Structure and Lithology of the Oceanic Crust: What do we Know Today?

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INTRODUCTION

The last forty years have been marked by a fantastic international effort for exploring the deep sea floor, especially the worldwide mid-ocean ridge system, thanks to the continuous development of new technologies and tools: high resolution multibeam sonar systems and side scan sonars (mapping and acoustic imagery of the ocean floor), sophisticated drilling ships (international DSDP, ODP and IODP programmes), deep submersibles, high performance geophysical tools, etc. These efforts have resulted in a much better knowledge of the immerged part of the Earth's crust.

Our knowledge of the lithological structure and composition of the oceanic crust is based on three main data sources:

- (1) the geophysical data, mainly the seismic refraction and reflexion profiles realized in the oceanic basins, combined with gravimetric and magnetic surveys;
- (2) the geological sections and rock samples collected directly from the ocean floors, using dredge hauls, deep sea submersibles and drilling ships through the DSDP-ODP-IODP long-lived international programme;
- (3) the ophiolites, fragments of fossil oceanic lithosphere from the oceans of the past, that can be studied on land in mountain belts of various ages, and which give access to the deepest parts of the oceanic crust and its transition to the oceanic mantle.

SEISMIC STRUCTURE OF THE PRESENT-DAY OCEANIC CRUST

The seismic structure of the ocean floors is studied since more than half a century. The thickness and general structure of the oceanic crust were first estimated from the indirect seismological methods, revealing three major characteristics: seismically, the ocean crust is *thin* (6-7 km), of *constant thickness*, and exhibits a *layered structure*, controlled essentially by the physical properties of the crust with depth (porosity, thermal state, etc.), much more than by its lithological composition.

The Three Layers Model

Raitt (1963) was the first to propose a subdivision of the oceanic crust into three layers, each of them characterized by its mean seismic velocity and its average thickness. He noticed the remarkable fact that below Layer 1 (made of a variable thickness of marine sediments), Layers 2 and 3 present quite identical thicknesses and seismic velocity ranges in all oceans, *whatever the spreading rate*. The upper crust, essentially volcanic (basaltic flows and dikes), constitutes Layer 2, subdivided into Sublayer 2A (young, fractured and porous crust, with a high velocity gradient), Sublayer 2B (aged and hydrated oceanic crust, whose most of the pores are filled), and Sublayer 2C (deep upper crust, transition to Layer 3). The lower crust, mainly gabbroic, constitutes Layer 3, and includes sublayers 3A and 3B, whose velocity gradients are much lower (of the order of 0.1 km s^{-1}).

The Velocity Gradient Model

The model with homogeneous layers was replaced during the eighties by a more sophisticated model implying multiple thin layers with velocity gradients, based on new modelling methods (use of synthetic seismograms, inversion techniques, amplitude modelling, etc.). In this new conception, the oceanic crust consists in a discontinuous series of velocity gradients, the seismic velocities increasing with depth in each unit (Spudich and Orcutt, 1980; White, 1984, 1991).

The Crust-Mantle Transition

Several detailed studies of the crust-mantle transition have shown that the Mohorovicic seismic discontinuity may exhibit very variable characteristics, ranging from a sharp transition between crust and mantle velocities (>8.1 km s^{-1}), to a true transition layer with increasing gradient, or even a series of layers with alternating low and high velocities, over 2 km in thickness. Mapping the crust-mantle transition in ophiolites has revealed the same range of variations of the crust-mantle transition zone at the scale of a same ophiolite massif (Nicolas, 1989).

Seismic Structure of Fracture Zones

At the approach of fracture zones, an important decrease of the crustal thickness is observed, principally at the expense of Layer 3, which may disappear completely. The depth of the ocean floor increases correlatively. Layer 2, intensely fractured and hydrothermalized, rests directly over a strongly serpentinized upper mantle. The serpentinized zones have a tendency to ascend, but gravimetric data show that this process remains limited.

Lithological Identification of Seismic Profiles

The task of identifying the materials constituting the oceanic crust from geophysical data only is very difficult, if not impossible. The seismic velocities of the compression waves alone cannot be used to determine the nature and composition of the rocks, for the simple

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reason that extremely different rocks may present identical seismic velocities. For instance fresh gabbros, metamorphic gabbros, amphibolites and serpentinized mantle peridotites may exhibit quite identical seismic velocities. Inversely, a same material may present important velocity variations, according to its physical state (fracturing, porosity, thermal state, etc.). We know today that the physical properties and thermal state of the crust, as well as its hydrothermal and metamorphic transformations, are parameters perhaps more important than the original magmatic structure and lithology

SAMPLING AND LITHOLOGICAL STRUCTURE OF THE PRESENT-DAY OCEANIC CRUST

Until ~1975, the unique sources of information were dredged sample collections, with all the inconvenient linked to this kind of sampling (approximate locations, samples arriving in total disorder on the deck, etc.). Starting from 1975, the advent of deep submersibles able to realize true geological sections along the ocean floor, and the possibility to reenter the DSDP drill holes, gave new possibilities to study the deep crust (Fig. 1). The overall sampling of the oceanic crust, however, remains today extremely fragmentary with respect to its giant dimensions (360 .10^6 km^2, that is, between 2.1 and 2.5 10^9 km^3). The numerous data accumulated since more than thirty years have progressively shown *considerable differences in the crustal lithology and structure between fast- and slow-spreading oceanic ridges*:

Fast- to Intermediate-Spreading Oceanic Ridges show a *continuous crustal structure* 5-6 km thick, characterized by a thin volcanic layer (several hundreds of metres), a robust sheeted dike complex (>1 km), and a several km thick gabbroic layer, resting over a residual, *harzburgitic* upper mantle. The seismic Moho, in this case, corresponds to the transition between gabbros and mantle peridotites. This crustal structure is explained by a vigorous and sustained magmatic activity along fast-spreading ridges. Two successful deep sections were drilled in the Pacific crust, namely Hole 504B and Hole 1256D, this latter reaching for the very first time the gabbros of Layer 3.

Hole 504B Section

Seven legs were performed between 1979 and 1993 (representing 14 months of drilling) to deepen Hole 504B down to a depth of 2111 m below the seafloor, with a record penetration of 1836.5 m in the ocean crust. The age of the crust is 5.9 My, and the water depth is 3474 m.

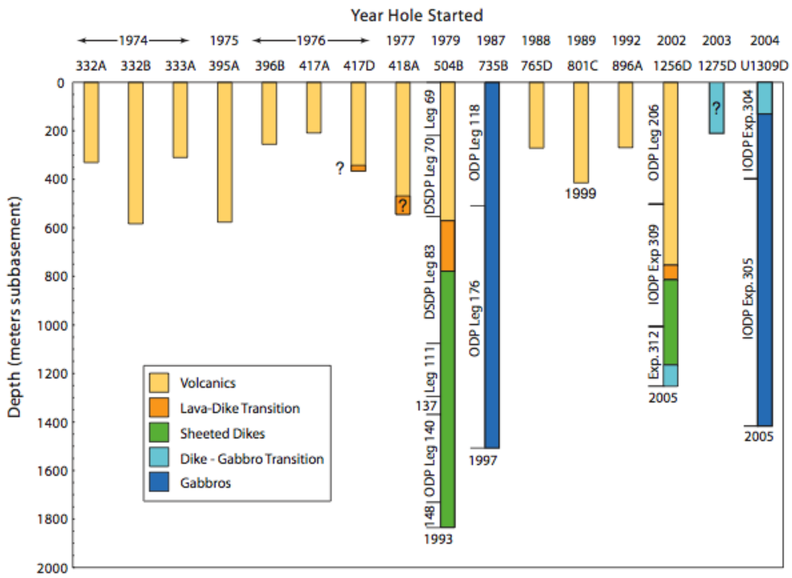

fig. 1. *Table of the Holes drilled in the oceanic crust (> 200 m) during the last 30 years. From 1974 to 1977, all crustal drillings were done in the Atlantic ocean, and more recently Hole U1309D also. Holes 504B, 896A and 1256D were drilled in the Pacific ocean, and Holes 735B and 765D in the Indian ocean. Only 4 Holes have passed one km in depth: two in the upper crust of the EPR fast-spreading ridge (Pacific ocean), and two in the lower crust of slow-spreading ridges (MAR and SWIR). After Dick et al. (2006)*

The lithological section of Hole 504B is the following: below the sedimentary cover (275 m thick), the *pillow lava zone* (571.5 m) is made of alternating pillow lava flows, hyaloclastites and flow breccias, and some massive flows. The *transition zone* (209 m thick) includes pillow lava flows and massive flows, cut by diabase dikes more and more abundant downward. The upper part of this zone is rich in brecciated pillows, and includes a mineralized zone, about 20 m in thickness, impregnated with hydrothermal sulfides (*"mineralized stockwork"*). The *dike zone* (1056 m thick, down to the base of the hole) is entirely made of diabase dikes with steep margins, intersecting each other. The gabbro layer was not reached.

Logging operations and down-hole measurements done in Hole 504B allowed to precise the physical characteristics of the crust, and to distinguish Layers 2A, 2B, 2C, and the transition to Layer 3, *in the middle of the sheeted dike complex*. To the great surprise of a number of specialists, *the Layer 2 / Layer 3 transition was not linked to a lithological or magmatic change (dikes/gabbros transition for instance), but to the variations of physical properties, particularly of porosity* (Detrick et al., 1994). Unfortunately, Hole 504B had to be abandoned before reaching the gabbros, which were not very far...

Hole 1256D Section

Hole 1256D was drilled on the Cocos Plate, in a zone where the oceanic crust, 15 Ma old, was formed by the EPR in super-fast spreading conditions (20-22 cm/year). The crust was supposed to be thinner, enhancing the chances to reach Layer 3 gabbros. Effectively, in December 2005, Hole 1256D, below 3635 m of water and at 1507 m below seafloor, *became the first oceanic drilling to reach the base of the sheeted dike complex and to penetrate into the oceanic gabbros, through a complete and intact upper oceanic crust* (Legs ODP 206 and IODP 309 and 312).

The lithological section is as follows (Wilson et al., 2006, Fig. 2): below 250 of sediments, 754 m of basaltic sheet flows and lava lakes (remarkable absence of pillow lavas), 57 m of transition zone (lavas/dikes), 345 m of sheeted diabase dike complex, and 101 m of transition zone including two gabbroic bodies intruding recrystallized

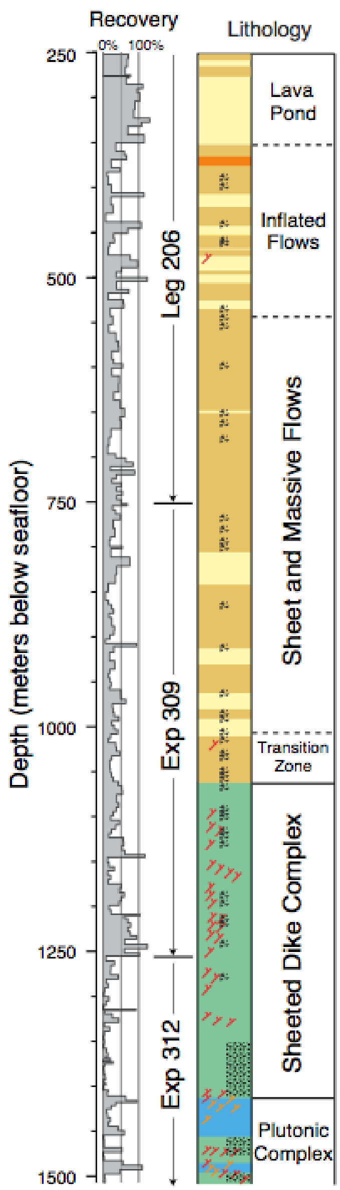

fig 2. Lithological section of Hole IODP 1256D (Cocos Plate, Pacific ocean). The first Hole to reach the gabbros of Layer 3, below an intact upper crust. After Wilson et al. (2006).

dikes. These oxide gabbros and gabbronorites evoke typically the upper isotropic gabbros described in ophiolites. Last year, during spring 2011, Expedition IODP 335 tried to deepen Hole 1256D in the gabbroic layer, but could only drill 15 m in two months, because of technical difficulties of all kinds (Teagle et al., 2011).

The Hess Deep section

Two diving expeditions and drill holes in the Hess Deep area (a propagating rift close to the Galapagos triple junction) allowed to complete these data and propose a 4-5 km thick section of the EPR oceanic crust, characterized by a thin extrusive layer, a robust sheeted dike complex (more than one km thick), and a 2-3 km thick gabbroic layer, including isotropic gabbros at the top (where are rooted the dikes of the sheeted dike complex), then gabbronorites and layered gabbros at the bottom, grading downward to wehrlites and plagioclase dunites, and finally to the foliated harzburgites and dunites of the residual upper mantle (Franchetaeu et al., 1990, 1992).

Slow-Spreading Oceanic Ridges (<6 cm/year) show a *discontinuous crustal tissue*. The dredging, drillings and submersible studies done along the mid-Atlantic ridge confirmed this fundamental fact: in many places of this ocean ridge, *upper mantle peridotites, associated with deep crustal gabbros, are outcropping in the axial zone*, or close enough to the axis to be covered by lava flows. DSDP/ODP drill holes have shown the frequency of this phenomenon, for various ages of the crust (Juteau et al., 1990; Lagabrielle and Cannat, 1990). These observations were interpreted admitting that in a slow accretion context, long duration "amagmatic" stages of pure tectonic extension alternate with relatively brief stages of magmatic production. During these amagmatic stages, the magmatic budget is low and the crust, particularly thin, is easily dismembered by the extensional tectonics, facilitating the access of mantle rocks and gabbros to the seafloor.

The Role of "Oceanic Core Complexes"

In 1996, both British and US expeditions to the slow-spreading Mid-Atlantic Ridge found remarkable seafloor edifices, each of which appears to have originated by long-lived slip on an individual normal fault (Tucholke, 1998). These features, first termed *“megamullions”*, and more recently *"oceanic core complexes"*, have two distinctive characteristics (Figs. 3A and B): first, a *domelike or turtleback shape* extending over a diameter of some 15 to 30 kilometers, and second, *conspicuous grooves or corrugations ("mullions")* that formed as part of the faulting process and that parallel the direction of fault slip over the domed surface. These megamullions were interpreted as footwall blocks exhumed from beneath normal faults, referred to as *“detachment faults.”* By identifying breakaway and termination ages from dated seafloor magnetic anomalies, it was established that the faults forming the North Atlantic megamullions accommodated slip *for periods between 1.0 and 2.6 million years,* with an average period of 1.5 million years (Tucholke, 1998).

Deep Drillings in the Atlantis Oceanic Core Complex

The Atlantis massif appears as a topographic dome at the junction between the MAR and the Atlantis fracture zone at 30ºN. This dome, interpreted as an *"oceanic core complex"* or *"megamullion"*, was drilled in 2004-2005 (Legs IODP 304-305), and a splendid section of 1415 m was recovered at Hole U1309D, with an excellent recovery rate of 75%. This section is quite entirely gabbroic, with the exception of three thin intervals of ultramafic rocks, and a number of diabase dikes, more abundant in the upper 150 m. The gabbroic section is composed of a great number of mutually intrusive units. Intersection relations show that the gabbros s.s. are intrusive in troctolitic gabbros and troctolites richer in olivine, and are themselves intruded by more evolved gabbros and gabbronorites richer in Fe-Ti oxides, and by leucocratic dikes (Ildefonse et al., 2006, 2007a,b). In this section, the gabbros are moderately altered, and weakly deformed. Ductile shear zones, with HT recrystallizations, are rare, and this is an important difference with the gabbros of Hole 735B in the Indian Ocean.

A number of OCC structures were discovered recently, not only at the intersections of the MAR with its fracture zones, but also at axial discontinuities of lower level (MacLeod et al., 2009). For instance, 45 OCC were identified along the MAR between 13ºN and 15ºN only (Smith et al, 2008), affecting about 35% of the ocean floor in that area. In total, recent estimations evaluate at *nearly 50% the surface covered by OCC structures* in the axial zone of slow spreading ridges (Escartin et al., 2008). Along the slow-spreading SWIR, in the Indian Ocean, a number of oceanic core complexes were also identified and one of them drilled in Hole 735B, giving a nice section of

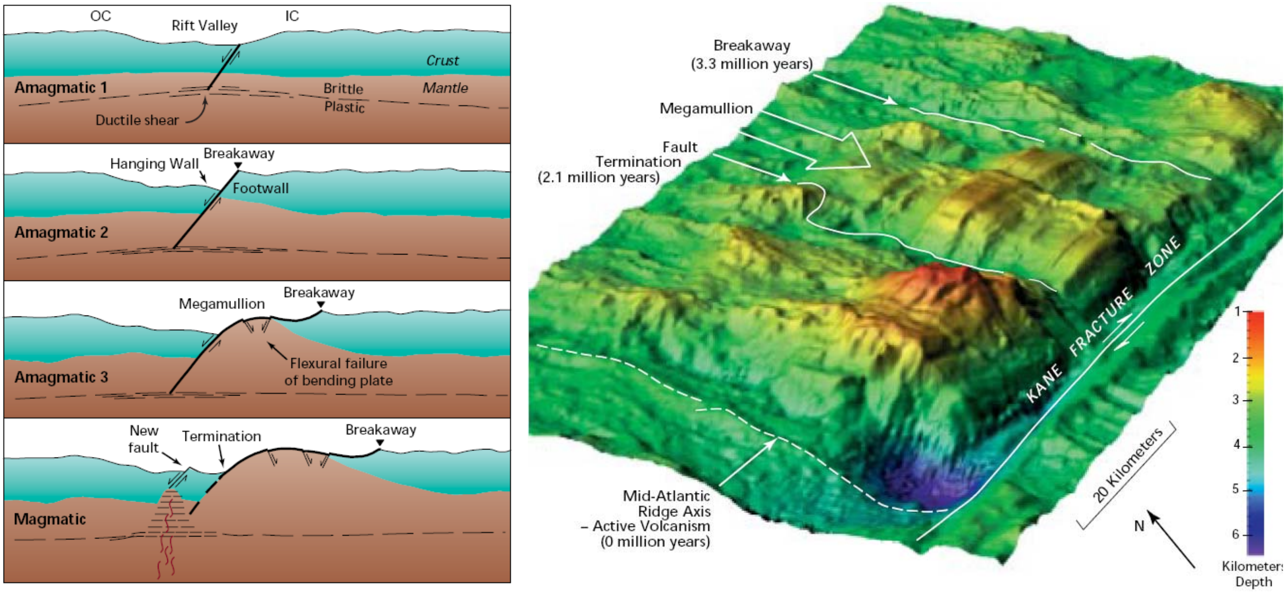

fig 3. A) "Megamullions" or "oceanic core complexes" of slow-spreading ridges. A. Schema showing how an "oceanic core complex" is created. The processus begins during an amagmatic phase of extension, with the activation of a long-lived detachment fault, resulting in the progressive exhumation on the seafloor of the deep crustal and mantle rocks (gabbros and peridotites). It ends with the abandon of the detachment fault, when a new fault develops in the crust of the axial rift, heated by a new magmatic episode (after Tuscholke et al., 1998). B). Block-diagram of the Kane megamullion (center), on the Mid-Atlantic Ridge. Note the large, slip-parallel corrugations on the detachment surface. After Tucholke et al. (2008).

1508m cored in the gabbros of Layer 3, with an excellent recovery (Legs ODP 118 and 176). These gabbros are similar to those of the Atlantis core complex, however they were *plastically deformed at high temperatures* corresponding to the crystallization, in the foliation, of metamorphic assemblages of the *granulite*, then of the *amphibolite facies*, suggesting that the gabbros were deformed in the presence of water in the immediate vicinity of the ridge some 11 My ago (Cannat et al., 1991).

Signification of the Moho

The paradox is that the depth of the seismic Moho below the ocean floor remains stable around 6-7 km below the Atlantic as below the Pacific. It seems that there is a contradiction between the geological evidences, showing a thin and discontinuous magmatic crust, *often reduced to zero at the very axis of the ridge*, and the seismic data, tracing invariably a regular seismic Moho at 5-6 km from the ocean floor. To resolve this contradiction, Cannat (1993, 1996) proposed an elegant solution (Fig. 4): Layer 3 in the Atlantic and slow-spreading ridges would consist of a serpentinized upper mantle, intruded by numerous isolated gabbroic pockets. The seismic Moho, in this case, would mark *the lower limit of serpentinization of the mantle*, and also *the lower limit of gabbroic intrusions* included in the serpentinized upper mantle: both materials exhibit the same V_p seismic velocities. It happens - and this is pure coincidence - that this lower limit of serpentinization (following roughly the 500ºC isotherm) is located at about 5-6 km depth below the seafloor, that is, the same depth than the crust-mantle transition on fast-spreading ridges.

Finally, the episodic and irregular character of the magmatic production at slow spreading ridges results in the creation of a discontinuous and very irregular crustal structure (Fig. 5). This is a main difference with the crust of the Pacific ocean, where nothing similar was observed: the high frequency of the volcanic eruptions and the sustained magmatic production have created there an homogeneous oceanic crust with a roughly constant thickness.

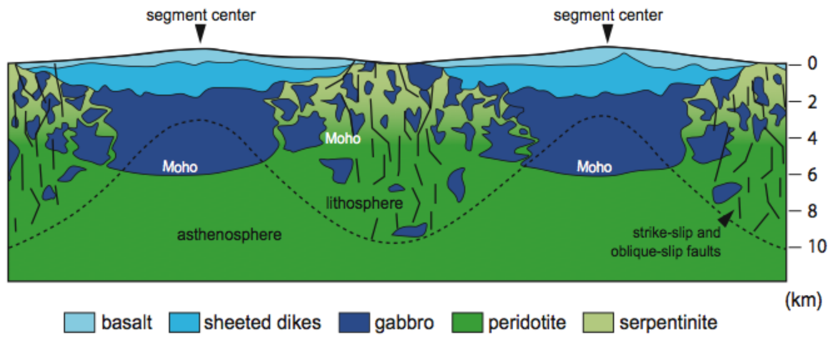

fig 4. Axis-parallel section of two accretion segments through a slow-spreading ridge. Note the shallower Moho and mantle rocks exhumation at the segment ends. After Cannat et al. (1995).

COMPARISON WITH OPHIOLITES, PIECES OF FOSSIL OCEANIC LITHOSPHERE

The "standard ophiolite model", as defined by consensus during the famous Penrose Conference about ophiolites in 1972, includes an "ultramafic" layer that represents the oceanic mantle, and an overlying crust formed from melt that rose buoyantly at a mid-ocean ridge from the hot, upwelling mantle. The comparison of ophiolites with the lithosphere of the present-day oceans must be conducted with caution and lucidity, because:

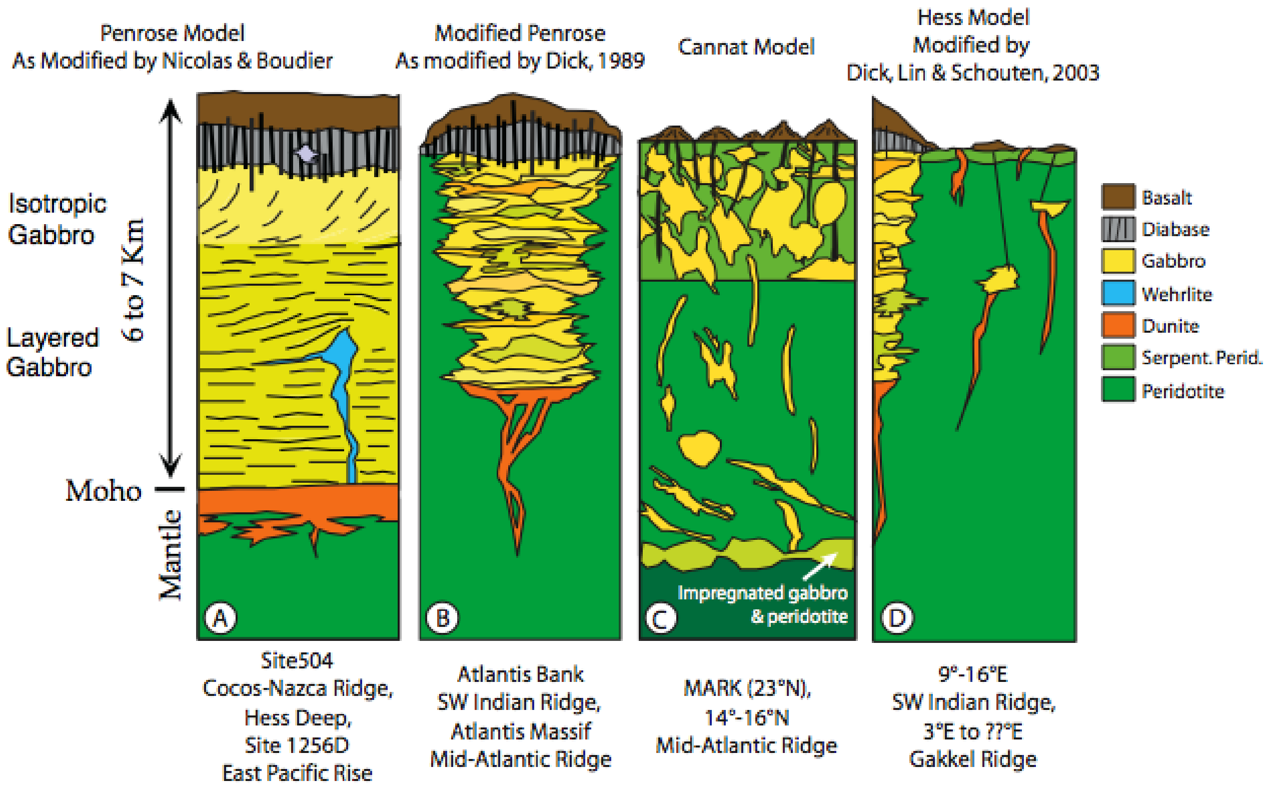

fig 5. *Models for crustal accretion at oceanic ridges of various spreading rates. A. Fast-spreading ridges, after data from EPR and Oman ophiolite (Penrose Model). B. Slow-spreading ridges, after data from the MAR. C. Anomalous segments of slow-spreading ridges, such as MAR between 14-16ºN. D. Ultra-slow spreading ridges, with sharp transitions between magmatic and amagmatic accretion. After Dick et al. (2006)*

- Our knowledge of the present-day oceanic crust is still very fragmentary. Layer 3 remains quite unknown. Layered gabbros for instance, so frequent and so spectacular in many ophiolites, have never been observed nor sampled up to now in the oceans. The transition zones Layer2/Layer3 and Layer 3/Mantle are poorly documented. Only the upper crust (Layers 1 and 2) is reasonably studied in the various oceans, but many uncertainties remain about the composition and structure of the deep crust.
- On the other hand, ophiolites which exhibit on land complete sections across the crust and upper mantle of disappeared oceans, present some complications unknown in the ocean domain, due to the fact that many of them were presumably formed in fore-arc, back-arc or inter-arc basins, with complex volcanic and plutonic sequences due to interaction of the magmas with subduction fluids. It is thus uncertain how representative they are of the crust beneath large ocean basins.

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