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ALBANIAN OPHIOLITES. II - MODEL OF SUBDUCTION ZONE INFANCY AT A MID-OCEAN RIDGE

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ABSTRACT

In the Albanian ophiolites, as well as in many other ophiolite complexes, tectonic, magmatic and geochronological evidences support the view that the intra-oceanic detachment preceding obduction is virtually contemporaneous with the oceanic accretion. Subduction zone infancy at a ridge axis has been numerically investigated by 2D thermal modelling of a convective upper mantle, with surface and subducting plates displacements prescribed by time-dependent kinematic conditions and with particular attention paid to the subducting oceanic lithosphere and the overlying mantle wedge. To explore the possible evolution of MORB, IAT, and boninitic magmatism with subduction progression, we overlaid reasonable chemical characteristics onto the thermal structures.

Our experiments indicate that the initiation of a subduction at a ridge axis does not immediately stops the ascending asthenospheric flow, but leads to a deviation of its upper part in the same direction as the subducting lithosphere. Preservation of high temperatures in the mantle wedge explains the presence of short-lived boninitic magmatism at the earliest stages of subduction initiation which is partly contemporaneous with the progressive extinction of MORB magmatism and the initiation of arc magmatism. At the same time, temperatures in the subducting oceanic crust lead to the development of high temperature-high pressure metamorphic rocks. Despite of its relative simplicity, this numerical model accounts well for observations in supra-subduction zone ophiolites.

INTRODUCTION

In many ophiolite complexes, tectonic, magmatic and geochronological evidences support the view that the intra-oceanic detachment preceding the obduction is virtually contemporaneous with the oceanic accretion (Nicolas, 1989). In the Albanian ophiolites (Bébien et al., 2000, this issue), a subduction zone infancy at or near a mid-ocean ridge is strongly suggested: (1) by the presence of island arc type magmatism (low- and very low-Ti magmatism, including boninites) in close association in space and time with magmatism showing a MORB affinity (high-Ti magmatism); (2) by the high temperature-high pressure metamorphism observed in the infra-ophiolitic sole; (3) by the similitarity of ages determined on magmatic rocks from ophiolites and metamorphic rocks from the infra-ophiolitic sole. Initiation of a subduction at or near a ridge, already proposed by Gjata et al. (1992) and Manika (1994), may account for most of these observations. On the one hand, the high temperature-high pressure metamorphism observed in the infra-ophiolitic sole can be related to the subduction of young, still hot oceanic lithosphere at a depth of at least 30-35 km. On the other hand, dehydration of this subducting lithosphere and release of H_2O into a hot, refractory overlying mantle wedge can induce low- and very-low Ti magmatism that is partly contemporaneous with a residual spreading ridge high-Ti magmatism.

In order to test these ideas, subduction zone infancy at a ridge axis has been numerically investigated by 2D thermal modelling of a convective upper mantle, with surface and subducting plates displacements prescribed by time-dependent kinematic conditions and with particular attention paid to the subducting oceanic lithosphere and the overlying mantle wedge (Insergueix, 1997; Insergueix et al., 1997). The results of this investigation will be compared with observations on Albanian ophiolites.

NUMERICAL MODELLING

The Earth's upper mantle is modelled by a rectangular box with an aspect ratio of four and a spatial resolution of 5 km. Fluid mechanics equations for isoviscous thermal convection are solved numerically with a 2D cartesian finite difference convection code that was originally developed for studying ocean ridges (Dupeyrat et al., 1995). Plate displacements and rigidity are taken into account by imposing the velocity of the upper boundary. To distinguish slow from fast plate motions, we consider the reference surface velocity value inferred from the balance between buoyancy and boundary forces (Gurnis and Davies, 1986). Assuming a mantle viscosity of $5x10^{21}$ Pa.s and a temperature contrast across the whole convective layer of 1900 K, realistic mean surface heat flow (about 75 mW/m^2) and acceptable melting zones at ridge axes (depth between 40 an 80 km, and lateral extent about 200 km) are obtained. Other typical input parameter values for the upper mantle are a Rayleigh number of about $1.2x10^5$ and a reference surface velocity in the order of 2.5 cm/yr.

The geodynamic scenario of our model is made up of three successive stages (Fig. 1). The initial stage corresponds to a stationary stage obtained for a symmetrical spreading at the uniform velocity V_r (Fig. 1a). A kinematic reversal is then imposed at a constant rate. Possible rapid plate motion changes, as an expression of the creation or destruction of major transform faults have been pointed out (Richards and Lithgow-Bertelloni, 1996). Therefore, we impose a rapid kinematic reversal rate of a few (cm/yr)/Myr. For instance, a rate of 1 (cm/yr)/Myr means that a period of 1 Myr is required to transform an initial spreading at 0.5 cm/yr to plate convergence at the same velocity. By prescribing this kinematic reversal rate, we obtain an intermediate stage characterised by motionless surface plates, and constituting the initiation of subduction at the former ridge

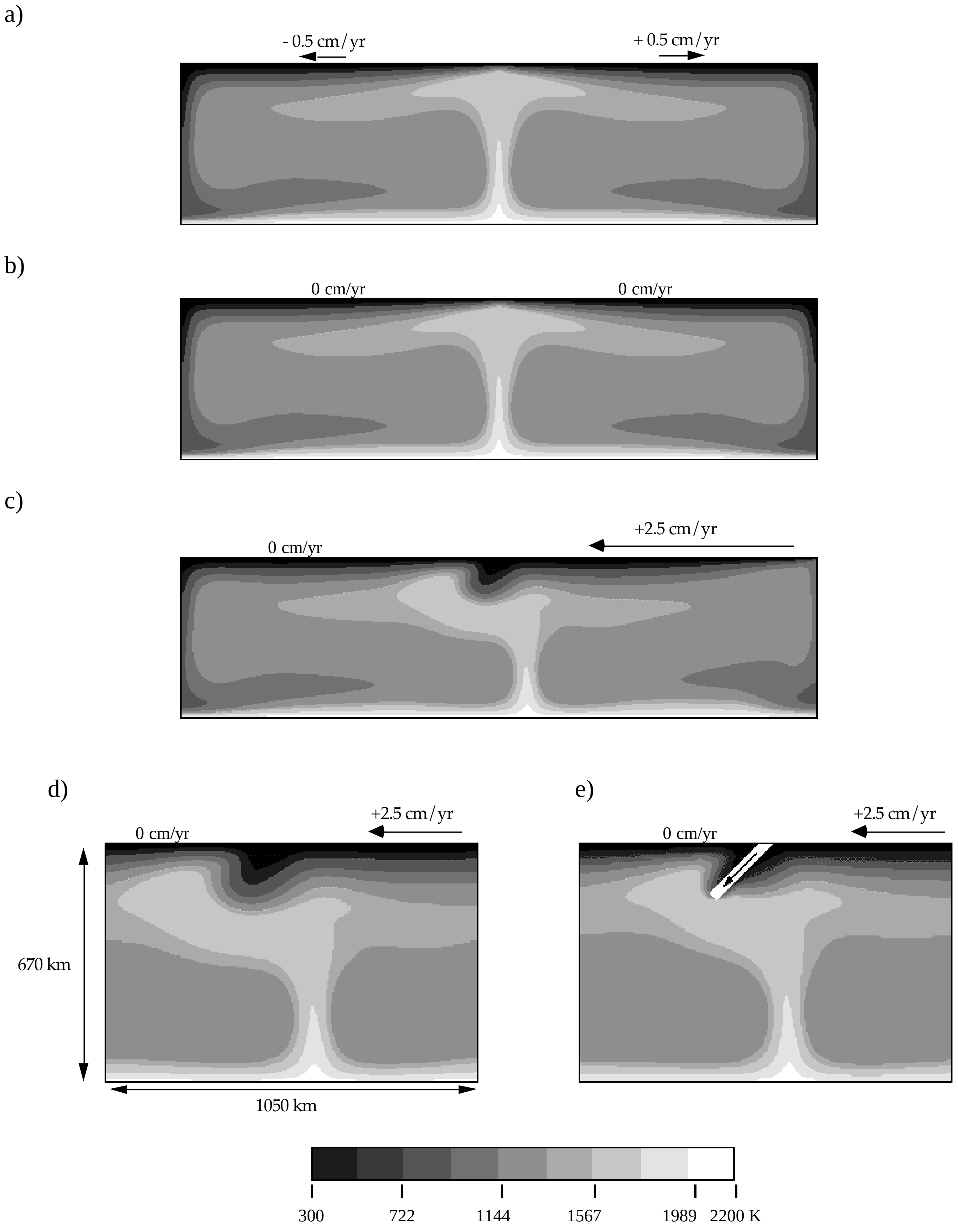

Fig. 1 - Temperature fields at the three stages of the dynamic scenario for the: a) initial state that is a stationary symmetrical spreading at $V_r = 0.5$ cm/yr; b) intermediate stage obtained after a kinematic reversal at a rate of 1 (cm/yr)/Myr : both plates are motionless; c) advanced stage in the case of no downgoing slab boundary conditions: the right plate moves towards the motionless overriding left plate at a final velocity $V_s = 2.5$ cm/yr. The convergent point is located on the former ridge's axis. Thermal focus on the ascending plume at the final stage: d) in the case of no downgoing slab boundary conditions corresponding to (c); e) in the case of a forced 45°-dipping subduction.

axis (Fig. 1b). The right plate will move towards the stable overriding plate at a velocity progressively increasing to a maximum value V_s (Fig. 1c-d). This simulation accounts well for an initiating subduction at a ridge but not for a shallow dipping, young subduction system. The movement and the geometry of the downgoing plate are accounted for by prescribing a kinematic boundary condition inside the box for a thickness of 40 km (Fig. 1e), which is a typical value for the mechanical lithospheric (Davies and Stevenson, 1992). Calculations are stopped when the downgoing plate reaches a depth of 150 km, which is sufficient for studying subduction infancy because arc magma source zones are limited to this depth. A systematic investigation has been achieved as a function of the kinematic reversal rate, the final subduction velocity V_s, and the subduction dip, for a given initial spreading velocity V_r.

DYNAMICAL IMPLICATIONS

First, we present the case where the subduction is not forced. Temperature fields are shown in Fig. 1 for the three successive stages of our model. Fig. 1a presents the initial stationary state (0 Myr) of slow symmetrical spreading at V_r = 0.5 cm/yr. By prescribing a kinematic reversal rate of (1 cm/yr)/Myr, both surface plates become motionless after 0.5 Myr (Fig. 1b). Then, the right plate begins to move towards the left one at a velocity that progressively increases at the rate of (1 cm/yr)/Myr up to V_s = 2.5 cm/yr. Fig. 1c illustrates an advanced stage of the model. In Fig. 1a, we verify that the flow rises symmetrically beneath the middle of the upper boundary. In Fig. 1b, we notice that the subduction initiates during a still active state of upwelling. A first important observation is that the kinematic reversal allows a non vertical but steep-dipping flow (Fig. 1c). Secondly, the initial hot ascending flow has undergone a deviation of a few hundreds of kilometres and has intruded the upper mantle wedge above the subducting plate.

We now investigate the deviation of the initial hot upwelling, first for the case of a non forced subduction (Fig. 1d), and second for the case of a forced, 45°-dipping subduction (Fig. 1e). Fig. 1e presents the final stage, since the downgoing plate has reached a depth of 150 km. It is noteworthy that the same hot upwelling deviation is observed whether the subduction is forced or not. We may argue that the movement of the right plate is combined with the ascent of the initial flow to cause the initial hot upwelling to deviate towards the right side at its base and towards the left side at its summit. We observe no difference in the thermal structure of the plume at its base. In contrast, the hot ascending flow looks more penetrating in the upper asthenospheric wedge in the case of a non forced subduction than in the forced, 45°-dipping subduction one. Fig. 1e suggests that a shallow-dipping plate is likely to constitute a barrier against the ascending flow.

MAGMATIC AND METAMORPHIC IMPLICATIONS

Our model suggests that the high temperatures do not immediately disappear after the reversal, and that they are more particularly located in the mantle wedge. This is likely to have important implications for magma production and metamorphism of the subducted crust.

To explore the possible evolution of MORB, island arc and boninitic magmatism with subduction progression, we overlaid chemical characteristics onto our thermal structures (Fig. 2a). It is now generally accepted that H_2O plays an important role in production of island arc and boninitic magmas (Tatsumi and Eggins, 1995). We assumed a lateral transport of up to 50km for the water released from the downgoing slab (Davies and Stevenson, 1992). In our model, water transport is instantaneous in the horizontal direction and evolves with the subduction progression in the downgoing slab direction. Moreover, the extraction of MORB magmas from a depleted mantle depletes it further. The resulting residual depleted mantle (O'Neill and Palme, 1998) is often considered the source from which the boninitic magmas are extracted (Crawford et al., 1989; Pearce et al., 1992). Thus, the upper mantle prior to subduction is supposed to be composed of depleted MORB mantle

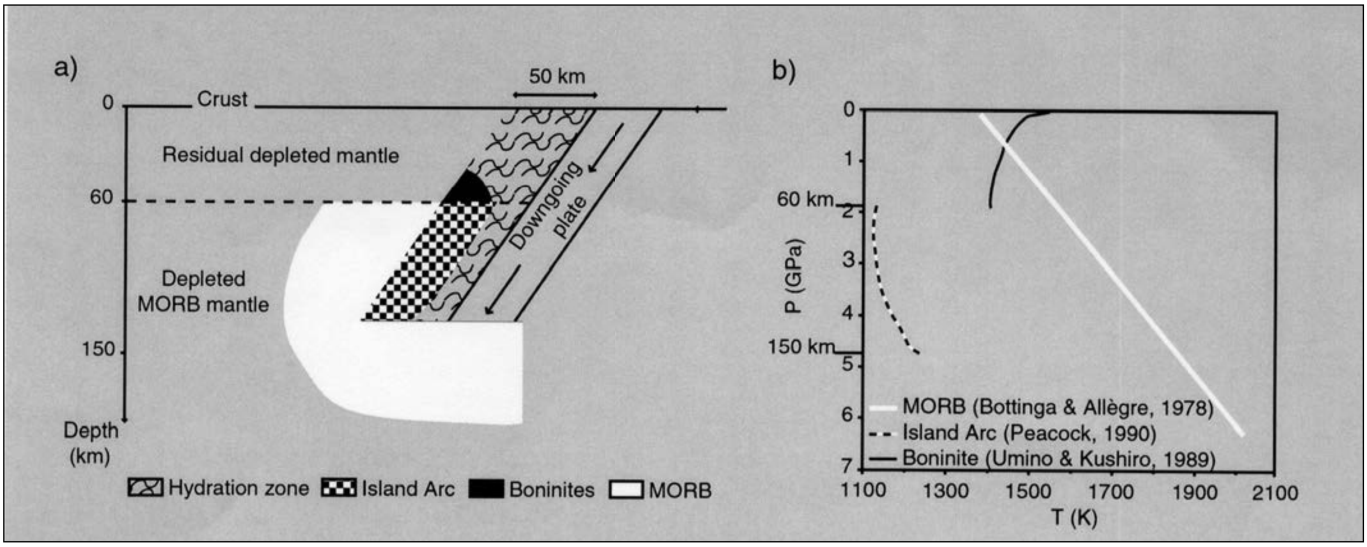

Fig. 2 - Model melting conditions for MORB, island arc and boninite magmatism characterised by:
a) chemical characteristics of the sources (island arc magmatism: hydrated depleted MORB mantle; boninites: hydrated residual depleted mantle; MORB: dry depleted MORB mantle);
b) solidus for a peridotite dry peridotite (MORB), for a peridotite wet peridotite (island arc), and for a water-saturated boninite.

below 60 km, and of residual depleted mantle above 60 km. In order to investigate the production of boninitic and island arc magmatisms respectively (Fig. 2b), we applied a water-saturated solidus for Chichi-jima boninites above 60 km (Umino and Kushiro, 1989; although boninites are not water-saturated, we estimate this solidus as broadly convenient for our purpose) and a peridotite wet solidus (Peacock, 1990) for depths between 60 km and 150 km in the hydrated zone. For the production of MORB in the anhydrous zone under 60 km, we applied a dry solidus (Bottinga and Allègre, 1978).

Fig. 3 depicts the initiation of a subduction zone with a forced, 45°-dipping subduction with the kinematic characteristics of Fig. 1. We can follow the evolution with time of melting zones, overlaid on thermal structures. After the beginning of the kinematic reversal, MORB magma generation does not stop immediately but decreases progressively. It is predicted that MORB magmatism is more likely to persist in the initiating upper mantle wedge than anywhere else. On the other hand, high temperatures above the subducting plate, associated with pecculiar chemical characteristics, are responsible for the presence of boninitic melting conditions around 50 km ofdepth. This magmatism starts between 3 and 4 Myrs after the subduction initiation, and reaches a peak a few million years later (around 2 Myrs. As the upper mantle wedge becomes colder with the progression of subduction, the magmatism progressively decreases. Partly contemporaneous with boninitic magmatism, the island arc volcanism takes place and increases as the subduction moves forward, so that the melting conditions after 10 Myrs are consistent with an island arc setting. Because MORB and boninitic magmatism are contemporaneous and melting zones are located above each other, there may be a mixing of both magma types by each over between 4 and 8 Myrs. Mixing may also take place between MORB and Island Arc magmatism, and briefly between boninitic and island arc magmatisms.

At the same time, temperatures in the subducting oceanic crust lead to the development of high temperature-high pressure metamorphic rocks. Fig. 4 shows the evolution of temperatures and pressures at the top of the subducting plate for different stages of the slab progression in case of a forced, 45°-dipping subduction with the kinematic characteristics of Fig. 1. Soon after the initiation of the subduction, the slab-surface temperature increases rapidly with depth. Later, as the subduction progresses, the temperature at a given depth gradually decreases. Greenschist and amphibolite facies P-T conditions in the subducted oceanic crust are reached about 2.5 Myrs after the subduction initiation, and the granulite facies appears a little later, about 3 Myrs. The P-T conditions then become progressively appropriate for the high pressure - low temperature metamorphism usually considered as more typical of subduction zones: blueschist and eclogite facies P-T conditions respectively appear about 4 Myrs and 5 Myrs after the initiation of the subduction.

APPLICATIONS TO ALBANIAN OPHIOLITES

Diversity of magma compositions

The diversity of the magmas involved in the genesis of plutonic and volcanic rocks constitutes one of the most striking feature displayed by Albanian ophiolites (Bébien et al., 2000, this issue). According to our model, the chemical and physical conditions for the formation of the different magmatisms can coexist during the initiation of subduction at or near a ridge axis. High-Ti basaltic magmatism attests for the persistence of an upwelling mantle flow in spite of the kinematic reversal from spreading to convergence. Temperatures near the subducted slab are high enough for the partial melting of residual mantle in presence of water for several million years, and to trigger a very low-Ti magmatism. The low-Ti magmatism can result from the tapping of less depleted mantle but also from the mixing of very low-Ti magmatism by high-Ti magmatism, due to the location of the respective melting zone in the mantle wedge (Fig. 3). Progressive compositional variations in the mantle and this mixing process can both account for the observed transitions between the high-Ti, low-Ti and very low-Ti magmatisms.

Distributions, relationships and ages

In the Albanian ophiolites, the different types of magmatism are now exposed along a belt which width does not exceed 80 km (Fig. 5). According to mutual relationships, low- and very low-Ti magmatism, which are particularly abundant along the eastern part of the belt, seem to follow in time a high-Ti magmatism mainly located to the West (Bortolotti et al., 1996; Bébien et al., 1998). Nevertheless, as far as we know, there is no break in either magma compositions or space and time. Fig. 3 shows that conditions for the production of very low-Ti boninitic magma, according to our model, are achieved about 4 Myrs after the begining of the kinematic reversal, at 60-70 km from the trench. At that time, high-Ti, MORB-type melts are still present in the mantle over an area that extends as far as 200 km from the trench beneath the motionless plate.

The creation of new lithosphere above an initiating subduction zone is probable but its mode of formation is still largely mysterious (see review in Bédard et al., 1998). Our model does not provide a full explanation about this subject, nevertheless, it strongly suggests a spreading process above the upwelling mantle flow (Insergueix, 1997). Two slightly different scenarios can account for the observed distribution of the various magma types in the Albanian ophiolite belt, both of them implying a westward dipping subduction (Fig. 5): (1) several spreading centres, more or less successively, give rise first to the high-Ti magmas to the west and then to the low- and very low-Ti magmatisms to the east; (2) high-Ti magmatic rocks are produced at a spreading centre and then are shifted westward during the production of low- and very low-Ti formations from the same centre.

Ophiolitic metamorphic soles

metamorphic sole, less than 0.5 km thick, occurs along both the eastern and the western sides of the ophiolite belt, between serpentinized peridotites and the substratum (Bébien et al., this issue). It mainly consists of amphibolites associated with gneisses and micaschists, grading rapidly downward into relatively unmetamorphosed rocks. On the basis of petrochemical data, the amphibolites clearly originated from basaltic and gabbroic protoliths, and seem to include only members of high-Ti series. The protoliths of micaschists and gneisses were probably siliciclastic sediments with pelitic components.

This metamorphic sole exhibits a steep and apparently inverted metamorphic gradient, with granulitic assemblages preserved close to the contact with the obducted peridotites,

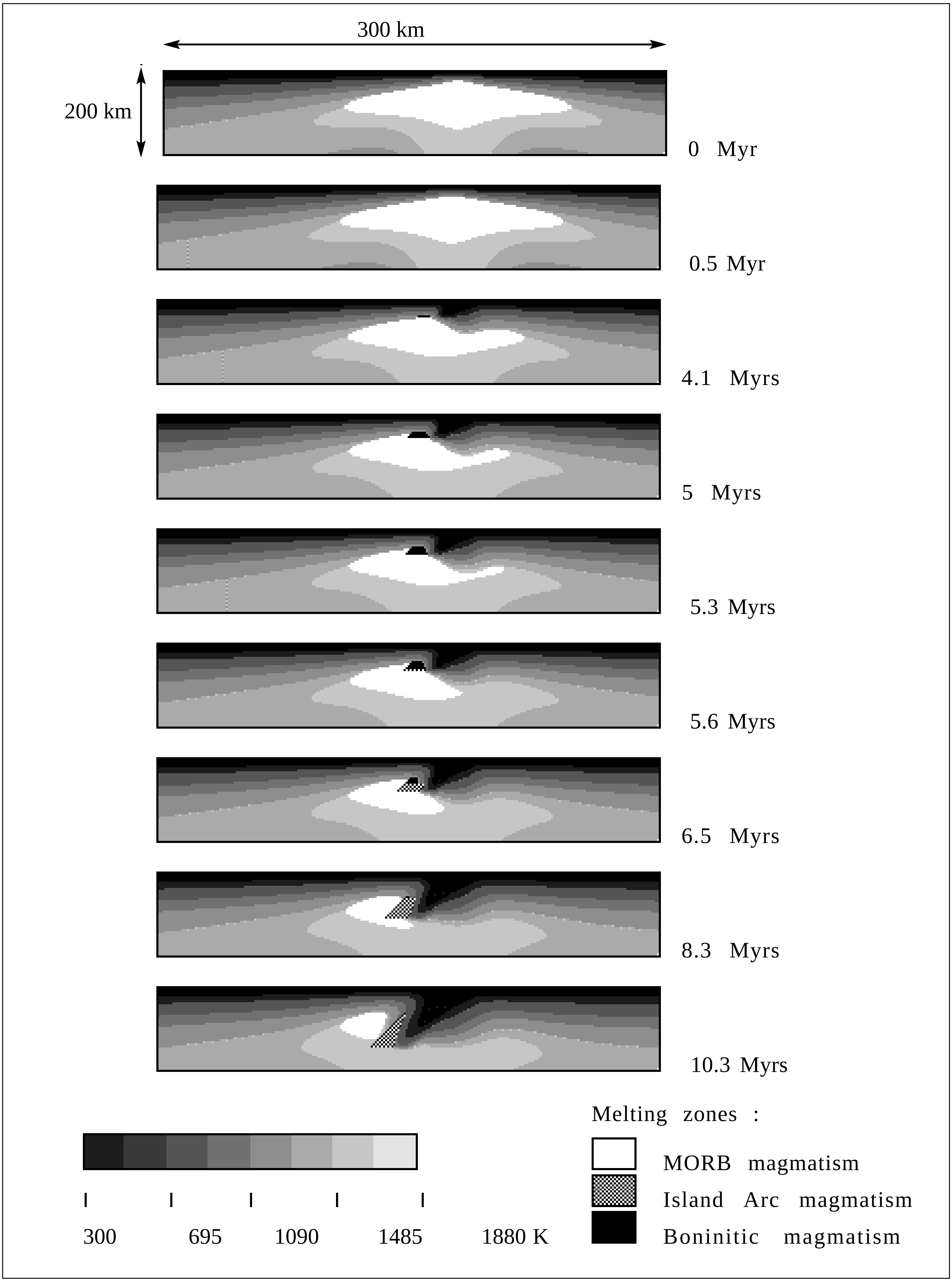

Fig. 3 - Evolution with time of the MORB, island arc and boninite magmatism for a forced 45°-dipping subduction with same kinematic characteristics as in Fig. 1.

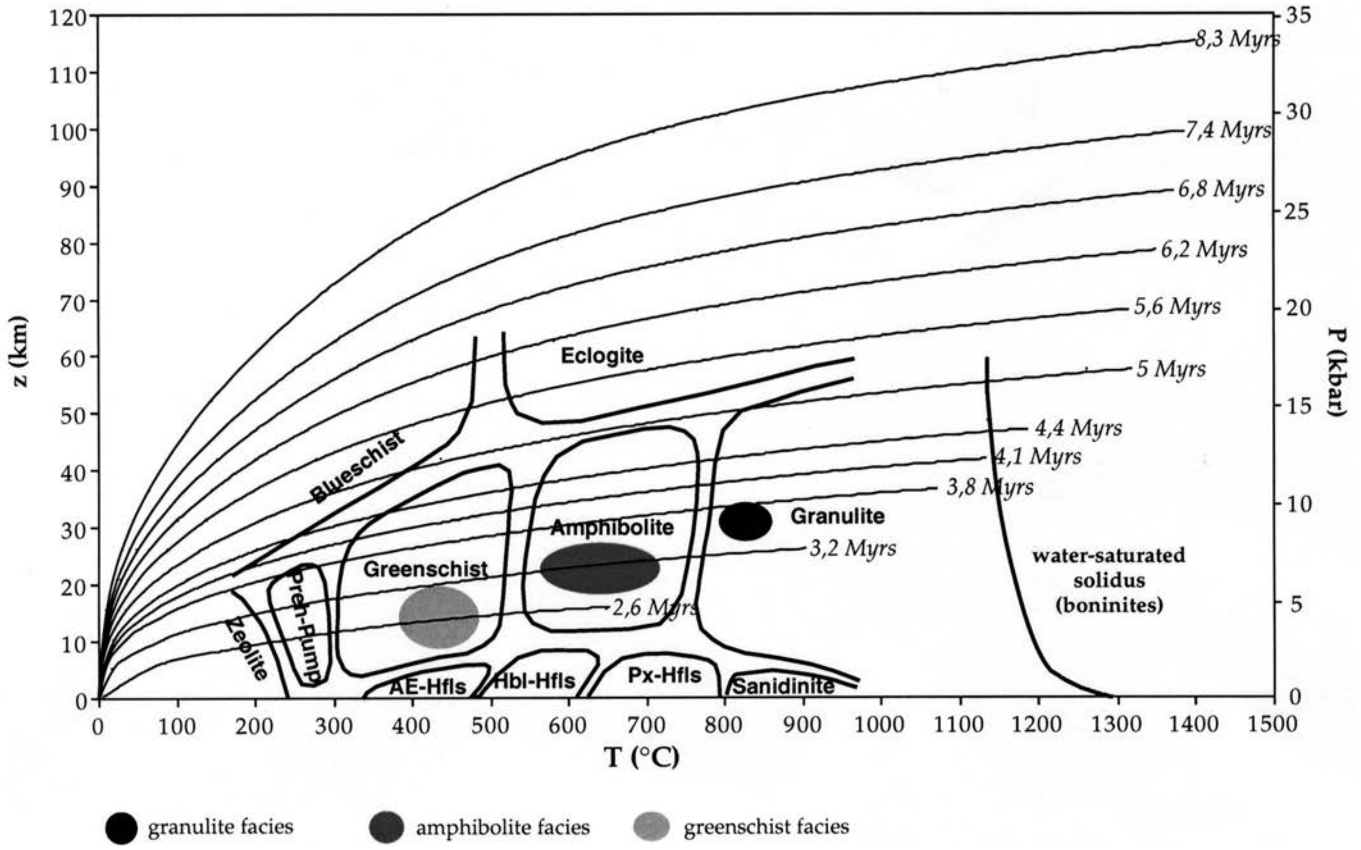

Fig. 4 - Evolution of the temperatures and pressures at the top of the subducting plate for different stages of the slab progression for a forced 45°-dipping subduction with the same kinematic characteristics as in Fig. 1. On this diagram, we have overlaid the water-saturated solidus for Chichi-jima boninites (Umino and Kushiro, 1989) and the P-T conditions of Albanian metamorphic rocks. The metamorphic facies boundaries are after Yardley (1989).

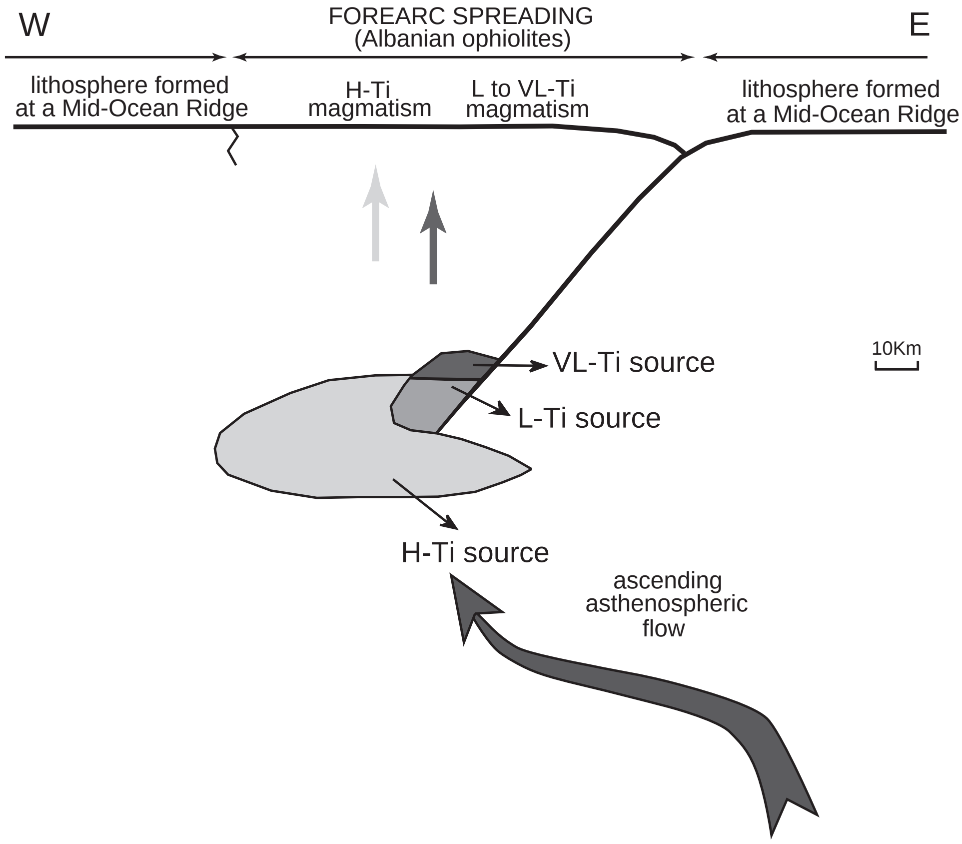

Fig. 5 - Model for the genesis of Albanian ophiolites in relation with the initiation of a subduction zone at a ridge axis (H-Ti: high-titanium; L-Ti: low-titanium; VL-Ti: very low-titanium).

grading downward into almandine-amphibolite sub-facies assemblages, amphibolite facies, then greenschist facies rocks. Estimated P-T conditions range from 800-850°C and 0.9-1.2 GPa in the granulite facies rocks to 300-400°C and 0.2-0.3 GPa in the greenschist facies rocks. Fig. 4 shows that these P-T conditions could be present at the top of the subducted slab between 2.5 and 4 Myrs after the beginning of the kinematic reversal, in case of a forced, 45°-dipping subduction with the kinematic characteristics of Fig. 1. According to our model, conditions for the production of very low-Ti boninitic magmas are also achieved in the mantle wedge at that time. This result is supported by the similarity of ages determined on magmatic samples from ophiolites and metamorphic samples from the infra-ophiolitic sole in Albania (Vergély et al., 1998).

CONCLUSIONS

In the Albanian ophiolites, magmatic and geochronological evidences support the view that oceanic accretion may be contemporaneous with an initiation of a subduction at or near a mid-ocean ridge. In order to test this assumption, subduction zone infancy at a ridge axis has been numerically investigated by a 2D convective domain modelling of the upper mantle where surface and subducting plate displacements are prescribed by time-dependent kinematic boundary conditions. The main results of this investigation are the following:

1) the onset of a subduction at a ridge axis does not immediately stop the ascending asthenospheric flow, but leads to a deviation of its upper part in the same direction as the subducting lithosphere;

2) the preservation of high temperatures in the mantle wedge favours the setting of short-lived boninitic magmatism in the earliest stages of subduction initiation which are partly contemporaneous with a progressive extinction of MORB magmatism and initiation of arc magmatism;

3) at the same time, temperatures in the subducting oceanic crust lead to the development of high temperature-high pressure metamorphic rocks.

These results account well for most of the observations made on the Albanian ophiolites as well as on many supra-subduction zone ophiolites.

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