## Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

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### I.3 Rock types and rock ages
Our study – providing new tools and concepts to help analyse how river fluxes of dissolved and particulate material are organised on the world’s continental area – needs reliable foundations for appropriate handling of the data.

The conventional / classical knowledge on rocks as such, as main providers of the material, i.e. the chemical, mineralogical and geological fundamentals of petrology, will be explained here as follows (section I.1):

- Conventional ‘Geo-Lithology’ will be summarised in the first part, section I.1.1.

Second, regarding rock occurrences and their regional associations, in particular how they constitute the continents, we have to consider geologic principles and modes of their distribution:

- Temporal and spatial aspects of the origin and evolution of the continents, according to the ‘new global dynamics’ (plate tectonic) paradigm, are treated in section I.1.2.

Section I.2 completes the explanations in chapter 3 and lists the necessary details for the establishing of the lithological map such as the exact design of certain polygons. Some ‘hydro’-lithological questions are treated as well, in particular more detailed information on the few subsurface (non Quaternary) evaporite occurrences depicted in our map.
I.1 Basics of our approach – conventional geology and lithology

In order to establish a comprehensive classification of rock types and to differentiate the needs of our new map we have to understand the mineralogical-petrological and geological fundamentals and problems of ‘geo’-lithological classification.

For the aims of our study – how river fluxes of dissolved and particulate material are organised on the world’s continental area – we need to know the rocks as main providers of the material, and we have given reasons for the creation of a new lithologic map for such studies.

In this Annexe we consider the fundamentals and the problems of lithological classification as base for ‘handling’ the data in appropriate manner.


I.1.1 Rock classification in mineralogy-petrology / geology – ‘Geo-Lithology’

I.1.1.1 Mixed composition of minerals and rocks

We will consider first the compositional (material) aspects of minerals and rocks, which are characterised by ‘mixtures’, following mineralogical-petrological rules.

I Composition of the Earth as a whole

The following fundamentals determine the average chemical composition of the Earth as a whole, and of the crust, as depicted in Figure I-1.

Earth has an iron core, surrounded by a mantle and a thin outer shell, the crust. Mantle and crust are composed of rocks which in turn consist nearly solely of silicate minerals, with some iron oxides and sulphides as very minor constituents.
At the Earth’s surface some other anomalous and rather rare non-silicate rocks exist, in particular carbonate rocks (limestones and dolomites) and evaporites made up by sulphates (gypsum, anhydrite) and salt rocks (mainly halite) – but their quantities are minor compared to the overall composition of the crust. Other compounds are of only local and negligible importance, for example some massive iron and aluminium oxide ores used as metal resources, or metamorphosed organic matter as peat, coal and bitumen. Many if not most of these non-silicate rocks are composed of more or less only one mineral species (mono-mineralic rocks) and have therefore normally clear-cut chemical compositions.

Figure I-1: Relative abundances of elements (given in weight %) in the Earth as a whole (crust – mantle – core) and in the Earth’s crust (modified after PRESS & SIEVER 1994).
Different – and representing the large majority of crustal rocks – is the case of all those rocks constituted of ‘rock-forming’ silicates. The fundamental constituent of silicates are SiO$_4$ tetrahedrons, bound together in various types of crystal lattices, most of which accommodate other elements like Al, Fe, Mg, Ca, K, Na and some other (too insignificant to be mentioned here or present only in traces).

II Composition of rock-forming silicates

A three-dimensional net of SiO$_4$ tetrahedra, firmly bound together over O-bridges, with the overall formula SiO$_2$, forms the mineral quartz, ubiquitous in SiO$_2$-rich magmatites. Quartz has enormous chemical and mechanical stability; it survives erosion and transport and is thus a major constituent of all ‘silici-clastic’ sediments. Quartz with its frame-type lattice is a ‘tectosilicate’.

If in some of the SiO$_4$ tetrahedra Si is replaced by Al, other cations can be bound within the crystal lattice, as in the tectosilicate group of feldspars, the most abundant group in the crust. The cations in this group are Ca, Na and K; they can replace each other to some extent, and thus feldspars occupy the whole compositional range between the three end-members that are pure Ca-feldspar, pure Na-feldspar and pure K-feldspar. Ca-rich feldspars characterise mafic or basic magmatites (gabbro – basalt), Na-rich and K-feldspars the salic or acid magmatites (granite – rhyolite). All feldspars don’t resist weathering processes when water is present; partly they are solved, partly transformed into clay minerals or Al-hydroxides, phases stable under normal surface conditions.

Clay minerals belong to the next structural – and also important – group of silicates, characterised by two-dimensional, sheet-like SiO$_4$-nets. Other members of this ‘phyllosilicate’ group are mica (biotite and muscovite), common in granite and gneiss, and chlorite, typical for low-grade metamorphic (greenschist facies) rocks. Various possibilities – combining the sheets to double or three-layer structures, incorporating cations and substituting them – make the phyllosilicates a group of remarkable versatility. Particularly clay minerals can hold rather loosely between the layers large cations or even water and other molecules, apt for rapid exchange. This capacity explains their importance as components – produced by weathering – in soils and also as ‘vessel’ during water transport as well as finest (pelitic) constituent of silici-clastic sediments. Clay minerals may also grow during early (near surface) stages of diagenesis, the ‘petri- or lithification’ of sediments into sedimentary rocks. During metamorphism within the crust, with rising temperature and pressure conditions, they are rapidly (re-) transformed to mica, chlorite and feldspar.

Inosilicates have single or double chains of SiO$_4$ tetrahedra, with pyroxene (i.a. augite) and amphibole (i.a. hornblende) as the respective mineral groups, with Al, Fe, Mg, Ca, and in rare cases also Na being the most important cations. Pyroxenes – and to a lesser extent OH-groups
bearing amphiboles – are, aside of Ca-rich feldspars, the main constituent of mafic magmatites. In medium-grade metamorphic mafic rocks amphiboles are the dominant mafic material, pyroxenes characterising only ‘water-free’ high-grade metamorphic rocks. Both amphiboles and pyroxenes show very little resistance during weathering.

Sorosilicates with small groups from 2 to 6 SiO$_4$ tetrahedra, bound together by cations, are without importance quantitatively.

The group of Nesosilicates, with Olivine – (Fe,Mg)$_2$SiO$_4$ – as prominent material, has isolated SiO$_4^{4-}$ tetrahedra. Olivine is the main component of most ultramafic rocks – the peridotites –, nearly alone or together with pyroxenes. Ultramafics constitute, as far as known, the Earth’s mantle. Olivine and its high-pressure polyphases are thus by far the most abundant mineral. At the surface olivine disappears by weathering even faster than other mafic minerals.

What has to be retained ? With the notable exception of quartz, nearly all rock-forming silicate minerals, by virtue of their chemical-cristallographic lattice characters, display certain ranges of composition concerning the few major elements Si – Al, Mg – Fe, Ca – Na and K – not to mention numerous others, quantitatively not significant.

### III Composition of rocks

A similar principle holds true for rocks as entities.

Contrary to biology where a living individual, a species, a genus are well defined, characteristically isolated from all neighbouring units, most rocks – except those produced biologically – are the result of an interaction of various inorganic processes and consequently are composed of varying mineral mixtures. The rock-genesis processes however produce only a limited variety of combinations and favour some, more common than others.

Rock names describe ‘common’ types, recognised primarily by field experience, corroborated by mineralogic-petrological analysis and statistic approaches; but they are defined more or less arbitrarily.

Table I-1 depicts the chemical composition of some typical magmatic and sedimentary rocks.
I.1 Basics of our approach – conventional geology and lithology

Table I-1: Average chemical composition of some important magmatic and sedimentary rocks (after DEGENS 1989). The SiO\textsubscript{2} number for ‘basalt’ (51,55 \%) is towards the upper end of the field of basalts (normally between 45 \textendash 52 \%) but corresponds to the most abundant type of basalt occupying the greatest volumes – the continental flood basalts and the basalts belonging to subduction processes, tending towards andesites.

<table>
<thead>
<tr>
<th>Weight %</th>
<th>Magmatic rocks</th>
<th>Sedimentary rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basalt</td>
<td>Granodiorite</td>
</tr>
<tr>
<td>SiO\textsubscript{2}</td>
<td>51,55</td>
<td>65,69</td>
</tr>
<tr>
<td>TiO\textsubscript{2}</td>
<td>1,48</td>
<td>0,57</td>
</tr>
<tr>
<td>Al\textsubscript{2}O\textsubscript{3}</td>
<td>14,95</td>
<td>16,11</td>
</tr>
<tr>
<td>Fe\textsubscript{2}O\textsubscript{3}</td>
<td>2,55</td>
<td>1,76</td>
</tr>
<tr>
<td>FeO</td>
<td>9,10</td>
<td>2,68</td>
</tr>
<tr>
<td>MnO</td>
<td>0,20</td>
<td>0,07</td>
</tr>
<tr>
<td>MgO</td>
<td>6,63</td>
<td>1,93</td>
</tr>
<tr>
<td>CaO</td>
<td>10,00</td>
<td>4,47</td>
</tr>
<tr>
<td>Na\textsubscript{2}O</td>
<td>2,35</td>
<td>3,74</td>
</tr>
<tr>
<td>K\textsubscript{2}O</td>
<td>0,89</td>
<td>2,78</td>
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<tr>
<td>P\textsubscript{2}O\textsubscript{5}</td>
<td>0,30</td>
<td>0,20</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Misc.</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>100,00</td>
<td>100,00</td>
</tr>
</tbody>
</table>

I.1.1.2 Petro- (or litho-) genesis and natural classification

The ‘geo-lithologic’ classification of rock types relies on ‘natural’ – genetic – criteria.

The natural evolution of rocks (petro- or lithogenesis) can be depicted in simplified form, where inside and outside the solid Earth, endogenic and exogenic domains are distinguished, and three main ‘natural’ groups of rocks: magmatic, sedimentary and metamorphic. Rocks of these three groups are different by genesis and structure and show specific associations, but they do not necessarily differ in chemical composition, due to the (different) modes of their natural recycling, the well known ‘rock cycles’ as visible in Figure I-5.

Basic / mafic silicate melts stand at the endogenic ‘primary’ beginning of rock formation. Initial magmas can evolve into intermediate and acid or salic (silica-rich) compositions. They cool down and solidify to become plutonic magmatites (within the Earth), or they erupt as lavas and chill to volcanic rocks. At Earth’s surface exogenic processes generate sediments and ultimately sedimentary rocks (= sedimentites).

Igneous or sedimentary rocks, by sinking down in the endogenic realm, may become metamorphic rocks by tectonic deformation and metamorphosis or partial re-melting; if completely re-molten they may also evolve into e.g. palingenetic granites.
I  Endogenic realm – magmatism and magmatic rocks

We will commence by describing the different magmatic rocks as they stand at the beginning of rock formation and are the primary constituents of the solid globe as a whole.

Since primeval planetary times the Earth – according to old hypotheses, supported and refined by modern geophysics and geochemistry – is constituted of an inner metallic (Fe-Ni) ‘core’ (radius about 3 100 km), surrounded by a ‘mantle’ (about 2 900 km thick) consisting of silicate minerals with, most probably, ultrabasic (peridotitic) bulk composition. Magmatic differentiation within the upper mantle leads to the formation of the Earth’s skin with the comparatively thin (normally 6 – 40 km) external ‘crust’, of average basic (gabbroic-basaltic) to silica-rich (‘salic’, granodioritic-granitic) composition (compare also chapter 4.1.1, with Figure I-7).

Several findings have led to today’s geodynamic ‘plate tectonics’ paradigm in geology and developed the actual view of petrogenesis:

The solid (thicker, 30 – 40 km) continental crust as well as the solid (thinner, 6 – 8 km) oceanic crust are underlain by a solid part of the upper mantle (80 – 150 km thick under continents, 50 – 70 km under oceans). Together – crust and solid part of the upper mantle – they form the solid external shell of the Earth, called ‘lithosphere’ (lithic sphere). It is segmented in plates, drifting slowly upon a less solid layer of the upper mantle, the ‘asthenosphere’ (= not solid sphere).

Mid-ocean rift-ridges are the sites where basic magma, created by partial melting in the asthenosphere, rises, and, by way of freezing, continuously creates new oceanic lithosphere. The ongoing spreading of young oceanic lithosphere is compensated at subduction zones where old oceanic lithosphere sinks down in the mantle, and continental crust and lithosphere is generated. The processes and consequences for today’s distribution of the continents and rock types on the continents and thus for today’s face of the Earth are described in part I.1.2 of this annexe and in chapter 4.

The main energy source within the endogenic realm is the heat flow – by radioactive decay and cooling – from within the Earth, the main agent being the convective ‘secular’ slow mantle flow (1 – 10 cm per year). Temperature and pressure conditions are the dominant parameters, characteristically increasing with depth along the respective gradients.

Rock forming and recycling processes, regarding continental lithosphere, can be summarised as follows:
**I.1 Basics of our approach – conventional geology and lithology**

Basic silicate melts, generated by partial melting within the ultrabasic upper mantle (asthenosphere), rise, then may stay for some time and differentiate in lithospheric or crustal magma chambers. However, normally – being hot (depending of depth of formation and composition about 1100 – 1200°C) and of low (oil-like) viscosity – they ascend rather quickly and erupt at the surface as basaltic lava, in sometimes enormous quantities, forming either huge flood basalt provinces or basaltic shield- and strato-volcanoes. Gabbro, the plutonic equivalent, is rare and occurrences are small.

Differentiation in magma chambers, by fractionated crystallisation, can lead to the evolution of gabbroic-basaltic melts into more silica-rich varieties, the intermediate diorite-andesites, and finally the silicic granites-rhyolites. Basaltic melts generated above subduction zones, particularly when rising through continental crust, tend to develop into andesites or sometimes even dacites (but in minor quantities). On small scale, generalising geologic maps, this rock group comprising basalts, andesites and dacites, appears combined as ‘basic – intermediate’ volcanics. Dacites, however, are often associated with rhyolites.

The vast majority of diorite-granodioritic-granitic rocks and their metamorphic (orthogneiss) equivalent which constitute the continental crust, have a more complicated genesis, involving repeated assimilation and palingenesis of sediments during plate tectonic cycles – as explained in chapter I.1.2.2. SiO$_2$-rich magmas, if some % of water are present, have low melting temperatures (650 – 800, rarely up to 1100°C) and high viscosities. They move slowly and mostly crystallise within the crust. Especially rhyolitic lava rarely reaches the surface. In the atypical case it does, it is erupted mostly during violent ‘initial eruptions’ in the form of ignimbrite (tuff-lava or welded tuff, literally ‘fire-rain’), covering huge areas. Thus, rhyolitic ignimbrites appear even on global maps, mostly depicted as rhyolites, for example in the Andes or around lake Toba in Sumatra. However, in reciprocal analogy to the volcanics, diorites seldom accompany gabbros; they rather appear as minor constituents in granodioritic-granitic ‘batholiths’, huge plutons, mapped mostly as ‘granites’ sensu lato.

The petrological classification and main characteristics of common magmatic rocks (mineral content, chemical composition) are illustrated in simplified form in Figure I-2. Omitted are the alkali-richer varieties with special names; they occur comparatively rare, in minor quantities and special geotectonic settings – generated by partial melting rather deep in the mantle, e.g. in early stages of divergent break up, and they are usually not differentiated as such on small scale maps.
Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

### Magmatic rocks

<table>
<thead>
<tr>
<th>Mineral content</th>
<th>Olivine</th>
<th>Ca-rich Feldspar</th>
<th>Quartz</th>
<th>K-Feldspar</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extrusive volcanics</th>
<th>Basalt</th>
<th>Andesite</th>
<th>Dacite</th>
<th>Rhyolite</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ % weight</td>
<td>&lt; 40 –</td>
<td>45 –</td>
<td>52 –</td>
<td>63 –</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2,3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>0,9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>10</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>MgO</td>
<td>6,7</td>
<td></td>
<td></td>
<td>0,9</td>
</tr>
<tr>
<td>FeO + Fe₂O₃</td>
<td>11,7</td>
<td></td>
<td></td>
<td>3,4</td>
</tr>
<tr>
<td>Viscosity of magma</td>
<td>low ('oil' or ‘honey')</td>
<td></td>
<td></td>
<td>high ('asphalt')</td>
</tr>
<tr>
<td>Melting-T</td>
<td>high (&gt; 1 200°C)</td>
<td></td>
<td></td>
<td>low (&lt; 700°C)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intrusive plutonites</th>
<th>Peridotite</th>
<th>Gabbro</th>
<th>Diorite</th>
<th>Granodiorite</th>
<th>Granite</th>
</tr>
</thead>
</table>

Figure I-2: Common magmatites: classification, mineral content, and chemical composition (modified after DEGENS 1989, PRESS & SIEVER 1994).

### II  Exogenic realm – processes on Earth’s surface, sediments & sedimentary rocks

At Earth’s surface, the lithosphere enters into contact with the hydrosphere, atmosphere and life – the ‘biosphere’. Activity in this exogenic domain is maintained and driven by the sun’s radiation, fluctuating slightly in cycles of about 11 years duration – longer cycles, about 80 – 90 and 208 years, and possibly more, seem to exist. Due to the Earth’s spin and rotation around the sun – again with slightly changing parameters – the portions of radiation reaching Earth’s different latitudes change considerably – daily, annually and in longer astronomical (Milankovich’s) cycles.

Thus the ‘hard’ rocks of the lithosphere undergo – by way of exposure to changing temperature, to water and atmospheric gases – physical and chemical (and also biological) ‘weathering’.

A distinctive role is played by soils (the ‘pedosphere’ as boundary layer) as the in-situ-product of the interaction between litho-, hydro-, atmo-, and biosphere.

Erosion and transport is made possible by physical disintegration, chemical alteration and partial solution. Physical re-deposition, chemical precipitation, and sometimes also effective biological (nowadays also human) activity – both physical and chemical, produce sediments.

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Sediments can consolidate to become sedimentary rocks (sedimentites) at the surface; yet normally this process of lithification (or diagenesis) occurs in the upper endogenic domain by applied load of younger sediments and the implicated (geothermal) changes in temperature as well as by the work of pore liquids.

Three main classes of sediments and sedimentary rocks can be distinguished, normally different in formation and material: clastic (detrital), chemical and organic. Most 'clastic' (Greek = 'break to pieces') sediments consist of fragments of silicate rocks and/or of weathering-resistant minerals, i.e. quartz, as well as of the main product of weathering, clay minerals. This frequent case are the 'silici-clastic' sediments. By way of this narrow definition, fragmented reworked and re-deposited limestones, although clastic sediments, are excluded. In generalising maps they are mostly not distinguished from other 'normal' carbonate rocks.

Weathering and transport processes tend to separate and sort material, producing e.g. pure quartz-sand (-stone), pure clay (-stone) or pure precipitates. However, usually these sorting processes stop somewhere 'on the way' and consequently mixed ('impure' or 'immature') sediments result: Quartz-sandstone frequently contains silt and clay, and mixtures of silt and clay (mudstone) are far more abundant than the pure fractions. Sandy (-silty) greywacke is typically of mixed nature, containing considerable parts of lithic fragments (clasts). Most limestones are produced by biological action – not only those constructed as (e.g. coral-) reefs, but also carbonate 'sands' (with e.g. 'ooides') and even most fine-grained types formerly considered as inorganic precipitates. This holds equally true for most Phanerozoic cherts, biologically produced siliceous ooze before diagenesis. Reworking during or shortly after formation frequently occurs, carbonates then becoming mixed with (usually) clay (and silt), producing marl and marlstone as mixtures.

In Table I-2 some common sediments and sedimentary rocks are named. More and detailed information can be found in chapters 3.4.2.10 to 3.4.2.18.
Table I-2: Common types of sediments and sedimentary rocks (modified after DEGENS 1989).

<table>
<thead>
<tr>
<th>Silici-clastic sediments</th>
<th>Chemical sediments</th>
<th>Organic sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>unconsolidated</td>
<td>consolidated</td>
<td></td>
</tr>
<tr>
<td>gravel</td>
<td>breccia (angular)</td>
<td>carbonate rocks</td>
</tr>
<tr>
<td></td>
<td>conglomerate (rounded)</td>
<td>limestone</td>
</tr>
<tr>
<td>sand</td>
<td>(quartz-) sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>arkose (&lt; 25 % feldspar)</td>
<td>dolomite</td>
</tr>
<tr>
<td></td>
<td>greywacke (&gt; 25 % lithic clasts)</td>
<td>chert</td>
</tr>
<tr>
<td>silt</td>
<td>siltstone</td>
<td>evaporites</td>
</tr>
<tr>
<td></td>
<td>mudstone</td>
<td>gypsum / anhydrite</td>
</tr>
<tr>
<td>clay</td>
<td>claystone</td>
<td>halite (NaCl)</td>
</tr>
<tr>
<td></td>
<td>shale</td>
<td>other salts</td>
</tr>
</tbody>
</table>

Fine-grained siliciclastic rocks make up the major part of sediments (see Figure I-3). They have an overall intermediate ‘sialic’, (dioritic to) granodioritic composition, that is of greywacke and corresponding mudstone.

Figure I-3: Relative volume abundances of important sedimentary rocks (modified after PRESS & SIEVER 1994). If only non-carbonate rocks are taken into account the resulting numbers are; about 13% are conglomerates and sandstones and about 87% are silt, clay and shale.
In contrast to the endogenic – normally ‘slow-pace’ – dynamics, conditions change rapidly in time (from annual and pluri-annual changes to diurnal – day and night – changes to seconds) within the exogenic realm, except within the deep seas. Consequences are correspondingly fast changing conditions for sediment genesis and vertically narrow-spaced successions of different sediments. Conditions also change in space, locally over very short distances, at the Earth’s surface – where sediments originate, caused by topographic relief. Lateral changes concerning the ‘facies’ of sediments, conditioned by relief changes, can be observed on every beach, lake or sea, and at the toe of slopes, provided some accumulation has occurred.

The most important, quantitatively considerable amounts of clastic sediments are transported and deposited during catastrophic events as rock avalanches, mud flows, exceptional river floods or turbidity currents on continental slopes. They can be caused for example by earthquakes, volcano eruptions or by exceptional climate conditions.

Under normal (‘quiet’) conditions of sedimentation in vast basins like lakes or on the sea floor, long-term climate variations due to the astronomical change of Earth’s rotation parameters (Milankovich-cycles) result in regularly (usually cm- to m-scale) alternating successions of e.g. silt and clay, clay and marl or marl and calcareous ooze (later becoming limestone).

Geologic base maps (usually at 1 : 25 000 scale) show ‘mappable’ units, called ‘formations’, sometimes only some meter or deca-meter thick. Rather often these formations comprise cyclic successions of different rocks. On an overall scheme, some few common types of sediments occur repeatedly. Major changes of conditions arrive slowly, during ‘geologic times’, caused by plate drift, moving continental and epi-continental areas across latitudes, e.g. from cold high latitudes into warm equatorial areas.

On the whole, sediment geology as science relies on and depends on knowing of sediment chronology in order to reconstruct geologic history. Consequently – as base for further analysis and understanding – sediments are differentiated and ranked primarily according to their age on normal geologic maps. Lithological information is often only to be found in the explanatory notes accompanying geological maps.

A special problem arises when volcanic rocks become fragmented by and during the eruptions. Consequently then, they are distributed and deposited nearly like sediments. Together they form the class of pyroclastic rocks or pyroclastics, including rocks like volcanic breccias, lapilli-tuffs and ashes, also in the form of pyroclastic debris avalanches and flows (e.g. glowing clouds – ‘nuées ardentes’), and mudflows of pyroclastic material, lahars. The majority of these volcanic sedimentary rocks being integral parts volcanoes, they are normally treated together with volcanic rocks and are often not separated from them on generalising maps. Fine-grained ashes, however, can reach more than 20 km height in the atmosphere during violent eruptions and can be spread over wide distances (sometimes hundreds of km) by wind. In these cases they appear
as distinct layers in soils or interbedded with other sediments in lakes and the sea. Reworking and mixing with other sediments produces tuffites.

III  Endogenic realm – tectonic deformation, metamorphism, metamorphic rocks

Sediments enter the endogenic realm when they accumulate and sink down, often to far more than 10 km depth. This sinking is accompanied by the aforementioned lithification or diagenesis.

Deeper regions of the endogenic domain are reached when – during orogeny (the process of mountain building) – sediments as well as other rocks are forced to submerge by way of thrusting and folding into higher pressure and temperature conditions together with changing fluid regime conditions, the domain of ‘metamorphism’ and metamorphic rocks. This process occurs along regionally slightly different geothermal and geo-barometric gradients (shown in Figure I-4). The majority of metamorphic rocks are transformed sedimentary rocks (‘parametamorphics’); metamorphic magmatic rocks (‘ortho-metamorphics’, mostly foliated granitoids – orthogneiss) are less frequent.

Metamorphism essentially leads to mineralogical changes within the rocks concerned, adaptations to the P–T– conditions reached respectively. Along the average continental geothermal and pressure gradient several grades – or facies – of metamorphism are distinguished. Subsequent to diagenesis rocks pass into the very low grade or anchizonal domain (about 100 – 300°C), followed by the low grade / epizonal / greenschist facies domain (about 300 – 500°C) and afterwards the medium grade / mesozonal / amphibolite facies domain (about 500 – 700°C). Sediments and volcanics of mafic and intermediate compositions in particular display well the metamorphic mineral (facies) changes. Metamorphic rocks of granodioritic (the average ‘sialic’ continental crust) composition – the presence of some % of water being required – begin to generate granitic partial melts at about 650°C resulting in the formation of ‘migmatites’, variously structured mixtures of solid and molten rock portions. This process of ‘anatectic’ melting can proceed and end with the production of big volumes of ‘palingene’ (reborn) magma, first and most commonly of granitic composition. Being less dense than the relict rocks around, the magma attempts to rise and intrude into higher, mainly the middle levels of the crust, solidifying ultimately as (‘S-type’) granitic batholiths.

The remaining rocks, water-deficient, characterising the lower continental crust, often undergo still higher temperatures (about 750 – 1 000°C), the realm of high grade / catazonal / granulite facies metamorphism.

Two remaining domains still have to be mentioned:
1) **Contact metamorphism** is caused by hot magma rising into cooler environments, the extreme case being basaltic lava upon or in sediments at the surface. The extent of this process depends on the amount of heat provided and the time available for reactions.

2) In **subduction zones**, in contrast, huge volumes of cool crust descending into the mantle immediately experience high pressure conditions, but heat up slowly. Resulting is ‘high pressure – low temperature / HP – LT’ or blueschist facies metamorphism, and, again under water-deficient conditions, high pressure – high temperature / HP – HT or eclogite facies metamorphism. Recent discoveries (e.g. of diamonds in some eclogites, or the SiO₂-phase Coesite in former sandstones) and experimental studies show that fragments of continental crust can descend to more than 100 km depth into the mantle where they are subject to ultra-high (UHP) metamorphism.

The different modes and facies of metamorphism are shown in Figure I-4.

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**Figure I-4** : Pressure – temperature diagram for the different modes and facies of metamorphism. Depth numbers (in km) approximately valid for the continental lithosphere. Modified after BUCHER & FREY (1994) and other authors.
From the different modes of metamorphism only contact metamorphism is a static process.

All other modes, applied to rather big volumes of crust and therefore called ‘regional’ metamorphism, are generally connected with tectonic movement and deformation. These processes normally occur throughout orogeny, the mountain building processes by way of collision.

Such tectonic deformation – including fracturing, thrusting, folding, shearing and flattening of rocks (down to microscopic levels) – is the more penetrative the more it is intense. Quite often also sediments and sedimentary rocks near the surface are concerned.

An important remark is to be made here:

These tectonic structural processes are connected with or result in mechanical mixing of rocks, in a wide range of scales. Consequently for a generalised presentation of highly deformed and metamorphic areas on maps, geology needs summarising classes for certain groups of rocks. We will use ‘Complex lithology’ as an overall comprehensive class for areas with tectonic mixtures of virtually all rock types – sediments, volcanic, plutonic and metamorphic rocks –, inseparable or not known in detail. The class ‘Metamorphic rocks’ – both in generalising geologic maps as well as adapted in our map – serves for associations of diverse, mainly medium to high grade metamorphic rocks.

With this overview, following guidelines of petrogenesis, we have completed the great cycle leading from primary mafic magmatites within the endogenic realm of Earth up to its surface, the exogenic domain of weathering – erosion – transport – sedimentation, and then back into the endogenic realm of tectonic and metamorphic processes until the formation of palingenetic magma by remelting. Figure 1-3 (general introduction, chapter 1), repeated here in a simplified form to enhance comprehension of the rock formation and recycling processes (Figure I-5), shows that there are many shorter ways of recycling.

The complex nature and evolution of continental crust is further developed and discussed in chapter I.1.2.
I.1 Basics of our approach – conventional geology and lithology

I.1.1 Weathering and erosion

Sedimentation on land or in the sea

SEDIMENTS unconsolidated

Diagenesis

Metamorphism

Uplift

Cooling

Ascent

HIGH-GRADE METAMORPHIC ROCKS

(VOLCANIC ROCKS

Uplift

Rapid ascent

PLUTONICS

Cooling

Ascent

MAFIC MANTLE MAGMA

(MANTLE)

Sedimentary rocks consolidated

Deformation

rising pressure and temperature

Metamorphism

Remelting (Anatexis)

PALINGENE SALIC CRUSTAL MAGMA

METAMORPHIC ROCKS

Figure I-5: Summary of rock formation and recycling. Modified and completed after PRESS & SIEVER (1994).

I.1.2 Evolution and constitution of continents – today’s understanding


I.1.2.1 Temporal aspects

A general reservation has to be made first concerning the ‘state of the art’: geologic knowledge of the Earth’s history depends on documents – comparable to human history. The geological evolution is documented by the rocks, they usually allow to determine their age and
also to infer some circumstances of their formation. Especially useful are sedimentary rocks and the fossils therein – e.g. plant remains may tell about former climates. The older the rocks become, the more rare they are and consequently – by lack of documents – our knowledge becomes more incomplete.

Approximately 5% of the Earth’s history are fairly well known – these are the last 250 Ma of the Mesozoic and Cenozoic eras. For another 7% our knowledge can be called sufficient but has many blanks – concerned is the Paleozoic era beginning with the Cambrian period about 540 Ma ago. These eras together are the Phanerozoic times and are characterised by and named after the appearance and evolution of animals and plants. For most of the Precambrian (Archean and Proterozoic) times when only bacteria and primitive algae existed our knowledge is more than fragmentary.

The sun system with its planets, and thus Earth, are about 4 600 Ma old. Planetary accretion and differentiation led, during the ‘Hadeic era’, to formation of the Earth’s Fe-Ni core and silicate mantle, with a proto-crust, later a proto-ocean and a proto-atmosphere.

The oldest minerals and rocks known are of ‘continental’ type and date back to a little bit more than 4 000 Ma – the beginning of the Earth’s ‘Archaean Erathem’ lasting until 2 500 Ma ago. Following then were the early, middle and late Proterozoic Erathem until the beginning of the Phanerozoic Erathem with the Cambrian epoch 540 Ma ago.

Some small cratonic nuclei date back to Archaean times. Conditions on Earth during the Archaean to middle Proterozoic times were different from those today. Concerning the magmatites, there are to be found – within the early Archaean ‘greenstone belts’ – the komatiites. These are unique Archaean basalts with abnormal high MgO content which erupted as abnormally hot lavas. They can be found in the Canadian and African, maybe also the Australian, shield regions, but not in an extent widespread enough to be distinguished in our map, and we included them in our Vb class.

Proterozoic layered mafic-ultramafic near-surface intrusions in form of gigantic bowls (lopoliths), like the Bushveld complex in South Africa (65 000 km², max. 7 km thick; included as Pb rocks in our map), had dimensions never attained later.

Also, towards the end of the Archaean erathem 2 500 Ma ago and in later Proterozoic times, enormous volumes of sialic magmatism (anorthosites to granites) together with the rapid pace of continental crust formation seem to document a heat flow higher than normal later.

Table I-3 summarises the main stages of Earth’s history.
Concerning sediments, clasts of pyrite and uraninite can be found, presupposing an atmosphere without oxygen in order to be preserved during transport and sedimentation. Likewise, the Archaean and early Proterozoic iron oxides bearing jaspilites, known as banded iron formations (worldwide the most important iron ores), need special conditions to be formed, not yet fully understood. The occurrences of these sedimentary rocks are nonetheless too small to be distinguished in our map.

Later, with the beginning of middle Proterozoic times about 1 800 Ma ago, first ‘red bed’ sediments (with oxidised iron compounds; not mapped in our map) document the worldwide – probably slow – rise of the oxygen level, due to the ascent of cyanobacteria and primitive algae living by photosynthesis. Probably not before late Proterozoic times the actual oxygen level was reached and later it may have changed considerably – as well as the CO₂ level.

Spectacular late Proterozoic glaciations are known from many parts of the world. Recent investigations foster discussions that temporarily all continents and even the equatorial oceans
may have been covered by ice – the whole Earth being an ‘ice house’ or ‘snow ball’; and that soon afterwards – as a sort of automatic counter – the Earth turned temporarily into a very warm greenhouse, testified by massive carbonate sedimentation. These rocks are documented as Precambrian carbonates – only built up by bacteria and algae – in our map in southern Namibia and around Pretoria and Johannesburg in South Africa as well as in South East Australia North of Adelaide. Further speculations assume that these drastic changes incited the evolution of animal (and later also plant) life setting off shortly afterwards with the beginning of Cambrian – Phanerozoic times.

To name but two of the consequences due to the Phanerozoic evolution of life on Earth, these are

a) deposition of massive carbonate rocks, for the first time biogenic with sponges etc., in quantities not known before – documented in our map in many parts of the continental world that lay in equatorial latitudes at that period, e.g. Lower Paleozoic carbonates, for example in northern Eurasia, Siberia, Canada, Alaska etc.,

b) the formation of coal deposits as well as oil and gas producing sediments.

Rock formation, as already explained (general introduction, chapter 1), occurs in the endogenic (within-earth) domain as well as on Earth’s surface, the exogenic realm. Endogenic dynamics are governed by plate tectonics, so called WILSON-cycles after the explanations by WILSON (1965) – cf. sections I.1.2.2 and I.1.2.3; they are assumed to be active – essentially as observable nowadays – since early Proterozoic times.

Exogenic conditions – even if primarily driven by the sun’s activity –, concerning mainly the composition of hydrosphere and atmosphere, depend fundamentally on the evolution of plant life. The actual state of conditions was not attained before latest Proterozoic times. However, the geologic (Huttonian) principle of actualism allows for worldwide cooler (glacial) or warmer periods as well as for catastrophic events like meteor impacts or continent wide consequences of huge earthquakes and gigantic volcanic eruptions.

I.1.2.2 Spatial aspects

The fundamental geomorphologic difference on Earth is the one between continents, including their shelves, and the deep oceans. WEGENER (1915, 1936) assumed the ‘sialic’ continent rafts to drift upon the oceans’ ‘sima’ like icebergs in water. Modern geophysics and
geology have modified these ideas considerably and transformed into ‘plate tectonics’, also known as the new global geodynamics.

According to this theory the moving outer shell of Earth is divided into a number of in(ter)dependent plates consisting of the ‘crust’ above and a rigid part of the uppermost mantle underneath, together called the ‘lithosphere’, or sometimes, because of its rigid behaviour, the ‘sclerosphere’. The lithospheric plates move upon and with the ‘asthenosphere’ (gr. asthenos = non-rigid), the most mobile, upper part of the mantle and its supposed convective mega-currents as driving agents. The mantle is composed of silicates with an average ultramafic (peridotitic) composition. Partial melting of these rocks produces mafic (basaltic) liquids; and some percent of molten material are sufficient to provide the mantle its ‘secular’ mobility, compared sometimes to that of stiff honey.

The plates normally comprise oceanic as well as continental areas, both however fundamentally distinct from each other in composition, thickness and origin. Oceanic crust consists of basalts and plutonic mafic to ultramafic rocks below, normally 5 – 8 km thick; together with the underlying rigid mantle portion the oceanic lithosphere amounts to a thickness of about 60 – 80 km. Contrary to this is the continental crust of complex ‘sialic’, average granitic to intermediate composition, measuring about 30 km when young and up to 50 km in the case of old cratons. The total continental lithosphere arises thus correspondingly to about 100 to more than 250 km thickness.

Table I-4 summarises the Earth’s structure.

| Table I-4 : Shell structure of the Earth, oceanic vs. continental (continents including their shelves) lithosphere. |
|--------------------------------------------------|---------------------|---------------------|
| Earth Surface % | 65 % OCEANS | CONTINENTS 35 % |
| Dominant elevation | -3 000 to -5 000 m | + few hundred to - 2 000 m |
| Lower boundaries | km depth | |
| **CRUST** | **Lithospheric Crust** | 5 – 8 | Oceanic crust, ‘simatic’ | ‘Sialic’, reworked continental crust | 30 – 80 |
| **LOWER LITHOSPHERE** | **Lithospheric Mantle** | 30 – 80 | Oceanic lithosphere | Ultramafic mantle rocks | Poorly known subcrustal Continental lithosphere | 100 – > 250 |
| **ASTHENOSPHERE** | 200 – 400 | some % basaltic partial melts | 200 – 400 |
| **MESOSPHERE** | Ultrade | Silicate rocks |
| Phase-transition | ≈ 400 | Olivine → Spinel structures | ≈ 400 |
| **UPPER** | Ultramafic | Silicate rocks |
| Phase-transition | ≈ 670 | Spinel structures → Perovskite structures | ≈ 670 |
| **LOWER** | 2 900 | Ultramafic | Silicate rocks | 2 900 |
| **CORE** | Liquid | Molten Ni-bearing iron | 5 200 |
| **Outer** | Solid | Ni bearing Iron | 6 370 km |

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Plates are separated by either divergent, (crust-) constructive margins when moving apart from another, or by convergent (crust-consuming) margins, subduction-collision zones where oceanic lithosphere sinks into the mantle; or by conservative boundaries when the plates pass each other along strike-slip transform faults.

**Oceanic lithosphere is normally produced along constructive margins in mid-ocean ridges.** These are the locations of upwelling asthenosphere releasing basaltic melts. These melts may differentiate in subcrustal magma chambers and secrete ultramafic residues, but then cool to become gabbros or, after eruption, basalts at the (submarine) surface. Divergent flow of the asthenosphere carries away the new plates on both sides where they rapidly gain their normal thickness. The process is known as ocean spreading. Mantle currents, assumed to activate the mid-ocean spreading zones, have to be cylindrical and move rather continuous; however, observed in more detail, especially the magma generation and plutonic-volcanic emplacement are quite irregular in space and time. A related, but different type of important mantle activity are the ‘plumes’, vertical chimneys where material about 100°C hotter than usual, rises from probably the deepest mantle up to the surface. The surface locations of these plumes are the so called ‘hot spots’ (as a geological term). Plumes appear rather stationary compared to the drifting plates. Thus they produce chains of sea mounts / guyots and oceanic volcano islands (e.g. the Hawaii group, with Vb lithology), oceanic ridges and huge oceanic plateaus.

Oceanic lithosphere created at divergent mid-ocean rift zones drifts away, cooling and becoming heavier. When about 150 – 200 Ma old – at the latest, if not much earlier – it begins to be subducted, sinking back into the mantle down to several hundreds of km, or possibly down to the mantle-core boundary 2 900 km deep, thus providing new material for ascent and closing the mantle current circuits.

**Subduction zones** are zones of plate convergence compensating for the divergence of the ocean spreading. They are furthermore responsible for the production of primordial continental crust.

3 main collision types regarding the building of continental crust can be distinguished, they are illustrated in Figure I-6:
I.1 Basics of our approach – conventional geology and lithology

1) Primitive ("West-Pacific") - Type 1 : Ocean - ocean collision

2) Andean - Type 2 : Ocean - continent collision

3) Alpine (-Himalaya) Type 3 : Continent - continent collision

Figure I-6: The 'making of' and nature of orogenic belts by subduction and collision. To be distinguished (regarding the material) : 3 main collision types / mountain belt types.
Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

I) The process begins with ocean – ocean collision when oceanic lithosphere sinks and disappears under neighbouring oceanic lithosphere. Parts of the uppermost and lightest oceanic crust, sediments and volcanic rocks, are shoved together in an accretionary wedge. The remaining descending oceanic crust, when subducted to about 100 km depth, releases water, thus initiating a relatively high degree of partial melting in the overlying lithosphere. These magmas then differentiate into basalts slightly less mafic than those created in mid-ocean ridges and build up a volcanic island arc aside of the accretionary wedge. They consist mainly of stratovolcanoes, built by alternating mixtures of lava flows and pyroclastic rocks, as well as of sediments originating from immediate reworking of mainly the pyroclastic deposits. Long-lasting collision of this type creates a broadening and thickening bulge of island arc crust. Behind the arc a new ‘supra-subduction-zone / SSZ’ spreading zone may lead to a new and special oceanic ‘back arc basin’. Examples of such intra-oceanic island arc and back-arc basin systems are nowadays to be found in the westernmost parts of the Pacific ocean. Also early subduction and disappearance of back-arc basins can be observed there.

A next stage of evolution may begin with stepwise retrogression of the subduction zone. The magmatic arc is thus displaced in and on to the former accretionary wedge, where anatectic melting, assimilation and fractionation lead to silica-richer calc-alkaline magmas, namely andesites. Progressive reworking and differentiation of such type eventually result in the creation of primitive continental crust.

II) Evolution proceeds with a second type of collision, ocean – continent collision, that is the subduction of oceanic lithosphere beneath continental crust.

Examples are the north-eastern Indian ocean off Sumatra and western Java in South East Asia as well as the East Pacific ocean off the South American Andes.

The volcanism generated by subduction is of dominating andesitic nature whereas the plutonism within the crust, where anatexis / remelting of older crust plays an important role, ranges from dioritic to granodioritic composition.

III) Following plate theory – with exceptions admitted –, continental crust, once in existence, is too light to be subducted and stays thus virtually ‘immortal’ at the surface. Therefore, the third collision type takes place when continent – continent collision and orogeny occur. This is the case actually e.g. in the Himalayas and Tibet between Gondwana India and mainland Asia, or in the region East Turkey – Caucasus between Eurasia and Gondwana Arabia. The whole continental crust
with sediments, volcanics and the crystalline basement is compressed building a huge accretionary wedge, the orogen (sensu stricto) of cordillera or more precisely Alpine or Himalayan type. Such orogens tower up to several thousands of meters as mountain chains, and simultaneously – like icebergs in water – they sink down in the mantle about ten times their height, thus forming a bulge known as mountain root. It is assumed that within this bulge of continental crust radioactive and possibly also frictional heating cause re-melting of enormous volumes of rocks crystallising later in huge batholiths of granites, whereas more mafic high-pressure rocks may remain as relics in the lower crust.

Crust bulges are in an unstable state and re-equilibrate. High mountains not only disappear rapidly by surface erosion, but – at latest when the converging movement and compressive forces fade – the whole bulge of continental crust collapses gravitationally and stretches laterally under its own weight. At the same time, during convergence and then during gravitational collapse, what happens exactly with the lithosphere is not yet fully understood. Anyway the continental lithosphere is up to four times thicker than the oceanic lithosphere. The newly discovered existence in many orogens of some rare (e.g. Coesite bearing) metamorphic rocks of continental nature, metamorphosed at ultra-high pressures, shows that continental crust can be subducted down to more than 100 km into the mantle. Such rocks are possibly part of the subcrustal continental lithosphere.

The fundamental typification of collisions can be complicated by many variations and diverse combinations concerning the nature and movements of plates. Stages I – II – III normally follow each other to continuously form one complex orogen (see Figure I-7 as well as Figure I-6). Moreover, as already explained, continents grow by successive accretion of younger orogenic belts, often involving partial or total remobilisation of old continental crust during younger collisions.

A distinct role for the modification of plate movements is played by reorganisations of mantle plume and convection activity in the mantle. For example thermal isolation of mantle heat flow by old and stable continents, especially huge mega-continents, may initiate break-up and rifting processes resulting in new ocean spreading and later subduction-collision (WILSON) cycles. An example are actual processes in the Red Sea and geologically not long ago similar processes in the Indian and Atlantic oceans. Also major continent – continent collisions often seem to modify the global convection pattern.

The overall picture of plate tectonics is thus characterised by cyclic activity.
A distinct plate tectonic cycle begins with the break-up of a continent and formation of a new ocean by successive spreading. Steady state conditions prevail, when spreading is compensated by subduction of oceanic lithosphere with equal velocities. Faster subduction and/or ceasing spreading eventually result in continent-continent collision, ending such a cycle – called WILSON-cycle, after one of the pioneers of the ‘New Global Geodynamics’ (WILSON 1965).

Continents grow by repetition of WILSON cycles which build successively one mountain belt, i.e. one orogen, aside of the other.

I.1.2.3 The nature of continental crust

The main conclusions of our global spatial and petro-geologic considerations follow as:

There is a fundamental difference between oceanic crust / lithosphere – created by plate divergent processes – and continental crust / lithosphere – created by plate convergence, collisional processes. These processes build first island arcs and later continental mountain chains of cordillera type and are called, for one cycle of mountain building, ‘orogeny (sensu stricto)’. The attribute ‘sensu stricto’ is necessary as ‘orogeny sensu lato’ includes also divergent tectonic processes, faulting and rifting, which often result in ‘negative mountains’ within plateaus, exemplified by e.g. deep rift valleys.

The contrast between oceanic and continental crust and lithosphere is schematically illustrated in Figure I-7.

Continental crust – except for rather small constituents as ophiolite complexes and fragmented oceanic plateaus – is entirely of orogenic (sensu stricto, cordillera type) and thus complicated nature. It originates from plate collisions ranging from

I) ‘primitive’ ocean – ocean collisions resulting in (W-Pacific type) island arcs of intermediate composition to

II) ocean – continent (Andean type) and

III) continent – continent (Himalayan-Tibet type) collisions producing orogens of progressively sialic nature.
Orogenes (sensu stricto) of cordillera type have two principal features due to their plate collision and complex origin:

A) Tectonic-mechanical deformation and mixing by means of multiple faulting, thrusting and folding, shearing and flattening. Concerned are – in different extents and (km to mm) scales – diverse rocks from surface sediments and volcanics to lower crust metamorphics. Deformation during orogeny proceeds in time and space from older inner to younger outer parts of the orogens, usually not ceasing where it began. Therefore older parts of orogens normally undergo longer lasting and more complex deformations.

B) Inner, older and lower rocks of orogens generally experience metamorphism, in most cases concomitant with deformation, and adapted to and changing with the (fluid-) chemical and pressure (P) – temperature (T) conditions prevailing in those (internal)
parts of the crustal bulge attained by diverse rocks respectively during collision and subsequent re-equilibration.

Characteristically two metamorphic belts are associated as ‘paired belts’, the first being the deeper parts of the subduction zone – accretionary wedge compartments which suffered low temperature – high pressure (LT – HP / blueschist) metamorphism; the second being the magmatic arc crust with high temperature – low pressure (HT – LP) metamorphics and magmatites.

Orogens structurally can be subdivided, horizontally into different compartments, vertically into different storeys.

I Structural subdivision of orogens in map view

In cartographic view, as seen from the sky, the inner, central parts of orogens – the Internides – are the oldest, most deformed compartments and, being the most uplifted parts, usually consist of partially or totally metamorphosed rocks. The Internides contain all parts which – until the plate tectonic paradigm had been established – had been regarded as the former contents of an ‘eugeosyncline’: mainly accretionary wedge and magmatic island arc systems with their associated sediments from fore-arc basins and subduction trenches (‘flysch’), formed in early phases of development before continent – continent collision.

Furthermore ophiolite complexes are present – fragments of the otherwise subducted oceanic lithosphere, obducted and thus conserved. The may – if not transported far away as tectonic nappes – decorate ‘suture’ lines within the orogen where the oceans (small or large) disappeared. Ophiolite complexes are composed, when complete, of a characteristic succession beginning at the base with tectonised depleted ultramafic mantle peridotite, upwards followed by material from the base of the oceanic crust containing ultramafic cumulates, then layered gabbros, in their upper massive part with (sheeted) basalt dykes, covered by extruded pillow basalts and some scarce abyssal sediments, namely cherts.

Additionally Internides may contain ‘terranes’, that is more or less rejuvenated fragments of older (orogenic) continental crust, e.g. former micro-continents.

Situated on both outer sides of the Internides are the Externides, passive margin portions of the two continents formerly separated by the disappearing ocean and later connected to the Internides. They contain thick (‘miogeosynclinal’) shelf sediment piles which are then transformed to build up the external fold- and thrust-belts. Advanced frontal foreland (‘molasse’) basins may develop and successively be incorporated into the broadening orogen.
II  Orogens in vertical sections

In vertical sections orogen bulges – as explained by the principle of isostasy – reach down into the mantle about 8 to 10 times their elevation (above surface), to 50 – 80 km depth. Pressure and temperature conditions increase with depth as described by the continental geothermal and geobarometric gradients. Temperature on average climbs by 30°C per km and pressure rises dependant on rocks’ density, attaining on average 1 Gpa = 10 kb at the base of normally thick continental crust, reached in general at about 30 km depth.

Rising temperature and pressure change in a very distinct way the physical-chemical behaviour of minerals and rocks at certain characteristic limits.

For example, at about 300°C – corresponding to about 10 km crustal depth – quartz under directed stress begins to re-crystallise and thus all rigid quartz-bearing rocks slowly begin to flow. Concerning feldspar, another major constituent of many rocks (e.g. gneiss, amphibolite as the metamorphic equivalents of mafic magmatites), this process takes place at about 500°C. Towards 650 – 700°C e.g. gneiss of granodioritic composition begins to generate partial melts of granitic composition if sufficient amounts (some percent) of water and the necessary hydrostatic pressure (some kb) are provided.

Certain chemical reactions between different minerals at distinct boundary lines within the P-T field and often concomitant release of fluids (H₂O, CO₂ etc.) change mineral facies during metamorphism and thus determine the rheological (flow) behaviour of rocks.

These rheologic changes determine three different main storeys within orogens.

All three storeys are normally to be observed as they are exposed at the surface according to the specific erosion level. However, they correspond to only the upper and middle parts of continental crust.

The upper ("sedimentary") storeys consist mainly of non or locally very low grade ("anchi'zonal) metamorphic sediments, with occasionally added volcanic rocks, usually folded or thrust upon each other in duplexes or fold nappes, as for example in the external zones of the Alps in Switzerland or eastern France, or the eastern Calcareous Alps of Germany and Austria as well as the South-Tyrolean – Italian Calcareous Alps. Crystalline rocks show rigid behaviour in this storey.

The middle ("schist") storeys are characterised by nearly ubiquitous metamorphism reaching from very low to medium, on the average of low grade ("epi'zonal or greenschist facies) metamorphism, connected with development of penetrative schistosity to foliation in most rocks. Quartz-bearing crystalline rocks begin to behave in ductile manner, they flow. Examples are large parts of the actual Alps’ central zones, their Internides as parts of a young, not yet equilibrated orogen, and the external zones of the mid- and west-European Paleozoic Variscides –
Conventional geology and lithology, detailed explanations for the new lithology map

Caledonides, already rather deeply eroded and lifted from several – about 15 km orogenic depth to the actual surface.

The lower (‘migmatite-granite’) storeys are those of medium to high grade (meso- to katazonal) metamorphism and accompanying migmatisation (anatectic partial melting) and palingenetic granitisation of the, on the average sialic (granodioritic) material that is shoved together during continent – continent collision orogeny. Examples are the innermost (Moldanubian) zone of the mid-european Variscides and the high grade crystalline basement of practically all Precambrian shields or cratons on Earth.

Distinguishing the different storeys fosters a better understanding of the lithologic differences within orogens and thus within the continental crust, as seen in different erosion levels, according to the age of the orogens.

Figure I-8 visualises the three different rheological storeys of orogens.

The notion of rheologic storeys within orogens is in disagreement with the (geophysical) notion of ‘upper – middle – lower continental crust’ which normally ignores the thin sedimentary cover above crustal ‘basement’ rocks.

The sedimentary upper storeys of orogens, raised to mountain heights, generally disappear rather soon – from a geological point of view, (slowly) collapsing under their own weight and removed by erosion.

After the peneplanation of mountain chains, their low grade metamorphic middle – or schist – storeys of orogens constitute what is normally called the upper crust of continent-cratons.

The migmatic-granitic lower storeys of orogens make up the continental middle crust.

The lower crust is what formerly has been named the ‘simatic’ or ‘basaltic’ lower layer of continental crust, because of its, erroneously, presumed, overall mafic composition. Characteristic rocks are strongly flattened, water-deficient high pressure – high temperature (HP – HT) metamorphics like granulites, charnockites, eclogites and whiteschists of mixed, but mostly sedimentary origin. Normally they have lost granitic partial melts to the middle and upper crust and are thus not typically salic, but tend to intermediate – mafic (‘simatic’) compositions. Lower crust rocks appear at the surface only in few regions on Earth, e.g. in south-eastern India and Sri Lanka / Ceylon, as parts there of the other Precambrian / Pr and Acid Plutonics / Pa lithologies.
### I.1 Basics of our approach – conventional geology and lithology

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Figure I-8: Nature of orogens, in vertical sections; their rheologic storeys and erosion levels in relation to their age. Modified after various authors (e.g. DOTT & BATTEN 1976, MOORES & TWISS 1995).

Mountain belt (orogen) – aside – mountain belt – growth creates continents; continents are of throughout orogenic nature; generally: the older the deeper eroded – see: Europe: Precambrian, Caledonian ('mid-crust'), Variscan ('upper crust'), Alpidic, sediment cover. All continents grow through repeated ('WILSON') cycles of divergence – subduction and collision.

Summarising it has to be retained that truncated orogens with its metamorphosed deeper parts containing metamorphic and magmatic crystalline rocks constitute the ‘basement’ of all continents.
Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

III Sediments on continental plates

Following the analysis of the solid continental crust we will consider the evolution of continental and epi-continental (shelf) sediments.

The metamorphic and plutonic basement, i.e. the crust of cratonised continents, is normally affected along its margins by ongoing or newly starting (distensive or convergent) plate tectonic processes. Indirectly these processes are at the cause of the evolution of the sedimentary cover of continents. Young orogens growing at active margins deliver continental sediments, distributed upon the craton by rivers. When rivers reach the coast, epi-continental shallow marine and normally rather thin sediment successions are deposited on the shelves. The width of these shelves and thus the volume of epi-continental sediments varies to a big extent with the global sea level fluctuations. Only in basinal areas can be found piles – often many km thick – of clastic (mostly deltaic) or carbonate (especially reef) sediments.

Such sedimentary basins originate where the crust of cratons sinks. This may occur in the form of circular bowls, possibly because of an ‘underplated’ basic pluton, a former plume head cooling as heavy load at the base of the crust. An example is the Lower Paleozoic Michigan basin in North America, nowadays buried under mixed Upper Paleozoic sedimentary rocks, and Mesozoic silci-clastic rocks. However, the normal case within old huge cratons are mantle activities which, after a phase of considerable crustal uplift (e.g. the Upper Rhine area or in East Africa) result in linear divergent rifting processes, the formation of grabens and rift valleys with km-scale relief (‘taphrogenetic orogeny’). These processes can end with filling of the rift depressions as intra-cratonic ‘aulacogens’, quite frequent in the southern part of the Russian shield (southern parts of the Russian table land, the Ural foreland towards Black and Caspian Sea), in North America and in Africa. Today these structures are mostly buried under younger sediments, like Upper Paleozoic sediments and Mesozoic carbonate rocks for the Russian table land West of the Ural.

Otherwise rifting processes may proceed to precursor processes of ocean spreading. Then the rifted and stretched continental crust becomes a passive margin, sinking also under the rising load of clastic (deltaic) or carbonate sediments, with massive reef belts in subtropical and tropical seas along the continental edges. Today’s continental margins of that type are to be found e.g. off North America and NW-Africa as well as western Europe. These passive margin sediments are the already mentioned ‘miogeosynclinal’ sequences, often incorporated into colliding orogens at the end of ocean life, concluding a Wilson-cycle. Today these sequences can be found nearly in all orogens as the already described ‘Externides’ of e.g. the Alps or the European Variscides.

As a result, position and spatial configuration of sediment bodies – where and to which extent they can be deposited – are fundamentally controlled by structural-tectonic factors. Sea level fluctuations – the long term first order variations also being controlled by plate tectonics
due to ocean volume changes – play the next important role, as most sediments are formed either slightly above or under sea surface.

The nature of sediments however is principally determined by a combination of climate and relief: biogenic carbonates for example, especially reef carbonates, are only formed where it is warm enough and where no other sediments interfere; evaporites are built where higher temperatures coincide with aridity; considerable amounts of silici-clastic sediments can only be delivered with sufficient water supply from higher mountains, deposited mainly in deltas of sometimes huge dimensions (cf. the actual Mississippi, Ganges, etc.).

However, the ultimate cause is the activity of the mantle letting continents drift across the different climates of the different latitudes and causing orogens to grow. Consequently the lithologic nature of each continent reflects its individual geologic history.
I.2 Detailed explanations for the new lithology map

This section on lithology completes the explanations in chapter 3 and 4 and lists the necessary details for the establishing of the lithological map such as the exact design of certain polygons. Some ‘hydro’-lithological questions are treated as well, in particular more detailed information on the few subsurface (non Quaternary) evaporite occurrences depicted in our map.

The digitised UNH-geological base map (based on the map by DOTTIN et al. 1990) used to design the lithological map revealed to contain some serious differences from the Geological World Atlas UNESCO (CHOUBERT et al. 1980) in some parts of the world. Our base map is, especially in mountainous regions, not easily to be made consistent with the detailed UNESCO Atlas (the base map being rather general). Sometimes we had to decide to represent one distinct feature from the Geological Atlas and to omit others. In general we tried to identify the most important feature to be represented in our map. Minor polygon changes have been made in many parts of the world, major ones rarely, e.g. in New Zealand. Parts mainly of the geologically very complex orogenes as for example parts of central and SE Asia and the SE Asian islands region could still be corrected as some lithological features may not yet be implemented.

Yet, even considering the frequent critics on the coarse generalisation and possible errors on the base map (DOTTIN et al. 1990), it is already much more detailed and exacter than the other lithology maps available at the time we started our work. Furthermore, the amount of time and work required to digitise and assign lithologies to the maps from the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) are incomparably higher and require a team of specialists only destined to design the lithological map.

Throughout this Annexe, when a first attempt of assigning lithologies is mentioned, it concerns in most cases assignments made in the FAO lithological maps coming with the FAO-Unesco (1975) soil map.

When corrections ‘for geology’ are mentioned, it concerns changes made to the base map (DOTTIN et al. 1990), the term ‘for lithology’ signifies assignments to our new lithology classes. The polygons for both maps are the same, only the attributes differ (geology classes for the geology map, lithology classes for the lithology map).

The general and regional sources of information used to design the map have mostly been mentioned in the explanation of the different rock classes or in the continental descriptions of chapter 3 and 4; if special use of single sources has been made, it is mentioned here.

This Annexe describes characteristic changes we adopted for distinct polygons, but also general features not necessarily mentioned in the principal explanations in chapter 3 and 4. The
I.2 Detailed explanations for the new lithology map

I.2.1 Remarks on the different continents

I.2.1.1 Africa

The whole African continent, except its north-western and southern margins, is an old craton, which suffered its last (the PanAfrican) orogeny towards the end of the Precambrian period. Sedimentary cover rocks consist of epicontinental marine to terrestrial continental facies from the end of the Precambrian period on. Africa has been part of the Gondwana supercontinent during Paleozoic to Triassic times.

According to our information sources, the UNESCO hydrogeological map (DZHAMALOV et al. 1999) is probably only approximately correct for the African continent.

The Paleozoic or older volcanic formations designed on the Geological World Map on the Arabian peninsula (Arabian shield) correspond more or less to the Metamorphic formations west of the Red Sea, both formations consist mostly of Proterozoic rocks, they have been assigned accordingly as Pr. The rock type and geology is the same as in the South American cratons, but in the base map (Geological World Map, DOTTIN et al. 1990) these rocks had been assigned as Precambrian in South America whereas they could be found as Metamorphic formations or Paleozoic or older formations in Africa; thus for continuity reasons and as the geology/lithology is indeed Precambrian (according to our additional sources – see chapter 4) the changes mentioned have been applied to nearly the whole African continent (that is the Metamorphic formations as well as many Paleozoic formations – from the Geological World Map – have been changed into Precambrian rocks with Pr for lithology). Additionally few polygons in Zimbabwe, Mozambique and Zambia which had been assigned as Plutonic rocks have been changed to Precambrian rocks (Pr) as well.

Mesozoic volcanic rocks in Southern Africa and Madagascar are traces of the splitting of Gondwana, they have all been assigned as Vb for lithology (3 of these polygons had been assigned Ss following the FAO lithology maps in a first attempt).

In the bay of Zanzibar and in the region of Dar es Salaam and Mombasa in a first step in the north of this region the lithology has been assigned as carbonate rocks (Sc) and in the south as Su or Ad (semi-to unconsolidated sedimentary or alluvial deposits). In the bay the Jurassic and Cretaceous rocks are probably marine carbonate sediments deposited during the fragmentation of
Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

Gondwana and creation of Australia and India – i.e. the creation of the Indian Ocean; they have been assigned Sc for lithology accordingly; the Cenozoic and Quaternary sediments in the coastal parts of this region have been assigned Su and Ad respectively for lithology.

In a second step, some polygon alterations have been made in eastern Africa around Mombasa and Dar es Salaam. The Jurassic & Cretaceous rocks have been splitted to divide between the continental and the marine facies of these rocks. The rocks nearer to the coast have been assigned as marine facies which means carbonate rocks and Sc for lithology. Continuing towards the interior of the continent we find sandy rocks which have accordingly been assigned as Ss for lithology. Here we followed the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980).

The Cenozoic and Quaternary rocks on Madagascar have been assigned as Su and Ad respectively as they are unconsolidated sedimentary rocks in the most parts.

On Madagascar all the Jurassic & Cretaceous rocks have been assigned as carbonate rocks following our detailed maps. Also the eastern parts have been assigned Sc for lithology although the UNESCO (DZHAMALOV et al. 1999) and FAO lithological maps do not suggest such a lithology. The Triassic rocks are clastic sedimentary rocks so they have been assigned accordingly as Ss. The core of the old mountains on the island had been assigned as Lower Paleozoic rocks in our base map; following our detailed maps we think the most parts are more likely to consist of Precambrian rocks, this has been reflected by changing geology and lithology to Pr accordingly.

In the sedimentary basin of the Congo the Jurassic and Cretaceous rocks are clastic rocks, the sedimentary rocks in the basin are almost certainly of non-marine origin, so they have been assigned as Ss, the Quaternary rocks in the basin are unconsolidated alluvial deposits, they have been assigned accordingly to Ad. The northern border of the Congo basin (SE of Bangui) consists of continental Cretaceous rocks, so the rocks of this age in this region have been assigned as Ss.

Changes in Gabon / western parts of Congo: most of the Lower Paleozoic rocks designed in the base map have been changed to Precambrian rocks and Pr for geology and lithology for continuity reasons as these polygons had been assigned erroneously in the base map.

In western Africa the Plateau de Mandingue (NW of Bamako) consists of old shield rocks and different sediments. The Plutonic rocks here are part of the West African core craton.

In Morocco the old core of the Atlas mountains contains Precambrian rocks (this has not been reflected in the base map prior to our changes made).

The Lower Paleozoic rocks in this region have been assigned Cl for lithology as they are folded to a strong degree. They are part of the Variscan mountains (Mauretanides – the counterpart of the Appalachian mountains in North America) which have an extent further to the
south until Mauritania. So all Lower Paleozoic rocks, but also the Metamorphic rocks in the base map (part of the Variscan mountain system) until Mauritania have been assigned Cl for lithology. For continuity reasons the corresponding Lower Paleozoic rocks in Spain in the region of Malaga have been assigned Cl for lithology even if they are more likely to contain more sedimentary rocks.

Following the detailed maps available the Upper Paleozoic rocks are clastic rocks in the most parts, so they have been assigned Ss for lithology.

In the northern parts of Africa we often find marine carbonates in the Tertiary / Cenozoic rocks, they have been assigned accordingly as Sc.

LAHLOU (1988) describes different regions in Morocco with lithologies differentiated following their erodibility (high erodibility: marl, schist, micaschist, alluvium, shale and Flysch; medium erodibility: limestone, marl-limestone and shale-limestone; low erodibility: quartzite, granite), but these regions are not mapped and could thus not be determined with certainty.

Paleozoic dolerites (coarse grained basalt) in the south of western Africa had been digitised as Plutonic rocks in the base map, these are volcanic sills, so they have been assigned as Paleozoic or older volcanic rocks for geology and Vb for lithology (they are basaltic extrusive rocks).

The Cenozoic rocks as well as the Quaternary rocks in western Africa are mostly non or semi consolidated sedimentary rocks and alluvial deposits so they have been given Su or Ad for lithology respectively.

In the Hoggar mountains (Ahaggar in French) and the joining mountains in the southwest (Siforas) in the base map some rocks had been digitised as Lower Paleozoic rocks, but following the detailed maps available they have been changed to Precambrian rocks and have been assigned Pr for lithology. In the Hoggar some polygons have been added and equally been assigned as Precambrian rocks and Pr respectively. 2 polygons of the Jurassic + Cretaceous rocks and polygons surrounding the core of the Hoggar have been assigned Lower Paleozoic rocks for geology and Ss for lithology. The rocks surrounding the Hoggar contain rocks from the youngest Proterozoic era expanding into the Lower Paleozoic era. These rocks are sedimentary rocks. These rocks can also been found in the core of these mountains but are too small in their extent to be designed explicitly in our map.

A bit to the west 1 polygon has been changed following our detailed sources to Jurassic / Cretaceous rocks and Ss for lithology.

Southwest and south of the Hoggar some of the Jurassic / Cretaceous rocks consist of marine Cretaceous rocks, some polygons have been changed following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) and have been assigned Sc accordingly.
1 small polygon west of this region consists of Mesozoic volcanic rocks, this has been reflected in the geology as well as for the lithology (Vb).

Southeast of the Hoggar mountains the Jurassic & Cretaceous rocks consist only partly of marine facies rocks, these have been assigned as Sc for lithology, the other rocks have been assigned as Ss.

In Togo, following our detailed sources polygons have been added to reflect the differences between the Precambrian and the Lower Paleozoic rocks in this region. The Precambrian rocks have been assigned as Pr and the latter ones as Ss respectively. In Nigeria some of the Jurassic / Cretaceous rocks in the Niger basin consist of carbonate rocks, they have been assigned as Sc accordingly.

1 polygon in the form of a small stripe in Zimbabwe has been changed from Precambrian to Plutonic rocks and Pb for lithology. It is the famous Great Dyke with Basic – ultra-basic Plutonic rocks.

NE of the Great Dyke a half ring of Jurassic & Cretaceous rocks has been assigned as Ss, the Mesozoic volcanic rocks in the centre of this half ring have been assigned as Vb.

The Bushveld complex in South Africa near Pretoria has been designed following its nature as a basic intrusion (Pb). The intrusion is a funnel shaped Lopolite forming a bowl. In the base map (DOTTIN et al. 1990), digitised at UNH, only the inner Plutonic acid rocks (Pa for lithology) were taken into account. We added an additional ring of Plutonic ultra-basic to basic rocks (Pb) for lithology. All these rocks are of Precambrian age but have been left, due to their nature, as Plutonic rocks for geology. The complex is famous for its noble metal mines. Here the main gold, platinum and also chromium mines of South Africa can be found.

In the Transvaal region surrounding polygons have been altered to better reflect the actual situation (too coarse in the original map). The external ring of younger Precambrian (assigned as Precambrian rocks for geology) dolomites has been added. As for lithology this ring has been assigned as Sc because of the relatively high carbonate content of the rocks although these rocks could also have been assigned as Sm for the dolomitic rocks as they may partly already be clastic. The first ring of surrounding rocks is the so called Pretoria and Dolomite group. To the outside are following mixed but not carbonated rocks containing Quartzite, assigned as Ss for lithology. To the NW the rocks of Upper Paleozoic age have thus also been assigned Ss for lithology to reflect the silici-clastic sedimentary character of the rocks. Directly north of the Bushveld also the Precambrian rocks are of sedimentary nature and have been assigned accordingly (Ss) for lithology. We have treated the sedimentary surroundings of the Bushveld complex following the Geological Atlas of the World (UNESCO, CHOUBERT et al. 1980), partly also following KRENKEL (1957).
I.2 Detailed explanations for the new lithology map

The volcanic rocks SW of the Bushveld are the so called Ventersdorp volcanites from the younger Algonkian (Proterozoic).

N of the Bushveld complex 1 polygon of Plutonic rocks (for geology) has been changed to Precambrian rocks and Pr for lithology (following the more detailed map in the UNESCO World Atlas of Geology, CHOUBERT et al. 1980), 1 polygon of Mesozoic Jurassic & Cretaceous rocks has been changed to Mesozoic volcanic rocks and Vb for lithology.

In Owamboland (northern Namibia, NE Windhoek) 2 polygons which initially had been assigned as Jurassic & Cretaceous rocks have been changed to Mesozoic volcanic rocks and Vb for lithology, 1 polygon of Jurassic & Cretaceous rocks north of Windhoek consists of clastic rocks and has therefore been assigned as Ss for lithology.

1 polygon south of Lake Victoria had been assigned as Plutonic rocks initially, following our detailed sources it has been assigned as Paleozoic or older volcanic rocks and Vb for lithology.

In the southernmost part of South Africa the Lower Paleozoic rocks are heavily folded and have been assigned as Cl for lithology.

Following KRENKEL (1957) two polygons of Jurassic & Cretaceous rocks which had in a first attempt been assigned as Ss have been changed to the mixed sedimentary class for lithology (Sm), these are indeed mixed sedimentary rocks but also contain many clastica.

In Namibia and towards the South African border 3 polygons of Upper Paleozoic rocks have been assigned as Ss.

2 polygons of Precambrian rocks in Namibia actually contain carbonates, so they have been assigned as Sc for lithology.

I.2.1.2 Asia

I.2.1.2.1 South West and Central Asia (especially mountain belts)

From North to South the mountain belts are younger and younger (from overview article in geology of Asia in MOORES & FAIRBRIDGE 1997). The base systems are the Fennosarmatian, Siberian and Chinese cratons. Joining on the Angara (Siberian) craton are first late Cambrian and mainly Lower Paleozoic mountain systems (corresponding to the Caledonian orogeny – but this expression should not be used in the region treated here). The mountain systems are pushed together and many of the rocks metamorphised. During the orogeny also granites appear. During the Middle and Upper Paleozoic era mountain belts in the S and W are added (corresponding to the Variscan orogeny in Europe). The formerly existing ocean is subducted and the associated
flysch is integrated into the accretionary wedge. Here ophiolites and volcanics appear. Only late when the mountain belts are already pushed together Plutonic rocks appear.

The Late Paleozoic and Mesozoic rocks, mainly Triassic – Jurassic rocks (corresponding to the Cimmerian orogeny) build up today’s Tibetan plateau and the Kunlun mountains.

The Tarim block is filled with Quaternary material originating from Mesozoic mountains (but the current base material is somewhat unclear).

Concerning the mountain belts just described, it results for current lithology that nearly all Paleozoic rocks (Lower and Upper) are of very complex nature, they have thus been assigned as Cl. The Mesozoic rocks in the northern belts are mostly made up of clastic material.

In a similar way the Paleozoic rocks N of the Yangtze craton consist of complex material (Cl for lithology).

Likewise, in the Middle Asiatic mountain chains around SW China and Thailand, some of the Paleozoic rocks (Lower and Upper) contain granites and have in general a complex structure, they have been assigned for lithology accordingly (Cl).

The Permo-Carboniferous (Upper Paleozoic) rocks in N Tibet consist of carbonate rocks and have been assigned accordingly (Sc) for lithology.

The Jurassic & Cretaceous rocks in Tibet consist of mixed sedimentary material (Sm for lithology) whereas in the mountain belts further to the north these rocks are pure silici-clastic rocks (Ss for lithology).

In Tibet most of the Cenozoic rocks identified in the map consist mostly of glacial moraine material and are thus from the Quaternary. They have been assigned as such for geology as well as Ad for lithology.

In Kashmir (northern border between India / Pakistan) 4 polygons of Jurassic & Cretaceous rocks had been assigned as carbonate rocks (Sc) in a first attempt, they are of more mixed nature and have been assigned accordingly for lithology (Sm).

1 spot N of Islamabad / Rawalpindi in Pakistan had been assigned as Quaternary rocks, but following the UNESCO Geological Atlas (CHOUBERT et al. 1980) these are in fact Precambrian metamorphites, they have thus been assigned as Metamorphic formations (Mt for lithology).

In a first attempt – following the FAO lithological maps – too many carbonates had been designed in central Persia / Iran W of the border to Afghanistan. This has been corrected where necessary to Sm or even Ss for lithology.

In the region of the Lut block (W Zahedan in Iran) and east of it 3 polygons of Cenozoic rocks (Lower Cenozoic) are of similar lithology as other rocks more to the south. It is principally
a flysch belt consisting of clastic rocks (Ss for lithology). In this region we find remains of Gondwana surrounded by suture structures. As a consequence of the subduction here we also find synorogenic volcanics.

W of the frontier Afghanistan / Pakistan / Iran we have added new polygons: 3 new polygons of basic Plutonic rocks (ophiolites) have been added (Pb for lithology). 2 polygons of existing Plutonic acid rocks have been modified / separated to create 1 polygon of basic Plutonic rocks (Pb), 2 new polygons of Quaternary volcanic rocks (Vb for lithology) have been created and 1 polygon of Recent volcanic rocks has been changed to Quaternary volcanic rocks (lithology unchanged as Vb). Another new polygon has been added and 2 others altered to reflect granite occurrences (Pa for lithology). 2 polygons of mixed complex sedimentary rocks (with radiolarites, Flysch, etc.) containing metamorphic and non-metamorphic rocks have been changed following the UNESCO Geological Atlas (CHOUBERT et al. 1980) and assigned a complex lithology (Cl). These rocks are mainly from the Jurassic & Cretaceous era (Cretaceous flysch). 1 polygon of the Jurassic & Cretaceous rocks here had been assigned as carbonate rocks in a first attempt, it consists in fact of the described complex rocks and has thus also been assigned as Cl for lithology.

W of this region 2 polygons have been inserted in some Cenozoic volcanic formation to reflect the granite occurrences here (Pa for lithology). The western part of the Cenozoic rocks have been separated as they consist of basic volcanic rocks, the northern part of acid rocks, and the southern part again of basic volcanic rocks, all of Cenozoic age (Vb, Va and again Vb respectively).

In the Upper Paleozoic rocks south of this region 1 new polygon has been added reflecting the occurrence of Precambrian rocks (Pr for lithology) here.

In the border region Afghanistan / Pakistan 3 polygons of basic Plutonic rocks (ophiolites – Pb for lithology) have been added, 1 polygon in a polygon of Jurassic & Cretaceous rocks, 1 polygon in Cenozoic and 1 polygon in Triassic rocks.

N of the Aral Sea between the Ural and the Paleozoic folded belt to the E (middle Kazakhstan) – in the region of the water divide between the Aral Sea and the Ob basin there is 1 polygon of Mesozoic rocks designed in the geological base map (in the middle of a Cenozoic basin). This polygon can not be found in several other more detailed geological maps, instead of that there are several small lakes here – we have eliminated these ‘mysterious’ Mesozoic rocks.

3 polygons SW of the Aral Sea of Cenozoic age had been assigned as carbonate rocks in a first attempt, but similar to the rocks S – SE of the Aral Sea these are more clastic rocks (Ss instead of Sc for lithology), in later attempts also dunes and loess have been added in this region. Further to the west the Cenozoic rocks consist in fact of carbonates. The rocks shown here are in fact young Mesozoic rocks from the end of the Cretaceous era and the beginning of the
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Cenozoic. The Cretaceous parts of these rocks are not carbonated so the ensemble (geology = Mesozoic) has been assigned as mixed sedimentary for lithology (Sm), whereas the rocks assigned as of Cenozoic age have been left as carbonated rocks (Sc for lithology).

In middle Kazakhstan (NE Aral Sea) the Upper Paleozoic rocks consist of material similar to the Alpine molasses (Su), but they are of more consolidated nature and have thus been assigned as mixed sedimentary rocks (Sm for lithology).

We have corrected polygons SE the Aral Sea following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980).

The Triassic rocks at the border of Turkey / Iraq are carbonate rocks and have been assigned accordingly (Sc).

In central Turkey the metamorphic formations are very complex as they are to be found in the centre of an orogen. These rocks have thus been assigned as complex lithology (Cl).

Several polygons around and NE Adana in Turkey of Plutonic rocks are ophiolites and have thus been assigned as basic rocks (Pb).

Many of the Neogene basins in Turkey (e.g. around Erzurum) had been assigned as carbonates in the FAO lithological maps; these are in fact semi- or unconsolidated rocks (Su for lithology).

2 polygons of Jurassic & Cretaceous rocks in the western parts of the Taurus mountains contain some few ophiolites but also different other sedimentary rock types, they have thus been assigned as most likely to be mixed sedimentary rocks (Sm).

Several polygons of Upper Paleozoic rocks N Adana had been assigned as Ss for lithology in a first attempt, they contain in fact complex material and have thus been assigned for lithology accordingly (Cl).

1 polygon of Metamorphic rocks in E Turkey had been assigned as Cl in a first attempt (following the FAO lithological maps) and has been corrected to Mt for lithology.

In E Turkey, some polygons have been altered and changed to better reflect the situation as depicted by CHOUBERT et al. 1980:

1 polygon S of Van lake has been added containing Metamorphic rocks (Mt for lithology). SSW of this region 1 polygon of Recent volcanic rocks has been added surrounded by Mesozoic mixed sedimentary rocks (Sm). Continuing to the W 1 polygon of Metamorphic rocks (Mt) has been added. Still continuing to the W 1 polygon of complex Upper Paleozoic rocks has been added (Cl). 1 polygon of Cenozoic volcanic rocks as well as 1 polygon of Plutonic rocks (assigned as Pa in a first attempt) consist in fact of ophiolites (Pb for lithology). 1 polygon in-between has been added containing complex Jurassic & Cretaceous rocks (Cl). E of Van lake parts of the
Mesozoic volcanic rocks have been separated and assigned as Jurassic & Cretaceous rocks (Sc for lithology).

In the northern Caucasus mountains the central Plutonic rocks of DOTTIN’s map (DOTTIN et al. 1990) (assigned as Pa in a first attempt) are of very complex nature just like the neighbouring ‘Triassic’ rocks. The ‘Plutonic rocks’ contain mixed Paleozoic rocks, ophiolites from the Paleozoic era, many metamorphic rocks and rocks originating in the formation of an island arc. They have been assigned as Cl for lithology. The surrounding Jurassic & Cretaceous rocks had been assigned as pure carbonate rocks in a first attempt, they are in fact of more mixed nature (Sm for lithology). The same applies for the corresponding Mesozoic rocks on the Crimea.

S of the Caspian Sea polygons have been corrected. SW of Teheran 1 polygon had been assigned as metamorphic rocks, these are in fact acid Plutonic rocks (Pa). 1 polygon of Metamorphic rocks and 1 polygon of Upper Paleozoic rocks have been changed to reflect the situation found in the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) to Jurassic & Cretaceous rocks with complex lithology (Cl). Surrounding these rocks are mostly Cretaceous rocks with many carbonates (Sc for lithology).

Around the Caspian Sea we added some polygons to delimit alluvial deposits (Ad).

E of the Caspian Sea (S Karabogaz) in the continuation of the northern Caucasus chains the Jurassic & Cretaceous rocks are not pure carbonate rocks but mixed sedimentary rocks (Sm for lithology).

The Zagros suture line has been added to separate the outer (more to the south) from the inner Zagros chains. This was first a passive border of Gondwana (the Arabian peninsula was part of Gondwana), colliding later with Eurasia (formerly separated by one of the Tethys oceans). Resulting are for the inner chain very complex Cretaceous and Triassic rocks (more complex in the Triassic) which have been taken into account for lithology (Cl). 1 polygon at the eastern border of this structure has been added to reflect the occurrence of ophiolites (Plutonic rocks Pb).

In N Iran the Kopet Dagh mountains towards the border with Turkmenistan are in the end nothing else than the further continuation of the Caucasus. So also here the Jurassic & Cretaceous rocks are more mixed sedimentary than pure carbonate rocks (see above). Only in the Upper Jurassic era carbonates were deposited here, the other rocks from the Jurassic & Cretaceous era contain conglomerates and silici-clastic sediments. So a classification as mixed sedimentary for lithology (Sm) seems justified. Furthermore, 1 polygon of Plutonic rocks consists of basic rocks and has been assigned accordingly for lithology (Pb). 2 polygons of Cenozoic rocks had been assigned as carbonate rocks in a first attempt, but they consist mostly of clastic rocks (flysch) and have thus been changed to Ss for lithology.
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In E Afghanistan in the Helmand block the Jurassic & Cretaceous rocks had been assigned as carbonate rocks in a first attempt, they contain in fact very complex material and have been assigned accordingly for lithology (Cl).

In a similar way the Lower Paleozoic rocks in the border region between Uzbekistan and Tajikistan as well as in S Kazakhstan are not pure sedimentary rocks (assigned as Sm in a first attempt) but complex (Cl). These rocks are all relatively highly folded (probably from the Variscan orogeny).

I.2.1.2.2  China

We have tried to delimit carbonate rocks in China following the map of soluble rocks of China (DATONG et al. 1985). For example, in a first attempt we had designed Lower Paleozoic rocks in Mid-East China as well as SW of Beijing to be of Complex lithology (Cl), following the China map of soluble rocks we can find many Carbonates in rocks of this age here. They have been assigned accordingly (Sc). In a similar way more polygons of Lower Paleozoic rocks have been assigned as Carbonate lithology (Sc) in the Yellow River (Huang He) basin towards the eastern end of the loess occurrences (following the China map of soluble rocks, DATONG et al. 1985). The Lower Paleozoic rocks further to the SE are not pure Carbonates; they are folded and very complex (Cl). Furthermore some Quaternary rocks mapped after the Geological World Map are in fact Jurassic & Cretaceous rocks which consist of Consolidated Silici-Clastic rocks (Ss). They have been corrected accordingly following the Geological Atlas of the World (CHOUBERT et al. 1980) and the China map of soluble rocks (DATONG et al. 1985).

In S China the Triassic rocks seem to contain many carbonates in some parts following the China map of soluble rocks. Some of the Upper Paleozoic rocks had been designed as pure Silici-Clastic sedimentary rocks in a prior attempt, many may contain carbonates and have thus been changed to a Mixed Sedimentary lithology (Sm) to reflect this situation. 5 polygons in E China have been assigned in a similar way. In Mid-E-China 15 polygons had been assigned as complex lithologies as well and have been changed to carbonates. 4 polygons of Lower Paleozoic rocks in the HuangHe basin towards the eastern end of the loess occurrences had been assigned as complex lithologies in a first attempt, following the China map of soluble rocks (DATONG et al. 1985) they seem to be pure carbonate rocks and have been assigned accordingly for lithology (Sc). The rocks further to the east are complex in lithology.

W of the Sino – Korean craton (W of Beijing) the Cretaceous rocks had been assigned as mixed sedimentary rocks in a first attempt, but these rocks are of pure continental origin (Ss for lithology).
In E Asia / China many of the Quaternary occurrences are alluvial deposits and have been assigned accordingly for lithology (Ad). Using other sources (UNESCO Geological Atlas of the World and China map of soluble rocks, CHOUBERT et al. 1980 and DATONG et al. 1985) polygon of Quaternary rocks (assigned in a first attempt) has been corrected to Jurassic & Cretaceous rocks with consolidated silici-clastic lithology (Ss).

Loess has been designed in China following the map by ROUSSEAU & WU (1997), also loess covering old bedrock has been delimited (see chapters 3 and 4). In a first attempt we had only designed loess on the Quaternary surfaces already distinguished in our geological base map. New polygons delimiting loess have been added S of the big Huang He bend covering Precambrian rocks as well as further to the E.

The occurrences of loess have been checked with HILGEMANN & KETTERMANN (1975): The general presence of loess in the HuangHe regions has been identified here, too. Our other sources seem to be more detailed for the lower HuangHe regions, and the presence of re-deposited loess in the alluvial deposits of the Chinese deep plains seems natural (but qualified as alluvial deposits for lithology in our map). The presence of a small stripe of loess just N of the Nanshan mountains is also identified by HILGEMANN & KETTERMANN (1975) whereas the further extent of this stripe towards the South of the Tarim basin assumed by other sources has not been identified by these authors. As the map by HILGEMANN & KETTERMANN (1975) is a very general map of China’s landscape forms we believe our other sources to be more trustworthy.

I.2.2.3 Siberia

In Siberia the Mesozoic rocks are not unconsolidated rocks, as designed in a first attempt (following the FAO lithological maps), they may be covered by unconsolidated rocks, and detailed sources suggest less carbonates compared to the FAO lithological maps.

The Jurassic & Cretaceous rocks show continental sedimentary characteristics and are consolidated (assigned as Ss instead of Su as in a first attempt). Some of these rocks are covered with unconsolidated rocks and these have thus been distinguished by adding new polygons. Following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980), most of the Jurassic & Cretaceous rocks surrounding the Volcanic rocks on the Putorana plateau are clastic sedimentary rocks (Ss) but many of them are covered by loose Quaternary rocks. We have added very roughly (not disposing of very detailed maps) new lines to distinguish new polygons in order to differentiate the Quaternary cover from the underlying sediments and ground rocks. The SW border of the Siberian bowl (Siberian craton) consists of Paleozoic or older volcanic rocks and has been assigned as Vb for lithology; in a first attempt we had assigned all old volcanic rocks as
Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

Sedimentary rocks due to their age. Here the rocks are Trap basalts (continental tholeitic basalts): this type of basalt rocks outflowing on continental areas may partly be slightly acid but is basic in the most parts. The Upper Paleozoic and Triassic rocks here are pure silici-clastic rocks containing no carbonates and have thus been assigned accordingly for lithology (Ss). On the other hand the Cambrian and Ordovician rocks (Lower Paleozoic) here are mostly carbonated (Sc for lithology). 1 polygon of Cenozoic rocks in the Kolyma region had been assigned as Sm for lithology in a first attempt but is in fact semi- to un-consolidated rocks (Su). In the Indigirka region the Lower Paleozoic rocks (inner part of the Verchojansk-Kolyma region) are mostly silici-clastic sedimentary rocks but can contain carbonates so they have been assigned as Sm for lithology. North of the Siberian craton in the region of Taimyr the Precambrian and Paleozoic rocks seem to contain some carbonates so assigning them as Sm for lithology seems appropriate (the UNESCO hydrogeological map (DZHAMALOV et al. 1999) shows few carbonates here). The Upper Paleozoic rocks in the southern fault zone here are pure silici-clastic rocks and have thus been assigned as Ss for lithology. In a same way the Triassic rocks here (2 polygons) and more to the east (3 polygons) are of silici-clastic origin (Ss for lithology).

Many of the Mesozoic volcanic rocks towards the Pacific region in the east of Russia and down to Korea are of acidic nature (Va for lithology). Most of these rocks identified in our map could be found in a similar extent in the Geological Atlas of the World (CHOUBERT et al. 1980) except for 2 small polygons we could not identify in the Atlas (but have been assigned in a similar way to Va for lithology for continuity reasons).

In the north-easternmost regions of Siberia (towards the Bering Strait) we can find some Cenozoic basalts (Vb for lithology), these rocks have been separated with new polygons from the Cretaceous rhyolites.

When comparing polygons in the Geological Atlas by Choubert et al. (1980) with the polygons in our base map (Geological World Map by Dottin et al. 1990) it becomes rather apparent that in this region our base map is designed in a very general way and many details seem to be omitted.

9 polygons of Upper Paleozoic rocks N of Precambrian rocks are mixed sedimentary rocks (Sm for lithology), 1 large stripe of Triassic rocks S of the Precambrian rocks has been corrected following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) to Plutonic rocks (Pa). Another polygon of Triassic rocks further to the south is in fact from the Jurassic & Cretaceous era and has silici-clastic lithology (Ss). 4 polygons of Lower Paleozoic rocks in the region towards the Bering Strait may contain some carbonates and have thus been assigned as Sm for lithology. 1 polygon of Cenozoic rocks (still on the Russian side of the Bering strait) has been corrected to Jurassic & Cretaceous rocks with silici-clastic lithology (Ss) following our detailed sources (the lithology could be confirmed by the FAO lithological maps here).

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The Lower Paleozoic rocks on the Siberian shield have been identified as carbonate rocks (GORDEEV & SIDOROV 1993).

Outside of the shield, in southern Siberia, Lower and Upper Paleozoic rocks are of very complex material (Cl for lithology).

The Siberian Lena river system has been counterchecked for lithology with GORDEEV & SIDOROV (1993): The Lena river is the eighth largest river in the world for water discharge and the second largest after the Yenisei for water discharge to the Russian Arctic. During the greater part of the year Bicarbonates and Calcium ions predominate in the lower reaches of the river. During winter Lena waters are transformed to a Chloride class with Sodium and Potassium becoming predominant over Calcium due to the increasing role of groundwater input. The chemical composition of the groundwaters is mainly controlled by widespread limestone and dolomite occurrences in the upper and middle reaches of the river. These findings match our other sources and can thus be regarded as corroborated.

More new polygons have been added in Siberia and others corrected following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980). Quaternary alluvial deposits near the coast have been separated (Ad for lithology). 1 polygon of Jurassic & Cretaceous rocks has been corrected to Cenozoic basic volcanic rocks (Vb for lithology).

In the Ob region we have added some and changed some other polygons to Quaternary Ad, we have considerably reduced the parts of Cenozoic semi- to unconsolidated rocks (Su), designed in a first attempt, here.

I.2.1.2.4 India

Surrounding the Trap basalts in W India (Vb) are many Precambrian rocks. Some had been assigned as Volcanic rocks in the base map (Geological World Map, DOTTIN et al. 1990), but they have been changed following the Geological Atlas of the World (CHOUBERT et al. 1980). Some of the Precambrian rocks are in fact Carbonate rocks, similar to some of the Precambrian rocks in Africa, they have been assigned as Sc for lithology accordingly.

In the first Himalayan chains (Northern India, Nepal, Bhutan) many rocks which had been assigned as Paleozoic rocks in the base map (Geological World Map) are in fact Precambrian rocks, they have been changed accordingly for geology (Precambrian rocks) and lithology (Pr).

Our findings following our primary sources have been counterchecked for Southern India (Godavari, Krishna and Cauvery river basins) geology / lithology with map and text from VAITHIYANATHAN et al. (1988). The general pattern is similar to ours with mostly hard granite rocks from the Precambrian to the south and the Deccan traps to the west. The location of the
Sedimentary rocks seems more uncertain. As VAITHYANATHAN et al. (1988) don’t make a differentiation of the sedimentary rocks we cannot verify the presumed presence of Carbonate rocks with this article. VAITHYANATHAN et al. (1988) suggest great influence of the local lithological compositions in the basins to the sediment yields.

Our findings have been counterchecked for northern India (Ganges-Brahmaputra river system) with SARIN et al. (1989). The importance of the Ganges-Brahmaputra river system is underlined by the fact that it is, on a global scale, the first in terms of sediment transport (nearly 3 % of the global river flux; the chemical denudation rates are 2 to 3 times higher than the global average) and fourth in terms of water discharge to the oceans (HOLEMAN 1968, MILLIMAN & MEADE 1983, SARIN et al. 1989). Following SARIN et al. (1989), the river chemistry of the highland rivers in this region is dominated by carbonate weathering. As for the lowland rivers, silicate weathering and/or contributions from alkaline/saline soils and groundwaters could be important sources of major ions. The highland rivers are also characterized by weathering of acidic rocks whereas the other rivers flow initially through basic effusives. Some of the geologic features described by SARIN et al. (1989) could be identified in our map, for others the lithologic descriptions were not clear enough. The outer Himalayas consist of Cenozoic sediments constituted by sandstones, clays and conglomerates (Ss in our lithology classification). These rocks could be identified and are thus corroborated. The rocks described by SARIN et al. (1989) in the central lower Himalayas could only be identified partially. Especially the Precambrian rocks also found in our other sources could be identified. North of the principal Himalayan chains our Mixed sedimentary rocks from the Jurassic & Cretaceous period have also been identified as unclassified Mesozoic formations (mainly sandstone, shale and limestone) by SARIN et al. (1989). The alluvial plains may contain as much as 30 % of calcareous matter. To the south the rocks of the Archean shield with crystalline igneous and metamorphic rocks as well as the Deccan traps have been clearly identified. We were also able to identify the limestones of the Vindhyan system (also from the Precambrian).

Our main problem remains the unsufficient description of carbonate rocks in the Himalayas.

I.2.1.2.5 Ural mountains and surrounding regions

The Ural mountains region has been treated mostly following information in BRINKMANN (1977, 1980) and in CHAIN & KORONOVSKIJ (1995).

E of the Ural, many of the Lower and Upper Paleozoic rocks are more likely to be mixed rocks with clastic sediments and also carbonates, so we have assigned Sm for lithology for some
of the Upper Paleozoic rocks. Furthermore, most of the remaining rocks of this age are heavily strained and may be metamorphised, so they have been assigned Cl for lithology.

3 polygons of Precambrian rocks in the southern Ural had initially been assigned as metamorphic lithology (Mt), following our added sources they seem in fact closer in lithology to the Pr class.

I.2.1.2.6 Insulinde, Japan etc. – particular remarks

Some particularities have been noticed while working on this region: The Plutonic rocks here are often ophiolithes (Pb). The base map (UNESCO Geological Map of the World, DOTTIN et al. 1990) seems to contain quite a few errors in this region which might be due to the necessary generalisation required for a global map. We have tried to add or correct the map according to the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) in a degree to reflect at least the special characteristics of this region.

On Halmahera 1 polygon of Quaternary rocks and 2 polygons of Plutonic rocks from the original map are in fact tertiary basic volcanic rocks and have been assigned accordingly for geology and lithology (Vb).

New polygons have been added to represent the Cenozoic volcanic rocks on the island. Furthermore 2 polygons of Cenozoic Semi- to un-consolidated rocks (Su) have been added, 2 polygons of Quaternary alluvium (Ad) and 1 polygon of Cretaceous rocks with mixed sedimentary lithology (Sm).

On the island of Hlor between Flores and Wetar the Cenozoic rocks are of volcanic nature, this has been corrected in our map (Vb for lithology).

1 polygon of Plutonic rocks in the north of middle Java could not be identified in the Geological Atlas of the World (CHOUBERT et al. 1980), following this source these are recent volcanic rocks of basaltic nature (Vb for lithology).

In NW Sumatra (S of the city of Medan) around lake Toba (the lake itself being too small to be reflected in our map but name-giving for the rocks) we can find the famous Toba rhyolites (assigned as Va for lithology). Here many km$^3$ of liquid magma most probably exist underneath the surface (DÜRR 2001 pers. comm.).

Most of the Mesozoic rocks on Borneo and on other islands in the region present very complex lithologies and have thus been assigned accordingly as Cl for lithology. Some had been assigned as carbonate rocks in a first attempt and could still be identified as such. They have therefore been left as Sc for lithology where appropriate.
On Borneo 1 polygon of Precambrian rocks has been changed to Plutonic rocks with Pa for lithology. 1 polygon of Plutonic rocks has been assigned a complex lithology (Cl).

1 small island SW of Seram had been assigned in a generalizing way as Quaternary rocks, but the prevailing rocks on the island (following the UNESCO Geological Atlas of the World, CHOUBERT et al. 1980) are Cenozoic volcanic rocks, they have been assigned accordingly for lithology (Vb).

2 polygons of Quaternary rocks on Seram and Buru had been assigned as silici-clastic sedimentary rocks (Ss) in a first attempt, but have been changed to Ad for lithology.

1 polygon of Cenozoic rocks on Seram had also been assigned as Ss for lithology, this has been changed to semi- or unconsolidated rocks (Su).

In the northern part of Borneo new polygons have been added to reflect the occurrence of rhyolites here. In the NW 4 polygons of Cenozoic volcanic rocks are acid volcanic rocks (Va for lithology). 3 polygons of basalt rocks (Vb) have been distinguished as well (2 polygons from the Quaternary era, 1 polygon of the Cenozoic era).

On the southernmost of the Molucca islands (Obi) – south of Halmahera – 1 polygon of Precambrian rocks is in fact highly metamorphised material and has been assigned accordingly for geology and lithology (Cl). Furthermore on this island 1 polygon of Cenozoic rocks from the base map has been identified as Cenozoic volcanic rocks (basalts) and has been assigned accordingly (Vb).

In a similar way very old rocks found on Buru and Ceram islands (Lower Paleozoic for geology) have a complex metamorphic structure and have thus been assigned as such for geology and lithology (Cl).

On Flores island 1 polygon of Cenozoic rocks consists of volcanic rocks and has thus been assigned accordingly (Vb).

1 polygon of Cenozoic rocks on Tanimbar island initially assigned as carbonates (following the FAO lithological maps) could not be identified as such following our other sources; we believe it to be more of semi- to unconsolidated lithologic nature (Su for lithology).

In a similar way on Schouten island 2 polygons of Quaternary rocks have been assigned as Ad (Sc in a first attempt) and 1 polygon of Cenozoic rocks has been assigned as Su for lithology (prior also Sc).

On Timor island 2 polygons of Cenozoic rocks have been identified as mixed sedimentary rocks (Sm, prior Ss and Sc); another polygon of Cenozoic rocks could not be identified as such, it has been found to be Jurassic & Cretaceous rocks of complex lithology (Cl).
On Sumba island some Cenozoic rocks could not be identified as carbonates with certainty and have thus been assigned a mixed sedimentary lithology (Sm).

All polygons of Quaternary rocks on Sumatra have been found to be alluvial deposits (Ad for lithology). 1 polygon in the SW of the island had initially been assigned as Triassic rocks but following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) the prevailing geology here is Quaternary and has thus been assigned as Ad for lithology. 1 polygon amidst the rhyolithic volcanic rocks had been assigned as of Cenozoic age in a first attempt, the rocks here are in fact from the Upper Paleozoic with complex lithology (Cl) as different rock types can be found, e.g. granites.

As for the recent island arc of Sumatra – Java – Banda, the Cenozoic rocks form an accretionary wedge (see chapter 3 and 4) containing the typical series with Molasse, Flysch, overthrusted / obducted fragments with ophiolithic and high pressure (blue schist) fragments; in general they are of mixed sedimentary nature and have been assigned accordingly for lithology (Sm); they had been assigned as unconsolidated rocks in a first attempt. All the older rocks in this region are highly stressed or metamorphised and have thus very complex lithologies (like the Mesozoic rocks which have thus been assigned as Cl as well).

Following the detailed geological maps (e.g. CHOUBERT et al. 1980) and the Encyclopedia of MOORES & FAIRBRIDGE (1997) we have corrected some polygons on the N Philippines. Parts of the Quaternary rocks in our base maps are in fact from the Jurassic & Cretaceous and are of complex nature (Cl for lithology), 2 more polygons of Jurassic & Cretaceous rocks had been assigned as silici-clastic sedimentary rocks (Ss) in a first attempt, they are in fact also of complex nature (Cl for lithology).

On Mindoro in the north, Lower Paleozoic rocks had been assigned as unconsolidated rocks in a first attempt, they are also of complex nature (Cl).

On a small island SE from Luzon 1 polygon of Cenozoic volcanic rocks had been assigned as silici-clastic rocks (Ss for lithology), these are in fact rocks from the Lower Tertiary period mixed with Cretaceous rocks containing mainly sedimentary rocks with some carbonates. They have been assigned as Cenozoic rocks with mixed sedimentary signature (Sm).

On the southern tip of Luzon island, 1 polygon of Lower Paleozoic rocks has been separated and changed following the UNESCO Geological Atlas of the World map (CHOUBERT et al. 1980) of this region to metamorphic formations (Mt for lithology) and Cenozoic volcanic formations (Vb for lithology). Still further to the south 1 polygon of Quaternary rocks has equally been changed to Cenozoic volcanic rocks and Vb for lithology. 1 polygon of Cenozoic rocks had been assigned as pure silici-clastic rocks (Ss) in a first attempt, these are in fact mixed rocks (Sm for lithology).
2 small islands E of Mindoro had been assigned as Cenozoic rocks, they are in fact of metamorphic nature.

In a similar way more polygons have been changed and updated on the Philippines, Luzon, Mindanao etc. correcting polygons from our base map (DOTTIN et al. 1990) and adding details following the UNESCO Geological Atlas of the World (CHOUNERT et al. 1980).

We have added some polygons on Bohol island and on the surrounding islands. We have separated a small island W of Leyte (it had been connected in our base map) and added a small island S of Leyte to better represent the actual geographic situation.

2 polygons on Sulawesi and 1 small island SW consist of basic Plutonic rocks (ophiolites) – Pb for lithology. 1 polygon of Lower Paleozoic rocks in the base map (DOTTIN et al. 1990) has been corrected to Triassic rocks with complex lithology. 1 polygon of Quaternary rocks has been corrected to Jurassic & Cretaceous rocks consisting of mixed sedimentary rocks (Sm for lithology).

On Taiwan we have completely replaced the polygons of the base map as they seemed to be too generalised or erroneous and we judged it better to design the polygons here in a new way. We have designed the island following the UNESCO Geological Atlas of the World (CHOUNERT et al. 1980) and the MOORES & FAIRBRIDGE (1997) Encyclopedia. The island consists of Quaternary and Cenozoic rocks in the west (Alluvial deposits and silici-clastic rocks – Ad and Ss respectively for lithology) and of complex Mesozoic rocks (Cl) as well as Cenozoic basic volcanic rocks (Vb) in the East. In between more Alluvial deposits can be found as well as Quaternary basic volcanic rocks in the north and 2 polygons of basic Plutonic rocks (ophiolites – Pb) more to the south.

In Korea 2 polygons of Lower Paleozoic rocks had been assigned as mixed sedimentary rocks in a first attempt, they seem to be pure carbonates and have been assigned accordingly for lithology (Sc).

On Japan on the main island (Honshu) in the SW we can find Cretaceous rhyolites. In a similar way we can find Jurassic rhyolites NE of Taiwan. These rocks have been assigned accordingly for lithology (Va).

On the N part of Kamchatka we have distinguished a paleo-valley, probably a proglacial channel / urstromtal; we have assigned it accordingly for geology (Quaternary) and lithology (Ad).
1.2.1.3 Australasia

1.2.1.3.1 New Guinea

The metamorphic rocks and 1 polygon of plutonic rocks on eastern New Guinea have a complex lithology (Cl). 1 polygon of Jurassic & Cretaceous rocks (in the base map, DOTTIN et al. 1990) have in fact been identified as Cenozoic volcanic rocks (Vb).

1 small island between New Britain and New Guinea had previously been assigned as Cenozoic rocks but the prevailing rocks here (following the UNESCO Geological Atlas of the World, CHOUBERT et al. 1980) are Recent basic volcanic rocks (Vb for lithology).

The Quaternary rocks on New Guinea are for the most part Alluvium (Ad for lithology). 1 polygon of Jurassic & Cretaceous rocks and 1 polygon of Triassic rocks have complex lithologies (Cl). 2 polygons on Aru island and 2 polygons on Kai island of Cenozoic rocks are semi- to unconsolidated rocks and have been assigned accordingly for lithology (Su). 1 polygon of Cenozoic rocks in the northern part of New Guinea has been assigned in a similar way to Su for lithology – it had been assigned as consolidated rocks (Ss) in a first attempt. 1 polygon of Mesozoic rocks and 2 polygons of Paleozoic rocks (1 from the Upper Paleozoic and 1 from the Lower Paleozoic period) have complex lithologies (Cl).

1 small island W of New Guinea (in front of the ‘birds head’ of western New Guinea) has basic Cenozoic volcanic rocks (Vb).

1.2.1.3.2 Australia

In general here the geological base map digitised at UNH (Geological World Map, DOTTIN et al. 1990) shows limited matching with the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980).

The Precambrian rocks in the region north of Adelaide are carbonate rocks from the Younger Proterozoic era (similar to the rocks surrounding the Congo basin in Africa) and have thus been assigned as Sc. The folded Lower Paleozoic rocks here have been assigned as Cl and the Upper Paleozoic cover rocks as Sm, like in eastern Australia.

The Paleozoic or older volcanic rocks in this region have been assigned as Vb (as they are basaltic volcanic rocks).

The Precambrian rocks in the rest of Australia have been assigned as Pr following our initial convention on general assigning of lithology types for the different geology types.
The mountains in East Australia are an orogen from the Paleozoic era, following the Geological Atlas of the World (CHOUBERT et al. 1980) we have assigned the Lower Paleozoic rocks as Cl (heavily folded) and the Upper Paleozoic rocks to Sm (Mixed sedimentary).

The Mesozoic rocks in Middle and N-E Australia seem to be mostly clastic rocks with few carbonates (Ss for lithology).

Cenozoic rocks in southern Australia are mostly carbonate rocks, they have thus been assigned as Sc for lithology, the Quaternary alluvial deposits in the river beds surrounding these Cenozoic rocks have been separated (they were connected in the original base map) and assigned as Quaternary rocks for geology and Alluvial deposits for lithology (Ad).

NE from this region 2 polygons which had initially been assigned as Lower Paleozoic rocks are in fact of Precambrian age (following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) and the book of WOPFNER (1997) about Australian geology book) and have been assigned accordingly for geology as well as Pr for lithology.

The Paleozoic or older volcanic rocks in SW Australia have been assigned as Pr (Precambrian rocks) for lithology and Precambrian rocks for geology. Following the UNESCO Atlas (CHOUBERT et al. 1980) and WOPFNER (1997) they are similar to Precambrian rocks concerning lithology so they have been assigned accordingly.

The Upper Paleozoic rocks in this region are clastic sedimentary rocks and have been assigned as Ss for lithology.

NW Adelaide (S of Lake Gairdner) 1 polygon of Paleozoic or older volcanic rocks are Precambrian rhyolites and have thus been assigned as acid volcanic rocks for lithology (Va).

I.2.1.3.3 New Zealand, Tasmania etc.

Concerning New Zealand, quite important changes have been made with respect to the base map by DOTTIN et al. (1990). The generalisation error for the islands seems quite big due to the fact that in a relatively small space many different lithologies can be found. Many features have been newly implemented using the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980).

In the middle of the northern island 2 polygons have been altered in a polygon representing Recent volcanic rocks (Va for lithology) – previously they had been assigned as Triassic rocks. Just north in the Bay of Plenty 1 polygon of Metamorphic rocks are in fact Quaternary alluvium (Ad for lithology).

On the north-western tip of the island 1 polygon of Jurassic & Cretaceous rocks are in fact well of Mesozoic age but volcanic in nature. This has been corrected for geology and lithology (Vb).
On the northern island the Mesozoic rocks have been assigned as follows: The Jurassic & Cretaceous rocks are of silici-clastic nature (Ss for lithology), the Triassic rocks have a more mixed sedimentary nature (Sm for lithology).

The Upper Paleozoic rocks in the NW also present a similar lithology (Sm).

Some of the carbonate rocks designed in the UNESCO hydrogeological map (DZHAMALOV et al. 1999) could not be identified. Following our sources they may occur in some of the older Tertiary / Cenozoic rocks but probably not to a big extent. To follow the findings in the hydrogeological map, some polygons of Lower Cenozoic rocks (but assigned as Cenozoic rocks in general for geology as we do not have a category for Lower Cenozoic rocks on its own) have been separated from Upper Cenozoic rocks on the northern island and assigned as carbonates for lithology (Sc).

On both islands the Metamorphic rocks (3 polygons in total – 1 very small on the northern island, 2 bigger polygons from the Carboniferous – Permian period on the southern island) are of complex nature – they contain e.g. basic intrusive rocks next to the ‘typical metamorphic’ rocks – and have thus been assigned accordingly (Cl) for lithology.

On the southern island the Lower Paleozoic rocks (6 polygons) have a complex lithology and have been assigned accordingly (Cl).

Several new polygons have been added in the W and others have been altered to better reflect the geological and lithological situation identified in the UNESCO Geological Atlas of the World (CHOBERT et al. 1980). In the N of the southern island Durville island has been separated from the main island (had been connected in the base map) and the polygons have been changed to correctly reflect the locations of Lower Paleozoic (Sm for lithology) and Plutonic rocks (Pa).

1 polygon in the S had been assigned as Lower Paleozoic rocks, but as these are volcanic rocks here, they have been assigned as Paleozoic or older volcanic rocks for geology and basic volcanic rocks (Vb) for lithology.

The Jurassic & Cretaceous rocks have been assigned as silici-clastic sedimentary rocks (Ss) for lithology as no carbonates could be identified. The Triassic and Permian rocks here may contain some carbonates and have thus been assigned as mixed sedimentary rocks (Sm) for lithology. This corresponds to the findings on the northern island.

Furthermore metamorphic rocks and 1 polygon of Quaternary have been separated.

On Stewart island (S of southern island) the Plutonic rocks have been split into 2 separate polygons to depict the basic-ultrabasic Plutonic rocks (Pb) to the north and the acid Plutonic rocks (Pa) to the south.
Some more polygons representing Plutonic rocks in the south of the southern island have been added following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980). Some of them are basic-ultrabasic rocks and some acid rocks.

All remaining regions with Quaternary geology have been assigned as Ad for lithology. All remaining polygons with Cenozoic geology have been assigned as Su for lithology.

Using the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) the islands of Tasmania, King Island and Flinders Island have been checked and the following assignments for the lithology map have been done:

Triassic rocks in Tasmania (2 polygons) are clastic sedimentary rocks, they have been assigned accordingly for lithology (Ss). In the SW 1 polygon of Cenozoic rocks has been added and assigned as semi- to un-consolidated sedimentary rocks (Su) for lithology. The metamorphic formations and the Lower Paleozoic rocks in Tasmania and on King Island have been assigned for lithology accordingly to their complex nature (Cl). On Flinders Island, the polygons from the original base map (UNESCO Geological Map of the World, DOTTIN et al. 1990) have been changed to reflect the more dominant position of the granites (Pa for lithology).

### I.2.1.4 Europe

Permian rocks west of the Ural are carbonated (after the UNESCO hydrogeological map, DZHAMALOV et al. 1999 and geological maps).

1 polygon of Upper Paleozoic rocks as well as 1 polygon of Recent Volcanic rocks in SW Poland had been assigned as Mt in a first attempt, following the detailed maps and sources both consist of Upper Paleozoic rocks but have complex lithologies (Cl).

For Greece mainly information from JACOBSHAGEN et al. (1986) has been used. Various small islands (e.g. Santorin and Amorgos) have been newly depicted as well as the 3rd presque-île of the Chalkidiki, nearby polygons have been corrected.

In France: Metamorphic rocks from the Geological World Map have often been changed to Cl (Complex lithologies).

1 polygon of Cenozoic rocks around Perpignan (S France) had been assigned as complex lithology (Cl) in a first attempt, but consists in fact of semi-consolidated material like similar Cenozoic rocks in SW France. It has been assigned for lithology accordingly (Su).

On Corsica polygons have been changed following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980), metamorphic rocks in the E parts (complex lithology) and acid Paleozoic or older volcanic rocks (Va for lithology) (designed in a first attempt and in a different extent as Upper Paleozoic rocks) have been added.

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I.2 Detailed explanations for the new lithology map

On Sardinia polygons have also been changed, 6 polygons of acid Cenozoic volcanic rocks (Va for lithology) have been delimited and other polygons corrected.

As for the Alps: Flysch series in and east of the Alps: the Flysch sedimentation period in the Alps was in the Cretaceous until Cenozoic era, in our map these rocks are classified for geology as Jurassic & Cretaceous rocks. These rocks in front of the Calcareous Alps and the flysch belt around the Carpathian mountains are clastic sedimentary rocks (Ss for lithology). The Molasse parts in the forelands consist of mixed semi- to unconsolidated sedimentary rocks (Su).

N of Frankfurt (Germany) 3 polygons had been assigned as Recent volcanic rocks in a first attempt, these are in fact very old volcanic rocks in the middle (Paleozoic or older volcanic rocks for geology) and Cenozoic volcanic rocks to the W and E. They are all of basic volcanic nature (Vb for lithology).

In central Germany in the ‘Thüringer Wald’ region 1 polygon of Plutonic rocks (Pa for lithology) and 1 polygon of Lower Paleozoic rocks (Ss for lithology) have been separated from a polygon formerly assigned completely as Upper Paleozoic rocks.

In the S Czech Republic 1 polygon had been assigned as Jurassic & Cretaceous rocks in the base map (DOTTIN et al. 1990), these are in fact semi-to unconsolidated Cenozoic rocks in a basin (Su for lithology).

In Ireland we added polygons in order to differentiate between Ss in the south and Sc in the middle, than again Ss in the north as well as plutonic rocks etc. in Northern Ireland (but they were already there on the base map) – Ireland has mostly been designed following the hydrogeological world map (UNESCO, DZHAMALOV et al. 1999), in the middle of Ireland the carbonates are of Carboniferous age.

In Scandinavia, the rocks in the western parts, mostly assigned as metamorphic rocks in the base map, are rather of complex nature (Cl), in the southern and middle parts some rocks are of silici-clastic sedimentary nature (Ss).

For consistency reasons and to keep lithologically similar regions uniform on our map, the metamorphic rocks of the same age in Scotland and Ireland have also been assigned as Cl.

In southern Norway, Sweden, Finland and up to Russia the metamorphic rocks (as designed by DOTTIN et al. 1990) in the geological base map are of Precambrian age, so they have been corrected and changed in the geological map and assigned as Pr in the lithological map.

3 polygons E of Scandinavia (in Russia) had been assigned as Precambrian rocks in a first attempt, we have assigned them as Quaternary rocks (Alluvial deposits for lithology) following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980).
3 polygons in E Russia had been assigned as Paleozoic or older volcanic rocks (Ss for lithology) in a first attempt, following the geological map of Russia (1:5 Mio, NALIVKIN et al. 1970) these are granites (Plutonic rocks for geology, Pa for lithology).

In Finland 1 polygon had been assigned as Paleozoic or older volcanic rocks with Pb for lithology. All rocks here with Pb for lithology are dioritic intrusives (Plutonic rocks) – they have been assigned as such for geology and lithology.

**I.2.1.5 North and Middle America**

The UNESCO map of hydrogeological conditions (DZHAMALOV et al. 1999) is probably well done for Asia, especially Russia – as most of the authors are Russians, but this map may not be very reliable for North and South America.

Canada has been near the Equator during the whole Paleozoic period, so many carbonates from this period can be found, in the shields as well as in the mountain ranges / cordilleras. In Canada, carbonates have been assigned following the detailed map by FORD (1983) and the geological map of the Arctic / North America / Canada (LINK et al. 1960, GODDARD et al. 1965, DOUGLAS 1968). On the Perry Islands possibly some polygons remain to be verified and eventually to be changed (compare FORD’s (1983) Canada map).

The presence of carbonate rocks in the Lower Paleozoic in Southern Canada (Ontario) has been corroborated by a check with KOBLUK & BROOKFIELD (1982).

The carbonate rocks north and south the Great Slaves Lake (after FORD 1983) have not been identified in the geological map, we added new polygons in order to distinguish them as well as to separate Lake Athabasca; the Precambrian rocks south of the lake have been identified as carbonates (following FORD 1983 and the detailed geological maps).

Carbonate rocks surrounding the Hudson Bay have been added or corrected following the geological map of Canada (DOUGLAS 1968).

East of the Hudson Bay, we tried essentially to identify carbonate rocks following FORDS (1983) map, the UNESCO hydrogeological map (DZHAMALOV et al. 1999) as well as the other detailed geological maps of the region.

The carbonates identified after FORD (1983) east of the Hudson Bay are eventually not very certain, may contain errors (we have not been able to identify some in the other sources we used). The proposed bands of carbonate rocks east of the Hudson-Bay could not be found in the other sources we used, we couldn't identify them in the hydrogeological UNESCO map (DZHAMALOV et al. 1999) as well as in the geological maps used.
Most of the rocks in this region are of old Precambrian (Archean) age, they contain basic volcanic rocks which are partly metamorphic (amphibolites) as well as ultra-basic lenses (former deep ocean crust).

In Newfoundland the Lower Paleozoic contains carbonates, these have been added to the lithological map (new polygons) after the geological map of Canada (DOUGLAS 1968). Mainly the Ordovician and partly the Cambrian (from the middle Cambrian on) contain carbonates (following STANLEY 1994).

Anticosti island has been 1 single polygon in the base map, the northern half are carbonates (Sc), the southern half clastic rocks (Ss) – this has been reflected by adding the necessary polygons.

The Upper Paleozoic rocks on Prince Edward Island are Flysch of Carboniferous age, so they have been assigned as Ss.

The Long Island Sound has not been open to the sea in the base map digitised at UNH, we corrected the corresponding polygons.

Manitoulin island in the Huron Lake has not been identified as an island in the base map, so this island as well as Georgia Bay have been separated.

East of Lake Ontario polygons have been added to distinguish the carbonate rocks in this region.

The rocks of Precambrian age south of Lake Erie in the geological base (world) map (DOTTIN et al. 1990) have been identified as of Permian age in the detailed maps, they have been assigned geologically accordingly as well as Ss for lithology.

South of the Lake Superior there are in fact very few carbonate rocks, this has been verified using USGS digital documents on Wisconsin and Michigan as well as the UNESCO hydrogeological map.

The Precambrian rocks west of Lake Superior have been assigned Pr for lithology.

Lower Paleozoic rocks between Lake Superior and Lake Michigan and 2 polygons of the same geology southeast Lake Michigan have been assigned Sm for lithology as they may contain carbonates.

A little bit more to the south another Lower Paleozoic appearance has been assigned Sm, a Precambrian outcrop as Pr.

The remaining Lower Paleozoic rocks remained Sc as initially designed following GIBBS & KUMP (1994) as well as FORD (1983).
In the Appalachian mountains, the rocks of Triassic age have been assigned Ss, following the above mentioned thoughts, the rocks of Cretaceous (+Jurassic) age have been assigned Sm, the folded Upper Paleozoic rocks have been assigned Cl.

The rocks of Jurassic and Cretaceous age in Alabama and around have been assigned as Sm for lithology as they may contain carbonates. After STANLEY (1994), the Cretaceous rocks in Alabama east of the mouth of the Mississippi (southern borders of the Appalachian mountains) have intermittent carbonates.

In Florida, the carbonates (Sc) are recent reef constructions, so they are assigned as of Quaternary origin.

The Upper Paleozoic rocks in Texas are of mixed lithologies, they have been assigned as Sm.

North-west of Austin there are no volcanic rocks (as suggested in the geological base map), the prevailing rocks are of Precambrian age and have thus been assigned as Pr.

To the west of this region there has been one big polygon labeled as of Jurassic / Cretaceous age, this polygon has been divided and assigned Sc in the west, and as Sm in the east.

The Carboniferous and Permian rocks in central New Mexico north-east El Paso contain carbonate rocks, they have been assigned as Sc.

In the Rio Grande rift region near the Mexican border the rocks of Lower Paleozoic age have been assigned as Ss, the rocks of Jurassic / Cretaceous age have been assigned as mixed sedimentary (Sm).

One little spot of Jurassic / Cretaceous age in this region has been identified as in fact being a Tertiary intrusive body, so it has been assigned as Plutonic rocks for geology and Pa for lithology.

West of the Rio Grande river the rocks which are identified as Jurassic & Cretaceous in the geological base map are of Cretaceous age, this region has been the Mowry Sea in the Cretaceous epoch, the rocks formed during this period are mixed clastic and carbonate, towards the centre of the sea the rocks have more and more carbonate characteristics, so in the centre the rocks have been assigned as Sc whereas around the rocks have been assigned as the mixed sedimentary lithology class (Sm).

In Wyoming 4 polygons have been regarded as Plutonic rocks in the geological base map (DOTTIN et al. 1990), following the detailed geological maps we dispose of, they are of Precambrian age, this has been reflected by changing geology in our map and assigning them as Pr in our lithological map.
I.2 Detailed explanations for the new lithology map

One little spot in Wyoming has been Lower Paleozoic in the geological base map, following the detailed maps it should be Upper Paleozoic (Permian / Carboniferous) and carbonate rocks (Sc).

In the border region Wyoming / South Dakota there is a Precambrian outcrop surrounded by a ring of Lower Paleozoic rocks, these rocks in the ring could be carbonate rocks (Sc), they have been assigned accordingly.

4 polygons of Upper Paleozoic geology (mainly of Carboniferous age) in Montana and towards the borders to Wyoming and Idaho have been supposed to be carbonate rocks (following the UNESCO hydrogeological map), so they have been given the Sc signature, the same has been applied for 5 more polygons towards the north (in British Columbia and at the border Canada – USA / Montana), still following the hydrogeological UNESCO map, they have also been assigned to Sc.

The rocks of Jurassic & Cretaceous age east of the Great Salt Lake have a Ss lithology.

On Queen Charlotte Island there seems (following our more detailed sources) not to be Cenozoic volcanism, we believe that it is clastic marine Cenozoic / Tertiary, we have assigned Ss as lithology.

Towards the south of this region the Plutonic rocks have been changed to Jurassic / Cretaceous rocks, these are mixed rocks, they also contain Jurassic volcanic rocks, so they have been assigned a complex lithology (Cl) – this corresponds more or less to a continuation of the rocks on Vancouver Island.

South of Juneau the Upper Paleozoic rocks in the base map could not be identified to such an extent in the detailed maps, we changed them to Cenozoic volcanic rocks and Vb as lithology.

4 polygons of Jurassic / Cretaceous geology in British Columbia have been assigned to Ss (non-carbonate / clastic sedimentary rocks).

In Alberta north-west of Calgary the Lower and Upper Paleozoic contains carbonate rocks, so the lithology for these geologies has been assigned accordingly to Sc.

In the North West Territories – thus also the Mackenzie river basin is concerned, the northern parts of the Yukon Territories, the middle and North of Alaska, the Upper Paleozoic becomes mixed, so it has been assigned Sm for the lithology. Carbonates have only been assigned as such (Sc) where they are dominant.

In western Alaska all Jurassic / Cretaceous non-volcanic rocks are clastic rocks (Ss, no carbonates), this is not valid on the southern coast of Alaska.

The Upper Paleozoic in this region is more likely to contain carbonate rocks, we have reflected this in the lithology by assigning them the Sc signature.
Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

Along the border Alaska – Canada the Jurassic / Cretaceous rocks have also been assigned as Ss (in a first attempt following GIBBS & KUMP 1994 they had been assigned Cl).

We have added new polygons to better reflect some details on Baja California following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980).

Nearly all Metamorphic formations (geology) from Baja California (Mexico) towards the south consist of complex lithologies (Cl) as they are mostly to be found in the central and folded parts of the mountain chains. This attributing strategy has been applied throughout the mountain chains down to Argentina and Tierra del Fuego.

On Cuba we have added Carbonates after the hydrogeological UNESCO map (DZHAMALOV et al. 1999).

Some parts of the Cenozoic rocks in Mexico had been assigned as pure carbonate rocks in a first attempt, they seem to consist more of mixed sedimentary lithologies, this has been reflected by assigning them accordingly to Sm for lithology.

In the region of the 'bridge' between Middle and South America (Costa Rica, Panama, Colombia) the geologic maps (also in the UNESCO Atlas) have been established a long time ago, the region can be found both on the maps for N-America and S-America, and the differences on different maps for the same places are considerable. Even within the Geological Atlas (CHOUBERT et al. 1980) the differences between the sheets for North and South America are significant. Attributing lithologies has thus been rather difficult here. Assigning ‘hard’ rocks was feasible with good accuracy, but the assignments we have done for sedimentary rocks (Ss, Sc and Su) are somewhat uncertain.

1.2.1.6 South America

Following the FAO lithological maps all Cenozoic rocks in South America had been assigned as Ss for lithology in a first attempt, they are in fact more or less unconsolidated and have been assigned as Su for lithology accordingly. For example, the Cenozoic rocks towards the southern end of South America are similar to the Cenozoic rocks in front of the Alps in Europe, there they have also been assigned as Su for lithology.

All polygons with Quaternary sedimentary rocks for geology have been changed to Ad as this can be assumed for South America (no important reefs or other coastal carbonates, also in the dry regions of the Andes and in Argentina it are the rare rains which wash out the rocks from the mountains and form the Quaternary alluvial plains).
The southern Atlantic has only been opened / divided South America and Africa in the Cretaceous period, so the Mesozoic rocks in South America, e.g. on the Brazilian shield, but also in Africa, contain mostly continental Gondwana-series (series from the period when the southern continents have been one big landmass – starting from the Precambrian period on to the Cretaceous period) – they have thus mostly been assigned as Ss. Until the Jurassic period there are practically no marine series on either side of the Atlantic ocean; marine series in Gondwana are only – and very seldomly – found in some Graben structures. Some rocks from the Cretaceous period – when the opening of the ocean began – found towards the coast can contain carbonate rocks (e.g. one 1 spot of Jurassic & Cretaceous rocks near the Brazilian east coast, between Fortaleza and Natal, assigned as Sm).

The coastal Cretaceous rocks in Africa in the corresponding region have also been assigned as Sm for lithology (Sc in a prior attempt) as the pure carbonate character of these rocks is uncertain.

In the Amazon basin, around Santarem, a furrow of Quaternary rocks surrounded by Mesozoic and Paleozoic rocks to the N and S can be found. A profile of these rocks has been described by Zeil (1986) and a similar design of these rocks can be found in the UNESCO hydrogeological map (Dzhamalov et al. 1999). To the initially designed map (following the UNESCO Geological World Map by Dottin et al. 1990) has been added a polygon in the form of a small band. It has been assigned as Upper Paleozoic rocks for geology and Sc for lithology. These carbonates do not outcrop to the north of Santarem, the remaining Paleozoic and Mesozoic rocks have clastic character. Following Zeil (1986) the carbonates should be found a bit more to the south than we actually designed them but we did the positioning following the UNESCO hydrogeological map (Dzhamalov et al. 1999) as we trust it more for the location of these carbonate rocks than the rather coarse profile drawing in Zeil (1986).

On the shields (Guaporé in the southern Amazon region, San Francisco shields and Guyana shield with the Roraima table mountains – mesas) Paleozoic or older volcanic rocks can be found. They are Precambrian volcanic rocks but have in fact kept their acid volcanic character and have thus been assigned as Va for lithology (after Zeil 1986). They are rhyolitic (volcanic) rocks from the Older Proterozoic era; these rocks are most probably not very heavily stressed or metamorphised and assigning them as Va seems justified. Similar thoughts have been applied to the same kind of rocks on the Brazilian shield (signature ‘ρPb’ for rhyolite in the maps of the UNESCO Geological Atlas of the World, Choubert et al. 1980).

Some carbonate rocks are designed in the UNESCO hydrogeological map (Dzhamalov et al. 1999) in the eastern parts of the Brazilian shield (W of Salvador, e.g. around Brasilia). Following Zeil (1986) the carbonate rocks designed in the UNESCO hydrogeological map may be part of the Bambui series (part of the São Francisco series) which in fact contain carbonate rocks but also slate. In order to design our map – according to the sources we used – in a first
attempt 5 polygons have been added following the coarse FAO lithological maps. In a second step these polygons have been deleted and replaced with 4 new polygons following the UNESCO hydrogeological map (DZHAMALOV et al. 1999). They represent carbonate rocks (Sc) from the Younger Precambrian era.

5 polygons of Upper Paleozoic rocks W of the Guyana shield had been assigned as Su for lithology in a first attempt following the FAO lithological maps; they are in fact mixed sedimentary rocks (containing some carbonate rocks) and have therefore been assigned as Sm for lithology (ZEIL 1986). The 4 remaining polygons of Upper Paleozoic rocks further to the west in the Andes cordillera chain in Venezuela and Colombia had been assigned as Sm in a first time, following ZEIL (1986) they should more likely be assigned as Ss for lithology. In some parts of the Devonian rocks marine series can be found but also rhyolites, and as a whole these Devonian and Carboniferous rocks are clastic sedimentary rocks. The Upper Paleozoic rocks in general are mostly clastic rocks, so our assigning them as Ss seems correct in the most parts (exceptions see above).

Following GERTH (1955) and ZEIL (1986) the Jurassic & Cretaceous rocks in N Venezuela and Colombia are all mixed sedimentary rocks, they have been assigned accordingly to Sm for lithology, even if this seems not completely certain for all parts.

The Upper Paleozoic rocks in the Cordillera Oriental in Bolivia are mixed terrestrial and carbonate rocks (ZEIL 1986) and have been assigned as Sm for lithology (3 polygons W of Santa Cruz are concerned).

The Jurassic & Cretaceous rocks around the Colombian capital city Bogotá are more exactly from the Cretaceous period and contain marls and carbonates – the carbonate content is relatively high (ZEIL 1986) – these rocks have nonetheless only be assigned as Sm for lithology as they were not identified as pure carbonate rocks especially in the UNESCO hydrogeological map of the world (DZHAMALOV et al. 1999).

The (younger) Precambrian rocks W of Bogotá are the same carbonate rocks as the rocks around Brasilia and have thus been assigned as Sc for lithology.

1 small polygon S of Bogotá had been assigned as Plutonic rocks in a first time, this revealed to be in fact rocks from the Cretaceous period and has thus been assigned accordingly for geology (Jurassic & Cretaceous) and lithology (Sm) (following GERTH 1955).

Following our previous thoughts on Paleozoic rocks a polygon towards the coast in the Peru / Ecuador region has been assigned as Ss for lithology.

As already explained, nearly all Metamorphic formations (for geology) from Baja California (Mexico) south throughout the South American mountain chains down to Argentina and Tierra
del Fuego have been assigned as Cl for lithology as they are mostly rocks in the central parts of the mountains with very complex lithologies.

The Paleozoic rocks in the central Andes seem to consist mostly of clastic rocks (Ss).

In southern Peru W of Arequipa 1 polygon had been described as Metamorphic rocks in a first attempt, following our more detailed sources these are Precambrian rocks (for geology) and have thus been assigned as Pr for lithology.

Concerning the volcanic rocks S of Lima towards the Chilean frontier some changes to the base map have been implemented. In the base map (DOTTIN et al. 1990) only one big polygon is distinguished. The map in the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980) designs quite well the difference between basalts and rhyolites in this region. These differences have been implemented in our map and new polygons have been designed to mark the difference between acid volcanic rocks (Va for lithology) to the south and basic volcanic rocks (Vb for lithology) in the north. In the same way a small polygon of acid volcanic rocks has been distinguished between Lima and Arequipa. Around the Peruvian / Chilean frontier and towards the south many of the Cenozoic volcanic rocks are acid volcanic rocks and have thus been assigned as Va for lithology. These acid volcanic rocks in the middle and southern Andes are Quartz keratophyrs similar to the Triassic rocks around Mendoza in Argentina (Va) and neogene rhyolitic rocks in the middle Andes (but only there). Small occurrences of Ignimbrites in this region have a too small spatial extent to be implemented in our map at this stage.

All remaining Mesozoic rocks in the Andes reaching from Ecuador down south until Patagonia have been summarised and assigned as Sm for lithology. Following the structural description of the Andes (ZEIL 1986) these are mixed clastic pelitic rocks containing some carbonates but not enough to qualify them as pure carbonates (and assigning them as Sc for lithology).

Between Coquimbo and Antofagasta (Chile) some polygons of Upper Paleozoic rocks had been assigned as Su in the FAO lithological maps, they are in fact Ss (ZEIL 1986). In Argentina (still E Coquimbo) in the Lower Paleozoic rocks there may be carbonates so they have been assigned as Sm for lithology.

In the Andes E of Concepcion (Chile) 2 polygons of Jurassic & Cretaceous rocks may be of marine origin and thus contain carbonates (ZEIL 1986) – they have been assigned as Sm accordingly. The Mesozoic sedimentary rocks in the high cordillera consist to the west partly of thick marine series; towards the E continental series can be found (mostly they have been assigned as Sm for lithology).
Annexe I Conventional geology and lithology, detailed explanations for the new lithology map

1 polygon of Jurassic & Cretaceous rocks NW of Córdoba (Argentina) had been assigned as carbonate rocks (Sc) in a first step, but we could not confirm this with our detailed sources so this has been corrected to possibly slightly carbonated sedimentary rocks (Sm).

2 polygons of Upper Paleozoic rocks further to the W had been assigned as Su for lithology (following the FAO lithological maps), but our detailed sources suggest assigning them as Ss for lithology.

The Triassic rocks W and N of Mendoza (NW Argentina) – 2 polygons – are acid volcanic rocks (Quarzt keratophyr) and have been assigned accordingly as Va for lithology.

3 polygons of Upper Paleozoic rocks east of the Brazilian part of the Pantanal had been assigned as Su for lithology following the FAO lithological maps, but they are in fact consolidated sedimentary rocks and have thus been assigned as Ss for lithology.

In NE Brazil (SE from the mouth of the Amazon) 1 polygon of Lower Paleozoic rocks had been assigned as Su in an initial attempt (following the FAO lithological maps), this has been corrected following our detailed sources to Ss for lithology.

The Llanos between the Andes and the old shields to the east (e.g. Paraguay, N Argentina, E Bolivia) date from the Pleistocene / Holocene period. Many different rock types are contained: sands, fluvitile sandstones, volcanic ashes, loess, some sweet water carbonate rocks, towards the south small salars and silt / clay can be found (Zeil 1986). This situation is difficult to be described lithologically uniform for the widespread Quaternary geology in this region. For our purposes assigning these rocks as Ad (or loess where appropriate and verifiable) seems correct. Erosion still occurs along the river streams, some erosion occurs in the northern parts of the Llanos due to the dense vegetation.

In the downstream regions of the Paraná river towards its mouth (NE Argentina) a small band of Cenozoic (and not Quaternary as we would expect here) rocks can be found from east of Resistencia via Santa Fe to Rosario. This seems to reflect correctly the geological and lithological situation here as the river has cut its bed into the younger sediments and the older Cenozoic sediments reappear at the surface, these rocks are assigned as Su for lithology.

Triassic rocks here (Mesozoic rocks as part of Gondwana) – in Paraguay as well as in Brazil are terrestrial and as such clastic non-carbonated rocks which have been assigned accordingly to Ss for lithology (they had been assigned as Sm in a first attempt) (Zeil 1986).

Some changes have been made in S Paraguay with respect to the base map (following Zeil 1986 for lithology and the UNESCO Geological Atlas of the World (Choubert et al. 1980) for the form of the polygons). The Lower Paleozoic rocks here are from the Silurian and Devonian era and clastic sedimentary rocks (Ss for lithology), the Jurassic & Cretaceous rocks may contain
I.2 Detailed explanations for the new lithology map

some basalts which are too small to be distinguished in our map – in general they are terrestrial sedimentary rocks as well (Ss for lithology). 1 polygon of Plutonic rocks is an occurrence of a Cenozoic granite and has been assigned as Plutonic acid (Pa) for lithology.

In the Argentinean part of Patagonia some of the Mesozoic volcanic rocks may be acid volcanic rocks, but as we could not verify this none have been separated for the time being.

2 polygons in the Chilean part of S Patagonia which had initially been assigned as Cenozoic and Quaternary rocks are in fact glacier fields and have thus been corrected for ‘geology’ and ‘lithology’ to Ice (Ig).

6 polygons of metamorphic formations (for geology) in Tierra del Fuego have been assigned as Cl for lithology, they are complex metamorphic rocks as part of a young orogeny from the Middle – Upper Mesozoic era.

1 small polygon in Tierra del Fuego has been changed from Cenozoic rocks to Ice (Ig).

Following the description in ZEIL (1986) the Mesozoic rocks in S Patagonia and Tierra del Fuego seem to be mostly clastic sedimentary rocks (as part of the Gondwana continent) so here the description as Ss is more likely to be correct than a description as Sm for lithology.

I.2.2 Particular designs adopted for distinct lithology classes

I.2.2.1 Basic-ultrabasic Plutonic rocks (Pb)

We have, among others, distinguished ophiolites in the following regions : Yugoslavia, in the Alpidic chain from Italy via the Dinarides, Turkey, Zagros, Cyprus, N Syria on to Oman; furthermore in the recent chains of the Insulinde (Zulawesi, Halmahera …), New Guinea, New Zealand, New Caledonia, Philippines. Most probably there are no more ophiolithes to be found further to the north in Japan.

Several ophiolites on the western margins of the Pacific ocean, in the Ural region as well as other basic – ultrabasic rocks in Scandinavia have been assigned as Pb for lithology.

On the W coast of Newfoundland the Lower Paleozoic rocks consist of ophiolites, this has been reflected for geology (Plutonic rocks) as well as for lithology (Pb).

The Basic Plutonic rocks on the eastern Canadian shield (as found in the Geological Atlas of the World, CHOUBERT et al. 1980) are not distinguished in our map as they are too small to be taken into account in our resolution.
Annexe I  Conventional geology and lithology, detailed explanations for the new lithology map

N of Lake Huron the Sudbury and neighbouring Plutonic rocks are also basic rocks and have been given the corresponding lithology (Pb). The Sudbury complex, an ultrabasic-basic economic deposits complex now interpreted as the result of a meteorite impact (Dürr 2001 pers. comm.), is similar to the Bushveld complex in S Africa in its petrology even if the origin and genesis are different (see the corresponding section on Bushveld).

I.2.2.2 Basic volcanic rocks (Vb)

Following our basic assumptions we assigned Vb to all basic volcanic rocks. It should be remarked that older volcanic rocks (mainly Paleozoic or older volcanic rocks) are likely to have lost some of the volcanic signature, they may actually appear more like mixed sedimentary or complex rocks.

Old volcanic rocks (diagenetically – tectonically changed and or metamorphically altered) are less easily erodible, they are not easily to be washed out. Young basic volcanic rocks (often tuffs, ashes, fresh lava) are unaltered, they are more easily eroded, altered and washed away.

The differences between diverse ages for volcanic rocks are more important than the differences between old and young rocks in the complex lithology category.

I.2.2.3 Acid volcanic rocks (Va)

Acid volcanic rocks can be found in orogenes, in this class we mainly find rhyolites and Ignimbrites (rhyolitic tuff) e.g. in New Zealand. In general they are seldom to be found as they are easily erodable and are only to be found in very few places, but where they are found they occupy quite large surfaces.

Acid volcanic rocks can be found as described in chapter 3 and 4, e.g. on the Guyana shield, in New Zealand, in Sumatra (young and widespread), in South America around Mendoza in Argentina (Triassic age) and S of Lima. The occurrences in Germany as well as in and Austria (Quartz-porphy in the Alps of Permian age) are too small to be mapped in our map. The Yellowstone famous acid volcanic rocks are also too small in their spatial extent to be taken into account and thus to be distinguished in our map for the time being (even if locally important and famous in the geological world).

In Iran the northern part of the Pash-I-Lut desert / block contains rhyolitic volcanic rocks. The Mesozoic volcanic rocks here also contain rhyolites (Va for lithology).

SE and NE of Bangkok 4 polygons of Cenozoic volcanic rocks consist of rhyolites and have been assigned accordingly (Va).
I.2 Detailed explanations for the new lithology map

I.2.2.4 Sedimentary consolidated rocks

We should bear in mind the differences between siliciclastic and carbonate clastic rocks. Whereas the latter rock type of broken carbonate rocks is relatively seldom to be found the first type is one of the most widespread type of sedimentary non-carbonate rocks (mostly sandstones containing Quartz and Feldspars) – for example the Ss lithology type rocks in the Mackenzie basin are of this type. Carbonate rocks on the contrary are mostly biologically produced rocks (reef carbonates, constructive carbonates, oolites, organo-detritic carbonates etc.). Between these 2 distinctive rock classes we can find mixed sedimentary rocks, they have been assigned as Sm and give a rock class between pure carbonate and pure siliciclastic rocks. Rocks of this type can for example be found in Texas.

Meybeck (2002 b pers. comm.) remarked on the differences between shales and sandstones concerning erodability (in addition to the analysis in chapter 3): the difference between shales and sandstones consists mainly in the different grain size. Shales have mud grain size, they contain clay minerals and organic matter and can thus develop pyrite. This is important especially for mechanical erosion (less for chemical erosion). Mechanically shales are more easily erodable than sandstones, they present much less resistance and consistency when facing erosion.

I.2.2.5 Carbonate rocks – consolidated (Sc)

It has to be kept in mind that the formation / origin of the carbonates can be widely different, so our class regroups a great variety of carbonate rocks (e.g. in North America from Quaternary reefs in Florida to Precambrian carbonate rocks south of Lake Athabasca in Canada).

Carbonate rocks have been mapped on a global map by Ford & Williams (1989): The mapping here is approximate and seems very generalised (the world on one ~A5 size book page). Ford & Williams (1989) have omitted many very small outcrops and possibly some larger ones. Some may also be exaggerated in size or could not be identified with our other sources. Some of the errors may also be due to the small size of the map. Aggregated the carbonate rocks occupy about 12 % of the Earth’s dry and ice-free land following this source. The extent of carbonate terrains with distinctive karst landforms and / or karst groundwater circulation is estimated to be less, around 7 – 10 % of the area. Following Ford & Williams (1989), carbonate rocks are more abundant in the Northern Hemisphere (see also our actual numbers in chapter 3 and 4). The southern continents consisting of old Gondwana parts have comparatively small outcrops except around their margins where some large spreads of Cretaceous or later age (post-breakup of the super-continent) can be found (see also chapter 4 for our actual map). Ford & Williams (1989)
estimate that 25% of the global population is supplied largely or entirely by karst waters and that large numbers of people live on carbonate rocks.

The carbonate rocks described by FORD & WILLIAMS (1989) on parts of the NW side of the southern island of New Zealand could not be identified in our more detailed sources. But as described earlier, the geological situation on New Zealand is very complex with many small scale changes and we had to generalise in many ways. The general characteristic features of New Zealand’s geology have been designed in our map and assigning rocks with many small scale changes as complex for lithology (Cl) seems justified.

Western Australia carbonate rocks following FORD & WILLIAMS (1989) could not be identified with certainty in our map, but we have mapped many rocks here as mixed sedimentary rocks (Sm) with some carbonate rock occurrences. Anyway, this region is arid with mostly no perennial runoff, so an eventual error seems not too important, especially when taking into account runoff weighted lithologies.

In Hungary the Paleozoic carbonate rocks N of Lake Balaton described by FORD & WILLIAMS (1989) have been identified by us as of Triassic age but nonetheless as carbonate rocks.

I.2.2.6 Evaporites (Ep)

In all regions with sufficiently humid conditions the surficial evaporates are washed out and diluted and / or covered and confined by comparatively insoluble hats of residual clays or other sediments. All present / Quaternary surface occurrences are to be found in arid regions.

The salt occurrences delimited in the geological maps we used are latest Tertiary to Quaternary intercontinental or near coastal salt pans / sabkhas. We designed them following the UNESCO Geological Atlas of the World (CHOUBERT et al. 1980). On the geological maps and in the UNESCO Geological Atlas of the World we used, only alluvial evaporites (Quaternary) are delimited.

5 polygons of evaporites (salinars) have been added in S America, 7 polygons of salinars and 2 more polygons of Neogene rocks have been added on the Arabian peninsula, they have also been delimited in N Africa and Australia.

Most of the worlds massive evaporites over larger areas consist of marine evaporites (evaporated marine border basins). Most of the Cambrian (Near East Asia, Siberia), Middle Paleozoic (Sverdrup basin in the Arctic, Devonian basin near Moscow, Permo-Carboniferous basins in Europe and N and S America), Jurassic (Mexico), Upper Mesozoic basins (Khorat basin – Mekong), Messinian (Mediterranean) salt deposits can be characterised like that, a well know example are the Zechstein salt deposits in northern Germany. The salt of practically all of these
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basins appears at the surface only as diapirs in too small spatial extent to be delimited in larger geological maps used in our study. These salt occurrences are only exceptionally in contact with surface waters (S America in Peru, Mackenzie basin, see the concerning sections below), all other occurrences are sealed to the surface and not in contact with surface waters. Evidently water for example in karstic regions (e.g. in the Muschelkalk formations containing gypsum) is much harder than water from other regions but similar surface formations, but these water chemistry changes due to rock differences in the ground water cannot be captured by our approach. Some examples of presently isolated (covered) evaporites are: Lower Carboniferous (Visean) evaporites in Northern France and Belgium (ROUCHY et al. 1987); Middle Muschelkalk evaporitic deposits in Eastern Paris basin (GEISLER-CUSSEY 1987); Miocene rocks in the Tarim basin (China), now covered by Quaternary rocks (mostly dunes) (DONGZHOU 1987).

The Late Proterozoic evaporites in the Sichuan province in China described by XIAOSONG (1987) are another example for now covered rocks not appearing at the surface. The prevailing surface rocks here are from the Mesozoic era (lithology described in section I.2.1.2.2). The Triassic rocks may contain some evaporites (YINGLIN & YANGJI 1987) but are mainly carbonates following this and other sources; they have thus been assigned accordingly (Sc).

The Precambrian evaporite occurrences in Australia (MUIR 1987) seem also be described by WARREN (1999), but we could not localise them closely enough to design them in our map. In fact many of the evaporite crystals have been replaced by other minerals, and most of the rocks concerned in Australia are over terrains with no runoff so our error here – introduced by omitting these rocks – seems not too important.

The Miocene evaporites in the Gulf of Suez and the Red Sea (MONTY et al. 1987) adjacent (shoreward) to the massive carbonates (also of Cenozoic origin) are too small to be designed in our map.

Most of the evaporitic rocks described and mapped by FORD & WILLIAMS (1989) are now buried by later carbonate or clastic (detrital) rocks. Furthermore, many occurrences have been partially removed by dissolution or have much reduced in geographic extent by folding and thrusting (e.g. in the Andes). FORD & WILLIAMS (1989) estimate that nevertheless gypsum and/or salt deposits can be found under about 25% of the continental surfaces, figure seriously to be doubted. Gypsum and salt karst that is exposed at the surface is much smaller in extent than the carbonate karst (see above).

Concerning the few subsurface occurrences mapped (see chapter 3, turquoise asterisk on our map), the following additional comments and details can be given:

These occurrences are difficult to evaluate as the rocks mostly do not outcrop but are nonetheless solved and affect surface waters. We have marked with a star on our map regions
where major hydrologically important salt sources have been confirmed (WARREN 1999, MEYBECK 2002 b pers. comm.); these are, as mentioned beforehand in chapter 3, the occurrences of salt in the Devonian halite strata in the Elk Point Basin (Mackenzie river basin), in the Andes (Permian age, Urubamba valley), late Miocene evaporites in the Jordan basin, Cretaceous evaporites in the Khorat basin, a subbasin of the Mune basin contributing to the Mekong basin; furthermore East Siberian Salt occurrences have to be mentioned:

Salt sources important for the hydrogeochemistry of surface waters of parts of the North Canadian Mackenzie basin have been described by HITCHON et al. (1969), REEDER et al. (1972) and FORD & WILLIAMS (1989). Evaporites comprise 5.7% of the (subsurface) rocks in the southern part of the western Canada sedimentary basin and are present in 11 stratigraphic units from Middle Jurassic to Ordovician. Halite is present, although often in small amounts, in all these units except the Middle Jurassic. In most units either the amount of halite is small or it is located deep in the basin far from the influence of near surface groundwater. Only the updip portion of the halite in the Elk Point group of Middle Devonian age are considered a source of saline groundwater affecting river composition (HITCHON et al. 1969). These salt sources are heavily affecting rivers flowing entirely or in part on Middle Devonian strata in the region south of the Great Slave Lake. They have chloride contents considerably in excess of 5 g/l. The importance is furthermore underlined by the naming of the ‘Saline River’, found in this region.

Numerous salt inputs to surface waters can be seen by the numerous ‘Cachiyacu’ (salt waters) designated on maps of north-central Peru, the most important salt springs being observed in the Urubamba valley, an Amazon tributary, near Macchu Picchu. They have been described for example by GIBBS (1972), STALLARD & EDMOND (1983), STALLARD (1985) and WARREN (1999). Often the evaporite minerals are dispersed in red beds and outcrop in the formations in which they were deposited. Buried massive evaporites are brought to the surface as salt plugs or domes. Their extrusion rate is such that they are pronounced topographic highs, even though rainfall is approximately 1.5 m/year. Here the active tectonics lead to salt formations rising faster than they can enter into solution and be carried away or be covered by solution residues.

Within the Dead Sea rift valley, the river Jordan, before reaching the Dead Sea, flows through the late Miocene (100 to 20 Ma BP) Lisan formations mainly made of marls and gypsum. These formations are leading to saline groundwaters affecting the Jordan river in its southern / lower parts. They are derived from natural leaching of salts of the Lisan formation thus controlling the salinity of the river (VENGOSH et al. 2001).

In SE Asia, high Cl- inputs in river waters derived from evaporite occurrences are described by CARBONNEL & MEYBECK (1975), MEYBECK & CARBONNEL (1975), MEYBECK (2002 b pers. comm.). WARREN (1999) attributes them to the Khorat basin, a subbasin of the Mae Nam Mun (or Mune) basin, itself a right hand tributary of the Mekong in Thailand.
Evaporites influence in East Siberia is most evident in the Lena basin where evaporite rocks of the Cambrian East-Siberian platform lie close to the surface (Tsirkunov et al. 1998). Groundwater discharge into some basins leads to highly mineralised waters with high chloride and sulphate concentrations during low-flow periods (USSR Surface Water Resources 1972a and b, cited by Tsirkunov et al. 1998). The effects are most pronounced with very high natural salt concentrations on some very few rivers among right bank tributaries of the middle reaches of the Vilyui river – itself a left bank tributary to the Lena. For example the high salt content in the Kampandaee river, one of the Vilyui tributaries, is due to the dissolution of the fractured Kampandaee salt domes (Tsirkunov et al. 1998, also mentioned by Gordeev & Sidorov 1993).

I.2.2.7 Alluvial deposits (Ad)

In general, all Quaternary rocks not attributed in the different other lithology classes, have been assigned – after roughly checking their lithological character – as alluvial deposits (Ad).

No distinction has been made between marine fluvial, pure fluvial, and other alluvial deposits, including moraines and glacial till.

On Iceland, Greenland, and arctic islands in N America and the high plateau of Tibet (all parts which are not currently covered by ice) we have changed all Quaternary rocks to consist of Alluvial deposits (this generalisation seems justified to us).

In Mexico the remaining Quaternary rocks which had been assigned as Semi- to unconsolidated rocks in a first attempt have been assigned as Alluvial deposits (Ad for lithology) as well.

I.2.3 Rock types and rock ages

Some remarks can be made regarding the question of differentiating the different rock types following their ages:

Can Paleozoic or Paleozoic and older volcanic formations eventually be assigned as ‘ancient complex’ rocks? Is differentiation in Alpine and older complex lithologies feasible and necessary?

Such a differentiation seems difficult as many of the rocks concerned in the Alps and elsewhere are designed as Metamorphic or Plutonic rocks for geology on our base map (Dottin et al. 1990) and no rock ages are given. There is a difference in the metamorphic rocks in Scandinavia and in the Alps. In the Alps – contrary to Scandinavia – mainly material from the
Mesozoic and the Tertiary is implied in the mountain formation but inside the mountain chains also much older material can be found.

Precambrian (shield) rocks (Pr class) are normally very close to granitic or metamorphic rocks. The biggest parts of the Precambrian crystalline rocks are of granodioritic nature (‘old shields’).

As for the rock composition there is no difference between young and old rocks excepted for some of the old greenstone belts and some very old basaltic rocks which can contain more magnesium than younger rocks. But from the Upper Proterozoic era on there are no differences between older and younger rocks concerning rock composition.