# Improved chronostratigraphic reference curve of late Neogene seawater $^{87}Sr/^{86}Sr$: Comment and Reply

## COMMENT

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The purpose of my Comment is to warn other researchers that factors unrelated to $^{87}Sr/^{86}Sr$ of open-ocean sea water may determine the strontium isotopic ratio of carbonate deposits. This cautionary note is necessary because potential users of Farrell et al.'s (1995) reference curve may interpret incorrectly the ages of their samples.

In my work on modern carbonate sediments of the Sinai subplate (Friedman, 1995), strontium isotopic variation is at variance with the data that Farrell et al. (1995) have generated. *Glycymeris* shells in a cemented matrix form a coquinite. Although their strontium isotopic ratio of 0.709137 (11)[1] falls slightly below the Farrell et al. (1995) curve, it is still consistent with that of modern sea water. The strontium isotopic ratio of the matrix between the shells at 0.708988 (13), however, dated by radiocarbon as 6300 yr B.P., is equivalent to seawater ratios near the Miocene-Pliocene boundary of Burke et al.'s (1982) graph and approximately 5 to 5.5 Ma on the curve of Farrell et al. (1995) (Fig. 1). The isotopic composition of modern hypersaline pool carbonate samples shows likewise disequilibrium with respect to sea water. Their strontium isotopic ratios are 0.708043 (14) and 0.707862 (14). On the Farrell et al. (1995) graph, these modern carbonate sediments cannot be plotted because they fall below all their data, and on the Burke et al. (1982) graph a mid-Miocene age is indicated. Yet radiocarbon dates range between 26 and 1050 yr B.P. (Friedman, 1995). A sample from a modern sabkha showed the strontium isotopic composition of carbonate sediment to be consistent with that of Cretaceous seawater 0.70756 (10)[2], yet its radiocarbon age gave 11,190 ± 290 C-14 yr B.P. (C-13 corrected).

The modern carbonate sediments that I have sampled are from various settings of the Mediterranean and Red Sea, including the Dead Sea transform at the plate boundary that separates the Arabian from the Sinai plates. Either strontium isotopic ratios in these modem carbonate facies have changed since precipitation, or they precipitated from a less radiogenic fluid than modern sea water. Perhaps the low strontium numbers relate to paleoseawater expelled from depth during compaction, to fluids derived from the mantle, or to recycling from older bedrock.

Users of the "chronostratigraphic reference curve" presented by Farrell et al. (1995) may wish to assure themselves that their samples relate strictly to seawater $^{87}Sr/^{86}Sr$. Yet geologic variables are far more complex than even geologists themselves sometimes

[1]The Sr analyses are normalized to $^{86}Sr/^{88}Sr$ = 0.11940. Analyses of NBS 987 averaged 0.710241 (09) ($n$ = 39) during the period of these analyses. Errors on $^{87}Sr/^{86}Sr$ are given as 2$\sigma$ (95%) in the last two digits.

[2]The Sr analyses are normalized to $^{86}Sr/^{88}Sr$ = 0.11940. Analyses of NBS 987 averaged 0.710230 (11) during the period of these analyses. Errors on $^{87}Sr/^{86}Sr$ are given as 2$\sigma$ (95%) in the last two digits.

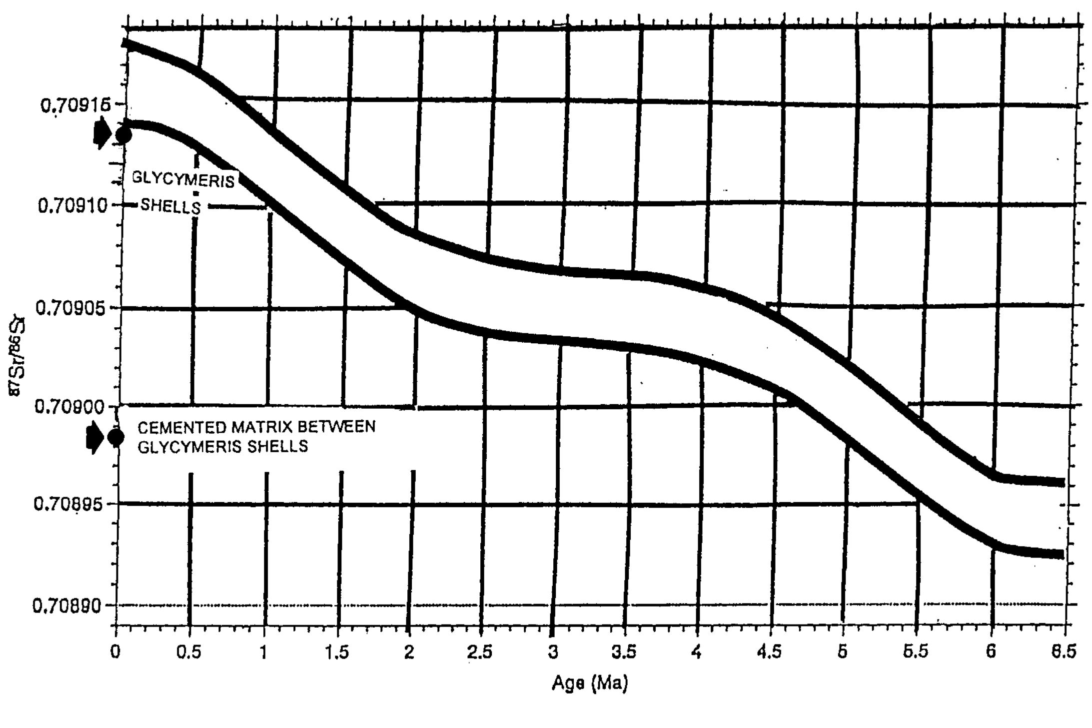


**Figure 1. Plot of $^{87}Sr/^{86}Sr$ of marine carbonate ages taken from Farrell et al. (1995) on which strontium isotopic values from Friedman (1995) have been superimposed (0.000 006 values for both samples have been subtracted from these data to bring the data in line with those of Farrell et al.).**

care to admit. Thus, this cautionary warning should be heeded that inappropriate use of the Farrell et al. (1995) curve may not provide chronostratigraphic information.

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Farrell, J. W., Clemens, S. C., and Gromet, L. P., 1995, Improved chronostratigraphic reference curve of late Neogene seawater $^{87}Sr/^{86}Sr$: Geology, v. 23, p. 403–406.

Friedman, G. M., 1995, Diverse origin of modem dolomite in the Levant: Carbonates and Evaporites, v. 10, p. 65–78.

## REPLY

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Our seawater $^{87}Sr/^{86}Sr$ reference section from Ocean Drilling Program Site 758 (Farrell et al., 1995) is a record of the Sr isotopic evolution of the globally well-mixed ocean. The intended use of this and other such records (e.g., Burke et al., 1982; McArthur et al., 1994; Jones et al. 1994; Oslick et al., 1994; Hodell et al., 1991), is for chronostratigraphic correlation among sections containing carbonate materials that are known (or reasonably inferred) to have precipitated from waters in Sr isotopic equilibrium with the global ocean, and that have remained unaltered by diagenesis. Sediments referred to in Friedman (1995) precipitated from hypersaline pools overlying Cretaceous carbonate bedrock and from thermal hotsprings along the Dead Sea transform. These sediments clearly do not meet the above criteria for $^{87}Sr/^{86}Sr$ dating. As such, their known ages and associated Sr isotopic compositions are not at variance with our reference curve. Instead, Friedman's results confirm that his samples precipitated from (or exchanged with) fluids closer in isotopic composition to extant ground waters and/or hydrothermal fluids. Rock samples that precipitated in environments such as these should certainly not be dated by correlation to the seawater $^{87}Sr/^{86}Sr$ record.

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# Is the Taconian orogeny of southern Quebec the result of an Oman-type obduction?: Comment and Reply

## COMMENT

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Pinet and Tremblay (1995) stated that since "the advent of plate tectonics the accepted model for the Taconic orogeny . . . involved an arc-continent collision, during which both oceanic and continental-margin rocks were imbricated in an accretionary wedge along an east-dipping subduction zone." The model is attributed to Osberg (1978) and Stanley and Ratcliffe (1985). However, Figure 19.11 of Osberg (1978) shows that he considered obduction of oceanic crust and the resultant Taconic imbrication to entirely predate formation of the Ascot-Weedon arc. Arc collision was therefore not the causative event in Osberg's model of the Taconic orogeny. Collision of the Ascot-Weedon and Bronson Hill arcs only culminated the Taconic orogeny during closure of a hypothetical ocean located between the Chain Lakes continent and the Bronson Hill arc. Furthermore, regional considerations along the length of the Laurentian margin and the recent isotopic studies of Sevigny and Hanson (1995) suggest that the arc rocks exposed within the domes of the eastern Connecticut Valley synclinorium, supposed by Stanley and Ratcliffe to be the equivalents of the collided Bronson Hill arc, represent postobduction arcs formed within the Laurentian margin. The model of Stanley and Ratcliffe may be incorrect, but not for the reasons suggested by Pinet and Tremblay.

The noncollisional Oman-type obduction model favored by Pinet and Tremblay for the western Appalachians is very similar to that proposed by Stevens (1970) to explain the "Taconic" problem of western Newfoundland. Furthermore, the similarity of the Fleur de Lys–Shickshock–Sutton Bennet metamorphic complexes, the Baie Verte–Thetford Mines and Betts Cove–Chain Lakes ophiolite belts, and the Exploits–Tetagouche–Bronson Hill arc rocks along the length of the northern Appalachians had also rendered it evident that the same obduction model could be applied to the New England sector of the Appalachians (Church, 1972, 1977). Again, with respect to the problem raised by Pinet and Tremblay of distinguishing collisional deformation from earlier deformation related to subduction or obduction, the Newfoundland data had already permitted the conclusion that it was "unlikely that ophiolite emplacement marks subduction zone activity as is represented by the . . . Franciscan melange of California or continental collision marked by orogenic events late during the tectonic cycle" (Church, 1972).

The Oman-type model is nevertheless deficient on two counts.

First, it is unlikely that ophiolites represent normal oceanic crust. The Appalachian ophiolites may rather represent primitive arc-related spreading centers; formed perhaps as a consequence of oblique subduction involving southeast-directed consumption of a section of the Iapetus oceanic crust marginal to Laurentia (Church, 1987). Obduction models tacitly assume that consumption of oceanic crust may lead to the formation of a primitive island arc oceanward of the oceanic plate being consumed, and that the ultimate underthrusting of the arc by the continental margin will lead to metamorphism of subducted continental and oceanic material—e.g., eclogites in the Fleur de Lys of Newfoundland and eclogites and blueschists in the metamorphic core of Vermont. The Taconic orogeny may well have resulted, therefore, from an arc-continent collision; the arc was, however, neither the Ascot-Weedon nor the Bronson Hill.

Second, the obduction event entirely predated the formation of the Ascot-Weedon arc. The "boninitic" mafic schists and Katevale serpentinite unit of the Ascot-Weedon Formation are perhaps intercalated slices of older obducted material, whereas the intermediate-felsic units of the Ascot-Weedon may have formed above a west-dipping subduction zone at ca. 460 Ma, much later than the ophiolite obduction event. Similarly, the Middle Ordovician calc-alkalic Burlington Granodiorite—which clearly intrudes the Betts Cove ophiolite and the overlying volcanic Snooks Arm Group—and the Western Arm Group arc rocks of the Notre Dame Bay region of Newfoundland could have formed above a west-dipping subduction zone in Middle to Late Ordovician time, as did perhaps also the amphibole-bearing alkalic Bail Hill volcanic rocks of southern Scotland, the Slieve Aughty volcanic rocks of Ireland, and the arc plutons exposed within the domes of the eastern Connecticut Valley synclinorium (Sevigny and Hanson, 1995). The presence of grains of chromite and of inherited Grenville zircons (David and Marquis 1994) in felsic volcanic and volcaniclastic units of the Ascot-Weedon indicate that the felsic arc was developed on an obducted ophiolitic substrate overlying either Grenville basement or Grenville-derived sediments such as are perhaps represented by the "chromite-absent" psammites of the Bunker Hill Formation. Furthermore, if the chromite-absent psammitic rocks of the Chain Lakes massif are also Laurentian passive margin deposits, a Laurentian isotopic signature is only to be expected in volcanic rocks west of the Connecticut Valley–Gaspé synclinorium. Faunal and isotopic data favor the interpretation of the Bronson Hill arc as an equivalent of the Tetagouche of New Brunswick and the Exploits zone of Newfoundland, all three sequences representing subduction along the southeastern Avalonian margin of Iapetus. In this sense the Iapetus suture should be located between the Ascot-Weedon and Bronson Hill arcs (cf. Church and Gayer, 1973; Church, 1977, Fig. 1) rather than between the obducted ophiolites and the Ascot-Weedon arc as preferred by Pinet and Tremblay.

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## REPLY


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The main purpose of Pinet and Tremblay (1995a) was to point out timing problems associated with arc-collision models for Ordovician (Taconian) deformation in southern Québec and New England (e.g., Stanley and Ratcliffe, 1985; Tremblay, 1992a, 1992b). Pinet and Tremblay (1995a) proposed an alternative model based on a comparison with the Oman-Iran transect where deformation and metamorphism of the Arabian margin occurred during the obduction of an oceanic slab, prior to arc magmatism. Arguments in favor of an obduction model for the Québec-Maine Appalachians have been extensively discussed by Pinet and Tremblay (1995b), to summarize: (1) The Baie Verte–Brompton line that divides the continental margin rocks from the ophiolitic rocks and mélange units in southern Québec (Williams and St-Julien, 1982) is a steeply dipping tectonic boundary that does not represent the root zone of the oceanic slab (Tremblay and Pinet, 1994); (2) the southern Québec and western Maine ophiolites are interpreted to record the opening of a single oceanic basin obducted onto the Laurentian margin; (3) in southern Québec, continental margin rocks were deformed earlier and more intensely than the overriding ophiolitic sequence, as in classical obduction settings; (4) the Ammonoosuc volcanics and Patridge Formation found in the Bronson Hill anticlinorium of New England are in part composed of arc volcanic rocks very similar in lithology, chemistry, and age to the Ascot Complex of southern Québec; the Bronson Hill anticlinorium also contains gabbroic and tonalitic gneisses that Tucker and Robinson (1990) interpreted as intrusive rocks that form a magmatic arc; (5) radiometric ages from arc rocks (Tucker and Robinson, 1990; David and Marquis, 1994) are younger than deformation and metamorphism that occurred along Laurentia in Ordovician time.

In the first and second sections of his Comment, Church argues that Pinet and Tremblay (1995a) in opportunely referred to Osberg (1978) for an arc-continent collision in the Québec–New England Appalachians. Osberg (1978) sketched an obducted oceanic crust along the Laurentian margin prior to arc volcanism, but he also clearly stated that "the collision of this arc (Bronson Hill magmatic rocks) with basement A (Laurentia) and B (Chain Lakes) *culminated* the Taconic orogeny." The main point of our contribution was to suggest that Taconian peak metamorphism did not culminate with the arc-continent collision. Church also states that our model is very similar to those proposed for Newfoundland (e.g., Stevens, 1970) and that along-strike regional correlation *rendered it evident*.

Although we agree that the obduction *mechanisms* are the same, we suggest that the oceanic basin(s) and island-arc(s) found in Newfoundland are not directly correlative to those found in Québec and northern New England. In agreement with models proposed for Newfoundland (e.g., Cawood and Suhr, 1992), Pinet and Tremblay (1995a, 1995b) argued that Appalachian ophiolites originated from unrelated small oceanic basins that formed in reentrants of the Laurentian continental margin. Such an interpretation is consistent with models that attribute both the ophiolite generation and its subsequent emplacement to plate-convergent settings (Edelman, 1988).

In the third section of his Comment, Church argues that our model is deficient because "it is unlikely that ophiolites represent normal oceanic crust." Ophiolitic volcanic rocks of southern Québec and western Maine include island-arc tholeiites and boninites, suggesting a supra–subduction-zone setting (Laurent and Hébert, 1989). We believe that ophiolite genesis took place in a setting very similar to the initial stages of the Mariana or South Scotia subduction zones, in which "back-arc" spreading occurred *before* an arc was constructed (Taylor and Karnes, 1983). In such a setting, it would be inadequate to refer to "back-arc," "arc," or "fore-arc" basins, for a reference arc that does not even exist (Sengör, 1990). For the Appalachian orogen, such a supra–subduction-zone setting implies that obducted oceanic lithospheres represent small oceanic basins rather than Iapetus sensu stricto crustal segments.

The fourth section of Church's comment contains the main point. On the basis of apparent lack of inherited zircons in arc volcanics of the Bronson Hill anticlinorium and abundant xenocrysts (zircon and chromite) in the Ascot Complex volcanics, Church concludes: (1) that the Ascot Complex arc was formed over the Laurentian continental margin; (2) that the Ascot Complex is therefore different from arc rocks of the Bronson Hill anticlinorium, and (3) that the Iapetan suture zone should be located between the Ascot Complex and the Bronson Hill anticlinorium. We must point out here that there is no detrital chromite in any rocks of the Ascot Complex (Tremblay, 1992b). We agree that the presence of inherited zircons in the Ascot Complex volcanics can indicate underlying Grenvillian-like basement. However, Tremblay et al. (1994) proposed an alternative hypothesis in which the Grenvillian-like component originated from the attempted subduction, and consequent delamination, of the Laurentien margin itself. Compositional differences between the Ascot and Bronson Hill volcanics would then be attributed to distinct magmatic pulses and melting events of a compositionally zoned crustal source. It is important to note that inherited zircons with ages $>$1402 Ma have been found as well in arc intrusive rocks of the Bronson Hill anticlinorium (Tucker and Robinson, 1990).

Since Tucker and Robinson (1990) published age data for the Ammonoosuc and Partridge volcanics and associated gneisses of the Bronson Hill anticlinorium, it has been obvious that there is a problem to attribute the Ordovician deformation of the Laurentian margin to the accretion of the Bronson Hill arc rocks, because these rocks are younger than most Taconian deformation. We note that Church mainly agrees with our interpretation of the obduction stages of Taconian deformation but questions the inferred correlation between arc rocks of southern Québec and New England. Although the precise correlation between arc rocks of southern Québec and New England is still problematical, we believe that our obduction model is viable and should be used as a basis for more detailed analysis.

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