The late-Precambrian geodynamic evolution of the Armorican segment of the Cadomian belt (France):

Distortion of an active continental margin during south-west directed convergence and subduction of a bathymetric high*

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L'évolution géodynamique à la fin du Précambrien du segment armoricain de la chaîne cadomienne (France) : déformation d'une marge continentale active pendant une convergence vers le sud-ouest et une subduction d'un relief bathymétrique

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Key Words: Cadomian Orogeny, Terranes, Models, Geodynamics, Plate convergence, Subduction, Armorican massif.

Abstract

Within the Cadomian belt, the North Armorican composite terrane (NACT) records late-Precambrian subduction-related magmatism and accretionary tectonism at an active continental margin. The NACT comprises four terrane elements separated by steeply-dipping ductile shear zones and brittle faults. From north to south these elements are: the Trégor-La Hague terrane (TLHT), a continental arc; the St. Brieuc terrane (SBT), an intra-arc basin; and the St. Malo (SMT) and Mancellian (MT) terranes, representing behind-arc marginal-basin to within-plate basin settings. U-Pb, Pb-evaporation, $^{40}Ar/^{39}Ar$, and selected Rb-Sr whole-rock and mineral ages imply a complex, polyphase tectonothermal history for the Armorican segment of the Cadomian belt. The generally southward-younging inferred age of sedimentation of Brioverian supracrustal sequences and age of major tectonothermal events from terrane to terrane records regionally diachronous and hinterland-propagating orogenic deformation. As the plate-boundary zone started to deform, sinistral oblique subduction was partitioned into contractional and strike-slip components in the TLHT, but inboard intra-arc extension, volcanism and syn-orogenic sedimentation continued. These features are interpreted to reflect a singularity at the obliquely convergent plate-boundary zone, such as the entry into the trench of an ocean floor bathymetric high. A model is developed in which it is proposed that an aseismic ridge or young oceanic island arc impinged upon the trench at c. 610 Ma. Subduction of this feature led to tectonic segmentation of the continental margin, regional sinistral transpression, terrane accretion and progressive distortion of the continental margin as deformation propagated inboard. Moderate thickening of the behind-arc marginal-basin sequence, supplemented by advection of mantle-derived magma, resulted in intracrustal melting to generate the St. Malo migmatites. Further inboard, the Mancellian granites were emplaced into a structurally simple, upper crustal environment. Higher heat flow to generate these magmas may reflect extension during the interval c. 570-540 Ma in the zone peripheral to the collision of the bathymetric high with the trench, as well as advection of mantle-derived magma. Subsequent inboard propagation of the deformation at c. 540 Ma reflects weakening of the crust during anatexis and accommodation of sinistral transpression by migration of melt upward to higher structural levels.

Version française abrégée

L'évolution géodynamique du segment armoricain de la chaîne cadomienne à la fin du Précambrien a été interprétée comme une agglomération de complexes d'arc continental calco-alcalin, de complexes associés de bassin intra-arc et de séquences allant de bassin marginal d'arrière arc jusqu'au bas-

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sin intra-plaque, dans une zone de convergence oblique en limite de plaques le long de la marge nord du supercontinent du Gondwana (par exemple Cogné et Wright, 1980 ; Graviou et al., *1988 ; Strachan* et al., *1990). Bien que le magmatisme, le métamorphisme et la déformation de la chaîne cadomienne englobent toute la période allant de la fin du Néoprotérozoïque à l'Ordovicien-Silurien (tabl. 1), le modèle géodynamique présenté dans ce document concerne la période 610-530 Ma environ dans la région située entre Belle-Isle-en-Terre et Caen (fig. 1).*

Dans cette région, la zone de cisaillement nord armoricaine (NASZ) sépare des éléments du "terrane" composite nord armoricain (NACT), composé de bassins sédimentaires et volcaniques du Briovérien à structure inversée et déformée au cours de l'orogenèse cadomienne, du "terrane" centre armoricain (CAT) dans lequel la principale déformation et le métamorphisme régional des séries sédimentaires briovériennes sont varisques. Il est probable que le NASZ représente une structure cadomienne majeure, réactivée ultérieurement au cours de l'orogénèse varisque (cf. Watts et Williams, 1979). Le NACT comprend quatre blocs qui sont séparés par des cisaillements ductiles et subverticaux et des failles cassantes (fig. 1). Du Nord au Sud, se trouvent les "terranes" du Trégor-La Hague (TLHT) et de Saint-Brieuc (SBT) de type arc, qui sont séparés par la zone de cisaillement sénestre décrochante de la Fresnaye (FSZ) des "terranes" malouin (SMT) et mancellien (MT) à caractère de bassin marginal d'arrière-arc ou de bassin intra-plaque (fig. 1). Les âges U-Pb sur zircon et sur monazite (par exemple Guerrot et Peucat, 1990), ceux obtenus sur monozircon par évaporation (par exemple Guerrot et al., *1994), les âges* $^{40}Ar/^{39}Ar$ *de refroidissement sur minéraux (Dallmeyer* et al., *1991a, b, 1992a, 1993, 1994 ; D'Lemos* et al., *1992b ; Ruffet et al., 1991), certains âges Rb-Sr sur roche totale et minéraux (Autran* et al., *1983 ; Bland, 1984 ; Guerrot et Peucat, 1990) indiquent une évolution thermo-tectonique cadomienne polyphasée et complexe (tabl. 1).*

Dans le TLHT, à Guernesey, les âges U-Pb sur zircon des diorites quartziques déformées ont été interprétés comme manifestant leur cristallisation autour de 700 Ma (Dallmeyer et al., *1991a, 1992b), mais ils peuvent aussi être interprétés comme manifestant une cristallisation plus proche de 600 Ma (Auvray* et al., *1992). Ces stocks de diorites quartziques se sont mis en place, de façon syn-cinématique, pendant le cisaillement régional (Tribe* et al., *1994), et les âges d'environ 610-595 Ma obtenus par corrélation isotopique* $^{40}Ar/^{39}Ar$ *sur hornblende pour ces roches et les amphibolites encaissantes sont interprétés comme manifestant le refroidissement régional postérieurement à la déformation et au métamorphisme (Dallmeyer* et al., *1991a). Le magmatisme d'arc continental, à peu près contemporain, est représenté dans le Trégor par le batholite nord-trégorrois daté à* 615^{+13}_{-7} *Ma (U-Pb sur zircon ; Graviou* et al., *1988) ; les âges* $^{40}Ar/^{39}Ar$ *d'environ 605-600 Ma sur biotite indique que le refroidissement régional était également du même âge que celui de Guernesey (Ruffet* et al., *1991). A l'intérieur du SBT, les âges U-Pb et ceux obtenus sur monozircon, par évaporation semblent indiquer une cristallisation des complexes calco-alcalins dans l'intervalle de 750-650 Ma et de 600-585 Ma environ (Guerrot et Peucat, 1990 ; Guerrot* et al., *1994). Les âges* $^{40}Ar/^{39}Ar$ *de refroidissement à 570-565 Ma, obtenus sur les minéraux de l'intrusion dioritique/quartzique tardi-à post-tectonique et sur les roches supracrustales métamorphisées indiquent que le refroidissement post-métamorphique, qui a suivi la déformation transpressive et le transport tectonique vers le sud ou le sud-ouest (Brun et Balé, 1990 ; Le Goff* et al., *1994), était d'environ 30 Ma plus jeune dans le SBT que dans le TLHT (Dallmeyer* et al., *1991b).*

Bien qu'elle ne soit pas aussi bien contrainte, la succession chronologique des événements plutoniques cadomiens à La Hague montre des similitudes avec les événements dans le STB et semble indiquer une transition du TLHT au SBT à La Hague. Notre interprétation est que ces deux "terranes" ont formé une unité tectonique latéralement continue, représentant un arc magmatique et un bassin intra-arc se développant avant que ne commence leur séparation autour de 610 Ma. Le soulèvement et l'exhumation de l'arc magmatique interviennent à une époque contemporaine de la période principale de volcanisme et de sédimentation dans le bassin intra-arc.

Par opposition, le SMT et le MT se caractérisent respectivement par des migmatites dérivées par anatexie d'une série de bassin marginal (SMT) et de plutons granitiques d'origine intracrustale mis en place dans les niveaux supérieurs d'une séquence plus distale de bassin intra-plaque (MT) (Darlet et al., *1990 ; Dabard, 1990 ; Brown* et al., *1990 ; Brown et D'Lemos, 1991 ; D'Lemos et Brown, 1993). Le contraste géologique entre le TLHT/SBT et le SMT/MT se manifeste également dans leur signature géophysique (Brun et Balé, 1990), qui indique que le FSZ est une structure cadomienne majeure, certainement active à partir de 570 Ma environ et vraisemblablement active auparavant (cf. Brun et Balé, 1990). Cependant, il n'y a pas d'argument convaincant pour que le FSZ représente le site de la subduction cadomienne, dirigée vers le nord, comme l'implique le modèle de P. Graviou (1992). A l'intérieur du SMT, des âges U-Pb sur zircon et monazite, et les âges Rb-Sr sur roche totale d'environ 540 Ma ont été obtenus sur le granite d'anatexie intrusif dans les migmatites de Saint-Malo (Peucat, 1986), ceci en accord avec un âge obtenu sur monozircon, par évaporation sur le granite de Cancale (Guerrot* et al., *1994). Des âges sur monazite allant de 550 à 540 Ma ont été mis en évidence pour le complexe granitique de Vire-Carolles dans le nord du MT (Pasteels et Doré, 1982), bien qu'un âge Rb/Sr de 521±11 Ma, par isochrone sur roche totale et minéraux légèrement plus jeune, ait été mis en évidence pour le granite de Fougères (complexe granitique de Louvigné-Gorron) au sud du MT (Autran* et al., *1983) , ce qui est compatible avec les âges plateau* $^{40}Ar/^{39}Ar$ *sur muscovite d'environ 525 Ma du complexe granitique de Bonnemain à l'ouest du MT, interprétés comme symptomatiques du refroidissement post-magmatique (Dallmeyer* et al., *1993). La mise en place des granites*

dans le SMT et le MT accompagne la transpression sénestre régionale (Strachan et al., *1989 ; D'Lemos* et al., *1992a).*

L'âge probable de la sédimentation des séquences briovériennes est de plus en plus jeune vers le sud, de "terrane" en "terrane", ce qui est en accord avec le modèle de rajeunissement des principaux événements thermo-tectoniques à l'intérieur du segment armoricain de la chaîne cadomienne. Ces caractéristiques sont interprétées comme enregistrant la déformation orogénique, diachronique à l'échelle régionale, qui se propage dans l'arrière-pays à travers une zone de limite de plaques à convergence oblique. Le refroidissement post-métamorphique pendant l'intervalle 610-595 Ma dans le THLT est interprété comme manifestant le soulèvement et l'exhumation associés à une accrétion progressive de ce segment d'arc contre le bassin intra-arc du SBT, au cours de la déformation transpressive régionale qui est associée à un système de failles décrochantes parallèles à l'arc, qui lui-même se déformait progressivement. Cette déformation est interprétée comme étant une réponse à une certaine singularité le long de la limite des plaques, telle que l'entrée dans la fosse d'un relief bathymétrique, par exemple une dorsale asismique ou un arc insulaire jeune. La propagation vers l'arrière pays de la déformation résulterait de l'anomalie provoquée par la subduction de ce relief.

Le TLHT et le SBT ont suivi une histoire commune concernant le magmatisme calco-alcalin post-tectonique, daté autour de 570 Ma. Le refroidissement post-métamorphique, environ 570-565 Ma dans le SBT, est considéré comme reflétant le soulèvement et l'exhumation dus à une accrétion progressive des "terranes" composites THLT/SBT avec les unités du bassin d'arrière arc et du bassin intra-plaque, représentées par les "terranes" composites SMT/MT. La déformation liée à cette accrétion a conduit à une inversion du bassin, qui a entraîné la déformation polyphasée dans le SMT, et ultérieurement le développement d'une phase de plis redressés à schistosité subverticale dans le MT (Brown et D'Lemos, 1991). Les observations structurales, pétrographiques, géochimiques et isotopiques semblent indiquer que le SMT et le MT représentent différents niveaux structuraux d'une même unité tectonique (Brown et D'Lemos, 1991 ; D'Lemos et Brown, 1993). D'après le modèle de P.-Y. F. Robin et A.R. Cruden (1994), un cisaillement simple transcurrent dans la croûte inférieure pourrait être lié par des décollements sub-horizontaux dans la croûte centrale à des zones faillées verticales mais courbes dans la croûte supérieure (MT). L'absence de preuve d'un épaississement crustal important au cours de l'orogénèse cadomienne implique que l'activité orogénique n'a pas culminé dans une collision continent/continent. Ceci est en accord avec l'interprétation de la chaîne cadomienne comme étant un orogène périphérique situé en bordure d'un supercontinent précambrien (Murphy et Nance, 1991 ; Nance et Murphy, 1994). Un flux de chaleur plus fort à travers la lithosphère distendue pourrait avoir facilité l'anatexie pendant la relaxation thermique des séries de bassin marginal à structure inversée et sans épaississement important.

Cependant, un surcroît advectif de chaleur dû à des intrusions sous-crustales ou intra-crustales de basalte riche en alumine, mises en évidence par des complexes basiques de petit volume à la fois dans les SMT et le MT, a été vraisemblablement nécessaire, en particulier pour générer le volume de granites mancelliens.

Dans le MT, l'extension et la sédimentation ont continué après 570 Ma, synchrones de l'inversion structurale dans le SMT. L'anatexie dans le SMT et à des niveaux plus profonds dans le MT a facilité la transpression sénestre, la déformation étant, au moins en partie, accomodée à la variation de volume due au transport de magma des zones profondes anatectiques vers les niveaux crustaux plus élevés.

Un modèle géodynamique pour l'évolution à la fin du Précambrien, du segment armoricain de la chaîne cadomienne est développé pour expliquer les caractères géologiques, ainsi que la nature diachronique et la migration spatiale de la déformation orogénique. Le modèle suppose la collision d'un relief du plancher océanique, tel qu'une dorsale asismique ou un jeune arc insulaire, au niveau de la fosse océanique le long de la limite des plaques, à environ 610 Ma.

La segmentation des domaines crustaux allant du bassin marginal et du bassin d'arrière arc jusqu'au bassin intra-plaque, en éléments de "terrane" distincts mais géologiquement associés, ainsi que leur accrétion diachronique subséquente en un unique "terrane" composite, est une conséquence de la subduction de ce relief et son effet progressif sur le champ de contraintes lors de la courbure de la marge continentale. L'accrétion de "terranes" exotiques et éloignés n'est pas nécessaire pour expliquer les éléments affleurants du segment armoricain de la chaîne cadomienne. Le modèle explique à la fois le diachronisme dans l'accumulation des sédiments et l'évolution thermo-tectonique allant du nord au sud, et de "terrane" en "terrane", ainsi que la configuration cartographique des "terranes" qui s'amincissent en se biseautant vers le sud-ouest lorsqu'ils s'incurvent autour de l'arc d'Yffiniac au fond de la Baie de Saint-Brieuc. Par ailleurs il apporte une explication appropriée du métamorphisme HT-BP et des granites cadomiens intracrustaux, qui précédemment, manquait aux modèles proposés pour ce segment de la chaîne cadomienne.

Introduction

Exposed within the northern part of the Armorican Massif of western France, the Armorican segment of the Cadomian belt is a key component in understanding the geology of western Europe, because here the Variscan overprint either is relatively weak, and easily separated from the Cadomian history (e.g. Dissler and Gresselin, 1988; Dallmeyer *et al.*, 1993, 1994), or has been too feeble to record any imprint, at least to the east of Belle-Isle-en-Terre (Figure 1). For this reason, the Armorican segment of the Cadomian belt has been the subject of renewed research interest during the past twenty-five years, research that has generated a substantial set of data on the basis of which realistic geodynamic models now may be proposed and tested. The development of regional models contributes to our understanding of the wider Avalonian-Cadomian orogenic cycle of the North Atlantic region.

One important advance during the past decade has been the accumulation of kinematic information that allows assessment of orogenic transport directions, and this has been coupled with the recognition of the role of major sinistral strike-slip shear zones within the Cadomian belt, particularly in its eastern part (e.g. Balé and Brun 1989; Treloar and Strachan, 1990). One consequence of this progress is that simple cross-sections transverse to the strike of the orogenic belt represent snapshots only, and geodynamic models must integrate map, cross-section and temporal data. A second important step forward has been the accumulation of age data likely to have geological significance, in particular ages based on the U-Pb system on zircon or monazite, the $^{40}Ar/^{39}Ar$ incremental heating method on hornblende, muscovite and biotite, the stepwise Pb-evaporation method on single zircons, and selected Rb-Sr whole-rock and mineral ages. There are now sufficient age data to permit the establishment of a reliable sequence of tectonothermal events within the Armorican segment of the Cadomian belt (Table 1). Such information is a prime requirement if useful models are to be developed that reflect sequential stages in the tectonic evolution of this region during the Cadomian. Finally, detailed petrographic and geochemical investigation of magmatic rocks and sedimentary sequences has shed light on the tectonic environment of their emplacement, eruption or deposition (e.g. Cabanis *et al.*, 1987; Lees *et al.*, 1987; Chantraine *et al.*, 1988; Dissler *et al.*, 1988; Brown *et al.*, 1990; Dabard, 1990; Dupret *et al.*, 1990; Rabu *et al.*, 1990; Thiéblemont *et al.*, 1994). This information is vital in providing constraints on possible plate tectonic models.

In this paper, I develop a geodynamic model for the main part of the Cadomian orogenic evolution between c. 610 Ma and c. 530 Ma. My purpose is to understand the basic elements of what happened during this time interval. Once these basic elements are explained, then the model may be modified to accommodate specific details of the regional geology, additional data can be acquired to test its overall validity, and the model may be projected back further in time to include the early arc stage of the Cadomian orogenic cycle.

Structure of the Armorican segment and timing of tectonothermal events

Although the relative role of thrusting vs. strike-slip displacements in the evolution of the rocks exposed around the Baie de St. Brieuc has been the subject of recent debate (Strachan *et al.*, 1989; Brun and Balé, 1990; Treloar and Strachan, 1990; Brun, 1992; Strachan *et al.*, 1992; Le Goff *et al.*, 1994), there is general agreement among these authors and others (e.g. Chantraine *et al.*, 1988; Brown *et al.*, 1990; Dupret *et al.*, 1990; Rabu *et al.*, 1990; Hébert, 1995) that the Armorican segment of the Cadomian belt is comprised of several distinct tectonic units. In one model, the evolution of the Cadomian belt has been interpreted in terms of the consolidation of calc-alkaline continental arc and intra-arc basin complexes with behind-arc marginal-basin to within-plate basin sequences at an obliquely convergent plate-boundary zone along the northern margin of a Gondwana supercontinent (e.g. Cogné and Wright, 1980; Graviou and Auvray, 1985; Graviou *et al.*, 1988; Strachan *et al.*, 1989; Brown *et al.*, 1990). In this model (Figure 1), the North Armorican shear zone (NASZ) separates elements of the North Armorican composite terrane (NACT), composed of Brioverian volcanic and sedimentary basins structurally inverted and deformed during the Cadomian orogeny, from the Central Armorican terrane (CAT) in which the main deformation and regional metamorphism of Brioverian sedimentary sequences were Variscan. I interpret the NASZ to represent a major Cadomian structure subsequently reactivated during the Variscan. M.J. Watts and G.D. Williams (1979) reached a similar conclusion based on penetratively ductilely deformed mylonites overprinted by more brittle structures, including pseudotachylite, which they correlated with brittle structures in shear zones that cut the Variscan Quintin granite.

The NACT comprises four terrane elements, similar to the domains in the perspicacious work of J. Cogné (1962, 1964; Cogné and Wright, 1980), which are separated by steep ductile shear zones and brittle faults. From north to south these include the arc-related Trégor - La Hague (TLHT) and St. Brieuc (SBT) terranes, which are separated by the Fresnaye shear zone (FSZ) from the behind-arc marginal-basin to within-plate basin sequences of the St. Malo (SMT) and Mancellian (MT) terranes. The FSZ records sinistral strike-slip ductile displacement in coastal outcrop (Brun and Balé, 1990; Treloar and Strachan, 1990), and represents a fundamental crustal structure as reflected in both the contrast in surface geology and the contrast in geophysical signature across this zone (Brun and Balé, 1990). However, there is no compelling evidence that the FSZ represents the site of northward-directed Cadomian subduction as implied in the model of P.F. Graviou (1992). Age data (principally U-Pb zircon and monazite ages, ages based on stepwise Pb-evaporation on single zircons, $^{40}Ar/^{39}Ar$ mineral cooling ages, and selected Rb-Sr whole-rock and mineral ages) indicate a complex and polyphase Cadomian tectonothermal evolution (Table 1). The southward younging of major tectonothermal events within the Cadomian belt (Table 1) is interpreted to reflect regionally diachronous and hinterland-propagating orogenic deformation across an obliquely convergent plate-boundary zone, consequent upon some singularity at the trench. Additionally, there is a southward-younging in the inferred age of accumulation of the Brioverian sedimentary sequences found in each of the constituent terranes, and across the NASZ to the CAT (Table 1). Unfortunately, vergence in ages of tectonothermal events and in the depositional age of supracrustal sequences within an orogenic belt are not reliable indicators of the polarity of subduction. For example, within the Mesozoic evolution of the

Andean plate-boundary zone of North Chile, arc plutonic complexes and volcano-sedimentary sequences both young inboard with the same vergence as the polarity of subduction (Grocott *et al.*, 1994), whereas during the Late Cretaceous-Tertiary evolution of the Shimanto accretionary complex in southwest Japan, the age of the sedimentary succession and its time of accretion both young towards the trench in a direction opposite to the polarity of subduction (Agar *et al.*, 1989). However, when age information is combined with sediment provenance studies and geochemical studies of basic volcanic rocks and granitoid plutonic rocks, to determine possible tectonic settings of deposition, eruption or emplacement, then reasonable conclusions about the polarity of subduction during the evolution of ancient orogenic belts often can be reached.

The Trégor-La Hague terrane

Within the TLHT are preserved the only remaining fragments of pre-Cadomian continental crust, the Paleoproterozoic Icartian basement (Calvez and Vidal, 1978; Auvray *et al.*, 1980; Vidal *et al.*, 1981; Piton, 1985). The discontinuous nature of the preserved remnants of the Icartian basement renders reconstruction of the pre-Cadomian continental geology impossible. The metamorphic grade of the Icartian basement prior to the Cadomian orogeny appears to have been amphibolite facies, of moderate- or low-pressure facies series type (Power and Roach, 1971; Velde *et al.*, 1971; Roach and Lees, 1993).

Recent work in the Channel Islands (Tribe *et al.*, 1994) indicates that the Icartian basement has experienced two main phases of metamorphism and deformation, of which the later, dominant deformation was related to the Cadomian orogeny and was coeval with the emplacement of quartz diorite plutons. The grade of Cadomian metamorphism was greenschist to lower amphibolite facies (Tribe *et al.*, 1994). Kinematic information for the dominant deformation (Tribe et al, 1994) in combination with $^{40}Ar/^{39}Ar$ hornblende isotope correlation ages (Dallmeyer *et al.*, 1991a) suggest southward-directed tec-

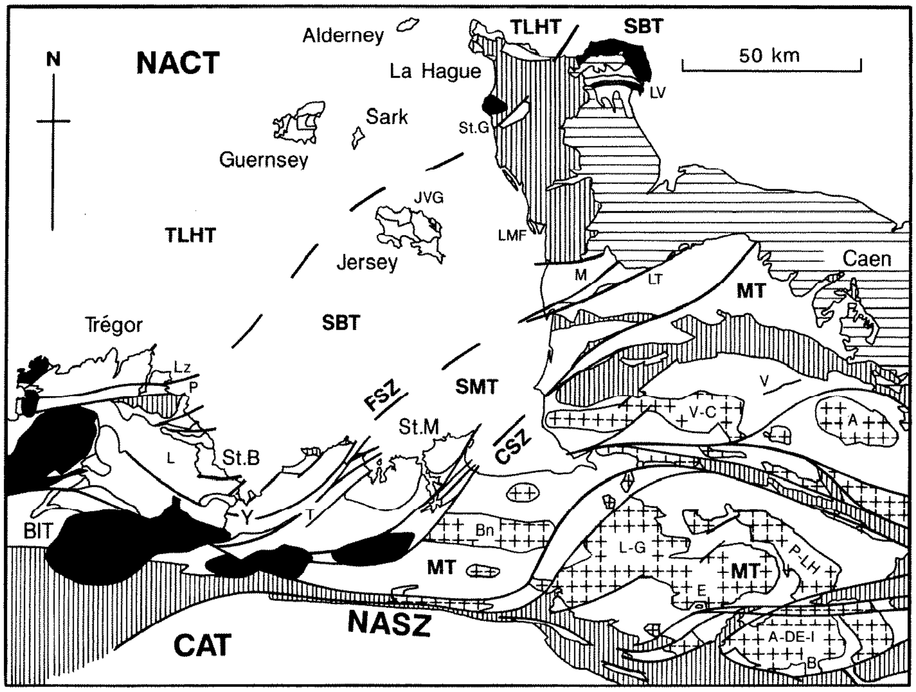

Fig. 1. – Simplified geologic map of the Armorican segment of the Cadomian belt to show the major tectonostratigraphic units, terranes and their bounding shear zones/brittle faults.
The Cadomian geology, including the Icaritan basement, is unornamented (except for the Mancellian granites, which are shown with upright crosses, and two small volcanic units at Le Vast and Vassy, shown in black) and may be keyed by reference to L. Dupret *et al.* (1990), M. Brown *et al.* (1990), J.-P. Brun and P. Balé (1990), and E. Le Goff *et al.* (1994). Post-Cadomian geology is ornamented as follows: Lower Paleozoic sedimentary sequences in vertical rule, Mesozoic sedimentary sequences in horizontal rule and Variscan granites in large areas of black. The North Armorican composite terrane (NACT) is comprised of the Trégor La Hague terrane (TLHT), the St. Brieuc terrane (SBT), the St. Malo terrane (SMT) and the Mancellian terrane (MT) and is separated from the Central Armorican terrane (CAT) by the multiple traces of the North Armorican shear zone (NASZ). N of BIT is the Belle-Isle-en-Terre area. The locations of Cadomian volcanic sequences are as follows: P = Paimpol; L = Lanvollon; V = Vassy; LT = La Terrette; M = Montsurvent; LMF = Les Mortes Femmes; and, LV = Le Vast. Major granite complexes of the MT are as follows: Bn = Bonnemain; L-G = Louvigné-Gorron; A-DE-I = Alexain-Deux Evailles-Izé; P-LH = Passais-Le Horps; V-C = Vire-Carolles; and, A = Athis. The basic complexes at Trégomar (T), Ernée (E) and Brée (B) also are located. Late Cadomian calc-alkaline volcanic successions are located at Lézardrieux (Lz), on Jersey (JVG), and at St. Germain-Le-Gaillard (St.G). Also shown are St. Brieuc (St.B), Yffiniac (Y) and St. Malo (St.M).

Fig. 1. – Carte géologique schématique du segment armoricain de la chaîne cadomienne montrant les principales unités tectonostratigraphiques, les terranes avec leurs éléments limites : zone de cisaillement/failles cassantes.
La géologie cadomienne, comprenant le socle icartien, n'est pas figurée sauf en ce qui concerne les granites mancelliens, qui sont indiqués par des +, et deux petites unités volcaniques Le Vast et Vassy, (indiquées en noir) et peut-être renseignée en se référant à L. Dupret et al. *(1990), M. Brown* et al. *(1990), J.-P. Brun et P. Balé (1990), et E. Le Goff* et al. *(1994). La géologie post-cadomienne est figurée comme suit : séries sédimentaires du Paléozoïque inférieur, hachuré verticalement, séries sédimentaires du Mésozoïque hachuré horizontalement et granites varisques : en large secteur noir. Le "terrane" mixte nord armoricain (NACT) comprend la "terrane" du Trégor-La Hague (TLHT), le "terrane" de St. Brieuc (SBT), le "terrane" malouin (SMT) et le "terrane" mancellien (MT). Il est séparé du "terrane" armoricain central (CAT) par de multiples traces de la zone du cisaillement nord armoricaine (NASZ). N of BIT correspond à la zone de Belle-Isle-en-Terre. Les positions des séries volcaniques cadomiennes sont indiquées comme suit : P = Paimpol ; L = Lanvollon ; V = Vassy ; LT = La Terrette ; M = Montsurvent ; LMF = Les Mortes Femmes ; LV = Le Vast. Les principaux complexes granitiques du MT sont indiqués comme suit : Bn = Bonnemain ; L-G = Louvigné-Gorron ; A-DE-I = Alexain-Deux Evailles-Izé ; P-LH = Passais-Le Horps ; V-C = Vire-Carolles ; A = Athis. Les complexes basiques de Trégomar (T), Ernée (E) et Brée (B) sont également indiqués.*
Les séries volcaniques cadomiennes calco-alcalines sont situées à Lézardrieux (Lz), à Jerzey (JVG) et à St-Germain-le-Gaillard (St G.). Sont également signalés St-Brieuc (St B), Yffiniac (Y) et St-Malo (St M).

	Trégor-La Hague terrane	
(1), (2), (3)	2200-1800 Ma	Icartian basement (Trégor, Guernesey, La Hague)
(4), (5), (6)	?700-610 Ma	Early arc plutonism (Guernsey, ?La Hague)
(7)	c. 615 Ma	Calc-alkaline magmatism (Trégor)
(4), (6), (8)	610-595 Ma	Deformation and metamorphism, post-kinematic plutonism, and regional cooling (Trégor, Gernsey, Sark, ?La Hague)
(8), (9)	570-560 Ma	Post-tectonic calc-alkaline gabbro and diorite complexes, and granites (Guernsey, ?La Hague)
	Cambrian	Ignimbrites des Lézardrieux
	St-Brieuc terrane	
(6), (11)	750-650 Ma	Early arc plutonism (Penthièvre complex ; ?La Hague)
(11)	c. 610 Ma	Tholeiitic volcanism (Paimpol)
	?600-?585 Ma	Brioverian volcanism and sedimentation
(6), (11), (12)	600-585 Ma	Tholeiitic magmatism (Belle-Isle-en-Terre, Lanvollon, Yffiniac, Fort-La-Latte, Coutances)
	585-570 Ma	Transpressional deformation and metamorphism
(13)	570-565 Ma	Regional cooling
(9), (13), (14)	570-560 Ma	Post-tectonic calc-alkaline gabbro/diorite complexes (St-Quay, S.E. Jersey ; ?La Hague)
(15), (16)	540-530 Ma	Late-Cadomian diorite stock (St-Brieuc), and calc-alkaline volcanism (Jersey, St-Germain-le-Gaillard)
(17)	550-480 Ma	Post-Cadomian granite complex (S.W. Jersey)
(14), (17)	475-425 Ma	Post-Cadomian diorite-granite complex (N.W. Jersey)
	St-Malo terrane	
	?600-?570 Ma	Brioverian sedimentation
	c. 570 Ma	Onset of basin inversion
	570-550 Ma	Progressive heating leading to high-T metamorphism and anatexis during sinistral transpression
(18)	550-530 Ma	Syn-kinematic emplacement of anatectic granites into S-vergent thrust shear zones and sinistral strike-slip shear zones
(21)	330-320 Ma	Reheating by sub-surface Variscan granite (SMT)
	Mancellian terrane	
	?600-?540 Ma	Brioverian sedimentation
(19)	550-530 Ma	Emplacement of Mancellian granites into tensile bridges developed between left-stepping segments of a major transcurrent fault zone
(20), (21)	525-520 Ma	Rb-Sr mineral/whole-rock age (Fougères granite, MT) and muscovite cooling ages (Bonnemain granite complex, MT)
	North Armorican shear zone	
	?570 Ma	Initiation of the zone as a sinistral transcurrent fault
(22)	c. 530 Ma	Emplacement of granite along the zone (Loc-Envel)
(21, (23)	330-290 Ma	Reworking of granite along the zone
	Central Armorican terrane	
(16)	?540-480 Ma	Brioverian sedimentation (Central Brittany)

Table 1. – Events within constituent terranes of the North Armorican composite terrane, Armorican segment of the Cadomian belt, and the Central Armorican terrane.

Tabl. 1. – Evénements intervenus au sein des terranes constituant les terranes mixtes nord armoricains, le segment armoricain de la chaîne cadomienne, et les terranes armoricains centraux.

(1) Calvez and Vidal (1978): U-Pb zircon; (2) Auvray *et al.* (1980): U-Pb zircon; (3) Piton (1985): U-Pb zircon; (4) Dallmeyer et al. (1991a): U-Pb zircon: (5) Auvray *et al.* (1992): Discussion; (6) Guerrot and Peucat (1990): U-Pb zircon; (7) Graviou et al. (1988): U-Pb zircon; (8) Dallmeyer et al. (1992a): $^{40}Ar/^{39}Ar$ hornblende; (9) Dallmeyer *et al.* (1994): $^{40}Ar/^{39}Ar$ hornblende; (10) Ruffet *et al.* (1991): (11) Guerrot et al. (1994): stepwise Pb-evaporation on single zircons; (12) Peucat *et al.* (1981): U-Pb zircon; (13) Dallmeyer *et al.* (1991b): $^{40}Ar/^{39}Ar$ hornblende, muscovite; (14) D'Lemos et al. (1992b): $^{40}Ar/^{39}Ar$ hornblende; (15) Hébert *et al.* (1993): Stepwise Pb-evaporation on single zircons; (16) Guerrot et al. (1992): stepwise Pb-evaporation on single zircons; (17) Bland (1984): Rb-Sr whole-rock isochron; (18) Peucat (1986): U-Pb zircon, monazite; Rb-Sr whole-rock isochron; (19) Pasteels and Doré (1982): U-Pb monazite; (20) Andriamarofahatra and de La Boisse (1988): U-Pb zircon; (23) Watts and Williams (1980): fault rocks cutting Variscan Quintin granite.

tonic transport on Sark linked to a major dextral wrench zone to the west on Guernsey at c. 600 Ma. Indeed, confirmation of the syn-kinematic emplacement of the quartz diorites on Guernsey by I. Tribe *et al.* (1994) supports an interpretation for the age of the Perelle quartz diorite closer to c. 600 Ma, as argued by B. Auvray *et al.* (1992), in contrast to the preferred interpretation of R.D. Dallmeyer *et al.* (1992b) of an age of emplacement at c. 700 Ma. In the North Trégor, one component of the North Trégor batholith was emplaced at c. 615 Ma (Graviou *et al.*, 1988) and may be coeval with arc plutonism in Guernsey and Sark. Geochemical characteristics of these early Cadomian plutonic rocks are consistent with magma generation within thick continental arc crust (Power *et al.*, 1990; Thiéblemont *et al.*, 1994).

The original continuity of this continental crust is indicated by the occurrence of Icartian basement fragments throughout the exposed extent of the terrane as far east as La Hague (Figure 1). Correlation of the La Hague area is ambiguous because the U-Pb ages reported by C. Guerrot and J.-J. Peucat (1990) of 645 ± 12 Ma for the Moulinet orthogneiss and 585 $^{+13}_{-12}$ Ma for the Moulinet quartz diorite, and the $^{40}Ar/^{39}Ar$ data of R.D. Dallmeyer *et al.* (1994), indicate some similarity in the pattern of magmatism and regional cooling with the SBT. This suggests that La Hague may have represented a lateral transition from the arc to a developing intra-arc basin at c. 610 Ma, and the present spatial configuration was a consequence of tectonic dismemberment and juxtaposition. The $^{40}Ar/^{39}Ar$ isotope correlation ages obtained on hornblende from units within Guernsey and Sark (Dallmeyer *et al.*, 1991a), which record cooling through a temperature of c. 500°C, together with one Rb-Sr biotite age from the Trégor (Guerrot and Peucat, 1990), which reflects cooling through c. 350°C, and $^{40}Ar/^{39}Ar$ isotope correlation ages obtained on biotite from units within the North Trégor batholith (Ruffet *et al.*, 1991), which record cooling through a temperature of c. 300°C, indicate regional cooling of the TLHT to ambient upper crustal conditions by c. 595 Ma (Table 1), possibly younger in La Hague (Dallmeyer *et al.*, 1994).

The tectonic interpretation of the TLHT is that it represents a continental arc at an active plate-boundary zone, with crustal thickness decreasing from North Trégor to La Hague (c.f. Graviou and Auvray, 1985; Graviou *et al.*, 1988; Strachan *et al.*, 1989; Brown *et al.*, 1990; Dupret *et al.*, 1990; Rabu *et al.*, 1990).

The St. Brieuc terrane

There are no exposed relics of the Paleoproterozoic Icartian basement within the SBT. The oldest units appear to be within the Neoproterozoic Penthièvre complex, which outcrops along the eastern side of the Baie de St. Brieuc. The Penthièvre complex represents an early Cadomian arc constructed from island-arc tholeiite and calc-alkaline plutonic rocks (Shufflebotham, 1989; 1990), probably during the interval 750-650 Ma (Guerrot and Peucat, 1990; Guerrot *et al.*, 1994). M.M. Shufflebotham (1989) recognized three separate episodes of crustal accretion within the Penthièvre complex, and the complex as a whole is interpreted to represent the roots of juxtaposed island-arc and continental margin terranes. These early arc rocks form the local basement to the Brioverian volcanic and sedimentary successions, and represent the "Pentevrian" crystalline basement of J. Cogné (1959). It is possible that the Penthièvre complex may be represented in La Hague by the Moulinet orthogneiss. The SBT represents an intra-arc basin formed by splitting the early Cadomian arc in response to subduction zone retreat.

To the east of La Hague, the volcanic succession at Le Vast is characterized by high MgO and has other geochemical characteristics similar to those of modern boninites (Dupret *et al.*, 1990). Although undated, L. Dupret *et al.* (1990) consider this volcanic sequence to represent the initial stage of Brioverian volcanism, possibly older than 600 Ma. In the west, the Paimpol basalts have geochemical characteristics similar to modern arc tholeiites (Thiéblemont *et al.*, 1994). An age of 610 ± 9 Ma has been obtained from these basalts by C. Guerrot *et al.* (1994), based on stepwise Pb-evaporation on single zircons; this age is consistent with an imprecise Rb-Sr whole rock age obtained by P. Vidal (1980). The main Brioverian volcanic successions and associated plutonic complexes mostly are tholeiitic, with the source composition changing from less depleted to more depleted from west to east, from the Lanvollon basin (Cabanis *et al.*, 1987; Thiéblemont *et al.*, 1994), including the Hillion-Erquy volcanic formation of G.J. Lees *et al.* (1987; Roach *et al.*, 1990), to the Les Mortes Femmes - Montsurvent - La Terrette sequences, which have geochemical similarity to recent basalts of intra-arc, arc and behind-arc environments, respectively (Dissler, 1988; Dupret *et al.*, 1990). It is thought that the volcanic sequences were erupted into ensialic extensional basins. Both the absolute age and the age equivalence of these volcanic successions are poorly constrained, although one age of 588 ± 11 Ma, based on stepwise Pb-evaporation on single zircons from the Lanvollon rocks (Guerrot *et al.*, 1994), suggests that these sequences may post-date uplift and cooling within the TLHT on the outboard side of the basin. The volcanic basins were filled with clastic sediments prior to Cadomian deformation and metamorphism, which occurred sometime during the interval c. 585-570 Ma, based upon $^{40}Ar/^{39}Ar$ isotope correlation ages on hornblende of 570-565 Ma interpreted to date cooling through c. 500°C (Dallmeyer *et al.*, 1991b), essentially consistent with the conclusions drawn by J.-P. Brun and P. Balé (1990). The sedimentary units within the SBT (e.g. Binic Formation) drew their detritus from both a volcanic arc source and a continental basement (Denis and Dabard, 1988); sedimentation must have been rapid, with the uplifted and eroding TLHT providing an important source of clastic material, and was interrupted by deformation, metamorphism and uplift of the SBT. Post-tectonic calc-alkaline plutonic complexes were emplaced into both the TLHT (e.g. the Northern Igneous Complex of Guernsey) and SBT (the St. Quay Intrusion, the SE Jersey Granite Complex, and in Alderney) during the period 570-560 Ma (Dallmeyer *et al.*, 1991b, 1992a, 1994; D'Lemos *et al.*, 1992b).

Interpretation of tectonic structures within the SBT has been controversial (Balé and Brun, 1989; Strachan *et al.*, 1989, 1992; Brun and Balé, 1990; Strachan and Roach, 1990; Brun, 1992). However, it now seems clear that sinistral oblique S-vergent thrusting and a steep foliation represent the dominant deformation style and structure within outcrops along the west side of the Baie de St. Brieuc (e.g. Brun and Balé, 1990; Brun, 1992), features confirmed by the recent work of E. Le Goff *et al.* (1994), and record heterogeneous flattening strains which reflect horizontal shortening. The direction of tectonic transport within the SBT, inferred from the rather variable orientation of mineral elongation lineations, sparse kinematic information and the geometry of the structures, on the west side of the Baie de St. Brieuc, was to the southwest and south (Brun and Balé, 1990; Le Goff *et al.*, 1994). Immediately east of St. Brieuc, in metasediments of the Binic Formation, the sense of rotation of staurolite porphyroblasts indicates a thrusting component to the south-southwest (Hébert and Ballèvre, 1993).

On the west side of the Baie de St. Brieuc, the regional metamorphism is characterized by an increase in metamorphic grade towards the southwest and south (Rabu *et al.*, 1983; Hébert, 1993; Le Goff *et al.*, 1994). The changes in mineral assemblage for similar bulk-rock compositions and the systematic variation in chemical composition of coexisting phases document this increase (Hébert, 1993). East of St. Brieuc, staurolite-bearing pelites yield P-T conditions of c. 550 ±50°C and 3-5 kbar (Hébert and Ballèvre, 1993). Further south, around Yffiniac, amphibolites yield P-T conditions of c. 700 ± 50°C and 9 ± 1 kbar (Hébert, 1993). These amphibolites are interpreted by R. Hébert (1993) to be metaplutonic rocks that represent magma trapped in the deeper levels of an active continental margin. These data suggest that the Cadomian orogeny was unlikely to have been the result of continent-continent collision, which commonly is characterized by higher values of peak-P (e.g. Brown, 1993), but was more likely the result of geodynamic processes at an active plate-boundary zone along a continental margin, as envisioned by P. Balé and J.-P. Brun (1989) and R. Hébert (1993). This is consistent with the interpretation of the Cadomian belt as part of a peripheral orogen located at the margin of a late-Precambrian supercontinent (Murphy and Nance, 1991; Nance and Murphy, 1994).

The basic-ultrabasic complex of Belle-Isle-en-Terre occurs to the south of the NASZ, at the west side of the region under consideration; it has been dated at 602 Ma by the U-Pb zircon method (Peucat *et al.*, 1981). The calc-alkaline chemistry of the metabasic rocks and the geologic context suggest that this complex represents part of the SBT. Its relationship with low-grade metasediments, micaschists, and gneisses and migmatites is unclear since all observed contacts appear to be brittle faults (Peucat *et al.*, 1981). I incline towards the view of J.-P. Brun and P. Balé (1990) that the Belle-Isle-en-Terre complex represents a klippe of the SBT preserved south of the NASZ (c.f. Le Goff *et al.*, 1994; Hébert, 1995).

The tectonic interpretation of the SBT is that it represents an intra-arc basin, built on thinned continental crust, the eastward and inboard extension of the TLHT, formed by splitting the Cadomian continental arc in response to subduction zone retreat, and bounded on its southern side by a major transcurrent fault, the FSZ (c.f. Rabu *et al.*, 1983, 1990; Cabanis *et al.*, 1987; Dupret *et al.*, 1990).

The St. Malo and Mancellian terranes

These two terranes are fundamentally distinct from the TLHT and SBT in having no exposed relics of the Paleoproterozoic Icartian basement, no evidence of the early arc plutonism within the Cadomian cycle, and in lacking evidence of the extensive tholeiitic magmatism which is characteristic of the SBT. A sequence of volcanic rocks occurs along the northern edge of the SMT adjacent to the FSZ, the Château Serein volcanic succession, which resembles recent volcanic rocks from extensional within-plate settings (Cabanis *et al.*, 1987). The Brioverian succession immediately adjacent, which outcrops in the Baie de la Fresnaye (Lamballe Formation) and further west (Callac Formation), is represented by a clastic sedimentary sequence with black cherts, interpreted to have been deposited in an immature marginal basin (Dabard, 1990). Inboard from this, the protolith of the St. Malo migmatite belt and the metasediments of the Rance Valley preserve calc-silicate lenses of volcanogenic origin within graywacke-type sediments that are similar to the Binic Formation of the SBT (Darlet *et al.*, 1990). It is part of this Brioverian succession that has been deformed and thickened leading to high-T metamorphism and anatexis (Brun and Martin, 1978; Brown, 1979). In the MT, which represents a higher structural level, the same events are represented by the Mancellian granites that have been emplaced into a structurally simple low metamorphic grade, predominantly sedimentary succession that includes only volumetrically minor volcanic rocks, such as those at Vassy (Dupret *et al.*, 1990; Brown and D'Lemos, 1991; D'Lemos *et al.*, 1992a). This higher structural level must be stratigraphically younger than the succession on the northwest side of the SMT, since the sedimentary sequence contains reworked black cherts presumably derived by pene-contemporaneous erosion of upper levels (outboard side) of the SMT and syn-tectonic sedimentation. The Sm-Nd isotope characteristics of anatectic granites within the St. Malo migmatite belt and the Mancellian granites suggest derivation from a metasedimentary source derived by mixing components from an early Cadomian magmatic arc and Brioverian succession volcanic rocks (D'Lemos and Brown, 1993), consistent with recently acquired Sm-Nd data from metasediments of the Rance Valley (Dabard *et al.*, 1994). These results suggest derivation of the sedimentary succession by erosion of older terrane elements to the north. The detailed petrographic and geochemical studies of M.P. Dabard (1989, 1990; see also: Denis and Dabard, 1988; Darlett *et al.*, 1990) have allowed distinction between the sedimentary succession of the SMT, which has an immature nature with chemical characteristics intermediate between those of continental arcs and active continental margins, and the sedimentary succession of the MT, which has a smaller contribution of volcanic fragments and likely reflects deposition within a marginal-basin or within-plate basin setting. Further, in this southern continental domain, the contribution of volcanic material decreased progressively southward as continental source rocks became more dominant. The SMT and MT are separated by the Cancale shear zone (CSZ) which records sinistral strike-slip ductile displacement in coastal outcrop (Brun and Balé, 1990; Treloar and Strachan, 1990).

Within the SMT, U-Pb zircon and monazite, and Rb-Sr whole-rock ages of c. 540 Ma have been reported from anatectic granite from the St. Malo migmatite belt (Peucat, 1986), consistent with an age based on stepwise Pb-evaporation on single zircons for the Cancale granite (Guerrot *et al.*, 1994). Monazite ages in the range 550-540 Ma have been reported from the Vire-Carolles granite complex in the N of the MT (Pasteels and Doré, 1982), although a slightly younger Rb-Sr mineral/whole-rock isochron age of 521 ± 11 Ma has been reported from the Fougères granite (Louvigné-Gorron granite complex) in the S of the MT (Autran *et al.*, 1983), which is consistent with muscovite $^{40}Ar/^{39}Ar$ plateau ages of c. 525 Ma from the Bonnemain granite complex in the W of the MT, interpreted to date post-magmatic cooling (Dallmeyer *et al.*, 1993). Emplacement of granites in the SMT and MT accompanied regional sinistral transpression (Strachan *et al.*, 1989; D'Lemos *et al.*, 1992a).

The migmatites and the granites are coeval, possess some similarities in geochemical features (Brown and D'Lemos, 1991) and have essentially the same isotopic signatures (D'Lemos and Brown, 1993). G.M. Power (1993) has reinterpreted the St. Malo migmatite and Mancellian granite geochemical data sets using both principal component and multi-dimensional scaling plots to emphasize significant statistical differences between the samples. Differences for some elements may reflect systematic changes in the sedimentary succession from the SMT to the MT, at the depth of anatexis, which was deeper to

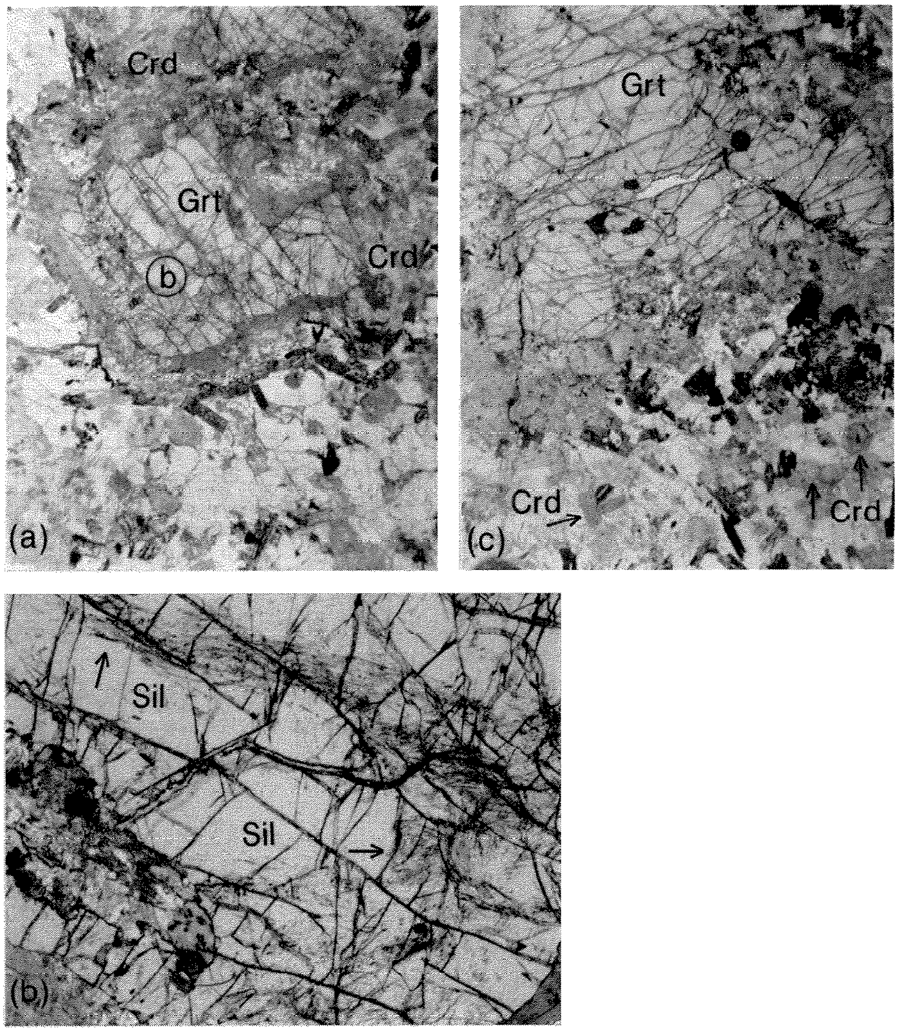

Fig. 2. – Photomicrographs to show pinnitized cordierite (Crd) rim around garnet (Grt) (a), trails of sillimanite (Sil) inclusions which preserve crenulation folds in the garnet (b), and rounded-to-euhedral pinnitized cordierite crystals in the matrix around residual garnet (c), in the vicinity of the Barrage de Rabodanges within the Athis granite complex, Mancellian terrane. Height of the field of view in (a) and (c) is *c.* 12 mm, and the width of the field of view in (b) is *c.* 3mm.

Fig. 2. – Microphotographies montrant un liséré de cordiérite pinnitisée (Crd) autour du grenat (Grt) (a), des traînées d'inclusions de sillimanite (Sil) conservant des microplis de crénulation dans le grenat (b), et des cristaux de cordiérite pinnitisée automorphes ou arrondis dans la mésostase autour du grenat résiduel (c), à proximité du Barrage de Rabodanges au sein du complexe granitique d'Athis, terrane mancellien. La hauteur d'échantillon photographié dans (a) et (c) est d'environ 12 mm, et sa largeur dans (b) est d'environ 3 mm.

the east, and/or an increased role for basaltic magma in the generation of the Mancellian granites, or some combination of the effects of depth of melting and degree of hybridization, for which there is support from experimental petrology (Patiño-Douce, 1995). In this regard, the volumetrically minor basic/ultrabasic complexes of Ernée and Brée in the MT (Le Gall and Mary, 1983; Le Gall and Barrat, 1987), together with the minor basic/ultrabasic complex of Trégomar at the north-western side of the SMT (Le Gall and Barrat, 1987), may be significant (Brown *et al.*, 1990). These inferred Cadomian basic/ultrabasic complexes comprise predominantly gabbro, norite and anorthositic gabbro, similar to the expected cumulate products of an AFC process between metasedimentary crustal rocks and high alumina olivine basalt (Patiño-Douce, 1995). Further, the calc-alkaline nature of the Mancellian granites (Brown *et al.*, 1990) is similar to the expected granitic products of such a process, and the major oxide compositions of the Mancellian granites correspond to the range of experimental glass compositions generated at c. 7 kbar by interaction between high alumina olivine basalt and a synthetic biotite gneiss (equivalent to graywacke) and pelitic schist (Patiño-Douce, 1995). A hybrid origin for the Mancellian granites is consistent with the available data.

Metamorphism in the migmatites is of a high-*T* - low-*P* type, in which biotite + sillimanite is stable, whereas garnet and cordierite occur rarely. *P-T* conditions were middle crustal, and anatexis likely occurred under water-rich volatile phase-present conditions (high a_{H_2O}). For the Mancellian granites, *P-T* conditions of magma generation were probably middle-to-lower crustal. In the north-eastern part of the terrane (Figure 1), in the vicinity of the Barrage de Rabodanges within the Athis granite complex, the granite has residual garnet, with included sillimanite needles (Figure 2a), that has been partly converted to cordierite around the rim. I interpret this texture to record decompression during ascent of the magma. Also, the matrix around the residual garnet includes distributed, rounded-to-euhedral cordierite crystals (Figure 2b). In the south-eastern part of the terrane (Figure 1), around Alexain in the Alexain-Deux Evailles-Izé granite complex, the granite has residual garnet that has been partly converted to biotite around the rim, presumed to record decompression during ascent of the magma. Melting likely occurred under water-undersaturated or volatile phase-absent conditions (low a_{H_2O}). A component of advected heat likely was necessary to generate the migmatites and the volume of intracrustal melt represented by the Mancellian granites, even though the latter are relatively thin "sheets" in three-dimensional form, as determined from interpretation of gravity data (J.-P. Lefort, personal communication 1991). The emplacement level of the Mancellian granites was into the upper crust. The geometric relationship between cleavage and the bounding faults in Mancellia is consistent with sinistral transpression (D'Lemos *et al.*, 1992a). Within the St. Malo migmatite belt, early recumbent deformation reflects contractional thickening, and homogeneous diatexite/anatectic granite commonly is located in shallow N-inclined top-to-the-S shear zones (moderate N-plunging stretching lineation), which are present at all scales within the belt, from the individual outcrop (Figure 3a, b and c) to the map scale. Marginal to the belt (Figure 3d), homogeneous diatexite/anatectic granite is located in ENE-striking sub-vertical sinistral strike-slip shear zones (shallow ENE-plunging stretching lineation), in the wall-rocks of which cordierite is stable (D'Lemos *et al.*, 1992a).

These features are best resolved within a model of ductile transpression (Robin and Cruden, 1994), in which the St. Malo region represented middle crustal levels and the Mancellian region represented upper crustal levels during the Cadomian. In this model, transcurrent simple shear in the lower crust could be linked through sub-horizontal décollement zones in the middle crust, represented by the St. Malo region, to vertical but curved zones in the upper crust. Transcurrent transpression and transtension could arise in the upper crust, depending on the local orientation of the upper crustal zone with respect to that of the zone in the lower crust (Robin and Cruden, 1994). Thickening of the Brioverian sedimentary basins was a consequence of the outboard arc-related terranes being driven progressively into the marginal-basin and within-plate basin sequences from c. 570 Ma. In part, high-*T* metamorphism may have been a consequence of thermal relaxation of the moderately over-thickened basinal successions. The basins may have been characterized by a high heat flow, to facilitate the high-*T* metamorphism by simple thermal relaxation, or the metamorphism may have been driven in part by heat advected into the crust by mantle-derived magmas. Indeed, as the St. Malo migmatite protolith started to thicken at c. 570 Ma, the MT basin still was receiving sediment during continuing extension. By c. 540 Ma, anatexis had weakened the crust, particularly within the SMT, and sinistral transpression propagated through the behind-arc region, which facilitated magma ascent to upper crustal levels by transpressive extrusion as well as buoyancy (D'Lemos *et al.*, 1992a). Anatexis was particularly important in enabling the deformation to propagate since the increasingly sinuous nature of the strike-slip shear zones would have made the geometry increasingly inefficient for transcurrent displacements. As the bends in the shear zones amplify so they impede easy strike-slip motion along the shear zones and prevent accumulation of significant lateral displacements of the wall rocks. This kinematic inefficiency is counterbalanced by volume loss due to deformation-enhanced melt segregation and transfer out of the system. Although the volume of magma that has migrated upward to higher structural levels is unknown, it was this significant volume loss, especially from the SMT, that facilitated contractional deformation during transpression and inboard propagation of the deformation front. The low a_{H_2O} volatile phase-absent melting evidenced for at least a component of the Mancellian granites requires temperatures of c. 850°C and likely requires advected heat, consistent with the geochemical arguments presented above. By c. 540 Ma transpressive deformation had propagated into the MT and ascent of the Mancellian granite magma is inferred to have been channelized along steeply-oriented strike-slip shear zones with emplacement into tensile bridges developed between left-stepping segments of a major transcurrent fault zone. Along individual granite pluton/country rock contacts, however, local space creation by stoping clearly was the method by which emplacement was completed.

To the west, anatectic migmatites occur inboard of the SBT in the Guinguamp high-temperature belt (Brun and Balé, 1990). The similarity in metamorphism, leading to high-temperature anatexis, and an age for the associated Toulporz granite of 542^{+7}_{-6} Ma (U-Pb upper intercept on zircon, Andriamarofahatra and de La Boisse, 1988), similar to that of the St. Malo migmatites, and an age of 526^{+14}_{-16} Ma (U-Pb lower intercept on zircon, Andriamarofahatra and de La Boisse H., 1988), similar to some components of the Mancellian granites, led J.-P. Brun and P. Balé (1990) and M. Brown *et al.* (1990) to correlate the Guinguamp high-temperature belt with the St. Malo migmatite belt. Recently, this correlation has been questioned on the basis of: 1) regional mapping interpreted to suggest a progressive deformation and metamorphism from N or NE to S or SW from the SBT to the Guinguamp high-temperature belt (Le Goff *et al.*, 1994); and, 2) overprinting of simi-

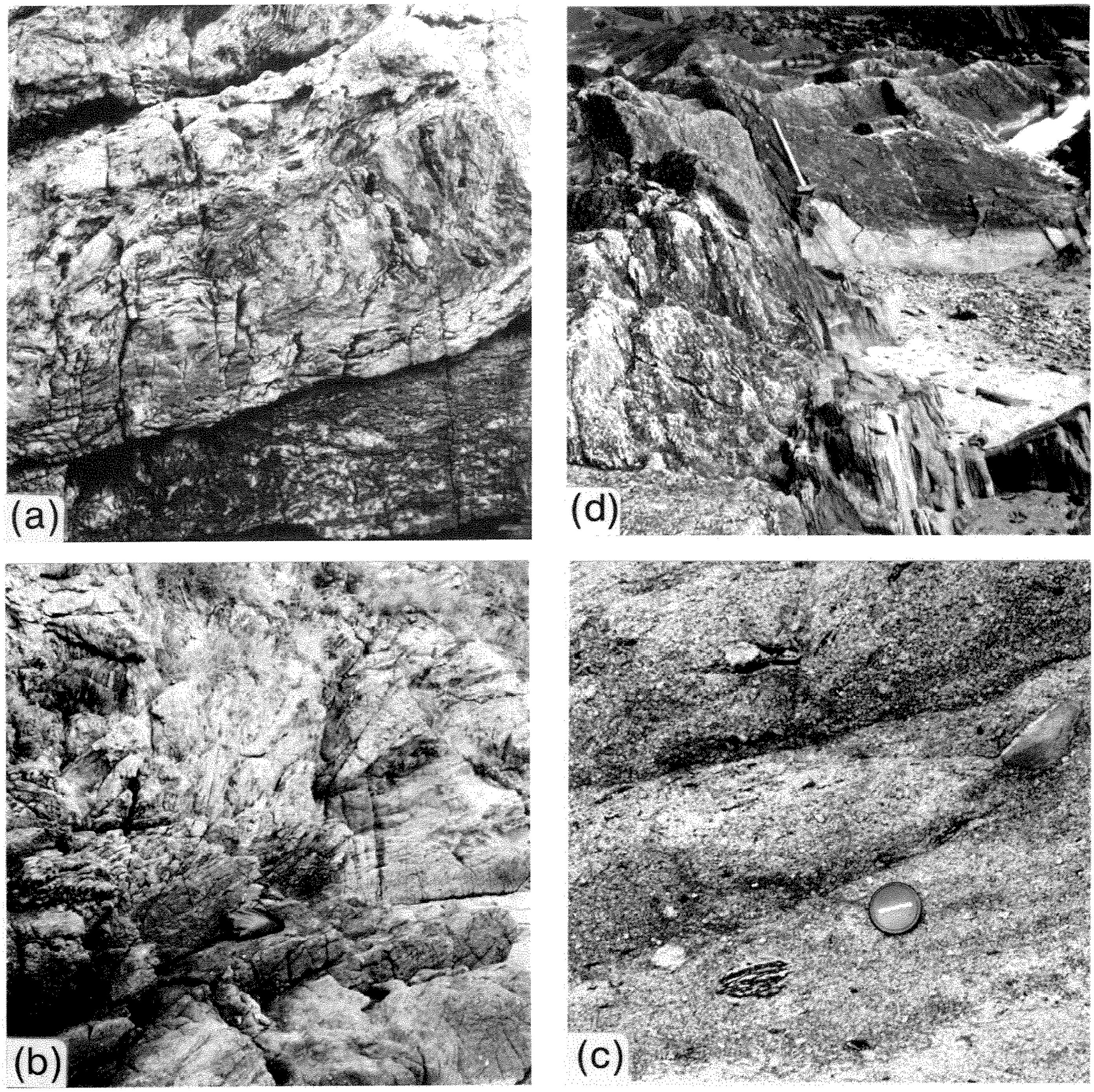

Fig. 3. – Migmatite/anatectic granite relationships within the St. Malo migmatite belt. (a) Meter-scale shallow N-inclined (to left) top-to-the-S shear zones (upper and lower parts of field of view) along which homogeneous diatexite has been emplaced (pnte du Bechet, St.-Jacut-de-la-Mer); (b) and (c) decameter-scale shallow N-inclined (to left) top-to-the-S shear zone (lower half of photograph) into which was emplaced homogeneous diatexite with occasional schlieren and enclaves, shown in (c), which is a closeup of the back cliff seen in (b) (pnte du Bechet, St.-Jacut-de-la-Mer); (d) steep foliation and shallow ENE stretching lineation at contact between Cancale granite (to N, left) and mylonitic Brioverian metasediments with cordierite porphyroblasts (to S, right) (Port Briac, N of Cancale).

Fig. 3. – Relations granite d'anatexie/migmatite à l'intérieur des migmatites de St-Malo (a). Zone de cisaillement vers le Sud d'échelle métrique à léger plongement nord (vers la gauche), (parties supérieure et inférieure du champ visuel) le long desquelles la diatexite homogène s'est mise en place (Pte du Bechet, St-Jacut-de-la-Mer) ; (b et c) Zone de cisaillement vers le Sud d'échelle décamétrique à léger plongement nord (vers la gauche) (moitié inférieure de la photo) dans laquelle la diatexite homogène s'est mise en place avec de rares schlieren et enclaves, indiqués dans (c), qui est un gros plan de la falaise déjà vue dans (b) (Pte du Bechet, St-Jacut-de-la-Mer) ; (d) foliation subverticale et linéation d'étirement ENE peu inclinée au contact entre le granite de Cancale (au nord, à gauche) et les sédiments mylonitiques briovériens à porphyroblastes de cordiérite (au sud, à droite) (Port Briac, nord de Cancale).

lar migmatites by contact metamorphism in the aureole of the St. Brieuc diorite complex (Hébert, 1995), which has an emplacement age of 533 ± 12 Ma (based on stepwise Pb-evaporation on single zircons, Hébert *et al.*, 1993). The tectonic position of the Guinguamp high-temperature belt, inboard of the SBT, is the same as the St. Malo migmatite belt, and the data used to argue for an older age for the deformation and metamorphism are compatible equally with the accretion of the TLHT/SBT composite terrane with the behind-arc marginal basin at *c.* 570 Ma, leading to progressive deformation during the interval 570-540 Ma and high-T metamorphism that culminated in crustal anatexis. *P-T* conditions are estimated to have been 5-6 kbar at *c*. 650°C (Le Goff *et al.*, 1994), certainly similar to those at St. Malo (Brown, 1979). Therefore, in the absence of compelling evidence that requires a substantially older age, I retain the correlation of the Guinguamp high-temperature belt with the St. Malo migmatite belt, and regard the Guinguamp high-temperature belt as the western extension of the SMT. This correlation essentially is one of tectonic setting, permitted by and consistent with the limited data. The correlation does not require that the age of the metamorphic peak and culmination of anatexis in both belts be identical, and, indeed, the peak may have occurred earlier in the west, in the Guinguamp high-temperature belt, than in the east, in the St. Malo migmatite belt. Such an interpretation would be consistent with evidence of unroofing in the Guinguamp high-temperature belt by top-to-the-E normal shearing and associated dextral wrenching (Le Goff *et al.*, 1994), that I interpret to be approximately contemporaneous with continued sinistral transpression within the SMT and the MT to the east. This deformation records the progressive distortion of the SBT/MT around the Yffiniac arc in response to a progressive change of orientation of the western part of the subduction boundary zone.

The tectonic interpretation of the SMT/MT is that it represents a behind-arc marginal-basin to intra-plate basin setting built on thinned continental crust and structurally inverted during the interval 570-540 Ma (c.f. Graviou and Auvray, 1985; Graviou *et al.*, 1988; Strachan *et al.*, 1989; D'Lemos *et al.*, 1992). The SMT and MT are interpreted to be different structural levels of an originally laterally continuous tectonic unit, the difference in exposed structural level reflecting displacement across the CSZ (c.f. D'Lemos *et al.*, 1992).

The North Armorican shear zone and the Central Armorican terrane

Although the NASZ clearly was an important Variscan structure, it must represent a reactivated Cadomian structure, since it separates Brioverian volcanic and sedimentary basins structurally inverted by Cadomian tectonism from Brioverian sedimentary sequences not significantly deformed until the Variscan. This is consistent with the data of M.J. Watts and G.D. Williams (1979), who implied that the earlier high-temperature mylonitic fabrics within the NASZ predated a low-temperature Variscan overprint. Support for this interpretation also comes from the work of M.P. Dabard (1990; Denis and Dabard, 1988) which indicates that the contribution of volcanic material to the sediments of the Brioverian succession decreased progressively towards the south where continental source rocks were dominant, and that deposition of the sequences located south of the NASZ occurred in a passive tectonic setting. Furthermore, zircons from part of the Brioverian succession of central Brittany belong to a homogeneous population with ages based on stepwise Pb-evaporation grouped between 580 and 540 Ma (Guerrot *et al.*, 1992). These data indicate that sedimentation of at least part of the Brioverian succession in central Brittany was post-orogenic. The tectonic line that separated the orogenic domain to the north from a non-orogenic domain to the south during the Cadomian was the NASZ. The uplifted and eroding Cadomian NACT clearly was an important source of detrital material for the Brioverian sedimentary sequences of the CAT.

The tectonic interpretation of the NASZ is that it was a major transcurrent fault that represented the southern boundary of Cadomian orogenic activity against a passive continental domain, the CAT, to the south.

Late- to post-Cadomian events

Although the Cadomian cycle can be defined as predating the Cambrian unconformity in Normandy, the style of Cambrian volcanism and the pattern of Cambrian sedimentation both reflect late- to post-Cadomian extension. Late-Cadomian calc-alkaline volcanic sequences are exposed (Figure 1) in North Trégor, the Ignimbrites des Lézardrieux (Auvray, 1975), in Jersey, the Jersey volcanic group (Lees and Roach, 1993), and in Normandy, the Ignimbrites de St. Germain-le-Gaillard (Boyer *et al.*, 1972), which have yielded an age of 531 ± 20 Ma based on stepwise Pb-evaporation on single zircons (Guerrot *et al.*, 1992). Some calc-alkaline plutonic magmatism on Jersey may be as young as Silurian, Rb-Sr whole rock ages for different components of the southwest granite complex range from 550 ± 12 Ma to 483 ± 13 Ma (Bland, 1984), and Rb-Sr whole rock ages for different components of the northwest granite complex range from 465 ± 10 Ma and 426 ± 14 Ma (Bland, 1984), consistent with a hornblende $^{40}Ar/^{39}Ar$ age of c. 475 Ma from diorite at the eastern side of the complex (D'Lemos *et al.*, 1992b). Whether any of these Rb-Sr whole-rock ages reflect resetting during Lower Paleozoic extensional deformation as a consequence of hydration in the manner described by J.A. Evans *et al.* (1995) remains an open question. The Jersey main dyke swarm has been interpreted by G.J. Lees (1990) as an example of late-Cadomian extensional magmatism. Post-Cadomian 'molasse-like' sedimentation occurred in a series of elongate E-W extensional basins, represented by the Erquy-Fréhel Group in North Brittany, the Rozel Conglomerate Formation in Jersey, and the Alderney Sandstone Formation in Alderney (Went and Andrews, 1990). To the southeast of the Cadomian belt, the Cambrian Maine half-graben represents a further example of post-Cadomian extension and extensive Cambrian pyroclastic volcanism and sedimentation (Le Gall *et al.*, 1975; Le Gall, 1993; Le Gall and Dupret, 1994). The duration of this period of post-Cadomian sedimentation and volcanism, c. 50 Ma from 530 to 480 Ma, is similar to that which followed the Variscan orogeny during the Permian.

A geodynamic model

A geodynamic model based on plate tectonics for any period of time before the Jurassic must make assumptions about the starting paleogeography and relative plate displacement vector across a convergent plate margin, because the ocean basins with their record of magnetic anomalies are recycled every *c*. 250 Ma. Although the chosen assumptions may not be unique, clearly they should not lead to inconsistencies with known geology. The main features that must be explained by a model for the late-Precambrian evolution of the Armorican segment of the Cadomian belt include: the occurrence of relics of Icartian basement and the petrographic and geochemical evidence for a basement component within some of the magmatic and sedimentary rocks; the plutonic magmatism, in particular the pattern of emplacement ages and the cooling history, in general younging southward, and the magma type and likely tectonic setting; the volcanism, in particular its restriction largely to the SBT, and changes in magma type and likely tectonic setting with time as revealed by geochemical characteristics; the sedimentation, in particular the apparent successive younging of the sedimentary successions from terrane to terrane southward, and the likely tectonic setting as revealed by provenance studies; tectonic structures, in particular the kinematic information that they reveal; and, the metamorphism, in particular the southward progression in age from terrane to terrane, and the low-*P* to medium-*P* and relatively high-*T* type of metamorphism in relation to tectonic setting. These geologic features constrain some elements in any geodynamic model.

Subduction zones have complex tectonic histories, progressing from a poorly understood initiation phase to maturation, commonly accompanied by opening of a back-arc basin and seaward migration of the trench, to cessation of convergence, often involving collision with a subduction-resistent bathymetric high, an arc or another continent. The fate of the subducting slab must be considered in the context of the time-dependent evolution of the associated subduction zone, particularly if there is a rapid interval of trench migration. This is because the geometry of the slab is controlled both by the position of the slab's leading edge and by the position of the trench. Factors that influence slab geometry are the relative rates of slab sinking (controlled by the age of the subducted material and the vertical viscosity structure encountered) and trench migration (coupled to the onset and vigor of back-arc opening). Stresses induced by the ambient pattern of mantle flow may distort slab geometry, slab penetration into the lower mantle may pin its leading edge to require horizontal deflection to accommodate trench migration, and collision with some kind of buoyant feature may lead to pinning of part of the trench and resistance to trench migration (bathymetric high), or even cessation of convergence and slab-detachment with consequent asthenospheric upwelling (arc or continent collision).

I interpret the tectonic setting of the Armorican segment of the Cadomian belt to have been an active continental margin above a subducting oceanic plate, and the relative displacement vector between the plates most probably was to the southwest, across an approximately ESE-oriented and SSW-dipping subduction zone. This contrasts with the suggestion by J.-P. Brun and P. Balé (1990) that the regional scale deformation "..could result from oblique convergence along an ENE-oriented and NNW-dipping subduction zone", and with the further development of the idea of NW-dipping subduction by P.F. Graviou (1992), who avoided the issue of crustal anatexis in the SMT and MT with the words "..cette nouvelle géométrie de la chaîne cadomienne implique qu'un autre mécanisme restant à préciser soit responsable de la fusion crustale à l'origine du magmatisme mancellien". Clearly, any geodynamic model for the region must offer a reasonable explanation for all of the main geological features, and such explanations are better achieved within a model that involves southward-directed rather than northward-directed subduction. The model needs to explain segmentation of the continental margin, displacement of the dismembered parts and their subsequent accretion, uplift and cooling; it can be tested and modified as necessary, this is the 'raison d'être' of any model.

Subduction of oceanic lithosphere often is cited as the driving force for deformation in arc and fore-arc regions. Although the deformational processes are known in general, complications arise from subduction of anomalous bathymetric features or highs. The more noticeable complications that arise from subduction of bathymetric highs have been argued to include relative seismic quiescence or gaps, volcanic-arc segmentation and/or quiescence, and rapid crustal uplift of the overriding plate (e.g. Gardner *et al.*, 1992). Bathymetric highs on the ocean floors vary in geometry from aseismic ridges to oceanic plateaus, and what happens when any of these features is forced into a subduction has been considered by P.R. Vogt (1973), A. Nur and Z. Ben-Avraham (1989) and M. Cloos (1993), among others. Preliminary analysis of the global distribution of seamounts (Craig and Sandwell, 1988) indicates considerable variations in population density and type across the present ocean basins; most notable among them are the absence of seamounts in the Atlantic, variations in population density across large age-offset fracture zones in the Pacific, the prevalence of small signatures in the Indian Ocean, and the existence of linear trends in the large seamounts of the west Pacific. Certainly, collision between seamounts and accretionary wedges can lead to dramatic deformation in the forearc region, as exemplified in the Japan trench (Lallemand and Le Pichon, 1987), including the formation of forearc basins, as exemplified along the New Hebrides subduction zone (Collot and Fisher, 1989).

Collisional orogenesis is defined by M. Cloos (1993) as a plate interaction of the sort that causes a rearrangement of plate motions, generally with the initiation of a new subduction zone and the creation of mountains. Buoyancy analysis (Cloos, 1993) indicates that only bodies of continental and oceanic island arc crust that are greater than 15 km thick make the lithosphere buoyant enough to jam a subduction zone. Oceanic island arc complexes built upon ocean crust typically must be active for more than *c*. 20 Ma to attain crustal thicknesses so that their attempted subduction causes collisional orogenesis. Oceanic plateaus where basaltic crust as much as c. 17 km thick caps 100-km-thick lithosphere are inherently subductible, these plateaus must have crustal thicknesses greater than 30 km typically to cause collisional orogenesis during subduction (Cloos, 1993). Short subducting seamounts (< 1-2 km tall) typically cause only temporary dents, but taller seamounts locally cause permanent dis-

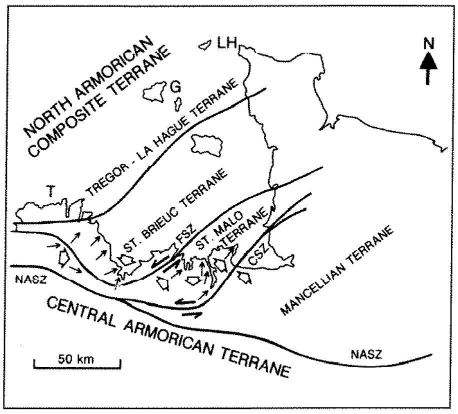

Fig. 4. – Simplified terrane map of the Armorican segment of the Cadomian belt. Thin arrows represent generalized orientations of the dominant stretching lineation, half arrows represent sense of shear along wrench zones and broad arrows represent generalized sense of tectonic transport. Abbreviations are the same as in the text, plus T - Trégor, G - Guernsey, and LH - La Hague.

Fig. 4. – Carte schématique de "terranes" du segment armoricain de la chaîne cadomienne. Les flèches minces représentent les orientations généralisées de la linéation d'étirement dominante, les demi-flèches représentent le sens du cisaillement le long des zones arquées et les flèches épaisses représentent le sens global du déplacement tectonique. Les abréviations sont les mêmes que dans le texte, avec en plus T-Trégor, G-Guernesey et LH-La Hague.

tortions as they bulldoze the front of the fore-arc block (Cloos, 1993). The direct tectonic effect resulting from the subduction of most bathymetric highs is only a temporary isostatic uplift of the fore-arc region of as much as several kilometers, followed by subsidence to original elevations.

Thus, there are various possible geodynamic processes that might lead to some modification of the continuity of subduction. In the Armorican segment of the Cadomian belt, the age progression of terrane accretion and sedimentation, magmatism, deformation and metamorphism successively younging southward suggests the arrival at the trench of some buoyant ocean floor topographic feature, the subduction of which would have caused progressive deformation of the continental margin. Furthermore, the subduction of a linear topographic feature, given an appropriate geometric configuration, would allow the point of entry of the feature into the trench to migrate along the trench with time and could generate the observed bending of the terranes around the Yffiniac arc at the head of the Baie de St. Brieuc (Figures 1 and 4). Subduction of an active spreading ridge is unlikely to be the feature involved since the style of metamorphism is inappropriate and unlike that recorded in other metamorphic belts thought to have been generated by ridge subduction, such as the Ryoke belt in Japan (Brown and Nakajima, 1994) or the Chugach terrane in Alaska (Sisson *et al.*, 1989; Sisson and Pavlis, 1993). On the other hand, the observed structural features and crustal displacements do not seem to be as extreme as those observed in central Japan as a consequence of the subduction of the Izu-Bonin arc at the Nankai trough. Here rotation of trench-parallel tectonic units through up to 90°, lateral displacement along major strike-slip fault zones and extensive contractional deformation along the Itoigawa-Shizuoka tectonic line all have occurred within the last 15 Ma (Taira *et al.*, 1989). This represents the culmination of a series of regional tectonic events related to changes in the motion of the Philippine Sea Plate during the past 40 Ma (Otsuki, 1990).

I consider that subduction of an aseismic ridge or relatively young oceanic island arc is the most likely ocean-floor linear feature to have been the cause of the crustal deformation in the Armorican segment of the Cadomian belt. P.R. Vogt (1973) predicted that cusps in plate boundary zones and associated arcs were the result of subducting aseismic ridges, owing to the buoyancy of the aseismic ridge segments of the oceanic lithosphere. Further, as pointed out by P.R. Vogt (1973), an aseismic ridge will not, in general, parallel the subduction vector, and thus will migrate along the plate boundary zone to cause migrating deformation. One analogue in the present-day Pacific Ocean Basin might be the subduction of the Kyushu-Palau Ridge beneath Kyushu Island at the junction of the Southwest Japan Arc and the Ryukyu Arc (e.g. Kamata and Kodama, 1994). An alternative analogue would be the subduction of the Izu-Bonin arc at the Nanki trough (Taira *et al.*, 1989; Otsuki, 1990), and crustal deformation in the Armorican segment of the Cadomian belt might have been caused by subduction of a less well-developed oceanic island arc in a fashion analogous to, but not as extreme as, this example in central Japan.

The application of this model to the Armorican segment of the Cadomian belt is shown in plan view as three time-frames in Figure 5, utilizing the terrane boundaries, main stretching lineation and inferred sense of displacement as summarized in Figure 4. It is implicit in the model proposed that the TLHT and the SBT are partial lateral equivalents, with the SBT interpreted to represent an intra-arc basin widening to the east. Thus, the thickness of the crust along the continental margin must have thinned from west to east, from the TLHT to the SBT, with La Hague representing approximately the line of transition, consistent with the more continental-arc affinity of magmatism within the TLHT in comparison with the SBT, and consistent with the generally ensialic nature of the volcanic basins within the SBT, according to interpretations of tectonic setting based on geochemical data. The volcanic succession of Le Vast, characterized by chemical similarity to modern arc boninites, and likely older than the inter-arc, arc and behind-arc volcanic sequences further to the south, would have been closest to the trench in this model, consistent with the petrogenetic requirements, and likely located at the east end of the original TLHT/SBT, where the arc setting was closest to oceanic. The TLHT/SBT was bounded on its S-side by a trench-parallel strike-slip transcurrent fault, now represented by the FSZ. I suggest that a bathymetric high located on the subducting oceanic plate arrived at the trench and impinged on the overriding continental plate from *c.* 610 Ma, and it was the progressive subduction of this feature that caused the sequence of geologic events recorded within the Armorican segment of the Cadomian belt (Figure 5).

Is there any evidence still preserved for the existence of such a bathymetric high as an aseismic ridge or an oceanic island arc? The well-known magnetic anomaly offshore to the northwest has been interpreted as a possible cryptic suture (Lefort and Segoufin, 1978); it is parallel to the surface projection of NW-dipping seismic reflectors and intersects SE-dipping seismic reflectors identified in the middle crust on the SWAT profile

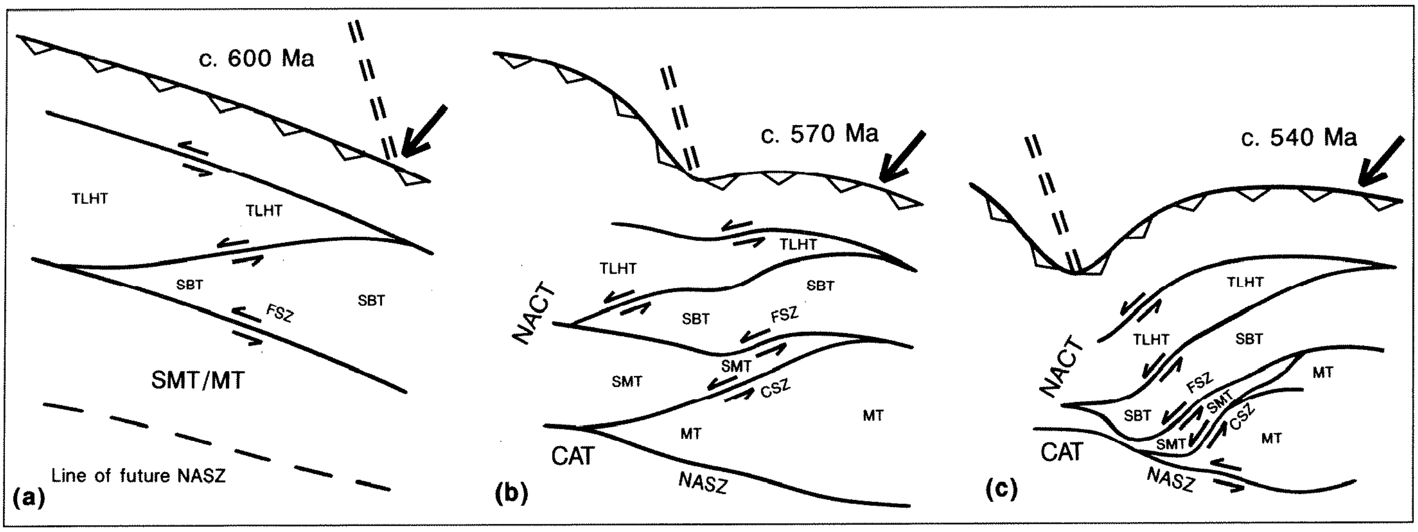

Fig. 5. – Series of time frames at *c.* 600 Ma (a), *c.* 570 Ma (b) and *c.* 540 Ma (c) shown in plan view to illustrate the geodynamic model proposed for the late Precambrian evolution of the Armorican segment of the Cadomian belt. The large arrow represents the relative displacement vector between the subducting oceanic plate and the overriding continental margin plate, paired dashed lines represent the aseismic ridge on the oceanic plate, and the solid line with teeth represents the line of the trench, the teeth indicating southward-directed subduction. Half-arrows show the sense of displacement along wrench zones. Abbreviations are the same as in the text.

Fig. 5. – Séries de schémas, vus en plan, à 600 Ma (a), 570 Ma (b) et 540 Ma (c) environ illustrant le modèle géodynamique proposé pour l'évolution à la fin du Précambrien, du segment armoricain de la chaîne cadomienne. Les grandes flèches représentent le vecteur de déplacement relatif entre la plaque océanique en subduction et la plaque continentale en obduction ; les lignes en doubles pointillés représentent la dorsale asismique sur le plancher océanique, et la ligne continue dentelée représente la trace de la fosse, les dents indiquant le sens (vers le sud) de la subduction ; les demi-flèches indiquent le sens de déplacement le long des cisaillements. Les abréviations sont les mêmes que dans le texte.

by J.-P. Lefort and P. Bardy (1987) and C. Bois *et al.* (1990). However, although the magnetic anomaly turns to a north-south orientation at its eastern end, to interpret any part of this anomaly to represent the trace of a former bathymetric high beneath the Channel would be nothing more than speculation.

The model contrasts in detail with the explanation for the arcuate tectonic features around the head of the Baie de St. Brieuc proposed by P. Balé and J.-P. Brun (1989; Brun and Balé, 1990) of a linked northward-dipping, southward-vergent thrust system and marginal transform fault with its associated syn-kinematic plutonism along the southeast side of the thrust system. Hinterland-vergent (antithetic) thrusting in the continental margin is consistent with SW-directed subduction, in contrast to oceanward-vergent (synthetic) thrusting that might be expected at the trench where the oceanic plate subducts beneath the leading edge of the continental margin.

The geometric configuration shown in Figure 5 implies that the point of impingement of the bathymetric high in the trench migrated slowly along the trench to the west, and its transport down the subduction zone to the southwest caused the complex deformation now observed in the overlying continental plate. The progressive subduction of the bathymetric high segmented the continental margin and drove deformation and metamorphism within each of the constituent terranes of the NACT, as well as their accretion, uplift, exhumation and cooling sequentially from north to south. The Brioverian volcano-sedimentary basins were developed successively in a southward progression on the hinterland side of each successively accreted terrane, some of the clastic debris being derived by erosion of each newly uplifted terrane to the north.

By *c.* 570 Ma, deformation of the behind-arc marginal to within-plate basins had begun, with the southern boundary of this zone being the newly-initiated NASZ. The SMT and the MT are regarded as lateral equivalents separated by the sinistral strike-slip CSZ. The progressive deformation resulted in structural inversion of the SMT protolith basin and thickening of the sedimentary sequences, together with the underlying thinned continental crust, which led to thermal relaxation and crustal anatexis, with additional advected heat from the mantle, suggested by the gabbro-norite complex at Trégomar (Figure 1). In the SMT, melting occurred in the presence of a water-rich volatile phase, the ingress of which may have been facilitated by the deformation style associated with subduction of a bathymetric high. In the interval c. 570-550 Ma in the MT, regional extension likely continued together with sedimentation, until around 550-540 Ma low a_{H_2O} volatile phase-absent anatexis led to reduced viscosities within the MT crust and allowed transpressive deformation to facilitate transport of granite magma upward through the crust, to be emplaced at a higher structural level in the MT. Ascent is inferred to have been channelized along steeply-oriented strike-slip shear zones with emplacement into tensile bridges developed between left-stepping segments of a major transcurrent fault zone. Along individual granite pluton/country rock contacts, however, local space creation by stoping clearly was the method by which emplacement was completed.

Transpressional deformation was accomplished in part by volume loss due to this escape of magma from the middle and lower crust.

Such a progressive model that involved tectonic dismemberment and lateral juxtaposition of originally continuous units argues against a ".. palinspastic separation of the contrasting Cadomian elements until at least the latest Precambrian" (Dallmeyer *et al.*, 1991b). The model explains both the diachroneity in sediment accumulation and tectonothermal evolution from north to south and from terrane to terrane, and the map shape of the terranes, which thin in a wedge-like fashion towards the southwest as they bend around the Yffiniac arc at the head of the Baie de St. Brieuc. Further west, around Lannion, Cadomian structures bend back to an E-W orientation, which may be a primary Cadomian feature, although the superimposed effect of the Variscan orogeny makes it difficult to be sure of such an interpretation. However, this interpretation would be consistent with the ENE-WSW orientation of the offshore magnetic anomaly, but such a coincidence is permissive rather than conclusive.

Conclusions

The late-Precambrian evolution of the Armorican segment of the Cadomian belt can be explained by a geodynamic model involving normal plate interactions at a convergent plate-boundary zone along a continental margin. Southward-directed subduction is preferred, rather than northward-directed subduction, because it is more consistent with the full spectrum of geological evidence, and because it leads to a simpler geodynamic model. It is argued that the Armorican segment comprises four discrete but related terranes formed by tectonic dismemberment of an active continental margin and juxtaposed during progressive crustal-scale deformation consequent upon impingement at the trench and subduction of an ocean-floor bathymetric high, such as an aseismic ridge or young oceanic island arc. The tectonic segmentation of once continuous units and the juxtaposition of the resultant terrane elements led to different tectonometamorphic histories, southward-younging ages of accumulation of Brioverian sequences, and hinterland-propagating deformation. Accretion of far-traveled exotic terranes is not required to explain exposed elements of the Armorican segment of the Cadomian belt.

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