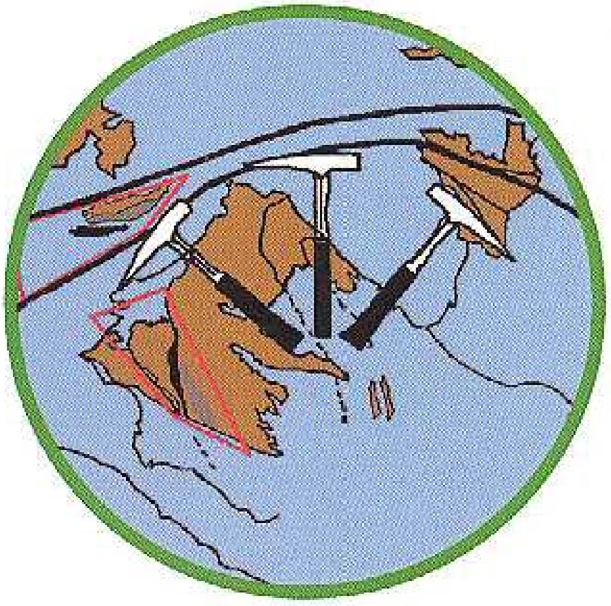
Journal of Conference Abstracts

Volume 4
Number 3
September 1999

XV Reunión de Geología del Oeste Peninsular



International Meeting on Cadomian Orogens

Annual Meeting of IGCP Project 376
"Laurentia-Gondwana connections before Pangea"

UNIVERSIDAD DEL PAÍS VASCO
EUSKAL HERRIKO UNIBERTSITATEA

UNIVERSIDAD DE EXTREMADURA

INSTITUTO GEOLÓGICO E MINEIRO PORTUGAL

IUGS UNESCO IGCP 376

ISSN 1362-0886
Cambridge Publications
1999

26 September - 3 October, 1999
Badajoz, Spain

Fecha de publicación: Septiembre de 1999
Depósito Legal: BA-437-99
Impreso en la Imprenta de la Diputación de Badajoz

XV Reunión de Geología del Oeste Peninsular
(International Meeting on Cadomian Orogens)

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(Laurentia-Gondwana connections before Pangea)

Extended Abstracts

Badajoz (Spain), 26 September – 3 October 1999

Editores:
J. A. Gámez Vintaned
L. Eguíluz
T. Palacios

Diputación de Badajoz
1999

or multiple lithospheric subduction and collision processes in excess of 100 Ma. In the case of older orogens such processes are often taken to have lasted even longer. For decades, major reasons for these hypotheses were wrong interpretations of geochronological data. However, a better understanding of the behaviour of the applied isotopic systems as well as improved and/or new geochronological techniques allows these mistakes be to corrected.

Under this premise we examined young orogenic belts as the absolute age errors are minimized when compared to older orogens. Additionally, a lower age limit (0 Ma) is given by the present exposure of such orogens, which is more difficult or impossible to assess precisely for older mountain belts.

Apart from classical techniques of estimating cooling ages via mineral dating (mainly Rb-Sr, various Ar-techniques, Sm-Nd and fission track), cathodoluminescence (CL) based ion microprobe (SHRIMP) analyses of different types of zircon domains allowed dating of prograde, peak- and retrograde metamorphism.

(a) Dating of initial stages of prograde metamorphism: No reliable geochronometer was found so far, that gave information on the onset of orogenic activities in high-grade terranes. The detection of hydrothermal zircons in early, deformed quartz veins lying concordantly within metasediments (Rubatto *et al.*, 1999; Liati & Gebauer, 1999; and unpublished data) is a major step forward to fill this gap. Such prograde quartz veins commonly form during initial subduction in a narrow T-interval of ca. 250-300°C. As the hydrothermal zircon domains can be shown to remain closed for U-Pb during highest grade metamorphic conditions of the quartz vein and its country-rock, an important age tag can be fixed on the prograde part of a PTt path.

(b) Dating of P- and T-peak: In many geological units petrological work argues that both P-and T-peak more or less coincide in the course of metamorphism or can not be differentiated. Thus metamorphic zircon domains or entire zircon crystals formed during partial melting in leucosomes would reflect peak-T conditions close to the P-peak. As it is known for a long time that U-Pb zircon systems can remain closed at T > 1,100°C (e.g. Gebauer, 1990), the blocking temperature concept can not be applied for zircons from metamorphic rocks. Recent CL-based SHRIMP-data allowed even to differentiate between the ages of the P- and T-peaks of eclogite facies rocks (Liati & Gebauer, 1999). This is due to the prograde release of fluids (breakdown of paragonite) at or shortly before the P-peak triggering a reorientation of zircon lattices and therefore resetting of ages. The T-peak follows with an analytically significant time gap of ca. 2 Ma and is based on the new formation of zircon in leucosomes within the *in situ* metamorphosed orthogneisses under granulite facies conditions (Liati & Gebauer, 1999). Dating the T-peak of ultramafic rocks (Gebauer, 1996; Ordóñez *et al.*, submitted paper) may be done by dating of HP or UHP melts, e.g. pyroxenites or primary magmatic eclogites.

(c) Dating of retrograde metamorphism: This can be achieved by CL-based SHRIMP-dating of zircon domains, but it is usually restricted to metamorphic stages only at or above amphibolite facies conditions. At lower T, conventional cooling ages of mainly amphiboles and micas as well as fission track ages are used. However, retrograde zircons that formed newly at ca. 300°C by precipitation from late metamorphic fluids at the end of the tectono-metamorphic cycle can be also used to date late stages of retrograde metamorphism. This was successfully done for zircons from late, undeformed pegmatoids crosscutting the metamorphic rocks of the Rhodope HP terrain in N Greece (Gebauer & Liati, 1997; Liati & Gebauer, 1999). The arising ages were in very good agreement with K-Ar biotite ages (Liati & Kreuzer, 1990).

Taking published thermobarometric data as well as zircon domain SHRIMP-data, subduction speeds and heating rates were determined for the first time in geochronological research. Values of ca. 1-3 cm/y (10-30 km/Ma), resp. 30-94°C/Ma were found for the Sesia Zone, the Zermatt ophiolites (both Western Alps) and the Rhodope (N Greece).

Exhumation and cooling rates including rocks from Ronda (Spain; Sánchez-Rodríguez & Gebauer, in press), Rhodope (Liati & Gebauer, 1999), Dora Maira (Western Alps; Gebauer *et al.*, 1997), Alpe Arami (Central Alps; Gebauer, 1996), Cima di Gagnone (Central Alps; Gebauer, 1994) and the Kaghan eclogites (Himalaya; Spencer & Gebauer, 1996) vary from 0.5-4.2 cm/y, resp. 50°C-130°C/Ma (with the exception of Ronda where cooling rates reach 340°C/Ma). Interestingly, exhumation rates are significantly higher for early exhumation of HP- and UHP rocks from mantle depths. This applies not only for felsic rocks, but also for mafic/ultramafic rocks arguing that the latter must have been attached to deeply subducted, buoyant continental crust.

For all rocks cited, the corresponding PTt-paths above 300°C were completed within ca. 9-30 Ma. Thus, mass transfer during subduction/exhumation closely follows typical speeds of plate motions. Together with the observed heating and cooling rates, existing models on the speed of mass and heat transfer need to be revised to fit the above age constraints.

Generally, it is much more likely that many orogens formed by one or more short lasting (ca. 10-30 Ma) rather than one or more prolonged subduction-collision cycles. This is also much better in tune with the presumed widths of oceans and presently observed speeds of plate motions.

METAMORPHIC EVOLUTION AND ORIGIN OF ALLOCTHONOUS COMPLEXES FROM THE NW IBERIAN MASSIF: FROM CONTINENTAL GONDWANA AND OPHIOLITIC BASAL UNITS TO AVALONIAN UPPER REGIONAL ALLOCHTHON. RESULTS AND PERSPECTIVES

J. I. GIL IBARGUCHI [1], B. ÁBALOS [2], C. PIN [3], J. L. PAQUETTE [3], M. MENDIA [1], F. SANTOS [1], P. PUELLES [1] & J. RODRÍGUEZ [1]

[1] Depto. de Mineralogía y Petrología. Univ. del País Vasco. Aptdo. 644. E-48080 Bilbao. Spain.
[2] Depto. de Geodinámica. Univ. del País Vasco. Aptdo. 644. E-48080 Bilbao. Spain.
[3] Département de Géologie. CNRS UMR 6524. Université Blaise Pascal. 5, rue Kessler. F-63038 Clermont-Ferrand. France.

Allochthonous complexes from the NW Iberian massif comprise:

1. A composite upper regional allochthon with metasediments and orthogneisses, eclogites, HP granulites and garnet-bearing ultramafic rocks. High-pressure rocks formed during an episode at 390-400 Ma from protoliths of Cambrian age or older, except for some of the ultramafic protoliths which appear to be distinctly younger (395-400 Ma). The more reliable reconstructions suggest that this allochton represents fragments of the Avalonian plate including portions from different structural levels of an active margin together with parts of the subducted intervening ocean (Rheic).

2. Underlying ophiolitic units formed around ca. 395 Ma record prograde metamorphism and deformation at ca. 380-390 Ma. This might be related to the progressive closing of that ocean and associated obduction of overlying eclogitic/granulitic massifs.

Ophiolite and Avalonian units were incorporated subsequently into the Gondwana continent through processes related to the Hercynian collision.

3. Remnants of the former passive margin of Gondwana continent form the lowermost regional allochthon. These were affected by HP metamorphism from ca. 360 to 340 Ma. These events mark the beginning of the continental accretion and blocking of subduction/obduction processes that preceded intracontinental Hercynian activity s. str. within the Iberian massif. Diachronism of HP metamorphism and marked regional variations in PT conditions suggest subduction processes in relation to an oblique collision.

Earliest deformation phases occurred at different moments within each domain. Yet, deformation regimes operative in the deepest HP metamorphic units (eclogites, HP granulites, Grt-bearing ultramafites) are characterized by regionally consistent stretching lineations subparallel to the orogenic trend and to associated isoclinal and sheath folds. The observed structures are consistent with shear zone deformation under HP conditions in one or more subduction realms, and reflect tectonic amalgamation related to eo-Hercynian NNE-directed oblique collision. Earliest deformation phases in foreland tectostratigraphic units should relate to the more or less coeval latest deformation phases recorded in the hinterland (which also occurred in shallow structural levels), instead of to the much older and deeper seated earliest ones.

MIDDLE CAMBRIAN CORRELATION IN THE MEDITERRANEAN SUBPROVINCE AND ITS PALAEOGEOGRAPHICAL CONSEQUENCES

Rodolfo GOZALO [1] & Eladio LIÑÁN [2]

[1] Depto. de Geología. Universitat de València. C/ Dr. Moliner, 50. E-46100 Burjasot. Spain. (e-mail: rodolfo.gozalo@uv.es)
[2] Paleontología. Departamento de Ciencias de la Tierra. Universidad de Zaragoza. E-50009 Zaragoza. Spain.

In the Middle Cambrian palaeobiogeography, the Mediterranean Subprovince (*sensu* Sdzuy, 1958, 1972) includes the outcrops of Germany, France, Italy, Spain, Morocco, Turkey, Egypt (Sdzuy *et al.*, 1999) and probably Portugal and Israel. These two last countries, where Middle Cambrian fossils have not been found yet, are included in this subprovince because geological characteristics and inferred palaeogeographical positions.

In recent papers, the biostratigraphical nomenclature proposed for Spain by Liñán *et al.* (1993) has been widely applied to Germany, France, Turkey and Sardinia. The analysis of the Middle Cambrian trilobite assemblages, from different localities of the Mediterranean area, and their comparison with the Spanish data have permitted us to propose new lines of correlation, in order to study the palaeogeographical evolution of the Mediterranean subprovince during Middle Cambrian times. The main point of correlation are the FADs of *Eoparadoxides mureroensis*, *Eccaparadoxides sdzuyi*, *Eccaparadoxides asturianus*, *Badulesia tenera*, *Pardailhania hispida*, *Solenopleuropsis ribeiroi* and *Bailiella levyi*, all included in the Leonian and Caesaraugustan Stages.

From late Lower Cambrian (Bilbilian) to early Middle Cambrian (Leonian) times, important carbonate facies developed in a central area of the Mediterranean region (including the Cantabrian Mountains, Montagne Noire, Sardinia and Turkey). It was surrounded by a peripheral area mainly occupied by siliciclastic facies, which included the Anti Atlas, High Atlas, Ossa-Morena, and Germany (Sdzuy *et al.*, 1999).

This carbonate sedimentation persisted in the Cantabrian Mountains, Sardinia and Turkey during most of the time of the Caesaraugustan Stage, and it was finally replaced by mainly siliciclastic facies from Upper Caesaraugustan to Upper Cambrian times. The lithostratigraphical boundaries are diachronous in most of the sequences considered herein.

Both Middle Cambrian trilobite faunas and facies of the Mediterranean Subprovince are analysed to propose a new palaeogeographical model.

Acknowledgements: we acknowledge the support from the Spanish Dirección General de Estudios Superiores Project PB96-0744, and Departamento de Educación y Cultura del Gobierno de Aragón. This paper is a contribution to the I.G.C.P. Project 366 "Ecogical Aspects of the Cambrian Radiation".

THE LUSITANIAN-MARIANIC AREA AS A NEW ZONE OF THE HESPERIAN MASSIF. STRATIGRAPHIC ARGUMENTS

P. HERRANZ [1], A. P. PIEREN [2] & M. A. DE SAN JOSÉ [2]

[1] Inst. de Geología Económica, CSIC. Fac. de Ciencias Geológicas, UCM. E-28040 Madrid. Spain.
[2] Depto. de Estratigrafía. Fac. de Ciencias Geológicas, UCM. E-28040 Madrid. Spain.

The boundaries between the Central-Iberian Zone and the Ossa-Morena Zone of the Iberian Massif, were described either in Los Pedroches batholith or in the Badajoz-Córdoba shear zone using different arguments. Based on mainly stratigraphic and palaeogeographic criteria, the definition instead of a new zone of the Iberian Massif is here proposed. The fact is that a zone which northern boundary is at present concealed by the Hercynian Los Pedroches batholith, and which southern zone is the Malcocinado fault shows distinctive main geological features here summarized:

1) The Proterozoic-Middle Cambrian basement is characteristic from the Ossa-Morena Zone. This basement cannot be correlated using several arguments with the Precambrian

rocks outcropping towards the NE of Los Pedroches batholith, even if the higher Alcudian-type sedimentary layers may have a Central-Iberian equivalent.

2) The Palaeozoic sequences younger than Middle/Upper Cambrian, present between the Malcocinado fault and the Pedroches batholith, have clear Central-Iberian affinities, and do not have anything in common with those of SW Ossa-Morena. With the exception of the Silurian, a persistent palaeogeographic high is marking a boundary in the core of the proposed zone, migrating in a parallel mode through time.

3) The proposed new Lusitanian-Marianic Zone shows more distinctive properties to be recognised as an independent entity, than other traditionally distinguished zones i.e. the Cantabrian, West Asturian-Leonese or Central Iberian, whose boundaries do not correspond to such significant palaeogeographic features as those from the zone here proposed.

The Cadomian unconformity of Thuringia and Lusatia, Germany: some biostratigraphical aspects

Thomas Heuse

Museum für Mineralogie und Geologie Dresden. Königsbrüker Landstraße 159. D-01067 Dresden. Germany.

Schwarzburg anticline (Thuringia).
The Schwarzburg anticline constitutes the type section of the German lower Palaeozoic (Ordovician-Lower Carboniferous) and consists of low grade metamorphic rocks overprinted by Variscan collision tectonics during the Early Carboniferous.

The Neoproterozoic successions (Cadomian basement) and the lower Palaeozoic sections of the Schwarzburg anticline were first described by von Gaertner (1932, 1934, 1944) and modified by Falk & Lützner (1991), Ellenberg *et al.* (1992), Lützner *et al.* (1986), and recently revised by Falk, Lützner and Mann in a stratigraphical compilation made by the German Commission on Stratigraphy (Stratigraphische Kommission Deutschlands, 1997).

Traditionally, and in comparison to the Barrandean sequences (Bohemia), the greywackes of the Katzhütte and Frohnberg Groups were lithostratigraphically correlated with the Precambrian, the Goldisthal Formation with the Cambrian and the Frauenbach Group with the Tremadoc. Von Gaertner (e.g. 1944) postulated an Assynthian (now Cadomian) unconformity between the Neoproterozoic greywackes and the overlying Goldisthal Formation whereas a concordant Proterozoic/lower Palaeozoic transition was favoured by Ellenberg, Falk and Lützner in the above mentioned publication.

The concept of concordant Proterozoic/lower Palaeozoic transition was first contradicted by the discovery of Upper Cambrian/lower Ordovician acritarchs in equivalents of the Goldisthal Formation on the northwest flank of the Schwarzburg anticline (Estrada *et al.*, 1994). Based on a comparison of relative sea level fluctuations of the lower Ordovician sequences from the Schwarzburg anticline and from the deep drilling 5507/77 near Gera, Linnemann & Buschmann (1995) opted for a Tremadoc age of the Goldisthal Formation.

Stratigraphy.
So far, no reliable biostratigraphical data exist from the Frohnberg Group. Lyddites from the underlying Katzhütte Group yielded poorly preserved acritarch assemblages considered to be indicative for a Late Vendian age (Heuse, 1989). This biostratigraphical date was recently confirmed by single zircon geochronology ($^{207}Pb/^{206}Pb$) of a granite pebble with an age of approximately 576 Ma by Linnemann *et al.*, (1998).

A poorly preserved Upper Cambrian to lower Ordovician acritarch association from the overlying Goldisthal Formation of the northwest flank of the Schwarzburg anticline was described by Heuse (*in* Estrada *et al.*, 1994). Recently, single zircon data were presented by Gehmlich *et al.* (1997, 1998). The age of the deformed Cadomian basement was fixed by granite intrusions at 538±3 Ma (Gehmlich *et al.*, 1997). The Blambach rhyolite at the base of the Goldisthal Formation was dated as 487±5 Ma. Thus the sedimentation of the Goldisthal Formation must be younger than 487±5 Ma and probably started in the Tremadoc.

Although significant palynodata are still missing from the underlying Frohnberg Group, and consequently this sequence may reach into the Early Cambrian, a stratigraphical hiatus between the Frohnberg Group and the overlaying Goldisthal Formation is obvious, probably covering the entire Cambrian Period (Cadomian unconformity).

The Goldisthal Formation is overlain by the Frauenbach Group. Inarticulate brachiopods from the Oberer Frauenbachquarzit Formation near Siegmundsburg reported by Loretz (1880), Koliha (1926), v. Gaertner (1944), Falk (1956) and Müller (1956) have been identified by I. Puura (pers. comm., 1998) as *Hyperobolus feistmanteli* (Barrande, 1879). In the Prague Basin this species occurs in the upper part of the Trenice Formation (Havlícek, 1982; Havlícek & Fatka, 1992). Recent single zircon data from the Bärentiegel-Porphyroid (Oberer Frauenbachquarzit Formation, 479±5 Ma; Gehmlich *et al.*, 1997) made a late Tremadoc age as very probable.

Lausitz Anticline (Lusatia).
The area of the Hohe Dubrau (Lausitz anticline) constitutes the type locality of the Cadomian unconformity in the Saxo-Thuringian Terrane (Linnemann & Buschmann, 1995). Tremadoc conglomerates, quartzites and silty shales are overlying tectonically folded Cadomian greywackes.

The sedimentation age of the Cadomian greywackes in Lusatia (Lausitz Group) has been under discussion for a long time. From thermally metamorphosed greywackes, Timofeev (1958) first described three new acritarch species which were reportedly indicative of an Early or Middle Cambrian age. Later the palynomorphs were regarded as laboratory contaminations by Burmann (1966, 1969). Succeeding investigations on the material originally studied by Timofeev led to a Precambrian (probably Vendian) age-determination (Burmann, 1966, 1969, 1972; Weber *et al.*, 1990).

The first single zircon evaporation ages from an ash layer (Wüsteberg tuff) with 564±4 Ma were published by Gehmlich *et al.* (1997) and interpreted as the sedimentation age of the Lausitz Group.

The first findings of inarticulate brachiopods from the superimposed Dubrauquarzit Formation by Geinitz (1873) were considered as unidentifiable by Koliha (quoted in Schwarzbach, 1934: 409). Recently, inarticulate brachiopods from the Dubrau quartzite have been identified by I. Puura (pers. comm., 1998) as *Westonisca arachne* (Barrande, 1879). This species has been described from the Bohemian Trenice Formation as *Lingulella arachne* and *L. variolata* by Barrande (1879) and Koliha (1924), and revised by Havlícek (1982) as *Westonisca arachne*.

Summary.
The biostratigraphical data, now confirmed by new geochronological informations corroborate the existence of a stratigraphical hiatus (Cadomian unconformity) above the Upper Proterozoic Thuringian and Lusatian greywackes, perhaps covering the entire Cambrian Period.

Laramide-style subduction of a Rheic Ocean plume: evidence from the Palaeozoic evolution of Maritime Canada

J. Duncan Keppie [1] & J. Brendan Murphy [2]

[1] Instituto de Geología. Universidad Nacional Autónoma de México. 04510 México, D.F. Mexico.
[2] Department of Geology. St. Francis Xavier University. Antigonish, Nova Scotia, B2G 2W5. Canada.

Previous work has shown that the Iapetus Ocean closed during the Ordovician and its vestiges were covered by the late Ordovician-Early Silurian Appalachian overstep sequence which extended from the Laurentian miogeocline to the Avalon terrane (Chandler *et al.*, 1987). This interpretation is supported by faunal linkages (Williams *et al.*, 1995), the first appearance of Laurentian Nd signatures in earliest Silurian sediment of the Avalon terrane (Murphy *et al.*, 1995), and the age of accretionary deformation (Keppie, 1993). However, the location of the Meguma terrane at this time is controversial. The Meguma terrane represents a Palaeozoic passive margin sequence that bordered either the southern margin of Avalonia (e.g. Keppie & Dostal, 1991) or northwest Africa until it was accreted to eastern Laurentia during the Devonian (e.g. Schenk, 1981). This has important consequences for (a) the location of the Rheic Ocean suture: either south of the Meguma terrane or along the Minas Fault between Avalon and Meguma terranes, respectively; and (b) the tectonic interpretation of the Acadian orogeny as either a Pacific-type orogeny or a collisional event between eastern Laurentia and NW Africa. Siluro-Devonian palaeomagnetic data show three different apparent polar wander paths that allow either possibility (Van der Voo, 1993).

The Meguma terrane consists of Cambro-Ordovician turbidites (Meguma Group) overlain by Silurian-Early Devonian (White Rock and Torbrook Formations) and Carboniferous shallow marine and continental rocks that occur mainly along the northwestern margin of the Meguma terrane. Poor age constraints in the Silurian part of the sequence have hampered detailed correlations with other Appalachian units. A new U-Pb nearly concordant zircon age at the base of the White Rock Formation yielded an age of 442±4 Ma (Keppie & Krogh, in review) straddling the Ordovician-Silurian boundary (Tucker *et al.*, 1990). This allows a detailed comparison between Siluro-Devonian units in the Meguma and Avalon terranes, which shows the following close similarities: (a) both have latest Ordovician-earliest Silurian, bimodal, subaerial, alkalic-tholeiitic, volcanic rocks extruded in an extensional environment, and with Nd isotopic data indicating a similar source (Keppie *et al.*, 1997); (b) both have Siluro-Devonian shallow marine sequences that switch from deepening to shallowing in the Ludlow and become subaerial in the Pragian (Schenk, 1995; Boucot *et al.*, 1974); and (c) both contain Rhenish-Bohemian Lower Devonian fauna (Boucot, 1975). This suggests that the White Rock Formation formed part of the Appalachian overstep sequence. This is supported by the SE to NW transition from an offshore sandbar to a beach sand in the White Rock Formation (Lane, 1976), and the continental basement source for the White Rock volcanic rocks (Keppie *et al.*, 1997). It is concluded that the Meguma terrane is underalin by Avalonian basement and forms the passive margin on the southern side of the Avalon terrane and that the Rheic suture lies south of the Meguma terrane.

Following Devonian deformation (*400-377 Ma, $^{40}Ar/^{39}Ar$ plateau ages; Keppie & Dallmeyer, 1987, 1995) of the Meguma terrane, voluminous granitic magmatism occurred between 380 and 370 Ma (Keppie & Krogh, in review). An Avalonian source is suggested by U-Pb upper intercepts of *660 Ma and *732 Ma (Keppie & Krogh, in review) and Pb isotopic data (Ayuso *et al.*, 1996). This was accompanied by intrusion of lamprophyre dykes (Clarke *et al.*, 1997), regional low pressure metamorphism (Keppie & Dallmeyer, 1995), and gold mineralization (Kontak *et al.*, 1990), followed by rapid denudation of 5-10 km (Keppie & Dallmeyer, 1987, 1995). These observations may be interpreted as the overriding of a mantle plume by the Laurentian margin (including the Avalon and Meguma terrane). Thermal erosion and penetration of the subducted oceanic lithosphere by the plume leads to rapid melting of the continental lithosphere producing voluminous granitoid magmatism in the Meguma terrane, coeval high temperature/low pressure metamorphism and gold mineralization (Murphy *et al.*, 1998, in press). Northward migration of the plume explains the diachronous magmatism occurring in the Cobequid Highlands (Avalon terrane) at *360 Ma, and the mid-Carboniferous plume-related intrusions around the Magdalen Basin (Pe-Piper & Piper, 1998). The beheaded top of the plume may be recorded by the 10-20 km thick high density lens at the base of the crust beneath the Magdalen Basin (Marillier & Verhoef, 1989). Cooling of this lens provides a mechanism for the sinking of the Magdalen Basin. Subduction of a plume also provides a viable mechanism for the Siluro-Devonian Acadian orogeny by analogy with the Laramide orogeny in the western United States of America (Murphy *et al.*, 1998, in press). It is inferred that flattening of the Benioff zone related to subduction of a mantle plume led to termination of arc-related magmatism in the Avalon terrane followed by a period of relative magmatic quiescence, and diachronous migration of the Acadian deformation front across the Appalachian orogen from *415 Ma in the southeast to *370 Ma in the northeast (Keppie, 1995; Robinson *et al.*, 1998). Such a model for the Acadian orogeny suggests that the Rheic Ocean survived into the Carboniferous, outboard from the Meguma terrane.