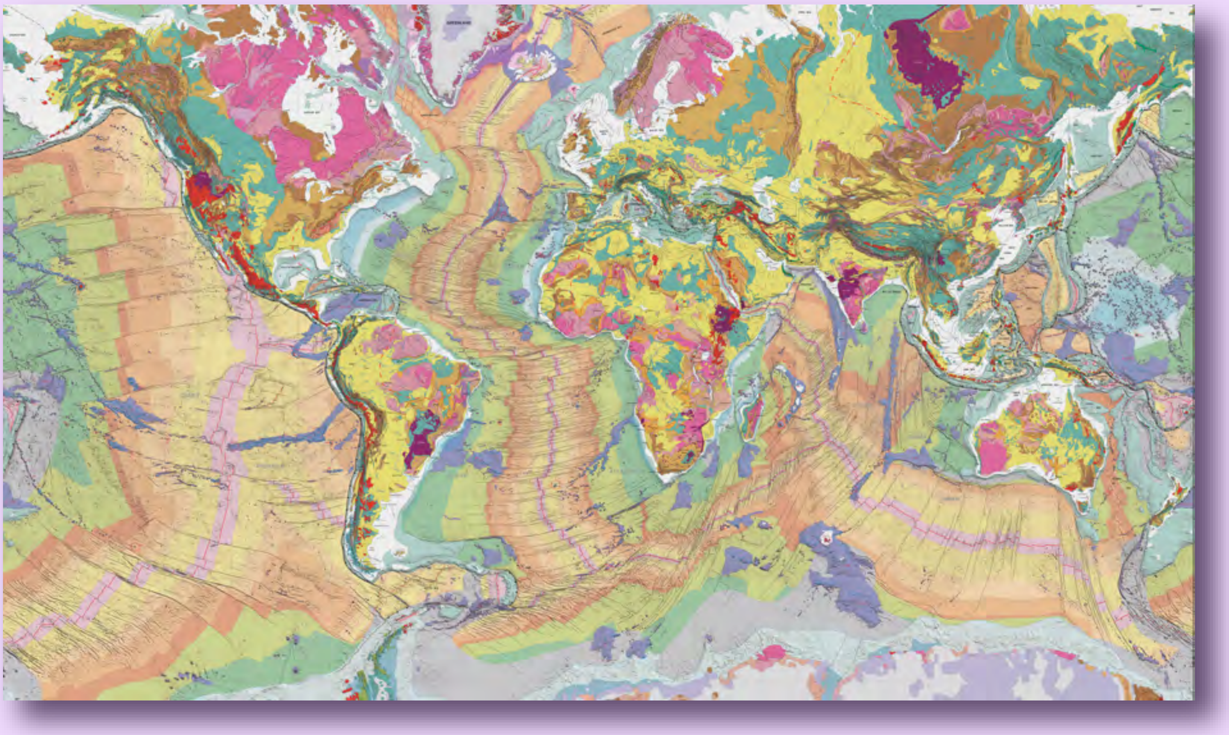
EXPLANATORY NOTES

By Philippe Bouysse

GEOLOGICAL MAP OF THE WORLD

3rd revised edition at the 1:35 000 000 scale

July 2014



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GEOLOGICAL MAP OF THE WORLD AT 1:35 000 000

(Third revised edition)

2014

EXPLANATORY NOTES

by

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SUMMARY

«*Ce qui est simple est toujours faux. Ce qui ne l’est pas est inutilisable*»
Paul Valéry (Mauvaises pensées et autres, 1942)

Foreword

The 3rd edition of the Geological Map of the World was published as follows:

Sheet 1. ***Physiography, volcanoes, astroblemes***. Scale 1:50 000 000 (2009); centred on the Pacific.

Sheet 2. ***Geology, structure***. Scale 1:50 000 000 (2009); centred on the Atlantic.

Single release, ***Geology Structure***. Scale 1:25 000 000 (2010). Three sheets allowing to centre the map either on the Pacific or the Atlantic oceans. The data on this map are identical to those featured in the map at the smaller scale.

Both editions of the ***Geology, structure*** map having run out of print, it was decided to print a new one that keeps almost the entirety of the geological and structural data with the changes detailed hereafter.

- A single sheet at the 1:35 000 000 scale, an intermediate scale between the two maps formerly released, and centred on the Atlantic. This scale allows a better legibility in relation to the 2009 edition and a handling much easier than the larger map published in 2010.
- A monochrome shaded relief map that highlights the structural features, in particular the oceanic area.
- Changes in the colour of some geological units of major interest such as: Cenozoic volcanism; traps; oceanic plateaus; hotspot tracks and seamounts. An homogeneous representation of the thrust fronts of all kinds (subduction zones, accretionary prisms, thrusts,…).
- Finally, from a point of view of the content, the new map amends the infographic mistakes of the 2010 edition.

The ***Physiography, volcanoes, astroblemes*** map of the 2009 edition at the 1:50 000 000 is still available and is an useful supplement to this new map for three reasons: 1) the world physiography is complete and detailed, including isobaths every 1000 m; 2) centred on the Pacific, this sheet gives a full view of this ocean where are found the majority of the subduction zones and hotspots of the planet; 3) it facilitates the visual correlation of the representation of the active volcanoes with the subduction zones.

The Geological Map of the World at 1: 35 000 000

(2014)

Explanatory Notes

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Preface

These Notes presented in a somewhat heterogeneous manner, combine regular peer-reviewed information dedicated to geoscience professionals – normal users of geological maps – with more basic information intended for a wider public including high school and college students who constituted a large section of the users of the former editions of this map.

It was not possible to address in these notes all the geologic, structural or geodynamic aspects that may be raised by the careful examination of the Map. The text, consisting mainly of comments on the legends, is aimed at shedding some light on a selection of examples that are, in our view, illustrative of each element of the Map.

It should be noted that a particular attention was given to the oceanic areas, the large magmatic events, and to the geodynamics.

INTRODUCTION

This bilingual document (English-French) is the result of a highly synthetic compilation given both the small scale of the map and its educational purpose. It is a tentative and (very) simplified representation of the entire solid surface of our planet and includes both continental and oceanic domains. This map takes into account the state of the geologic knowledge at the beginning of the XXIst century.

This map shows the distribution of the main lithostratigraphic units and the main structural features that make up the mosaic of the present-day surface of our planet, the result of 4.5 billion[1] years of unremitting "resurfacing". This map consists of a main map in Mercator projection, with the 2 polar areas in polar stereographic projections. The draft was carried out in vectorial mode.

The **Mercator** projection has only a true scale representation along the equator but allows an optimal visualization that does not favour the continents at the expenses of the oceans or vice-versa, unlike many other projections used for world maps. The main drawback of Mercator comes from the deformation that increases with the latitude to become infinite at the poles. For this reason, in this edition, the "upper" and "lower" latitude limits have been set at 72°N and 72°S for the main map. As a consequence, a large extent of the Antarctic continental coastline is visible with a better delimitation of the southern ocean. As for Greenland, only its southern half is visible. On the other hand, the Taymir peninsula has been severed from the far north of the Eurasian continent. The **circum-polar projections** extend to the 60°N and 60°S parallels. Greenland is now displayed in its entirety.

Nota: In the text that follows, words typed in **bold** characters correspond to the different items of the legends.

1- ONSHORE AREAS

1.1- Chronostratigraphic units

The onshore areas represent 29.2% of our planet's surface and correspond mainly to the rock formations of continental origin (or continentalized in the case of island arcs). They are classified using **8** broad **chronostratigraphic units**[2]: 1= *Cenozoic*; 2= *Mesozoic*; 3= *Upper Paleozoic*; 4= *Lower Paleozoic*; 5= *Neoproterozoic*; 6= *Mesoproterozoic*; 7= *Paleoproterozoic*; 8= *Archean*. A number of regroupings were made when necessary by the geological or cartographic contexts. In comparison with the previous edition, and for the sake of coherence, the Quaternary and the Triassic Periods respectively within the Cenozoic and Mesozoic eras have not been shown individually. Also the 3 eras of the Proterozoic Eon have been introduced as units 5, 6 and 7. Within these time units **3** main **lithological facies** ensembles were distinguished: • sedimentary formations or those of an undifferentiated nature (uneasy to define); • extrusive volcanic formations (**V**), corresponding to subaerial magmatism; • endogenous formations (**P**), representing rocks originating in the Earth's interior at depth and having undergone significant metamorphism or that correspond to plutonic magmatic rocks. The last two rock categories are illustrated by a scattering of superimposed dots (**red** for extrusive, **blue** for the endogenous). One exception was made for the **Cenozoic volcanism** (**V1**) that is identified by a uniform **strong red** hue. Actually, the volcanism of this era (which includes Quaternary and Present times) is, in many cases (e.g. subduction volcanism), the consequence of on-going geodynamic activity. It is therefore important that this volcanism be clearly perceptible to the eye. Another exception was also made for the oldest formations, the **Archean** ("8", older than 2.5 billion years/Ga), as here they are not differentiated for the sake of simplification. It should be noted that the largest Archean outcrops are located in Canada.

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[1] The abbreviation for *billion years* (10^9 years) is *Ga* (from *giga-annum*, official designation of international geological bodies). The author wonders why the accusative form "annum" was chosen instead of the nominative one "annus".

[2] i.e. geologic time slices. In the corresponding legend's table as well as in the oceanic crust ages (cf. 2.2.1), the dates indicated are those validated by the International Commission on Stratigraphy in the *Geologic Time Scale* published in 2008. The margin of error (2σ) was not mentioned for the sake of simplification.

1.2- Ophiolites

The ophiolites are remnants of oceanic lithosphere (from top to bottom: submarine basalts, gabbros, peridotites) which, in a final phase of *subduction* following the collision of two continental blocks (or continentalized in the case of island arcs), escaped from their usual recycling within the Earth's mantle to become exposed inside mountain chains. They are the evidence of a "lost ocean" (Jean Aubouin) and punctuate large *suture* zones. They can also be the product of an *obduction*, as in Oman, where a slice of oceanic lithosphere overthrusts the edge of a continental basement. At the scale of the Map, the extent of the ophiolitic formations (**bright green** hue) is relatively small and quite often hardly visible. The ophiolites plotted on this map are restricted to the Meso-Cenozoic times (younger than 250 million years[3]). Particularly noticeable are the ophiolites of the Alpine arc, the Dinarides/Hellenides, the Zagros (Iran) and the Himalayas.

As an example of an island of ophiolitic origin, it is worth mentioning the tiny Gorgona Island located on the continental Pacific margin of Colombia. Also Macquarie island (some thousand kilometers to the SSW of New Zealand) is the result of a *tranpressive* motion along the large dextral transform fault (see note 16) that separates the Indian Ocean (Indian-Australian plate) from the Pacific Ocean (Pacific plate) and uplifted a slice of Cenozoic oceanic crust. Also we note **Zabargad** island (formerly called St. John island) in the Red Sea (Egypt), known since Antiquity (Egyptians, Greeks and Romans) for its peridotite intrusion containing beautiful olivines (marked by a **green asterisk**).

1.3- Large igneous provinces: the traps

During some periods in the history of our planet large eruptive pulses of a relatively short duration (in some cases less than 1 million years) occurred in the Earth at mantle depth. These magmatic "crises" led to the vast and voluminous outpouring of basalts at the surface of the continents (**traps**) as well as on the ocean floor (**oceanic plateaus**). These huge lava flows are interpreted as the consequence of the ascent of a large mantle plume up to the base of the lithosphere to produce the head of a strong "hotspot", during the first phases of its life (cf. 2.2.7 et 3). These surface features are labelled "**Large Igneous Provinces**[4]" (abbreviation **LIP**). The lavas of the traps, very fluid, are also termed "flood basalts". In the 1st (1990) and 2nd (2000) editions of this map the traps were merged into the too large time slices used corresponding to the chronostratigraphic units of the legend (e.g. Upper Paleozoic for the *Siberian* traps, or Mesozoic for the *Deccan* ones in India). On the other hand, a number of traps straddle the large main stratigraphic boundaries of these units, e.g. Upper Paleozoic/Mesozoic (250 Ma) in Siberia; Mesozoic/Cenozoic boundary (65.5 Ma, also called K/T boundary[5]) for the Deccan event, in India. This might not be coincidental since, for a number of geologists (e.g. Courtillot and co-workers), the great mass *extinctions* that affected a number of living species[6] might be due to massive gas and noxious aerosols produced by these cataclysmic eruptions. This hypothesis is however in competition with (but also later associated to) the big meteoritic impact thesis, exemplified by the Chicxulub crater in the north of Yucatan in Mexico, for the K/T limit (see *Physiography* map).

In order to deal with these issues, we chose for this new edition to assign the same color (**deep purple**) to all the **traps**, with an indication in white of their average age in **Ma** (e.g. "16 Ma" for the *Columbia River/Snake River* traps in north-western USA). It is to be noted that the *Parana* traps in southern Brazil have the same age (133 Ma, earliest part of Cretaceous) as the less extensive *Etendeka* traps in Namibia. Initially, these two features formed a single entity, but are now separated by several thousand of kilometres of ocean floor. They were originally produced by the Tristan da Cunha "hotspot" (identified as **HG** in the inset at the botton of the map) and separated during the opening of South Atlantic which started shortly after, during the Early Cretaceous. Not too far from the *Etendeka* traps exists another slightly older ensemble of traps (183 Ma, Early Jurassic), the *Karoo*, that outcrop in southern Africa and were subsequently dismantled by erosion. A third large "LIP" in Africa are the *Ethiopian* traps (30 Ma, Oligocene) including also those of SW *Yemen* that are only separated by the narrow entrance of the Red Sea (Bab el Mandeb straits). Almost coeval with the Karoo traps, the remnants of the *Ferrar* traps (175 Ma) are associated with the sills of same age (marked on the Antarctic Polar projection by a **purple asterisk**). These are scattered along the large Transantarctic Mountains range. The temporal and geographic proximity of these two ensembles, when part of the Gondwana supercontinent, might indicate that they were generated by the same hotspot. Two small traps located to the NE of the Deccan traps do not belong to the latter; in the NE corner of the Indian shield is the *Rajmahal* (118 Ma, Early Cretaceous) and slightly to the east, *Sylhet* (116 Ma), near the Assam/Bangladesh boundary. The source of these two traps is thought to be the Kerguelen hotspot (HI). In later time this may have also generated the Ninetyeast Ridge (or 90° E Ridge, cf. II.2.2.7). The *Emeishan traps* formed in China towards 260 Ma (Paleozoic, at the limit Middle Permian/Late Permian). The huge **Siberia** traps mentioned above presently outcrop over the majority of the eastern part of the Siberian craton. Some remnants are found further to the north in the southern part of the Taymir peninsula (only visible in the Artic map in polar projection). Originally, these traps covered a much larger area (some authors give an estimate of about 4 million km^2, or even more). The **red dashed-dotted line** drawn on the West Siberian plain corresponds to a minimal estimate of their western extension beneath the Meso-Cenozoic sedimentary deposits (Reichow et al., 2002). Finally, a **large red dashed line** figures the boundary (that one can follow from the east of North America and the NE of South America to the west of Africa and Europe, drawn after J.G. McHone, 2003) of a sole large magmatic province. This boundary outlines the traps of the **CAMP** (*Central Atlantic Magmatic Province*) generated by a hotspot 200 million years ago (limit Triassic/Jurassic) shortly before the opening of the Central Atlantic dislocated this ensemble. Although the erosion caused the disappearance of piling-up of lava flows, the CAMP was reconstructed thanks to the occurrence of related sills and dykes (volcanic intrusive bodies), that underlay the surface outpourings. A last point to explain concerning the continental LIP: the **Seychelles Islands** are made of Neoproterozoic (**P5**) granites marked by an arrow because these islands are hardly distinguishable on the Map. These granites are intruded by 65 Ma old dykes (figured also by an arrow and a **red asterisk**). This is the evidence that the Seychelles micro-continent was part of India during the times of the Deccan traps eruption.

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[3] The abbreviation for million years (10^6 years) is *Ma* from the latin "mega-annum", see note 1.

[4] This term and its abbreviation LIP are currently used in the international geoscience community and were coined in 1994 by Millard Coffin and Olav Eldholm. *Rev. Geophysics*, 32 :1-36.

[5] "K/T" for Cretaceous/Tertiary. The use of the term «Tertiary» that corresponded to the Cenozoic without the Quaternary, should be avoided from now on.

[6] The large chronostratigraphic delimitations (eras, periods, epochs) were created in the XIXth century after the observation of sudden, very important and generalized changes, in the association of fossils and micro-fossils contained in the sedimentary deposits, mainly marine facies.

1.4- Glaciers, inlandsis

Glaciers of some importance were mapped in the far south of the Andes, along with those covering islands of the far North Canada and Eurasia. They were assigned the same color as the Greenland and Antarctica **ice caps** (**light grey**). For the latter inlandsis, the **zero meter level contour** (sea level) was drawn. The areas outlined by these contours represent the subglacial bedrock lowered by the ice loading were distinguished from the ice caps using a darker hue (**light purple**).

1.5- Structural features

With the exception of Iceland (cf. 1.6), the Afar (2.2.4) and the Makran (2.2.6), the onshore areas show only two structural features: the **large normal faults** and those of **undertermined nature** (**black line**); the *large thrust fronts* (**jagged black line**) curving round the large orogenic belts; "Alpine" (Alpes-Carpathian Mountains, Caucasus, Himalayas, Maghrebides, Rocky Mountains, Andes) or the older Hercynian (= Variscan: Urals, etc.), Caledonian (Appalachian, northern British Isles, western Scandinavia, ...) and even the roots of Precambrian belts (Canadian shield, etc.). Among the many large structural lineaments on the map, it is worth noting the following:

- A line extending from the south of Norway to the Black Sea (*Tornquist-Teisseyre line*) that separates the "Precambrian Eo-Europe", including the Baltic shield (more appropriately called Fenno-Scandian shield), and the Archean and Proterozoic outcrops in Ukraine, from the pattern seen in more recent European structures (Paleo-, Meso-, Neo-Europe).
- The continental rift system emplaced since the Oligocene which stretches across Western Europe from the northern North Sea to the Gulf of Lion via the Rhine valley and the Rhodanian corridor. It is punctuated locally by volcanic complexes (i.e. Vogelsberg and Eifel in Rhineland-Hesse, Cantal and Chaîne des Puys in Auvergne).
- The large Amazon graben which isolates the two Guyana shields from the Brazilian cratons (Central Amazonas and São-Francisco) to the south.
- A large and old SW-NE fracture cutting the Africa in two from the Gulf of Guinea across to the middle part of the Red Sea.
- The great East-African rift valley system, emplaced during the Cenozoic, and its relationship to the Afar hotspot (H1) and the opening of the Gulf of Aden and the Red Sea. The rifts are often occupied by great lakes. From north to south are: Turkana, Albert, Edward, Kivu, Tanganyika and Malawi lakes often punctuated by important volcanism. Should this continental rift and spreading persist, the East-African Rift will progressively become an oceanic lineament similar to the Red Sea and eventually be of the form of the Gulf of Aden and separate the "Somalia" plate from the rest of Africa, named "Nubia" plate by some geologists.
- The large faults that extend from the Pamir in a fan-like pattern between China and SE Asia. These wrench faults worked in response to the continuous push that the Indian sub-continent has been exerting against the east of the Eurasian continent for some 50 million years. Faults such as Altyn-Tagh (SW-NE) and Kunlun (W-E) carved out great basins such as Tarim (in the Xin Jian or Chinese Turkestan).
- Again in Africa, it is worth noting the existence of the "Great Zimbabwe Dyke", a narrow strip of intrusive Paleoproterozoic, stretching N-S for 550 km, whose width does not exceed ten kilometers.

1.6- The Iceland case

The entirely volcanic island of Iceland covers a significant area (103 000 km2) and has an exclusively oceanic origin. It was built on a substratum of oceanic crust modified by a powerful hotspot (marked **HD**) and is linked to the opening of the North Atlantic (north of 60°N). The axis of the Mid-Atlantic (spreading) Ridge runs across the island to separate two distinct geodynamic domains; the Eurasian plate to the east, and the North American plate to the west. Instead of mapping this island in the same way as the rest of the onshore areas (i.e. in "V1"), as in the former editions, it was decided to represent it as a surface of oceanic crust where Plio-Quaternary and Miocene basalts are distinguished from each side of the spreading axis.

2- OFFSHORE AREAS

The world ocean represents more than two thirds of our planet's surface (70.8%). It covers, on one hand, the submerged edges of the continents, the *continental margins*, and also the deep seafloor whose substratum consists of *oceanic crust* "produced" at the axes of the *spreading ridges*, also called "*Mid-Oceanic Ridges*". The average depth of the ocean is 3 680 m, a value much higher than the 840 m average elevation of the continents. The drawing of the offshore of the Map was constructed, for some elements (spreading axes, transform faults/fracture zones, subduction zone axes, oceanic plateaus, hotspot tracks and other *anomalous* reliefs), by superposing the tracing draft of this sheet over the original draft of the *Physiography map*.

2.1- CONTINENTAL MARGIN

2.1.1- Continent/Ocean Boundary (COB)

The boundary between the continental crust and the oceanic crust (**COB**) is shown by a **blue line**. This outlines the passive continental margins generated by the rifting of two separating continental blocks to form an ocean. Actually, this boundary is not that precise and one should include a transitional zone (OCT) between a well identified continental crust and a "normal" oceanic crust characterized by well identified magnetic anomalies. The transition zone often displays a stretched and thinned continental crust intruded by peridotites that rise from the underlying mantle (exhumation).

Along the active continental margins, characterized by a subduction zone, the COB is well defined (corresponding to the subduction trench axis) and the above mentioned COB blue line is completely overwritten in this cartography by the specific line depicting the subduction (cf. 2.2.6).

Considering the legal (and therefore political and economic) implications arising from the delimitation of the COB in the frame of the United Nations Convention on the Law of the Sea (UNCLOS), it is expressly stated that the drawing of the COB limit on this Map is only approximate and sometimes conjectural, and that it does not have any legal status and neither is any implied.

2.1.2- Microcontinents

Some tiny « rafts » of continental crust (therefore encircled by a specific blue line) are shown on this Map isolated within an oceanic basin. They are named *microcontinents* and result from the complex history of the break-up and seafloor spreading in the formation of an ocean. This is the case: (1) for the Seychelles platform (granites of 750 Ma, marked **P5**) in the Indian Ocean; (2) of the Jan Mayen microcontinent in the far North Atlantic; (3) of the Bollons seamount (60° S, 177° W) close to the New

Zealand continental margin in the Pacific; (4) the South Orkneys microcontinent detached from the tip of the Antarctic Peninsula among others. On the contrary, in this edition the Agulhas Bank (25°E, 40°S) to the south of South Africa, has no longer been assigned a continental nature. This is on the basis of recent works that suggest a volcanic origin of this quite large morphostructure built up on oceanic crust, as with the other large submarine reliefs of the SW Indian Ocean.

2.1.3- Island arcs

The island arcs follow the same mapping principle used for the continents and are bounded by the same medium blue line. It is known that they are the product of magmatic processes peculiar to the *subduction* events that lead to the formation of a "continentalized" crust (becoming thicker and lighter than the oceanic crust). It is probable that in a number of cases, such as in the Japanese archipelago, their substratum was detached from the nearby continent. This occurs through a general characteristic of the subduction mechanism known as "slab roll-back" that initiates the opening of a back-arc basin (or marginal basin; cf. 2.2.4 et 2.2.6).

2.1.4- Continental shelf

The *continental shelves* (or "continental platform", or "continental terrace") represent the innermost part of the continental margins. They extend from the coastline to the shelf break which tops the *continental slope*. The external limit of this shelf has an average depth of –132 m. For practical reasons, and given the scale of the Map, the commonly assigned **–200 m isobath** is used here to delineate the continental shelf since this depth is generally close to the shelf break. On this Sheet, and from a mapping point of view, the continental shelf was considered only from a morphologic point of view (a terrace) and conceals all other cartographic units it might overlay. Thus, the "continental" shelf of the Niger delta obliterates the oceanic nature of the underlying oceanic crust upon which the sedimentary fan of this large African river is prograding (i.e. it builds up seawards). The same applies to the "continental" shelf of Iceland, actually an island entirely generated by oceanic volcanism (cf. 1.6).

All the continental (and island arc) shelf areas represents about 7.5% of the oceans surface. On the Map, the continental shelf is characterized by a **very light beige color**. For practical reasons this cartographic unit also encompasses the shelves or terraces of atolls and volcanic islands that are not "genetically" continental but of oceanic origin (e.g. the Tuamotu Archipelago). Indeed, the term "continental shelf" has a broader meaning in the formulation of the Law of the Sea (UNCLOS).

The continental platform is very narrow along many sectors of the African coast (only a few kilometers off Mogadishu, Somalia) and along the Brazilian margin south of the equator. On the island arcs, it is not well developed either. On the contrary, it is very wide off the coast of SE Asia (East China Sea, Sunda shelf), off Argentine Patagonia (up to 600 km wide) and a maximum extension can be observed along the Arctic front of Northern Eurasia (up to some 900 km on the continental shelf of Eastern Siberia). The mapping of the continental shelf is one of the innovations of this third edition of the Map. It is an important element when considering the Quaternary palaeogeography of the world. It allows us to consider the withdrawal of sea level that occurred during the great *Würm regression* (ca. 20,000 years ago), the Last Glacial Maximum during which the sea level dropped by about 130 m. During this event, the volume of water removed from the oceans was transferred to build up the huge glacial ice caps in northern North America (up to 4 km thick above the Hudson Bay) and NW Eurasia. At that time, the English Channel and its Western Approaches were completely emerged. It was also possible to travel overland from the far north of the Gulf of Siam to Bali, and from New Guinea to Australia.

2.1.5- Continental slope

The part of the continental margin located seaward of the shelf break and extending down to the contact with the oceanic crust (i.e. COB) is called *continental slope*. This term applies also to the island arc margins, as explained above. This element of the offshore morphology is represented in a **greenish grey**. The continental slope can be quite extensive, such as off southern South America where the spur bearing the Falkland/Malvinas Islands projects itself to the east towards the South Sandwich island arc over more than 1500 km.

2.1.6- The Antarctic margin

The continental margin of Antarctica presents specific morphological characteristics owing to the isostatic loading excerted on the continental lithosphere for some 30 Ma by its huge ice cap. The most salient characteristics are: the frequent presence of a near shore depression (down to 1 000 m deep) and a continental terrace abnormally lowered (from –400 to –700) in front of the shelf break. Therefore the continental shelf and continental slope have been merged into a single map unit shown in a **light yellowish green** to differentiate it from that of the continental slope.

2.1.7- Ice-shelf

For glaciologists, an *ice-shelf* is a thick volume of ice creeping ("flowing" slowly) from the ice cap to beyond the coast and has the form of a glacial sheet floating above a continental terrace. Its thickness varies from 100 to 1000 m. These platforms are characterized on the Map by a **bluish grey** color. The ice-shelves of Greenland and Canadian Arctic Islands, too small at the scale of the Map, were not plotted. The Antarctic ice-shelves have a total surface of about 1.5 million km2 and could be highly affected by the ongoing climate change. The largest ice-shelves are the Ronne to the "north", and the Ross to the "south", the latter partially encircling Ross Island, location of the active volcano Erebus (cf. *Physiography Map*). Ice-shelves should not be mistaken for *pack ice*, the latter being a thin ice sheet (few meters thickness) of frozen seawater and their size significantly changes during the seasons of the year.

2.2- OCEANIC BASINS

Oceanic basins are that part of the seafloor whose basaltic substratum is made up of oceanic crust. They are overlain by sediments, except in the axial zones of the mid-oceanic ridges. Their history and structure differ drastically from that of the continents. Oceanic basins cover about 59% of the planet surface. Five main types of morphostructures are to be distinguished: • abyssal plains; • mid-oceanic ridges; • large fracture zones; • subduction trenches; • "anomalous" oceanic features, i.e. structure of volcanic origin whose genesis postdates the age of the oceanic crust on which they have been built up.

2.2.1- Age of the oceanic crust

In comparison with the age of the continents, whose oldest outcropping nuclei have been dated at some 4 Ga (billion years), the age of the oceanic basins substratum never exceeds 200 Ma (million years). In the present state of knowledge the oldest ages are Middle Jurassic (starting at 175.6 Ma). These are found off the eastern margin of the United States and off its conjugated margin of Western Africa (both margins fitted into each other before the opening of the Central Atlantic). They also exist in the Central part of Western Pacific. As *Earth volume is constant*[7], every piece of oceanic crust formed at the axes of mid-oceanic ridges prior to this limit of 200 Ma was necessarily entirely "swallowed" by the subduction process, trapped as slivers within continental collision or overthrust during an obduction (cf. 1.2). The mapping of the age of the oceanic crust was made by interpolation of the position of the magnetic anomalies generated by the effect of periodic inversion of the Earth magnetic field on newly formed crust (cf. Müller et al., 1997). In this Map we have displayed only the limits of the chronostratigraphic units: *Plio-Quaternary – Miocene – Oligocene – Eocene – Paleocene – Upper Cretaceous – Lower Cretaceous – Upper Jurassic – Middle Jurassic* (cf. the relevant legend). The colours for the different oceanic units are those currently used for CGMW seafloor maps. For the enclosed basins such as the Arctic basins, the remnants of the ancient Tethys Ocean (Eastern Mediterranean) and back-arcs basins, where the age of the crust is sometimes not precisely known, a larger age range was used (e.g. Undifferentiated Jurassic-Cretaceous for the Eastern Mediterranean, or Neogene for the marginal basin located to the south of the Banda Sea, Indonesia). Moreover in some sectors, where the colors might not be clearly discernible, the age is also given by the corresponding symbol in the legend (e.g. "j3" for the South Caspian basin, or "g" for the Celebes basin). Finally, shown in **grey** are a number of oceanic areas where the magnetic anomalies have so far not been identified by geophysicists and where the **age of the crust remains undetermined**. They are to be found mainly around Antarctica, and to the east and SE of Australia.

2.2.2- Abyssal plains

The abyssal plains are characterized by a very flat sea bed with a, sometimes quite thick, sedimentary cover that extends to both sides of the mid-oceanic ridges. Their depth (blue hues which can be seen on the *Physiography Map*) increases imperceptibly from some 4000 m to a little over 6 000 m. Schematically, the age, the density and the depth of the basaltic substratum increase with the distance from the axis of the mid-oceanic ridge. Likewise, the thickness of the sedimentary cover increases with the distance from the mid-oceanic ridge[8]. A good example of a well individualized abyssal plain, free of anomalous reliefs, is the Argentine basin – whose centre deepens to more than 6 000 m depth – surrounded by the South Atlantic mid-oceanic ridge, the Falkland spur and the continental margin of Argentina.

2.2.3- Mid-oceanic ridges

The *mid-oceanic ridges* (or *oceanic accretionary ridges*) form the largest mountain range in the world with a total length of nearly 80 000 km[9] that extends through the four oceans. Starting at the base of the continental margin of the Lena river delta (Eastern Siberia) in the Arctic, this system runs through the Atlantic from north to south, enters the Indian Ocean (with a northern branch running up to the Red Sea[10], generates a "triple junction" of ridges to the SE of Réunion island), then rounds the southern tip of New Zealand continental margin to step into the Pacific. In this latter ocean, the oceanic ridge is not in a mid-oceanic position but is largely offset to the east (justifying thereby its *East-Pacific Ridge/Rise* or *EPR* label) before "dying" in the Gulf of California (or Cortes Sea). From this long ridge, originate two branches extending to South America: the *South Chile Ridge* and the *Galapagos Ridge*. Farther to the north, the *Juan de Fuca Ridge* is located at some distance from the coast extending from the north of California to British Columbia. This small oceanic ridge is linked to the Gulf of California along the San Andreas transform fault system (cf. 2.2.5). The *Juan de Fuca* and the *EPR* formed a single continuous ridge before the now missing segment was "swallowed" beneath present-day California by the former subduction zone. With a width varying from 1 000 to 3 000 km, the oceanic ridges rise 2 500 to 3 000 m above the abyssal plains. The mean depth of the crest of these ridges is about 2 500 m beneath the sea level. They occupy nearly a third of the surface of the seafloor. The Mid-Atlantic Ridge, with its winding outline similar to that of the two sets of conjugated continental margins, is the type example of seafloor spreading and related continental fit.

2.2.4- Axis of mid-oceanic ridges

The axis of active mid-oceanic ridges marks the *boundary between two divergent lithospheric plates*. This boundary is characterized by seismic activity. The axes are represented by a **continuous red line**, a color that recalls the fact that they are a key element of the Earth volcanism since they are, geologically speaking, continuously providing magma. Depending on whether the *divergence rate* is low or high[11], the morphology of the ridge differs. At low spreading rates (2 to 3 cm/year), as in the Atlantic, the topography is rough and shows a deep axial valley (rift). At high spreading velocities (about 15 cm/year), as in the East-Pacific Rise, the topography is smoother without deep axial valleys. This contrast is strikingly noticeable on the Physiography Map).

The particular case of *Iceland*, with its subaerial oceanic accretionary rifts, was mentioned above (1.6). As for the *Afar* "triangle" (also located above a hotspot, marked **HA**),this represents a "triple junction" where the Gulf of Aden (a continuation of the active Carlsberg ridge in the northern half of Indian Ocean), the Red Sea oceanic rift and the Great East African Rift converge. Although the Afar is still largely of continental nature, three small segments[12] of oceanic accretionary axes are plotted somewhat schematically to figure the (possible) beginnings of a future oceanization (if the present geodynamic context remains unmodified, cf. 1.5).

Concerning the *back-arc basins* (or "marginal basins) that open "behind" an island arc (i.e. on the opposite side to the subduction trench), a micro-ocean forms and therefore the oceanic accretionary axis is represented by the **same red line** as for the oceans. This can be seen in the *marginal basin* of the *Mariana island arc* (Western Pacific), the *Lau Basin* that opens behind the Tonga island arc (SW Pacific) and the *South*

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[7] From the end of Fifties onward, the Australian geologist Samuel Warren Carey proposed the theory of the expanding Earth where the surface of our planet must have been increasing for the last 200 Ma which is correlative to the break-up of the supercontinent Pangea and to the continental drift. Consequently, he dismissed the existence of subduction zones. This theory was (almost) definitively abandoned.

[8] Their thickness can reach several thousand meters when approaching the foot of certain continental margins, in particular those where the terrigenous supply comes from the high sedimentary input of very large river systems (Amazon, Ganges/Brahmaputra, Indus...).

[9] The length goes down to some 60 000 km when taking into account only the cumulated length of the segments of oceanic accretionary axes.

[10] This branch heads first northwards with the Central Indian Ridge, then turns off north-westward with the Carlsberg Ridge, then runs westwards with the Gulf of Aden oceanic Ridge before connecting in a complex way, via the Afar zone, to the Red Sea.

[11] The figures correspond to average values over a certain time lapse; they don't necessarily mean the spreading occurs regularly every year.

[12] Because of the local superimposition of the red accretionary axes on the red Cenozoic volcanic units of the Afar, these 3 segments have been highlighted with a thin white border in the digital version of the Map.

Sandwich back-arc basin (formerly named Southern Lesser Antilles), a part of the loop linking southernmost Andes to the Antarctic Peninsula. An incipient stage of back-arc spreading is occurring in the *Okinawa Basin* to the NW of the Ryukyu island arc (southernmost Japan archipelago), with a series of small active *en echelon* segments that begin to cut out the continental margin of the East China Sea. A more advanced stage is found in the (very narrow) Bransfield *marginal basin* located at the rear of the South Shetland subduction zone within the Antarctic Peninsula.

The **extinct axes of oceanic accretion** are figured like the active axes (by way of a **red dashed line**), as e.g. in the Scotia Sea (between South America and Antarctica), or in the Tasman Sea east of Australia. These are zones where the divergence stopped inside an ocean or a back-arc basin. One of the most interesting examples is that in an area of the North Atlantic where the spreading process began between Canada and Greenland in the Paleocene, then hesitated between west and east of Greenland in the Eocene. Eventually, this divergence ceased in the Labrador Sea and the Baffin Basin, and the opening jumped east to separate Greenland from northwestern Europe. The Labrador Sea is an aborted ocean with Greenland that after a stage of dissociation from the North American plate, reintegrated the latter.

2.2.5- Transform faults and fracture zones

One of the salient characteristics of the morphology of the oceanic basins is their sectioning, or slicing, by a set of long faults (**black lines** on the Map) that cut perpendicular to the mid-oceanic ridges. Between the ends of two successive segments of active axes, the fault undergoes strike-slip motion and is seismically active. This part is called a **transform fault**. Beyond and along the fault, there is no longer any lateral displacement between the two sides of the fault and it becomes a seismically inactive **fracture zone** (F.Z.) representing the "scar" of the transform fault. This type of complex fault[13] frequently reaches a length of several thousand kilometers[14]. As one might expect, the largest fracture zones (some 6 000 km) are located in the Pacific Ocean: the Mendocino F.Z. (touching the eponymous cape, near the border between California and Oregon), the Clipperton F.Z., the Eltanin F.Z. system (between the Antarctica Peninsula and the continental margin of New Zealand) among others. Fracture zones are the markers of the rotation between two divergent plates controlled by plate tectonic geometries. The most remarkable example is provided by the Agulhas-Falkland F.Z. joining the tip of Southern Africa to the southern extremity of South Africa. This F.Z. traces a near perfect small circle arc that aids reconstruction of the fanlike opening of the South Atlantic. A good example of an important transform fault is the Owen FZ, in the NW Indian Ocean. This offsets the active ridge of the Gulf of Aden relative to that of Carlsberg Ridge[15] (located in the middle of the northern area of this ocean), and then links this accretionary system to the Makran subduction zone along the Pakistani and Iranian Baluchistans. This fault "*transforms*" therefore a divergent movement into a convergent one (cf. also 2.2.6). This SW-NE fracture ends up in front of Karachi, directly facing the thrust front of the orogenic belts bordering the west of the Indus valley and connecting to the Himalayan collision belts. The Owen transform fault with its dextral motion[16], constitutes the *boundary* between the Indo-Australian and the Arabian plates. On this map, only 22 examples of movements of large transform faults (or simply large wrench faults) are plotted (double half black arrows in opposite directions) either in an oceanic or continental domains. Only 3 examples will be mentioned here: 1- the transform faults that constitute the northern (left-lateral) and southern (right-lateral) boundaries of the Caribbean Plate; 2- the right-lateral transform fault of *San Andreas* (*sensu lato*) linking the opening system of the Gulf of California, cutting through all the west of California and ending up at Mendocino Cape, to the axis of the Juan de Fuca oceanic ridge; and 3- the left-lateral *Levant* fault joining the Red Sea to the collision zone of the Arabian plate with Anatolia, and where its locally step-like shape opens the small Dead Sea and Sea of Galilee basins[17].

2.2.6- Subduction zones, subduction trenches and other trenches

Like all *plate boundaries*, subduction zones are *seismically active*[18]. However, in the tectonics of *convergence*, the (heavier) oceanic lithosphere of a subducting plate dips as a more or less slanting slab beneath the edge of the overlying plate whose lithosphere is made of either the lighter continental crust (case of an *arc-cordillera*) or continentalized crust (case of an *island arc* behind which one finds a *back- arc basin*, or *marginal basin*, of oceanic origin). This is the reason why subduction zones are also denominated as *active margins*, in contrast to non-seismically active *passive margins* which result from the drifting of two continental blocks from either side of an initial rift (as in the case of the Atlantic). The subduction of oceanic crust generally produces a *volcanic line* that is at the origin of island or cordillera arcs (cf. also 2.1.3). These volcanoes (characterized by explosive, hence dangerous, eruptions) are located above a strip of the subduction slab, starting at a depth of some 100 km, where it begins to become dehydrated[19].

The total length of the subduction zones is approximatively y 55 000 km, a size comparable to that of the mid-oceanic ridges (cf. note 9).

The **active subduction zones** are shown by a **black line with solid black triangles** whose tops are situated on the leading (overlying) plate to indicate the direction of the subduction. The convexity of island arcs is always facing the subduction trench (e.g. Lesser Antilles in the Atlantic, Mariana in the Western Pacific), but a rectilinear shape may occur (e.g. the Tonga-Kermadec in the SW Pacific). On the concave side of the island arcs, a back-arc basin opens by separating itself either from a continent (as in the case of Japan where a small oceanic basin within the Japan Sea partially separates it from the eastern continental margin of Asia), or from another island arc that has become a *remnant arc*, i.e. extinct. The latter is illustrated in the case of the Mariana active arc → West Mariana (opening marginal) basin → West Mariana (remnant arc) ridge, or the

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[13] For English-speaking authors, the terms of transform fault and fracture zone seem somewhat synonymous.

[14] In spherical geometry, any movement corresponds to a rotation movement whose axis passes through the center of the Earth. The fracture zones consequently follow small circles centered on the plates' rotation poles (which are to be distinguished from the planet's rotation axis poles).

[15] See note 11.

[16] The strike-slip movement is defined by standing on either side of the fault and observing the direction of the motion of the opposite side. If it moves to the right, the movement is *dextral* or *right-lateral*, if it moves to the left, it is *sinistral* or *left lateral*.

[17] These small basins generated by strike-slip faults are more commonly called "*pull-apart basins*".

[18] A part of the earthquakes generated by the subduction are distributed along the dipping lithosphere. This seismic slab is called "Wadati- Benioff zone", after the name of the two geophysicists who discovered this phenomenon.

[19] The part of the dipping "slab" generating the subduction volcanoes is located at a depth rarely exceeding 150 km.

active Tonga arc → opening Lau Basin → remnant Lau Ridge.

The convergence zones are generally characterized in the submarine morphology by a subduction trench, a long and narrow depression normally delineated by the 5 000 or 6 000 m isobath. The greatest depth recorded is 10 920 m in the southern part of the Mariana Trench (see *Physiography Map*). Trenches are not always visible because, in some areas, voluminous sedimentary input is released into the ocean by large river systems that fill up part of the trench lengthwise. The upper part of the sedimentary cover of the dipping plate abuts against the backstop (i.e. the rim of the leading plate) instead of being swallowed by the subduction, and is hence "scraped off" (thus escaping absorption into the Earth's mantle). This becomes piled up as imbricate thrust slices in front of the arc. Hence an **accretionary sedimentary prism** forms, the deformation front of which is indicated on the Map by a symbol similar to that of the subduction, but with **small open black triangles**. In the region between this thrust front and the axis of the filled part of the subduction trench it was decided to show the age of the underlying oceanic crust, as yet to be subducted but, concealed by the sedimentary prism that would have otherwise been shown as part of the arc margin. The most remarkable illustration is provided by the *Barbados* accretionary prism, located in front of the southern half of the Lesser Antilles arc. As a consequence of a huge sedimentary input coming from the Amazon and Orinoco rivers, the maximum thickness of this accretionary sedimentary prism reaches some 20 km beneath the island of Barbados. Two other prisms are drawn on the Map: the *Mediterranean* complex located to the south of Calabria and Greece, and the *Makran*. An interesting feature of the latter is that the inner part of the prism has emerged and constitutes the coastal region of Baluchistan. This is the reason why, in this case, the axis of the subduction is plotted onshore and indicates the contact between, on one side, the "backstop" represented by the lithosphere of the leading plate (Eurasia), and on the other side the lithosphere of the subducting plate (Arabia).

There are very few places where an **incipient subduction** presently occurs. It represented on the Map by the symbol of active subduction (but with **large black open triangles**). This is the case of the *Mussau Trench* (about 149° E, 05° N) where the Caroline plate begins to dip beneath the large Pacific plate. This also occurs the north of the Lesser Sunda island arc (subducting southwards) in order to accommodate the docking of the Australian continental margin as a result of its northward convergence toward the Sunda arc.

It is worth noting a case of **extinct subduction** (represented by a similar symbol, but in **purple dashed/dotted line**) in the *Vitiaz Trench* whose maximum depth is only 5 600 m and stretches from the Solomon Archipelago to the northern tip of the Tonga arc. During the Miocene, the arrival of the Ontong Java oceanic plateau blocked the whole system (cf. 2.2.7) because it was not dense enough (buoyancy effect) to be absorbed by the subduction of the Pacific Plate which was previously subducting southwards under the Indian-Australian plate. This caused reorganization of the subduction as it now dips in an opposite direction under the New Hebrides arc.

The subduction zones are mainly concentrated around the Pacific rim and are the modern expression of the old fashioned term "*Pacific ring of fire*". In this ocean, there is a striking contrast between the island arcs (active or remnant) and their marginal basins which are exclusively distributed to the west, while to the east the subduction zones are only dominated by volcanic cordilleras (Andes, volcanic ranges of Central America, Rocky Mountains). Outside the Pacific only two subduction systems exist in the Indian Ocean, those in front of the Sunda Islands and that of the Makran, and two in the Atlantic, with the subduction of the Lesser Antilles and in the Scotia arc (between South America and Antarctica).

Not all submarine *trenches* are exclusively related to subduction. Some exist along *transform faults* that cut across the axis of mid-oceanic ridges, particularly when the spreading rate is low. The *Romanche Trench*, in Central Atlantic (centered on the equator by 18° W, 300 km long) has the record for this type of feature with 7 758 m depth.

2.2.7- "Anomalous" submarine features (seamounts, oceanic plateaus, hotspots tracks)

These are a large ensemble of all sized reliefs that affects the oceans and is represented by the same **greyish purple** recalling, in a subdued way, the colour of the traps on continents[20]. Actually, all these features result from a generally powerful magmatic activity postdating the age of the "normal" oceanic crust. This magmatism affects the oceanic crust initially produced at the axis of the mid-oceanic ridges. If the structure of the oceanic basins were controlled only by the plate tectonics principles, the ocean would only display mid-oceanic ridges, fracture zones, abyssal plains, and subduction trenches with their associated island arcs. All these features, thus being of volcanic origin, are generated by the activity of a hotspot[21] (whatever the signification attached to this concept) having, with some exceptions, a *relatively stationary position*. They are of three types:

- *submarine seamounts*, relatively small, mainly covered by sediments, and whose summit is sometimes flat (in this case called "guyots"), resulting from the erosion of a subaerial volcano sinking progressively beneath the sea under the effect of normal thermal subsidence.
- *oceanic plateaus* (cf. also 1.3).
- *hotspots tracks* (or *trails*)¸ formerly denominated "*aseismic ridges*" because these ridges lack of seismic activity compared to the mid-oceanic ridges located at plate boundaries.

Geologically speaking an **oceanic plateau** is generally built up during a short period of time from a pulse of intense hotspot activity. A number in red followed by **Ma** indicates the **average age** of the plateau (e.g. "123 Ma" for the age of the Manihiki plateau, to the NE of Samoa), or as two numbers separated by & when the build-up is believed to have occurred in 2 main pulses. When the age is uncertain inside a time lapse, the range is given by two hyphenated numbers. The age, sometimes quite approximate, is given only for 10 oceanic plateaus: in the Indian Ocean, the *Maud Rise* (73 Ma; 0°E/W, 65.5° S), the *Kerguelen Plateau* (119 Ma & 100 Ma), *Broken Ridge Plateau* (95 Ma; 95°E, 30°S); in the Pacific Ocean: the *Shatsky Rise* (145 Ma; 160°E, 35°N), the *Hess Rise* (99 Ma; 180° E/W, 35°N), the *Manihiki Plateau* (123 Ma; 165°W, 10°S), the *Ontong Java Plateau* (121 Ma & 90 Ma), the *Hikurangi Plateau* (120-100 Ma, close to the east of New Zealand); in the Atlantic Ocean, the *Caribbean Plateau* (90 Ma & 76 Ma), and the *Sierra Leone Rise* (73 Ma; 20°W, 05°N).

The *Ontong-Java* oceanic plateau, named after the atoll located north of the Solomon Archipelago, is by far the most remarkable. It has the largest surface area, estimated at some 2

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[20] Deep blue contours drawn inside these structures correspond to second order reliefs.

[21] See the reservations to be considered in relation to this statement in section 3.

million km^2, and a volume of some 40-45 million km^3 with an anomalous crust whose thickness can reach more than 30 km. It was formed in the middle of the Cretaceous Period, ca. 121 Ma, and probably also during a second magmatic pulse around 90 Ma. Some authors believe that this plateau was generated by the "plume" of the *Louisville* hotspot (marked HE on this Sheet) situated in the south of the Pacific (140° W, 50°S)[22]. As mentioned above (2.2.6), this plateau reached the former Vitiaz subduction zone some 20 Ma ago, then collided with the Solomon island arc about 4 Ma ago. This caused the blocking of the subduction because of its lower density compared to the normal oceanic crust (buoyancy effect).

According to the classical theory, a hotspot is located more or less deep beneath a lithospheric plate that is moving over it with a velocity and direction controlled by the accretionary axis where that plate is being generated. In its early existence, the hotspot generates a large plume. When reaching the overlying lithosphere, it produces a voluminous and relatively fluid volcanism at the surface in quite a short time lapse in geological terms. Subsequently, large outpourings are formed in contained, but somehow large, geographic areas: traps, onshore, and oceanic plateaus, offshore[23]. After dissipation of the plume, only the "tail" of the hotspot remains active, evidently at a lower rate but for a much more extended period of time. This activity is recorded in the moving overlying plate by a chain of volcanoes that drift away from the feeding hotspot, first as an active volcanic center, then extinct, and finally subsiding below the ocean surface. The links in this volcanic chain become progressively older with the distance from the hotspot.

The whole set of this linear chain forms the **hotspot track** (or hotspot trail). The most illustrative example is given by the *Hawaii hotspot* (code HC on this map) where the volcanic activity is at present located beneath The Big Island (Mauna Loa and Kilauea shield-volcanoes, and the submarine Loihi volcano[24] marked by a small blue triangle on the *Physiography Map*). The oldest part of this hotspot track still visible is the Meiji seamount (dated at 85 Ma), located just in front of the Kuriles subduction zone which will eventually subduct it. Notice that at halfway along its length (ca. 40 Ma), the orientation of the hotspot track changes from SE-NW to S-N direction, evidence of the reorientation of the motion of the Pacific Plate at that time.

In addition to the above mentioned Hawaii hotspot track, the **age of some different progression steps** for 5 other trails is indicated in the map with a **red number** without the "Ma":

- *La Réunion* (HF). A trail that links this island to the *Deccan* traps via Mauritius Island, Nazareth Bank, Chagos Bank, Maldives and Laccadives ridge. The subsequent opening of the Arabian Sea from the creation of the Carlsberg mid-oceanic ridge has cut this trail in two and offset the original alignment that also included the Saya de Malha and Seychelles banks (cf. also I.3).

- *Kerguelen* hotspot (Hi) probably at the origin of the Broken Ridge Plateau and the Ninetyeast Ridge[25] and perhaps of the *Rajmahal* and *Sylhet* remnant traps.

- *Louisville* hotspot (HE) whose trail (Louisville Ridge) ends up at the Tonga-Kermadec subduction zone (and maybe at the origin of the Ontong Java Plateau, as seen above[26]).

- *Tristan da Cunha* hotspot (HG), at the origin of the Rio Grande Rise to the west, and of the Walvis Ridge to the east, that are connected to the Parana and Etendeka traps respectively that, as seen before (cf. 1.3), formed a single LIP unit 133 Ma years ago, before the opening of the South Atlantic.

- *Easter Island* hotspot (HB) that produced the Sala y Gomez Ridge continued by the Nazca Ridge whose eastern extremity is subducted into the Peru Trench.

2.2.8- Distributed or diffuse plate boundaries

A **grey hatching** covers some oceanic areas where the transform boundary (strike-slip motion) between two lithospheric plates is ill-defined. It is distributed over an area of variable width, e.g. between the North America and South America plates, or on a part of the transform fault to the east of Azores separating Eurasia from the African plate. The largest region displaying this kind of diffuse boundary is located in the middle of the Indian Ocean where it links a segment of the Central Indian (accretionary) mid- oceanic ridge to the Sunda subduction zone (from the north of Sumatra to the middle of Java). This crosses the whole width of the so-called Indian-Australian plate. Actually, it is not yet a true boundary showing a clear separation between an Indian plate and an Australian plate, but a zone where the basaltic substratum is deformed by a compressive stress (in response to the collision of India against Tibet) and where diffuse seismicity also occurs.

2.2.9- Submarine volcanism related to the opening of the North Atlantic Ocean

A **red hatching** overprint shows the presence of SDRs (Seaward Dipping Reflector sequences), located from seismic reflection surveys, or **submarine basalt** bodies. The latter can be both outcropping or buried and all provide evidence of an extensive volcanic province related to the opening of the North Atlantic Ocean during the Paleogene (cf.2.2.4), and to the activity of the powerful *Iceland* (HD) **hotspot**. These dynamics had an effect on the conjugate continental margins of Greenland (and sometimes beyond), on one hand, and of the British Isles and Norway, on the other. This eruptive activity is known onshore (volcanism "V 1" in the legend) in Greenland, as well as in the Faroe Islands and Ireland (Giant's Causeway). It is interpreted that the SDRs correspond to a series of strata with alternated volcanic flows (lava and pyroclastic deposits) and non-volcanic sedimentary layers.

2.2.10- SDRs related to the opening of the South Atlantic Ocean

In the South Atlantic Ocean, oil exploration has more recently located **SDRs** (**blue hatching**) on the conjugated continental margins of Argentina and Namibia-South Africa. The presence of these reflectors is related to the opening of the South Atlantic Ocean and the presence of the *Tristan da Cunha* (HG) hotspot. The two examples of these Atlantic basins show that the passive continental margins (i.e. generated by an earlier continental rift and no longer constituting a plate boundary) are not solely "non volcanic", as previously presumed before the discovery of SDRs. It might give some evidence for the presence of a hotspot being required in the initial rifting of a continental block and the subsequent opening of an ocean.

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[22] The formation of the Ontong Java plateau by a hotspot was recently questioned by the hypothesis of a very large meteoritic impact triggering a cataclysmic magmatic output (cf. Ingle S. & Coffin M., 2004, E.P.S.L., 218 :123-134).

[23] At present, there are not known examples of trap or oceanic plateau in formation.

[24] The Loihi, located 34 km to the SE of Big Island and culminating at a depth of –1000 m (at the "Pelé Pit"), is the most recent expression of the Hawaii hotspot (see *Physiography Map*).

[25] The name of the ridge was coined after its specific geographic position located along meridian 90° E.

[26] In this case, the missing segment would have been progressively absorbed by this subduction, since the motion of the Pacific Plate was westwards.

3 – HOTSPOTS

The hotspot theory (cf. 1.3; 2.2.7) was proposed by the Canadian geophysicist John Tuzo Wilson who first proposed it in 1963 (two years before he developed the transform fault theory) taking Hawaii as a base model, and improved by the American W. Jason Morgan in 1971. This attractive theory had enormous success in consistently explaining the distribution of specific volcanism generally seen outside the plate boundaries (hence its name of intra- plate volcanism) and is particularly evident in the oceanic domain. The initial hotspot list included a score of cases, but its number rapidly expanded to 130 units, even more indeed (about 5 200 according to Malamud and Turcotte[27] in 1999). However at this point, quoting Don Anderson and Kimberly Schramm[28], "*this brings up the question of semantics*". Today, the list has been brought down to a more reasonable number varying between 40 and 50 hotspots. But not all of them meet the basic criteria of the original model (without addressing the geochemical domain). These are: a deep origin for the mantle plume and a long duration of the activity (several tens of million years) which determines the progression of a volcanic track in surface. Those cases, disagreeing with the classic model, are labelled *shallow, weak hotspots* or *hotlines*, etc. The latter is exemplified by the NE-SW Cameroon volcanic line where the age of the volcanism is not distributed according to a regular migration throughout time. It shows a more or less random mode, with the currently most active volcano being the coastal Mount Cameroon (+4 095 m) half-way between the extremities of the line located one at the north of the Cameroon Republic, and the other beyond the small Pagalu Island (ex-Annobon).

The polemics around the hotspot concept has been hardening since the early 2000s, when some researchers (anti-plumers, see e.g. the recent works of Don L. Anderson) denied the existence of a number of plumes. They proposed an explanation for the origin of *LIP* (Large Igneous Provinces, cf. 1.3) mainly attributed to dynamics related only to the plate tectonics *sensu stricto*, which induce shear stress in the lithosphere favoured by pre-existing lines of weakness such as fracture zones. This case seems to apply to the Central Pacific — see in particular the works of IRD/IPGP (Valérie Clouard and Alain Bonneville) and USGS (Marcia McNutt and collaborators)— with the hotspot track segment of Samoa(H27)-Rarotonga(H25)-Arago(H1)-Mcdonald(H21)-Foundation(H15), and with the Tahiti (H30)-Pitcairn(H24) segment. This current controversy is hosted by the very interesting web site: www.mantleplumes.org>, managed by the British geophysicist Gillian R. Foulger, who also published the authoritative book *Plates vs Plumes. A Geological Controversy* (2010, Wiley-Blackwell). Whatever it might be, it was considered of informative interest to **plot the exact or inferred position** of **45 hotspots** on the map (list given in the inset placed in the bottom of the Map).

They are categorized in 4 types of hotspots, taking into consideration the criteria of Vincent Courtillot and co-workers (2003) in particular:

1/ "primary" hotspots interpreted to correspond to a powerful plume, deeply rooted in the lower mantle and with a long duration, marked HA to HG (large **red continuous circle**);

2/ hotspots that might be considered as primary, shown Hh to Hi (**large red dotted circle**);

3/ less characteristic, problematic or controversial hotspots, noted H1 to H34 (**small red circle**);

4/ hotspots supposed to have been extinct since much over 1 Ma, but which would have left traces in the seafloor morphology (**small blue circle**). This would include the Great Meteor Bank (eH1) to the south of Azores that would have built the New England seamount alignment and Saint Helena (eH2).

The first three categories, considered as "alive" with an active, or recent (as in Hoggar) volcanism are mainly located at one extremity of the trail. Most hotspots are to be found in the oceans. Only 6 are onshore: Afar (HA), Cameroon (H17), Darfur/Djebel Marra (H13), Hoggar (H17), Tibesti (H32), Yellowstone (H34).

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[27] Cf. D. Anderson and J. Natland, (p.134), see complete reference in foot note 28.

[28] D. Anderson & K. Schramm use in their paper « The complete hotspot catalogue » in: *Plates Plumes & Paradigms* (Geol. Soc. Amer., Special Paper no. 558, 2005, p. 19-29), with some humour, the neologisms «Notspots» and « Crackspots » to refer to these "dethroned" hotspots.

By way of conclusion….

… It is to be noted that this Map can be used as a basis to explicitly trace the contours of the different lithospheric plates, sub-plates, and micro-plates that make up the present surface of our planet through a relentless confrontation between creation dynamics and destructive processes. Two maps formerly published at the 1:50,000,000 scale by CGMW usefully supplement the reading of this Map:

Plate tectonics from space (2006, N. Chamot-Rooke & A. Rabaute) displaying the present-day motions of the lithospheric plates, one in respect to the others;

Seismotectonic Map of the World (2002, A. Haghipour and coll.) showing the distribution of the earthquakes, particularly along plate boundaries, with different categories of magnitudes and focal depths of earthquakes.