–Tetagouche–Lushes Bight arc (BHTL). C: Fundamentally different reconstruction of Dalziel et al. (1994) that links Taconic orogeny in North America with Famatinian orogeny in South America in Laurentia–Gondwana collision in Middle Ordovician time.

TABLE 1. PALEOMAGNETIC SOUTH POLES AND PALEOLATITUDES USED IN THE RECONSTRUCTIONS OF FIGURE 2

Paleocontinent	Early Ordovician	Middle-Late Ordovician	Early-Middle Silurian	Reference
Laurentia	15°S / 339°E*	21°S / 328°E*	21°S / 311°E*	Mac Niocaill and Smethurst (1994)*
Gondwana	25°N / 356°E	43°N / 352°E	02°S / 352°E†	Van der Voo (1993)†
Baltica	30°N / 054°E	01°N / 027°E	19°S / 349°E	Torsvik et al. (1992)
Avalonia	56°N / 306°E§	11°N / 018°E	13°N / 271°E§	Torsvik et al. (1993)
Siberia	42°N / 310°E	22°N / 301°E	00°N / 290°E	Torsvik et al. (1995)

Unit in accreted terrane	Age	Pole	$\alpha_{95}$	k	Paleolatitude	Reference
Lawrence Head Formation	Llanvirn	25°S/049°E	11	36	11°	Todaro et al. (1996)
Moreton's Harbour Group	Arenig	29°S/315°E	7	23	11°	Johnson et al. (1991)
Winterville Formation	Llandeilo-Caradoc(?)	26°S/328°E	9	28	11°	Potts et al. (1995)
Bluffer Pond Formation	Caradoc	26°S/314°E	12	12	18°	Potts et al. (1993)
Stacyville Formation	Llandeilo-Caradoc(?)	14°N/008°E	12	12	20°	Wellensiek et al. (1990)
Robert's Arm, Chanceport and Summerford Groups	Llanvirn	08°S/317°E	6	374	31°	Van der Voo et al. (1991)
Tetagouche Group	Llanvirn	52°N/352°E	13	22	53°	Liss et al. (1993)

Note: Errors on the mean poles for the paleocontinents are of the order of 10°. k and  $\alpha_{95}$  are Fisher (1953) statistical parameters.  
 \* Poles were originally listed in European coordinates but are listed here in North American coordinates using a rotation about an Euler pole at 88.5°N, 27.7°E and a rotation angle of -38°.  
 † The Early to Middle Silurian pole for Gondwana is based on a spline interpolation of the 467–430 Ma and 429–415 Ma mean poles of Van der Voo (1993).  
 § These poles are used for paleolatitudinal positioning only, as they may have undergone tectonic rotations.

results for units associated with the Celtic brachiopod fauna have yielded intermediate to high paleolatitudes; i.e., the Summerford Group (Llanvirn) of central Newfoundland (31°S; Table 1) and the Tetagouche Group (Llanvirn to Llandeilo) of northern New Brunswick (53°S; Table 1). Thus, when the paleomagnetic and faunal data are combined, strong evidence exists that the Celtic brachiopod assemblages are restricted to terranes occupying intermediate to high paleolatitudes and are therefore important biogeographic markers in evaluating Early to Middle Ordovician paleogeography.

#### LAURENTIA–SOUTH AMERICA CONNECTION?

A Middle Ordovician collision between the Appalachian and Andean margins, producing the Taconic orogeny in eastern North America and the Oclöyic event of the Famatinian orogeny in South America, has been proposed (e.g., Dalla-Salda et al., 1992a, 1992b; Dalziel et al., 1994; Fig. 1C). The key element of these models is the tectono-stratigraphic affinity of the Precordilleran terrane of Argentina. The Precordilleran preserves a Cambrian carbonate sequence that exhibits strong stratigraphic and faunal similarities to that along the Appalachian margin of Laurentia (Ramos et al., 1986; Astini et al., 1995, 1996; Dalziel and Dalla-Salda, 1996; Thomas and Astini,

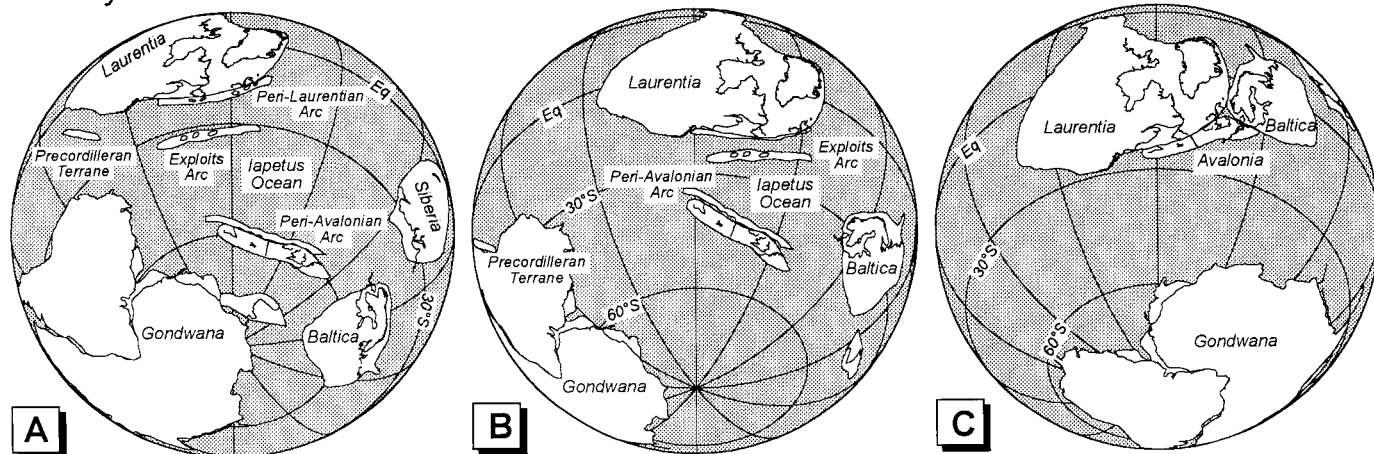
1996). Collision of the Precordilleran terrane with the Andean margin of Gondwana took place in Middle Ordovician time (Ramos et al., 1986; Dalla-Salda et al., 1992a, 1992b; Astini et al., 1995). The presence of cold-water, peri-Gondwanan, Hirnantian brachiopods and Late Ordovician glacial deposits in the Precordilleran indicates that, by the Middle and Late Ordovician, the terrane was located at much higher latitudes than those of Laurentia. Thus, most authors (see Dalziel and Dalla-Salda, 1996) agree that the evidence from the Precordilleran points to an initial Cambrian position for the terrane on the Laurentian margin, probably the Ouachita embayment (Thomas and Astini, 1996), and transfer of the terrane to the South American margin of Gondwana in the Middle Ordovician.

The position of the Precordilleran in the Early Ordovician and the mechanism of transfer, however, have been the subjects of considerable controversy. Dalla-Salda et al. (1992a, 1992b) and Dalziel et al. (1994) ascribed the transfer of the Precordilleran terrane to a continental collision between Laurentia and Gondwana in the Middle Ordovician. Subsequent separation of the two continents in Late Ordovician time excised the Precordilleran terrane from the Laurentian margin, leaving it in its present position as an allochthonous terrane in South America. In this model the Oclöyic orogenic event of

## Early-Middle Ordovician

## Middle-Late Ordovician

## Late Ordovician - Early Silurian



**Figure 2.** Ordovician evolution of Iapetus ocean as outlined in this paper. Paleomagnetic poles used to position major continents and paleolatitudes used in constraining positions of various arcs are listed in Table 1. Orthogonal projections.

South America would be the extension of the Taconic orogen of eastern North America. This model has been disputed by Astini et al. (1995) and Thomas and Astini (1996), who propose that the Precordillera existed as an independent block that rifted from Laurentia in the Cambrian, prior to accretion to South America in the Middle Ordovician. We favor the latter model for a number of reasons. As noted by Astini and colleagues, early Arenigian to early Llanvirnian brachiopod faunas from the Precordillera contain an increasing amount of Celtic genera over time. Because the Celtic brachiopod province occupied higher paleolatitudes than the Laurentian margin (Harper et al., 1996; this paper), the Precordillera must have been separated from Laurentia in Early to Middle Ordovician time. Moreover, the presence of Celtic genera in the Precordillera indicates that there must have been a degree of faunal exchange with the Exploits and peri-Avalonian arcs of the central and southern Iapetus to the east in the Middle Ordovician (Fig. 2A). If Laurentia and Gondwana were united after continent-continent Taconic-Famatinian collision (Fig. 1C), such exchange would be very unlikely. Furthermore, the evidence from the northern Appalachians indicates that, during Iapetus ocean closure, several arcs telescoped in multiple collision events throughout the Ordovician and Silurian (van der Pluijm et al., 1990, 1995; Hibbard, 1994; van Staal, 1994). Thus the Taconic and Acadian orogenies do not represent discrete tectonic events, such as the Laurentia-Gondwana collision, but a protracted history of deformation, terrane migration, accretion, and continental convergence. Such a complex tectonic history is exceedingly difficult to accommodate within the confines of a tight Laurentia-Gondwana fit in the Middle Ordovician; in other words, the Appalachian margin of Laurentia must have faced an open ocean instead of another continent.

### EARLY PALEOZOIC PALEOGEOGRAPHY

Our preferred paleogeographic scenario is presented in Figure 2. The Iapetus ocean was at its maximum extent in the Late Cambrian and Early Ordovician, and its closure was accompanied by a protracted, but punctuated tectonic history and a complex geometry, resembling, in many ways, the tectonic complexity of the modern southwest Pacific. By the Arenig, subduction had commenced at the northern margin of Iapetus, and a peri-Laurentian arc had developed (Fig. 2A). The correlation of the Notre Dame subzone of the Central Mobile belt with the South Mayo trough of western Ireland (Williams et al., 1995) would imply that this arc extended over several thousands of kilometres. It is the collision of this arc in the Early and Middle Ordovician that produced the Taconian orogenic pulse (Fig. 2B). The Precordilleran terrane had rifted away from the Ouachita embayment by the Late Cambrian (Fig. 2A), and had an independent drift history in Early to Middle Ordovician time, prior to collision with the South American margin of Gondwana during the Ocoyoc orogeny (Fig. 2B).

A peri-Avalonian arc had also developed on the southern margin of the Iapetus ocean by the Middle Ordovician and, similar to the peri-Laurentian arc, is likely to have been extensive, given the record of Middle Ordovician volcanism preserved from the Lake District of Britain through the Central Mobile belt. The paleomagnetic data from the Robert's Arm, Summerford, and Chanceport groups of central Newfoundland indicate the presence of a third arc system; the Exploits arc, located in the middle of the Iapetus ocean basin. We emphasize here that there may have been other arcs or rifted blocks in the ocean that have not yet been recognized as such.

The Middle to Late Ordovician marked the continued convergence of Baltica and Avalonia with Laurentia; the paleomagnetic evidence indicates that the ocean between Laurentia and Avalonia had narrowed to about 3000 km by this time (Fig. 2B). Deformation and terrane accretion continued with the arrival and collision of fragments of the more southerly arcs. Final closure of the Iapetus ocean seems to have been completed in the Silurian (Fig. 2C), although strike-slip motion continued into the Devonian in the northern Appalachians. The Silurian sequences across the Central Mobile belt in Newfoundland, and from Laurentia and Avalonia, have yielded similar paleolatitudes, indicating that they had been assembled at this time (Torsvik et al., 1993; Stamatakos et al., 1995).

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