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FACULTY OF NATURAL AND LIFE SCIENCES AND EARTH AND UNIVERSE SCIENCES
DEPARTMENT OF EARTH AND UNIVERSE SCIENCES
BRANCH : GEOLOGY
SPECIALITY: GEOLOGY OF THE SEDIMENTARY BASINS

THE BIOLOGICAL CRISIS : Paleontological and geological evidences

Domain: Geology
Branch: Master's degree of Geology of sedimentary basins

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This course is intended for: M1 students of geology of the sedimentary basins

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Summary

The exploration of mass extinction events throughout Earth's history reveals critical insights into the dynamics of biodiversity and ecosystem resilience. "Minor climatic fluctuations lead to species extinction in a conceptual ecosystem model," emphasizes that the evolutionary trajectory of life has been punctuated by significant extinction events, with 61 documented occurrences, several of which are classified as mass extinctions. The precedent works argue that these extinctions are often linked to major environmental changes, particularly elevated volcanic activity, which disrupts ecosystems beyond their resilience. Their conceptual model highlights that high biodiversity can paradoxically lead to inevitable extinctions when resource use reaches its maximum, underscoring the complex interplay between biodiversity and ecosystem stability. The specific impacts of climate change on marine bivalves over the last 66 million years. Their findings indicate that significant temperature fluctuations correlate with heightened extinction rates, while functional diversity remains relatively intact despite taxonomic losses.

During "Paleozoic–Mesozoic" period Eustatic Changes and Mass Extinctions: New Insights from Event Interpretation," takes a methodological approach to reexamining the relationship between sea-level changes and mass extinctions, including the "Big Five" by employing advanced analytical techniques, challenges simplistic correlations between eustatic fluctuations and biodiversity loss, advocating for a more nuanced understanding of these relationships. This course contributes to a broader framework that connects geological phenomena with biological responses during mass extinction events, providing a deeper insight into the mechanisms driving these critical transitions in Earth's history.

Further expanding on the ecological implications of mass extinctions, "Ecological dynamics of terrestrial and freshwater ecosystems across three mid-Phanerozoic mass extinctions from northwest China" examine a series of mass extinctions that may share common drivers, particularly the release of greenhouse gases leading to significant environmental changes. Their analysis of the Permian to Early Jurassic crises reveals varying magnitudes of extinction across terrestrial tetrapod genera, with losses ranging from 41% to 89%. This course highlights the importance of understanding terrestrial ecosystems beside marine environments, as the dynamics of community recovery and resilience are critical to comprehending the long-term impacts of mass extinctions. This course signals a shift in biodiversity studies, highlighting the importance of a comprehensive understanding of both well-known and obscure taxa.

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GENERAL INTRODUCTION

The current state of biodiversity corresponds to just one stage in the history of the living world: today's species represent only a tiny fraction of the total number of species that have existed since the dawn of life.

Today's biodiversity is only the temporary result of an ongoing process. In fact, 90 to 99% of the species that have ever existed on earth have become extinct. The vast majority disappeared as part of a process of normal species extinction, due to the limited duration of their biological existence. This varies from 1 million years (Ma) in the case of mammals, to 11 Ma in the case of certain marine invertebrates.

The study of alternations in biodiversity during the history of life on Earth (= paleo-biodiversity) is accessible thanks to fossils. It is from the Cambrian, around 570 Ma ago, that we discover numerous and diverse life forms in the fossil record.

Progress in evolutionary paleontology shows that there are usually filiations and intermediaries between successive forms and that no group disappears abruptly or immediately. Most species change over time: relative extinction.

However, it has been observed that there have been periods of severe decline in biodiversity on a planetary scale. The term "biological crisis" was coined to describe these periods of major cataclysm, when previously well-represented groups of animals and/or plants suddenly disappear, without descendants (absolute extinction), while others appear and develop.

A biological crisis, mass extinction, or great extinction, is a relatively brief event on the geological time scale (a few million years maximum) during which 50% of the animal species and plant species present on Earth disappear. These are periods when the rate of disappearance is much higher than the rate of appearance.

After a biological crisis, surviving species diversify by occupying the vacated environments, from which new species evolve to re-establish biodiversity and biological equilibrium.

To meet the criteria for a biological crisis, an extinction event must satisfy three main criteria:

- brutal mass extinctions;
- extinctions on a planetary scale, affecting all environments;
- diversification of post-crisis survivors.

There is a certain hierarchy in the importance of these biological crises:

- **minor crisis**: the disappearance of less than 30% of species, sometimes of genus, never of family or order. This type of crisis is very frequent on the geological time scale: it is estimated that there is one per million years (1/1Ma);
- **medium crisis**: the disappearance of 30 to 60% of species, some genera, families, and even (rarely) orders. Frequency: 1/10Ma (for minor and medium crises, these frequencies are confirmed by fairly precise geological/paleontological observations);
- **major crisis**: the disappearance of over 60% of species, as well as genera and families, orders and even classes(frequency: 1/100Ma).

Twenty or so more or less intense crises have occurred since the Cambrian. Most are linked to planetary events (intense volcanism, meteor impact, climatic variations, etc....); they alternate with longer periods of relative stability.

The crises studied in this course are the major ones; they are the most important and are considered as markers of the Earth's history used to establish the biostratigraphic scale. There have been five of them over the last 500 Ma (Fig. 1), from the most recent to the oldest: the Cretaceous-Tertiary crisis (associated with the end of the dinosaurs), the Late-Triassic crisis, the Permo-Triassic crisis, the Late-Devonian crisis and the Late-Ordovician crisis.

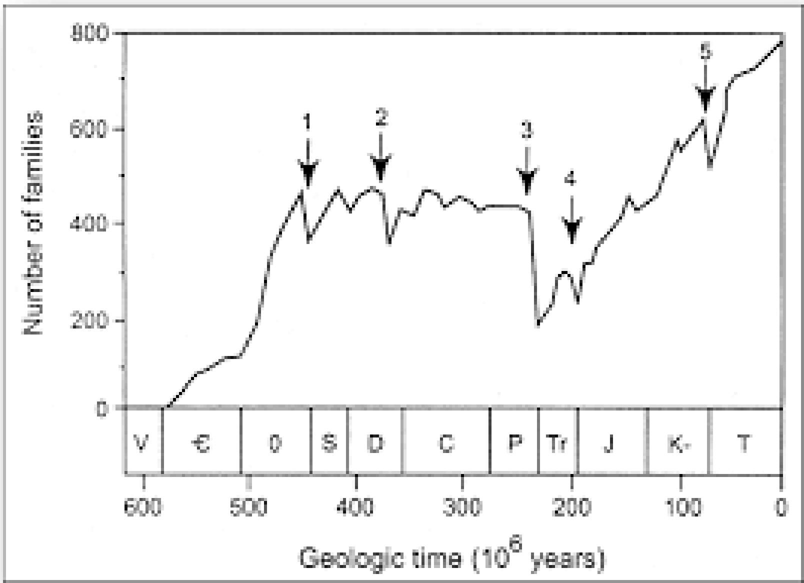

Fig. 1: Major biological crises over the last 500Ma (Lethiers, 1998).

Numerous geological studies (sedimentology, paleontology, stratigraphy, etc.) have been devoted to the study of these biological crises. Other specialists, notably physicists and chemists, are to be outdone. They have made several noteworthy forays into this field of scientific investigation.

THE LATE ORDOVICIAN CRISIS

I. THE LATE ORDOVICIAN CRISIS

I.1 Introduction

At the very beginning of the Ordovician period (fig. 2), animal life existed only in the sea. Towards the end of this period, the sea level was a hundred meters higher, and on land, there was absolutely no plant or animal life, and oxygen was much rarer than it is today.

At this time, life is exclusively marine. In particular, trilobites and brachiopods were numerous and varied. The first bryozoans appeared, as did coral reefs.

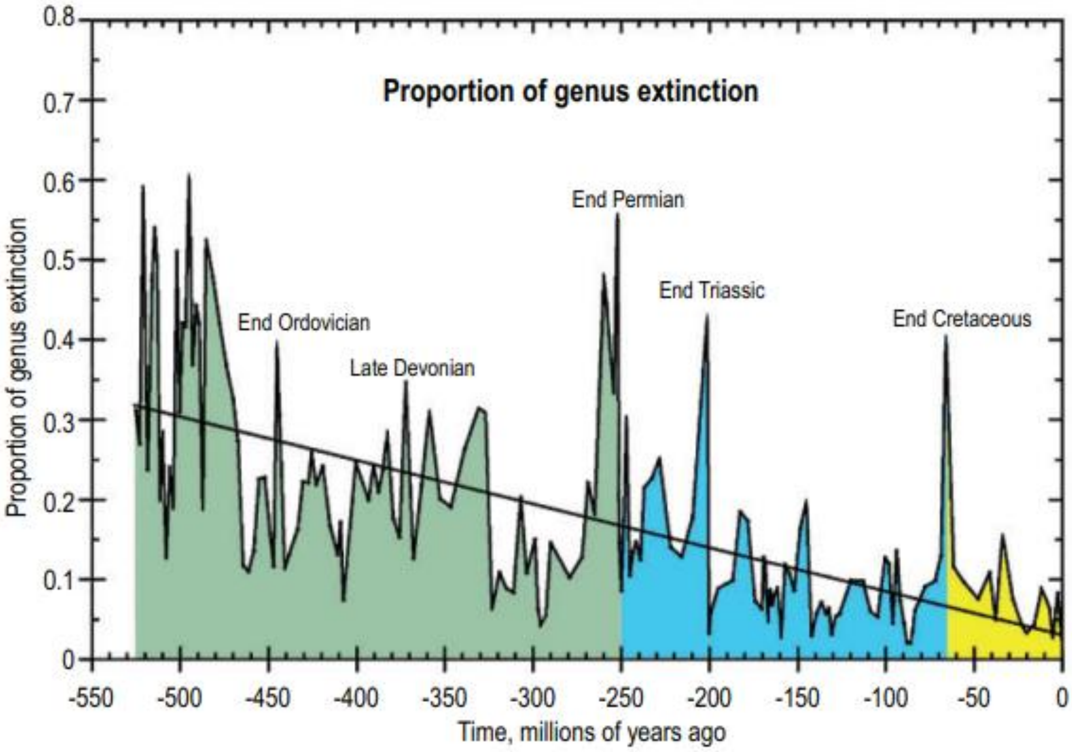

Fig. 2: Proportion of generic extinction during the Phanerozoic, highlighting the big five extinction events.

The Late Ordovician extinction is the first of five major extinctions in Earth's history. It took place between around -450 and -440 Ma, extending throughout for 1 to 2 Ma and marking the boundary between the Ordovician and Silurian periods. It took place in two phases (fig. 3):

1) the first occurs at the boundary between the Rawtheyen and Hirmantien stages;
2) the second one is during the middle of 'Hirmantien.

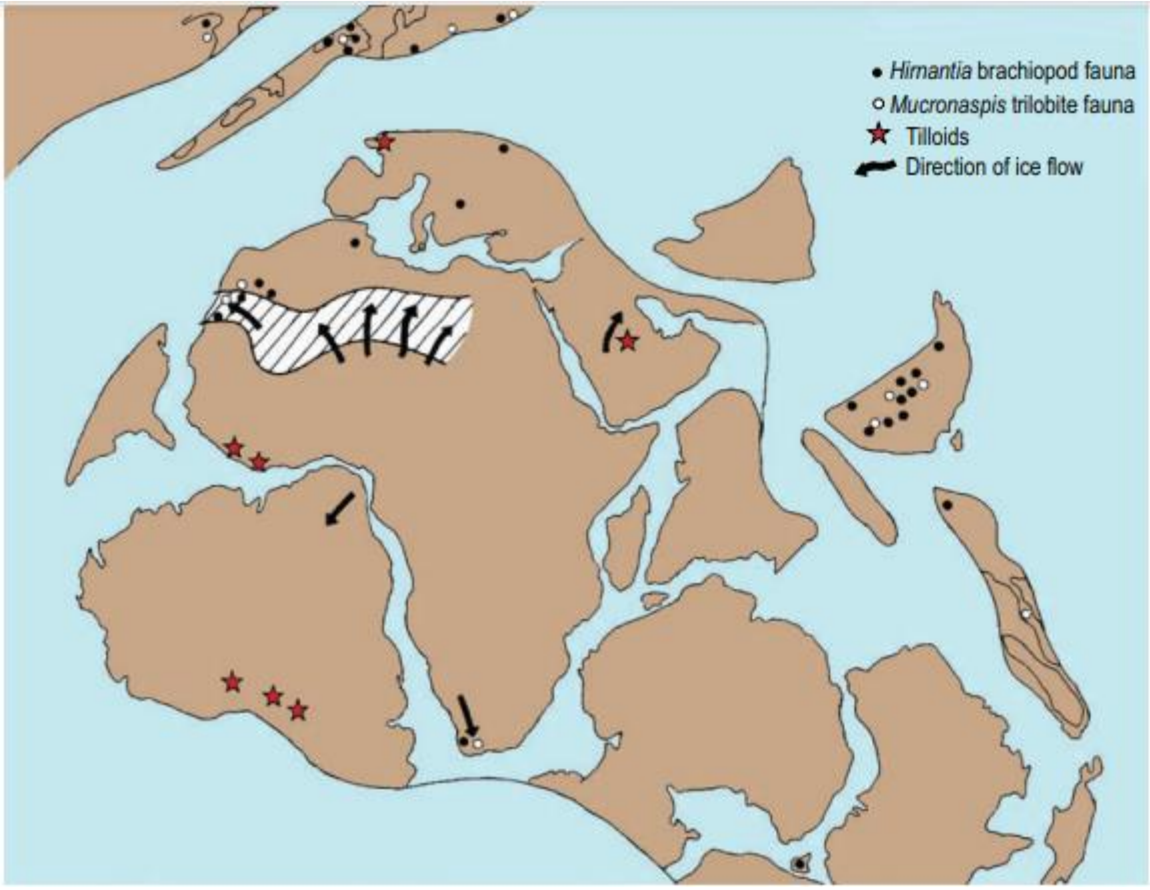

Fig. 3: Palaeogeographic reconstruction of Gondwana and its marginal areas during the Hirnantian. Directions of ice movement together with the location of key faunas are indicated (Cocks and Fortey, 1988).

I.2 Biological events

The Ordovician was a time of great diversification and expansion of many marine forms. Although organisms already present in the Cambrian were numerous in Ordovician, a variety of new taxa, such as cephalopods, corals (rugose and tabulate), bryozoans, crinoids, graptolites, gastropods, and bivalves have prospered.

The Ordovician communities generally display greater ecological complexity than Cambrian communities, due to the greater diversity of organisms. At the end of the Ordovician period, approximately 100 families died out, and brachiopods and bryozoans were destroyed, as were numerous families of trilobites, conodonts and graptolites.

- Trilobites increase from 38 to 14 families. There is a significant reduction in the number of species because genera often become mono-specific;
- nautiloids and brachiopods lose around 13 families;
- pelmatozoans (echinoderm subphylum) increase from 20 families, especially in cystoids and crinoids;

- ➢ reef builders, which reached a maximum of diversity at the base of the Ashghill, suffer extinctions with, for example, 75% of tabulate and rugose genera. The reef environment is virtually absent in the Upper Hirmantian and Rhuddanian;
- ➢ graptolites are on the verge of total extinction, with only two families surviving. Their evolutionary radiation from the Silurian is based on a few species;
- ➢ conodonts have fairly simple forms during the early Ordovician period, but are highly diversified from the Middle Ordovician, with a much more complicated morphology. They increased from 35 genera with around 100 species to 10 genera with around 20 species.

Other groups show little or no significant extinctions; these include ostracods, bivalves and may be chitinozoans (Silurian nannofossils), and acritarchs (organic-walled microorganisms).

Major extinctions take place during the first phase of the crisis. This is followed by an invasion by the residual low-diversity fauna, including the brachiopod genus Hirnantia; this cosmopolitan fauna is thought to originate from cold, oxygenated waters. The second phase of the crisis destroys the Hirnantia fauna.

I.3 Geological events

The Late Ordovician extinction was most likely triggered by the onset of a long ice age, probably the most severe ice age of the Phanerozoic. There is no evidence for extraterrestrial causes.

I.3.1 The Late Ordovician glaciation

During the Cambrian and most of the Ordovician, continental masses dispersed widely, leading to a remarkable evolutionary radiation: the Great Ordovician Biodiversification.

At the beginning of the Ordovician period, the movements of Laurentia and Baltica were reversed (fig. 4). A subduction zone with an island volcanic arc forms on the southeastern margin of Laurentia, and the Iapetus Ocean begins to close. A small continental plate is formed on the northern margin of Gondwana at the pole and moves northwards.

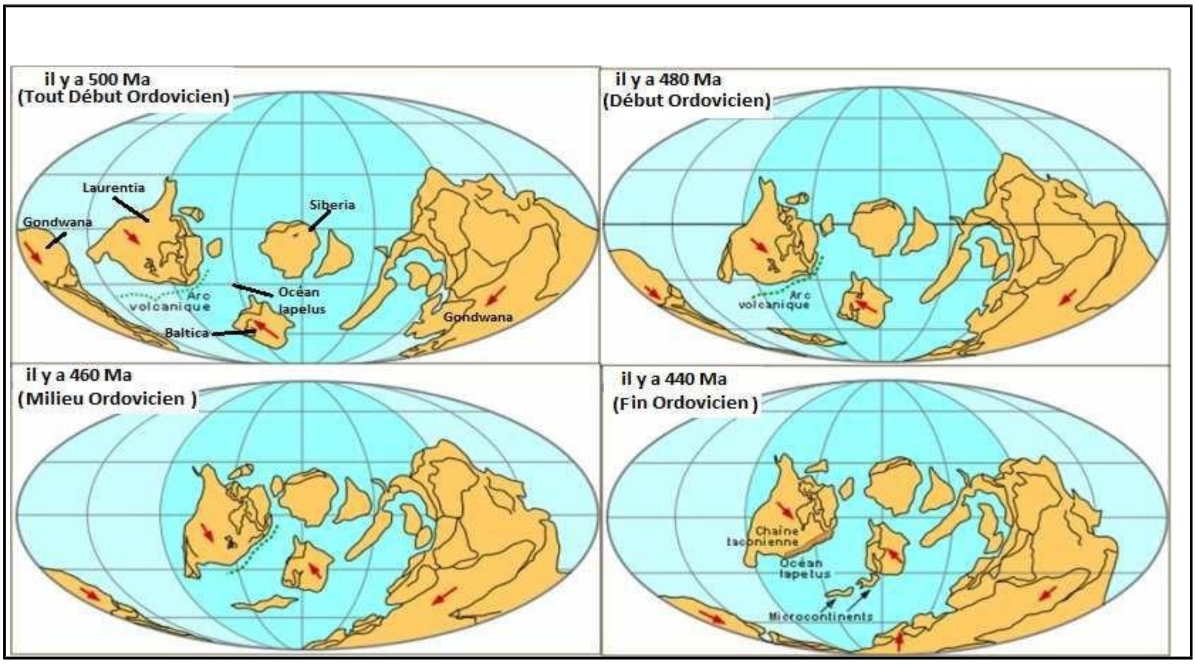

Fig. 4: Maps of the history of continents and oceans during the Ordovician period (Scotese, 1997).

From the middle of the Ordovician (fig. 4; 5), the island arc collided with the Laurentia margin, forming the Taconian chain. The small continental mass broke up as it rose, giving rise in particular to the continent known as Avalonia (corresponding to present-day England).

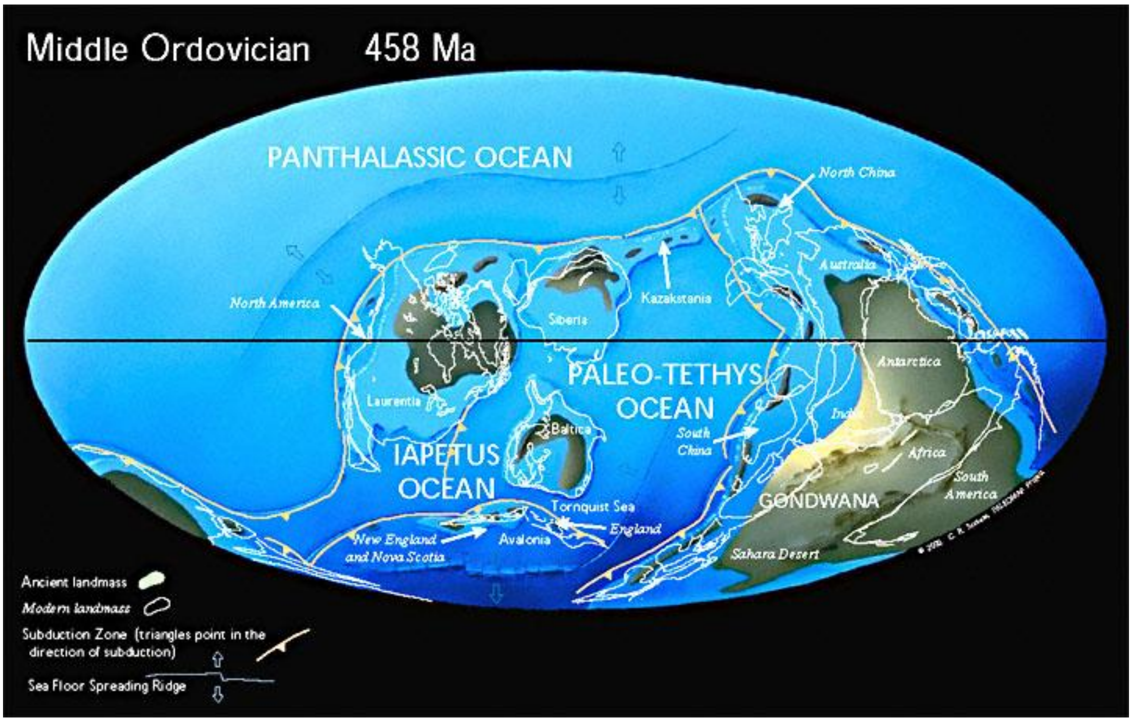

Fig. 5: Geodynamic map of Middle Ordovician (Scotese, 1997).

I.4 Glaciation and deep-water cooling

At the end of the Ordovician, the Gondwana margin (the southern hemisphere supercontinent that, according to plate tectonic theory, is broken into India, Australia, Antarctica, Africa and South America) occupied the South Pole (northern present-day Africa; Late Ordovician glacial deposits). This northern margin continues to break up and the sea surface is considerably reduced, marked by major cooling and the surrection of mountain ranges.

The migration of Gondwana over the South Pole forms ice caps; this glaciation, which was thought to be a relatively brief event, limited to the Hirmantian stage at the end of the Ordovician system, in fact, took place over a longer period and was more gradual the Rawtheyen, It dominated the Hirmantian period.

I.5 Glacio-eustatic regression

This glaciation event also caused sea levels to fall (fig. 6) around the world, as large quantities of water were immobilized in ice caps.

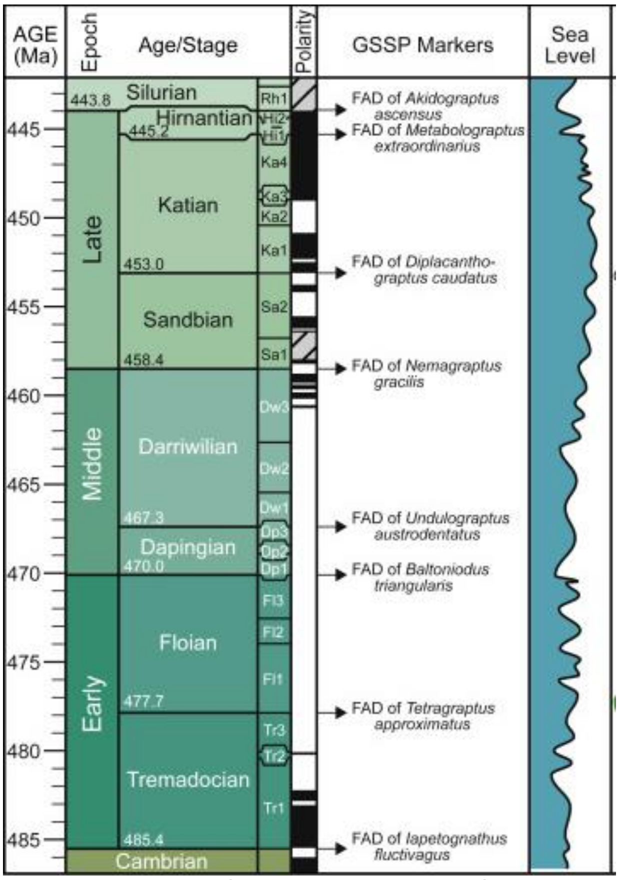

Fig. 6: Lower sea level during the Late Ordovician period (Cooper et al., 2001).

A combination of this lowering of sea level, in conjunction with the cooling caused by glaciation, are probably responsible for the mass extinction at the end of the Ordovician. After regression, the rise in sea level (marine transgression) is typically accompanied by a period of low oxygen (anoxic).

This low-oxygen event, which was detected during this crisis, is likely to have had an impact on the biosphere.

I.6 Conclusion

The late Ordovician extinction caused the disappearance of 70% of the species on the seabed, due to a period of great glaciation that resulted in the presence of a large ice cap at the South Pole.

The remarkable features of this extinction are :

- low-level systematic extinction (families, genera, species), while classes and orders remain with representatives;
- 60% of marine invertebrates died, including two-thirds of all brachiopod and bryozoan families;
- the groups affected belong to both the benthos (trilobites, brachiopods, crinoids) and the pelagos (certain trilobites, conodonts, nautiloids, graptolites).

Synthesis of Late Ordovician crisis

Crisis	**Late Ordovician**
Age (Ma)	-450 à - 440
Number of phases	2
Duration	1 to 2 Ma
Groups showing disappearances	Brachiopods Bryozoans Trilobites Conodonts [illegible]
Affected groups	Nautiloides Ostracodes Bivalves Chitinozoans Acritaches
Causes	Glaciation Regression Warming

THE UPPER DEVONIAN CRISIS

II. The Upper Devonian crisis

II.1 Introduction

The Upper Devonian crisis is one of five mass extinctions of plant and animal life recorded in the history of life on Earth.

In Devonian times, the planet was an immense ocean. A super-continent was located at the South Pole, and countless islands and archipelagos were scattered along the equator (fig. 7).

Fig. 7: Distribution of continental masses in the Devonian (-400Ma)(Scotese, 1997)

This Upper Devonian crisis mainly affected the oceanic realm. It took place between around - 380 and -360 Ma and marks the transition between the two Upper Devonian stages: the Frasnian and the Famennian. It took place in 3 stages, including two major ones, generally distinguished in chronological order:

1) the extinction at the end of the Givetian stage, around -383 million years ago, probably the least significant;
2) the extinction at the end of the Frasnian stage, around -372 million years ago. This is the main extinction peak of the Devonian;
3) the extinction at the end of the Famennian stage, around -359 million years ago, with estimated impact of 70% of that of the Frasnian extinction.

The Devonian extinction period would therefore stretch from around ten years (for the two main events) to more than twenty million years if we include the Givétian extinction, which is no longer consistent with the definition an extinction event which is supposed to be relatively short-lived (a few million years).

II.2 THE BIOLOGICAL EVENTS IN THE MARINE ENVIRONMENT

During this crisis, the most affected groups are those of the marine community.

II.2.1 Invertebrates

It is estimated that 70% of marine invertebrate taxa did not survive during the Carboniferous.

❖ **The manufacturing organizations**

The taxa most affected are warm-water and tropical species, and in particular, the main reef builders stromatoporoid, rugose and tabulate corals. Reef-building species were so severely affected.

These structures were virtually non-existent before the appearance of modern corals in the Mesozoic.

Reefs were ten times more developed in the Frasnian than they are today, and it is this benthic life that will be particularly affected by the events of the late Devonian.

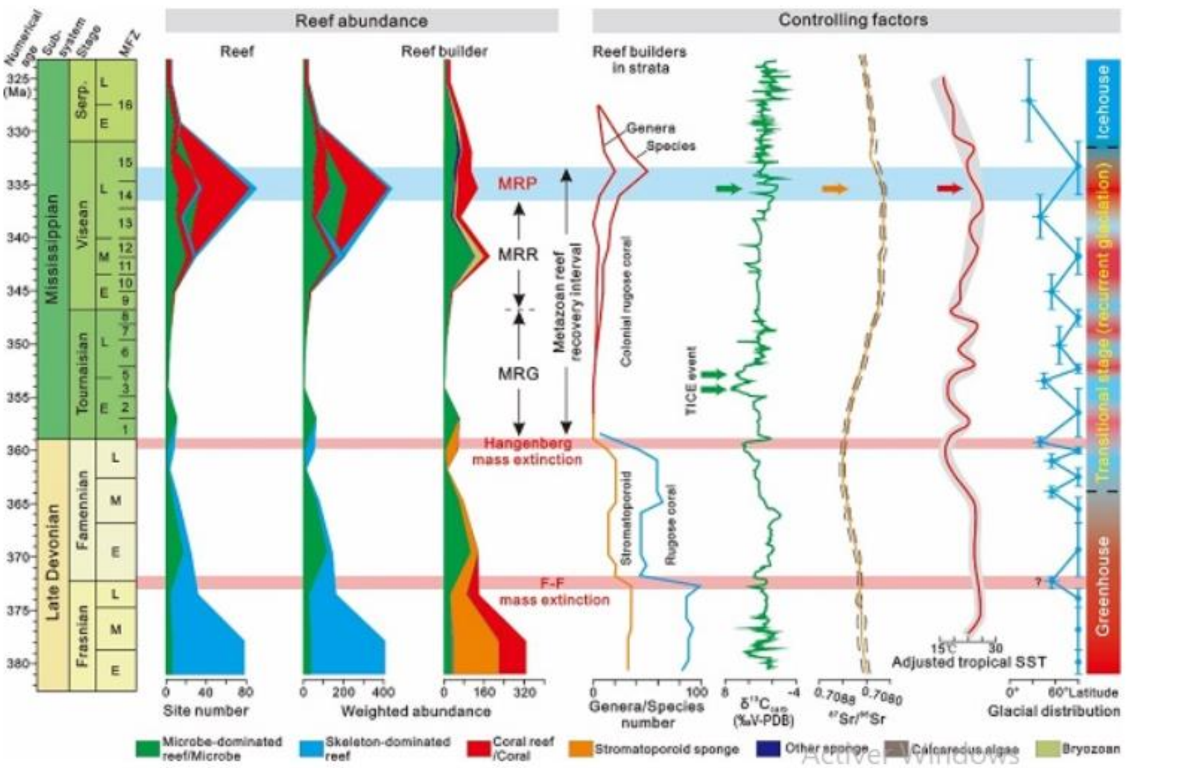

Fig. 8: Re-emergence of coral reef ecosystems after the Late Devonian crisis (Yao,. et al., 2019).

❖ **Other invertebrates**

- Bryozoans are little affected; the number of families decreases slightly at the end of the Devonian (fig. 8). However, it should be noted that they had already been in crisis since the Silurian. As far as they are concerned, the Devonian did not really make things worse.
- Trilobites: only five species survive; the number of families decreases as early as the Ordovician and during the Devonian, species continue to decline steadily (Fig. 9).

  The Devonian doesn't seem to make things worse, as the downward curve continues through the Carboniferous and Permian.
- Ostracodes (benthic crustaceans), 80% of species will be exterminated.
- Brachiopods: we can see that the Upper Devonian was a truly crucial time for many species: 86% of species are extinct, others were decimated, and others underwent period of expansion just after the Devonian, colonizing the spaces left empty by those that became extinct (fig. 9). The Pentamerida disappeared for ever.

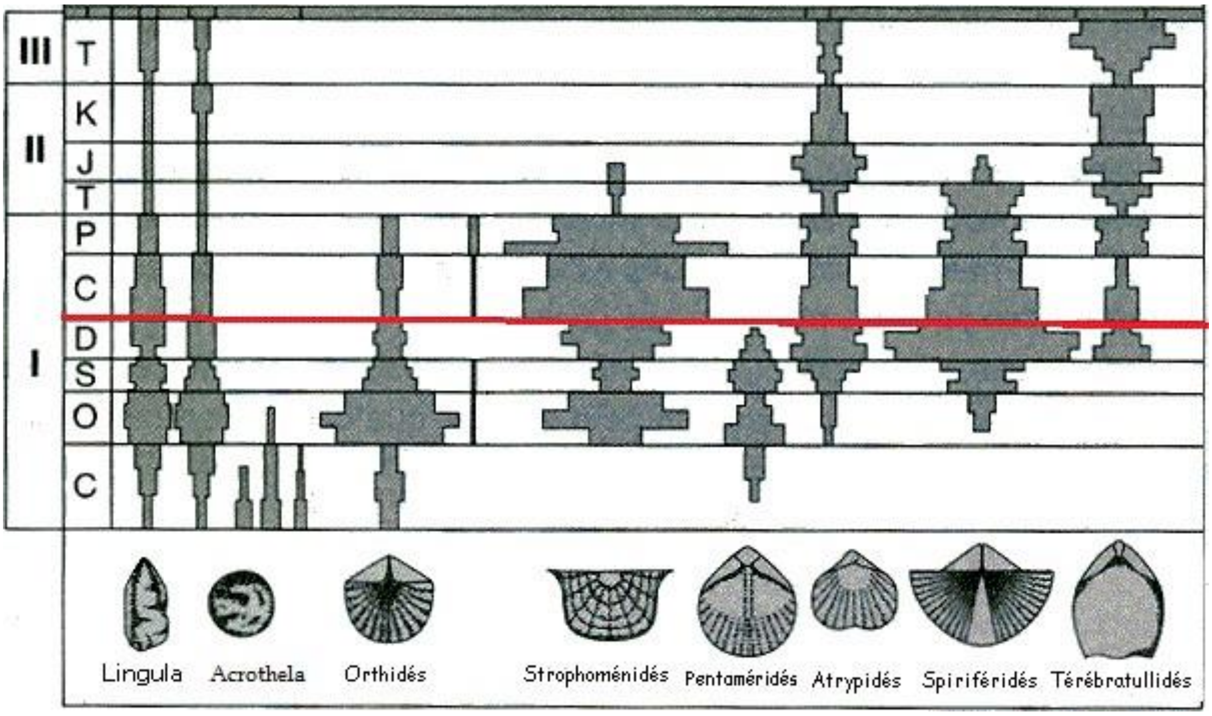

Fig. 9: Brachiopod evolution over geological time (Lethiers,1988).

- Foraminifera are on the verge of total extinction in the pelagos (floating or swimming organisms), Tentaculites will disappear. Other groups are little affected.

II.2.2 Vertebrates

- Fishes: it was towards the end of the Upper Devonian, some 370 Ma ago, that certain sarcopterygian fish developed very particular anatomical specializations. Their paired fins (pectoral and pelvic) lose their rays, leaving only the muscular lobe at their base. This first enlarges into a kind of swimming paddle armed with skeletal elements that become phalanges and fingers.

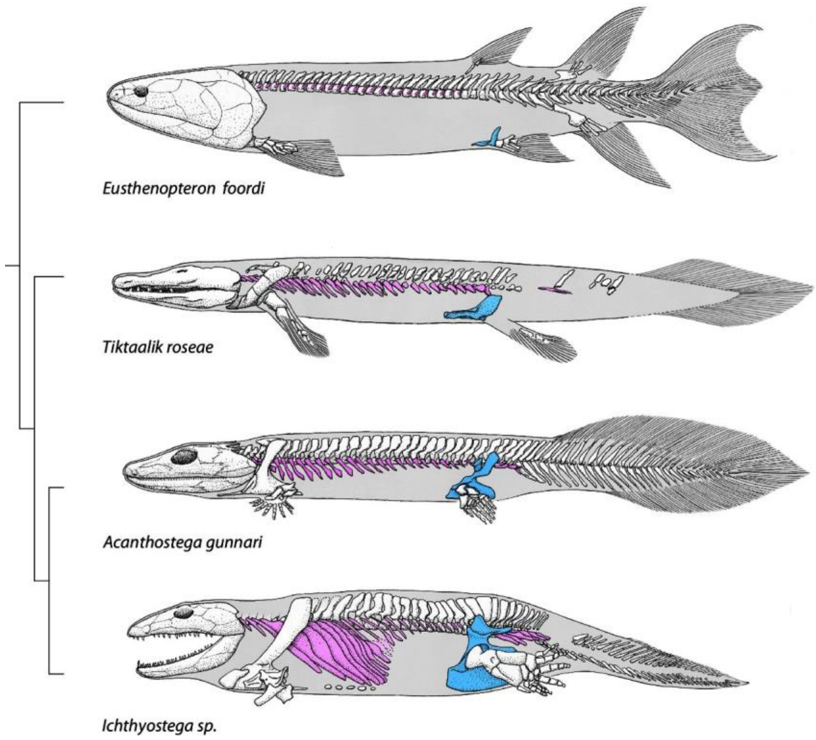

Fig. 10: transformation of the sarcopterygian fish into a semi-terrestrial tetrapod (Stewart et al., 2024).

The anterior part a salamander-fish fossil, the "Tiktaalik" (fig. 11), clearly showing the pectoral fin transformed into a kind of swimming paddle armed with skeletal elements that became phalanges and fingers, as well as the hypothesis of this animal's general appearance

Fig. 11: Tiktaalik fossil (Clack and Ahlberg, 2006)

Tetrapods: the appearance of individualized digits defines tetrapods. The first tetrapods were likely hardly more "terrestrial" than most of the fish around them. Their limbs were simply swimming organs, better adapted to life in muddy environments cluttered with plant debris.

It was only 10 to 15 million years later, in the Carboniferous period, that the members of the tetrapods presented the anatomical structures necessary for locomotion on land, such as those enabling elbow extension or flexion of the wrist and the ankle.

- The Agnathes will disappear.
- The Gnathostomes and Placoderms, fish with cartilaginous internal skeletons and bony armor, suffered major extinctions.

II.3 Continental environments

Terrestrial flora and fauna are little affected. The colonization of land by plants and animals has only just begun. On land, the bacteria and algae of the Silurian are joined during this period by primitive plants that created the first greasy lands and hosted arthropods, such as mites and scorpions, and myriapods; arthropods were already present on earth before the Devonian.

A. Plants

During the Upper Devonian, forests of primitive plants appeared: lycophytes, sphenophytes, ferns and progymnosperms. Most of these plants have true roots and leaves. Ferns evolved into giant tree-like forms.

At the end of the Devonian period, the first seed plants appeared. The rapid appearance of so many different plant groups is known as the "Devonian explosion".

Fig. 12: Devonian plants and trees landscape.

Plant evolution since the Ordovician (fig. 12) can be summarized as follows:

- Spores testify to the existence of land plants in the Ordovician period;
- In the Silurian, the primitive bryophyte and pteridophyte flora takes hold;
- The Devonian is the period of continental conquest by plants, with

diversification of lycophytes and arthrophytes.

B. Faunas

The first fossil traces of insects date from the Early Devonian. At the end of the Devonian period, the first amphibians and arthropods were well-known on earth. The primitive arthropods evolved with the plants described above. Dependence on the evolutionary link between insects and seed plants is characteristic of the modern living world and has its roots in the Devonian period. The first terrestrial vertebrates, terrestrial arthropods and plants are not affected by this crisis, this latter affected only marine organisms.

II.4 Geological events

A wide variety of causes, sometimes concomitant and often interdependent, have been put forward to explain the Devonian extinction. The multiphase nature of this event further complicates the search for direct causes, induced physical effects, and their repercussions on biodiversity.

II.4.1 Impact a meteor

A. Evidence of asteroid impact:

- Impact marks (fig. 13) :
  - Sweden, 1 crater 52 km in diameter at the Frasnian/Famennian boundary;
  - Quebec, 1 crater 46 km in diameter, Upper Famennian ;
  - Tennessee, Lower Frasnian;
  - Chad, 3 craters 10 to 17 km in diameter, Lower Famennian ;
  - Russia, 1 crater 15 km in diameter, Upper Devonian.

The discovery of an iridium anomaly in the Upper Devonian of Australia (1Ma above the limit) had suggested the impact of one or more asteroids as responsible for the late Devonian crisis. This anomaly has been shown to have been confined to Australia, and not supported by the observation of impact minerals. Furthermore, this Australian level is stratigraphically posterior to the late Frasnian extinction.

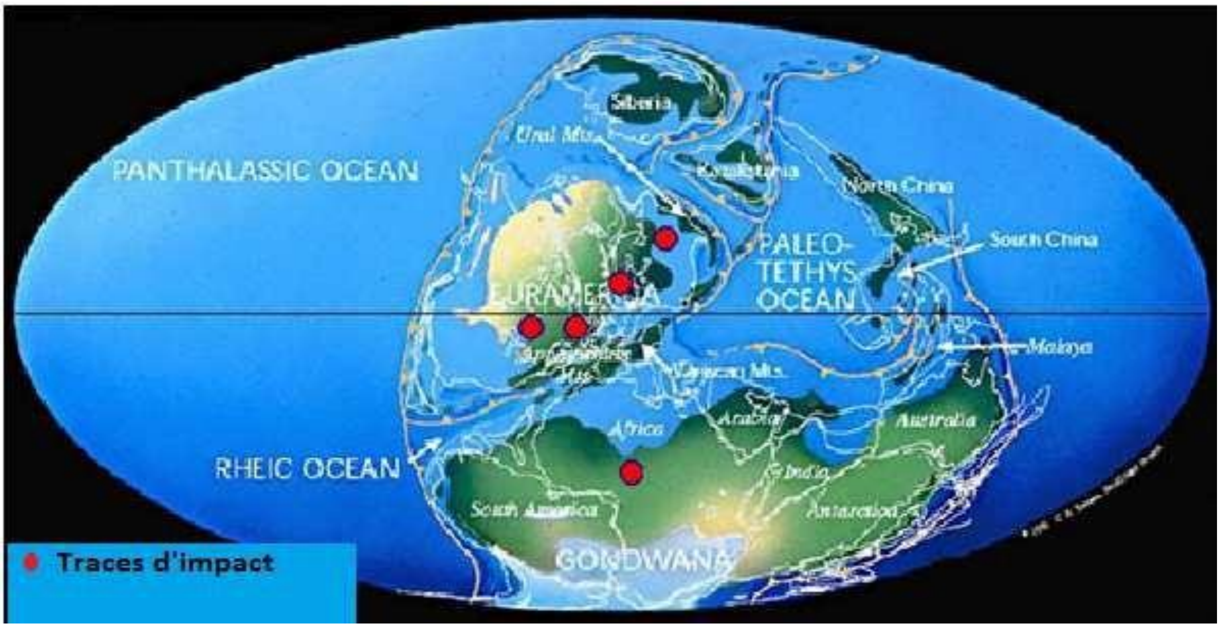

Fig. 13: Map Devonian meteoric impact tracks (Scotese, 1997).

II.4.2 Heat and anoxia in marine waters

At the Frasnian period, the global climate was warm, without glaciation. Sea levels are very high, as is the temperature. The maximum transgression was reached at the end of the Frasnian, with dysoxic waters. In these warm waters, oxygen dissolution was very low. With the warm climate prevailing throughout the planet, there is no marked latitudinal currentology. These two factors mean that there was no decomposition of organic matter in the oceans. At the same time, a planktonic bloom occurs. This is linked to the development of coastal vegetation, which increases root biomass; the flow of nutrients assimilated by algae then also increases, leading to an explosion of phytoplankton, eutrophication of the waters and destruction of the benthos.

- **Famennian cooling and regression**

At the base of the Famennian, the global climate cooled very rapidly, with the establishment of an extensive ice cap over northwestern Gondwana. Psychrospheric Ostracod faunas, markers of the deep cold currents of the Famennian, reappeared. They testify to a return to thermal stratification of the oceans.

- **Expansion of vascular plants across continents**

The development and expansion of more deeply-rooted vascular plants, including trees, on the continents during the Devonian period increased the weathering phenomena and pedogenesis, with the creation of thicker soils. During erosive episodes, these soils and their organic elements (plant debris, bacteria, fungi) reach continental shelf basins or depressions, creating eutrophic environments (enclosed waters enriched with nutrients) that stimulate toxic algal blooms.

This leads to the formation of anoxic zones virtually devoid of life, and the sedimentation of black clays rich in organic matter. In addition, the increased weathering of rocks, and silicates in particular, will enable the fixation of a large proportion of carbon dioxide.

Black clays deposited in anoxic environments are found at all three Devonian extinction peaks.

II.5 Conclusion

Two main events took place in the Devonian period:

- asteroid impacts;
- climate change and land plant expansion.

The late Devonian extinction is ecologically selective. It mainly affected reef and tropical environments and, more generally, shallow marine environments on continental shelves that were highly sensitive to the frequent fluctuations in sea level during the Upper Devonian.

This Upper Devonian extinction led to the disappearance of 19% of families and 35-50% of genera of marine animals.

The rate of extinction of marine animal families during this series of biological crises in the Upper Devonian, lasting around 10 to 20 Ma, is of the order of 8 to 10 families per million years,
i.e. double the "normal" rate of extinction in the Paleozoic, excluding extinction periods, which is 4 to 5 families per million years.

Summary of the Upper Devonian crisis

Crisis	**Upper Devonian**
Age (Ma)	-360 à -
Number of phases	3
Duration	10 to 20 Ma
Groups showing disappearances	Reef builders
Affected groups	Bryozoans Trilobites Ostracods Brachiopod s
Cause s	Asteroid impacts Maximum heating and anoxia Rapid cooling and regression

THE PERMIAN-TRIASSIC CRISIS

III. THE PERMIAN – TRIASSIC CRISIS

III.1 Introduction

The Permian-Triassic crisis, also known as the Permian-Triassic extinction event or the Great Dying, was the most severe mass extinction event in Earth's history. It occurred around 252 million years ago, marking the boundary between the Permian and Triassic geological periods.

III.2 Biological events

A. Biological events in the marine environment

In the marine environment (Fig. 14), 50 to 57% of families and 70 to 83% of genera present in the Permian disappeared in the Triassic.

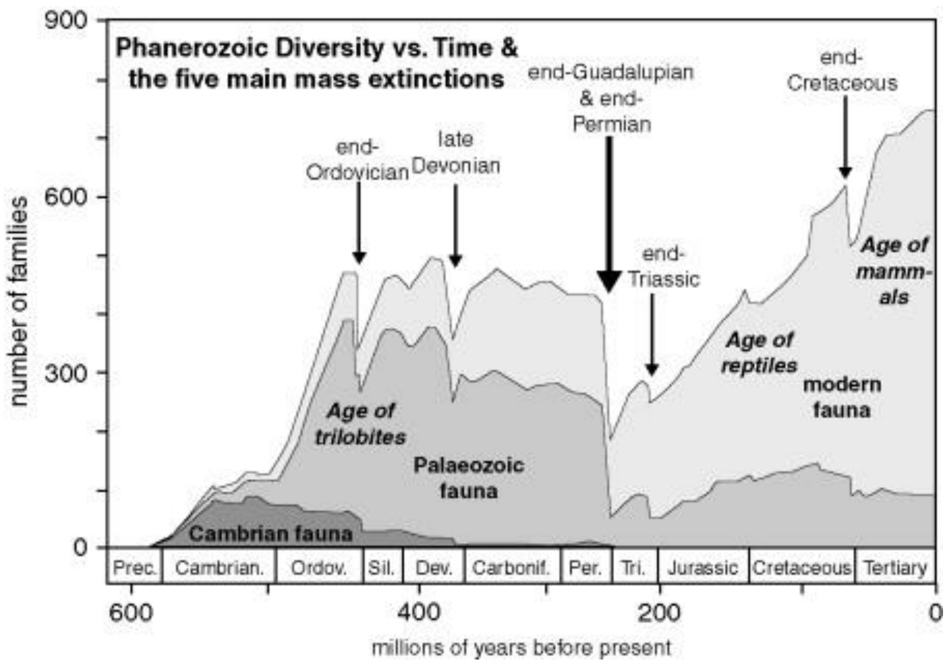

Fig. 14: Variation in the number of marine families over geological time (Sepkoski, 1986).

- Trilobites, tabulates, tetracoralliarids and some foraminifera disappear.
- Ammonoids have been decimated (-98% of species).
- 90% of brachiopod genera disappear (fig. 20) and 98% of echinoderm families die out. 75% of bryozoan families are eliminated.

Overall, the maximum percentage of species lost in the marine environment was between 85% and 96%.

- **Groups that disappear completely**

Trilobites (arthropods) (fig. 15): this group reached its peak in the Lower Ordovician and has been declining since. Only one family remains from the Middle Permian. It's a gradual extinction and a final blow to a class at the end of its life.

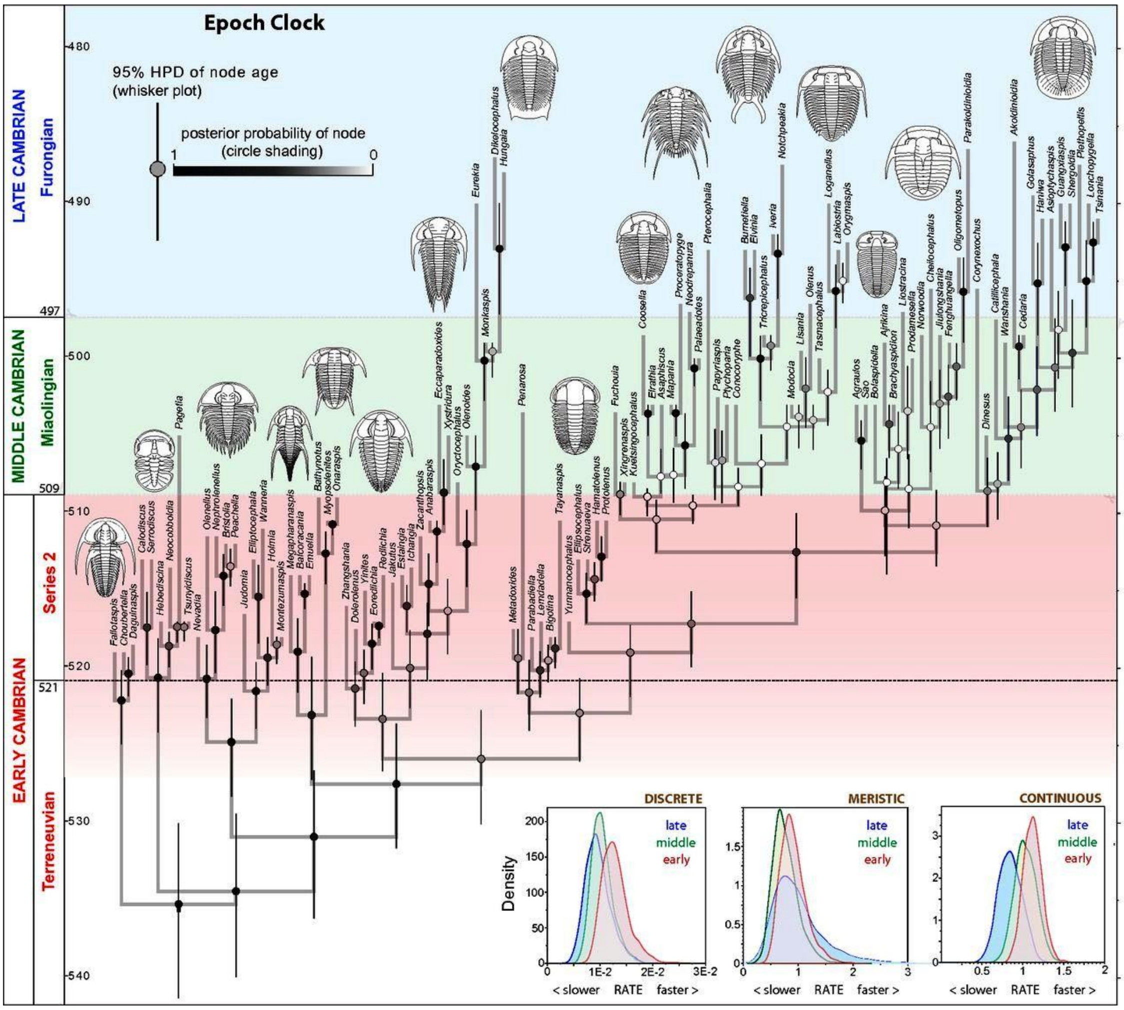

Fig. 15: Evolution of the number of Trilobite families from the Cambrian (Paterson et al., 2019).

- Fusulins (large benthic foraminifera): after a rapid decline during the Upper Permian, fusulins disappeared completely at the PERMIAN-TRIASSIC. As with the trilobites, this is also a gradual extinction with a final blow to the PERMIAN-TRIASSIC.
- Corals: in coral-rich Upper Permian deposits (South China), no gradual extinctions were observed. The reef environment disappeared from the seas during the Lower Triassic. The roughs and tabs disappear completely and brutally. For this group, it's a **brutal event**.
- Ostracods (micro-crustaceans) disappear completely and suddenly. For this group, it's a **brutal event**. Ostracods (bivalve micro-crustaceans) with a straight dorsal edge (Palaeocopes) became extinct shortly after the boundary.

1. Groups extinction without disappearing

- Cephalopods: they underwent a large number of extinctions, but later redeveloped.
- Brachiopods: highly diverse and abundant in the Upper Paleozoic. During the Upper Permian and Basal Triassic, this group lost 50 families, or 90% of genera.
- Echinoderms: they reached their peak during the Carboniferous. They declined considerably during the Permian. After a bottleneck at the Permian-Triassic boundary, they proliferated again, starting in the Jurassic.
- Crinoids show a bottleneck transition; 42 families disappear, or 98%, and only one genus survives into the Triassic.

Among the echinoids, only the *Miocidaris* genus survives, ensuring the descent of all Meso- Cenozoic echinoids.

- Bryozoans: there was a bottleneck in the Lower Triassic after a gradual decline in the Upper Permian, when 75% of families disappeared.
- Plankton: moderately affected, but with a drop in diversity among radiolarians (fig.16) (siliceous microorganisms) and acritarchs (microorganisms with organic walls).

In the case of radiolarians, the brutality of the event remains to be proven. After a halt in siliceous sedimentation in the Basal Triassic, the explosion of biodiversity in this group during the Lower Triassic is far more spectacular than the extinctions that occurred at the height of the Permian.

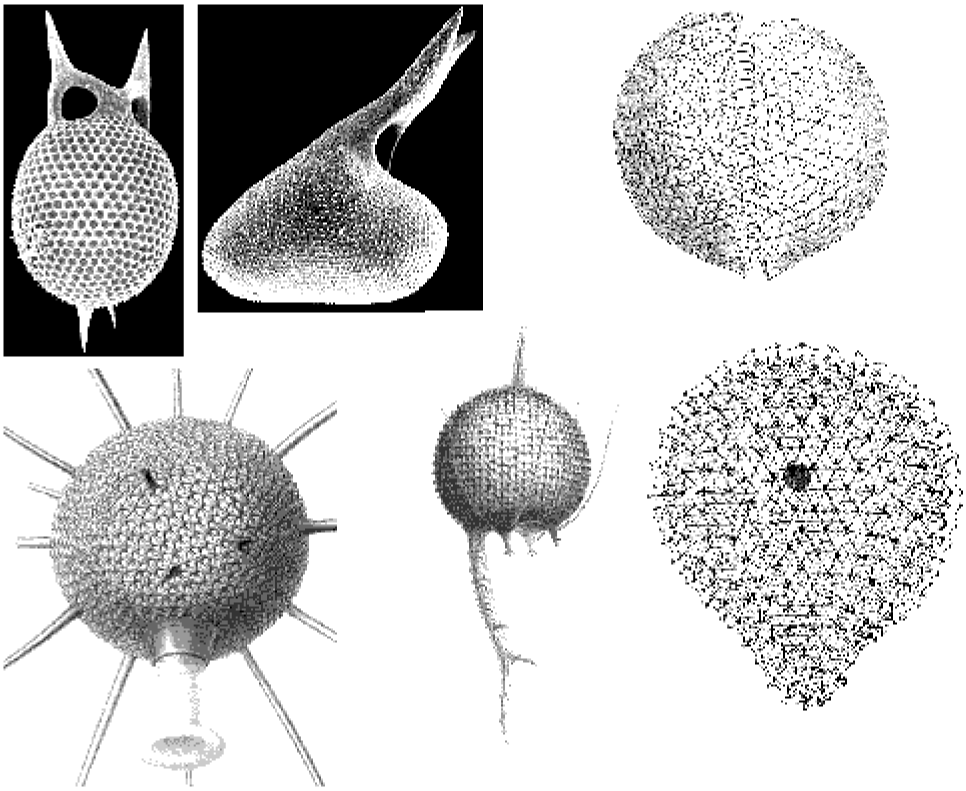

Fig. 16: Examples of radiolarians.

- Gasteropods: after a gradual decline in the Upper Permian, they seem to have disappeared by the PERMIAN-TRIASSIC.
- Bivalves and foraminifera, other than fusulins, appear to be little affected by permian-triassic events, although their populations are declining considerably in terms of the numbers of specimens.

B. Biological events in continental environments

- The large-leaved Permian flora (e.g. Pecopteris and Glossopteris), adapted to warm, humid environments, gave way to a new, cosmopolitan and undemanding coniferous flora. The swamp flora that had dominated throughout the Carboniferous and Permian periods disappeared in the Lower Triassic. Gymnosperms decline sharply above the limit, there is a reproduction of fungi associated with a high level of plant debris.

- Vertebrates have been hard hit: 70 to 77% of terrestrial vertebrate families have disappeared.

Small vertebrates are less affected. Freshwater reptiles are not affected and are diversifying. The mass extinction of PERMIAN-TRIASSIC is clear-cut and intense, especially in the marine environment. It is undoubtedly the most serious mass extinction on Earth: over 90% of all species have disappeared, both on land and in the oceans. We therefore need to analyze the global events likely to have caused this biological extinction.

III.3 Geological events

There is no proven asteroid fall:

- iridium "discovered" in China has never been found since;
- no impact crater;
- the rare shocked quartz found may have terrestrial (volcanic) origins;
- the origin of rare spherules is highly controversial.

In the Permian, a single continent (=Pangea) was formed by two branches (fig. 17; 18):

- to the south: **Gondwana** ;
- to the north**: Laurasia.**

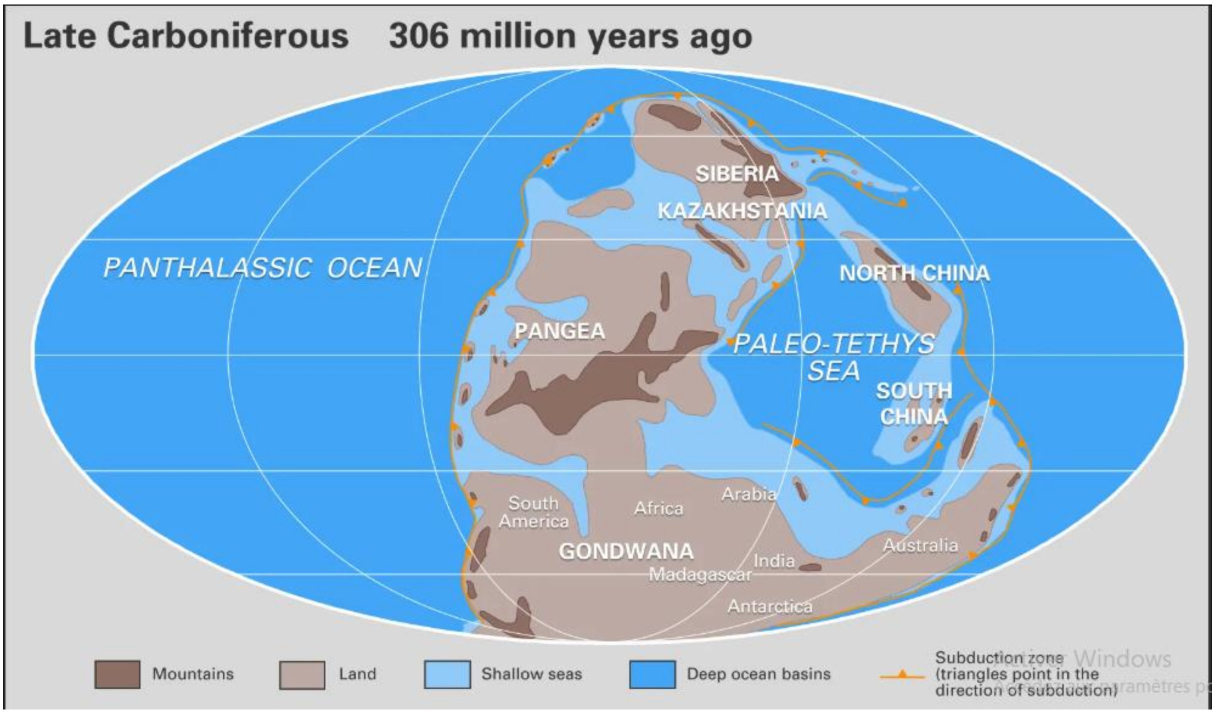

Fig. 17: Late Carboniferous paleogeographic map -306Ma (Scotese, 1997)

Fig. 18: Formation of Pangea during the Permian-255Ma (Scotese, 1997).

On this unique continent, six events follow one another:

1) climate change in the Lower Permian;
2) regression and formation of Pangea in the Late Permian;
3) lower salinity in the Upper Permian;
4) volcanism at the P-T boundary;
5) methane release in the Basal Triassic;
6) transgression with dysoxia in the Basal Triassic.

A. Global climate change

Between the Middle Carboniferous and Upper Triassic periods, the climate changed completely. A climate with glaciation gave way to an arid climate without glaciation.

- In the Lower Permian, the climate was one of glaciation.
- We pass into the Lower Triassic period without glaciation: this results in black clays and coal.
- In the Upper Permian and Triassic, we find red detrital layers (typical of desert climates) and evaporites. The trend towards aridity becomes more pronounced, especially between the Permian and Triassic periods: the climate shifts, becoming warmer and less contrasted between the poles and the equator. Deserts developed and, in particular, the humid equatorial zone became more arid.

✓ **Facies data**

In the Northern Hemisphere, Upper Carboniferous - Lower Permian argillites and coals are replaced by semi-arid red detrital series. In the southern Urals, for example, the Upper Permian and Triassic are represented by thousands of meters of red sediments.

South of Gondwana, a great glaciation reached its peak in the Upper Carboniferous. In the Lower Permian, glaciation persisted in the form of smaller ice caps. The last traces of glaciation lasted until 7Ma before the end of the Permian in Australia (fig. 19).

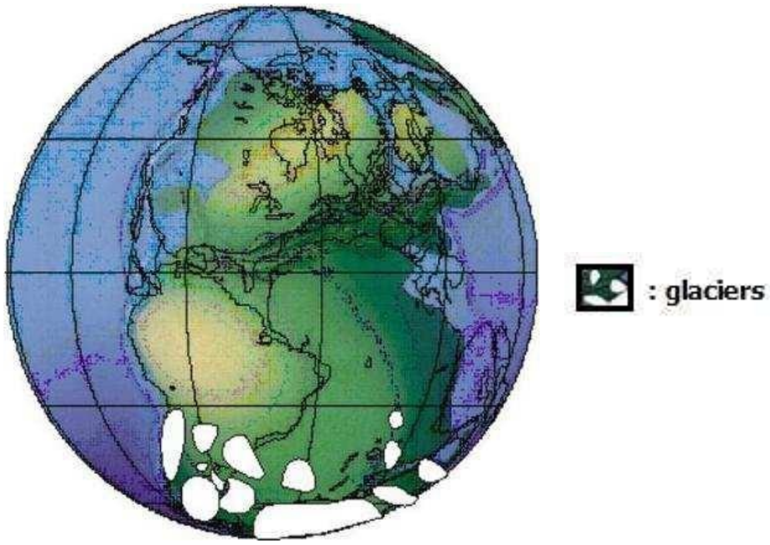

Fig. 19: Position of the last glaciers in the Late Permian (Lethiers, 1998).

Today's ocean is stratified into two layers:

- A variable-temperature upper layer known as the thermosphere;
- A lower layer at a constant temperature of 4-6°C, known as the psychrosphere.

The disappearance of the glaciers completely altered the ocean circulation system, eliminating the cold bottom waters of the Triassic period and the psychrosphere.

✓ **Climate models**

All models point to an evolution towards aridity. Indeed, from the LPT onwards, the climate becomes more continental, with very hot summers and very cold winters.

From traffic of mega-foams, operating all year-round, bring of the eastern edge of

Pangea.

Excessive warming of the seas in the Lower Triassic period favored dysoxic waters (warm waters do not dissolve oxygen well).

✓ **The causes of climate change**

In addition to the Earth's orbital variations, which are probably the main cause of these major climatic upheavals, geological events will support these trends: the final formation of Pangea (a continentalization of the global climate), the northward drift of the continents, rising atmospheric CO_2 levels and the decline of coastal environments with high biomass.

B. Marine regression in the Upper Permian

In the Upper Carboniferous-Lower Permian period, sea levels were raised by the melting of the ice caps and the expansion of the oceans.

During the Late Permian, sea levels dropped by 250 vertical meters, with the lowest level ever at the LPT, uncovering a very large part of the continental shelf. The best hypothesis to explain the origin of this regression is a halt in oceanic expansion for around 20Ma during the Permian.

➢ The Paleozoic and Mesozoic oceanic expansion systems are separated by a kind of "time- out" in mantle activity.

➢ Collapse of the ocean floor induces negative tecto-eustatism.

➢ Geophysical calculations show a close down in expansion, and therefore in ridge activity, for 10Ma.

The increase in continental surface area will produce climatic changes, erosion and oxidation of carbon, and a rise in CO_2. Numerous neritic benthic groups disappear and biomass falls.

The end of the formation of Pangea produces a supercontinent whose surface area is increased by the great regression. When the continents come together, the habitat of the continental shelves is lost. This continentalization leads to climatic degradation, as the buffering effect of the oceans is eliminated. The climate of the late Permian was characterized by high temperatures, marked seasonal alternation and severe storms. Pangea shifted northwards by 15° latitude from the Permian to the Triassic. This accentuated the rise in temperature over a large part of the supercontinent.

- transgressions-regressions are linked to the tectonic super-cycles "Pangea regrouping continent dispersal";
- emersion of Carboniferous and Lower Permian deposits that were rich in material plant. Organic carbon is oxidized, releasing CO_2 into the atmosphere and poisoning organisms;
- reduction of epicontinental surfaces, which increases the drop in biological productivity and the disappearance of ecological niches favorable to life release in marine salinity subsiding epicontinental basins, located in warm climatic zones, are the site of thick evaporitic deposits (Fig. 20), due to the evaporation of inland seas abandoned by regression.

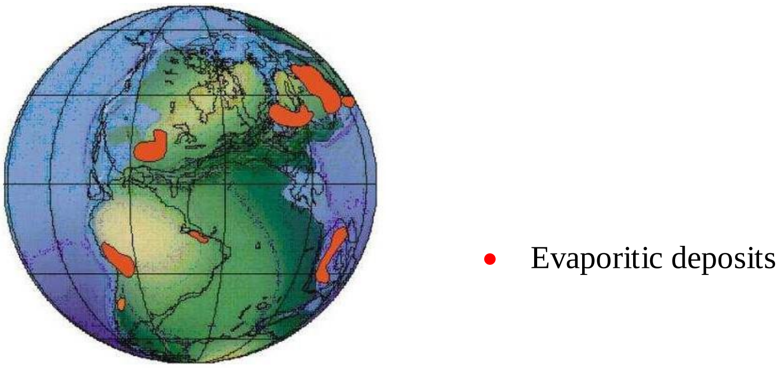

Fig. 20: Schematic distribution of the main Upper Permian evaporitic deposits (Durand, 1978).

- Stenohaline organisms, which can withstand only slight variations in salinity, are the first and most intensely affected (fusulinae, trilobites, corals, echinoderms, cephalopods).

- Euryhaline organisms gastropods, bivalves, etc.) can resist to the variations in salinity. (*Claraia*, inarticulate brachiopods - *Lingula*, some filter-feeding ostracods) cross the boundary.

C. VOLCANISM

1. **Siberian traps** (fig. 21)

Around -250 Ma, intense volcanism occurred on a very large scale: the Siberian traps, with an outcrop surface area of $2.5.10^6$ km²; it is estimated that the initial surface area was probably of km^2 and thickness of over 3 kilometers (fig. 21).

11 major eruptions have been identified at the boundary between the Permian and Triassic periods, over less than a million years (fig. 22).

Fig. 21: photos of Siberian Trapps.

Fig. 22: Supposed location of the Siberian Traps (Zolotukhin and Mukhamedov , 1998).

2. Consequences of volcanic eruptions

Initially, the ash obscured the sky, leading to short-term cooling. Huge quantities of SO_2 and sulfate aerosols were released, causing acid rains. This most certainly affected higher plants and insects.

The CO_2 associated with all volcanism produces a greenhouse effect that leads to warming of 4 to 5°C. A 5°C rise in temperature is not enough to explain the scale of the extinctions, but a 5° rise in ocean water temperature will destabilize unstable gases and darken the sky (dust).

D. Gas release

- Methane (CH_4)

Organic matter is deposited on the ocean floor and incorporated into sediments. Under the action of anaerobic bacteria, the organic matter is transformed into methane in the first few hundred meters of the sedimentary pile. A very large volume of methane is thus produced.

Within a well-defined range of temperature and pressure, some of this methane combines with water molecules to form a gas hydrate. Under specific pressures and temperatures, ice (H_2O) can form a kind of cage, trapping gas molecules. The resulting compounds are known as gas hydrates or clathrates (fig.23).

Fig. 23: Methane bubbles trapped in a frozen pond.

- Hydrogen (H_2S)

The ocean is in chemical equilibrium when no particular event disturbs its order. The chemocline is the interface between different layers of water when they do not mix. This implies that there is an equilibrium between the different water layers. In general, surface water layers are more oxygenated than deeper ones, since they are fed by the atmosphere. Anoxia in the lower layers may be caused by the high production of hydrogen sulfide by benthic micro-organisms.

The steps involved in destabilizing hydrogen :

1) volcanism, seen above, will release CO_2 and CH_4. The amount of methane released can be increased by clathrate melts;
2) As we have seen, water temperatures can rise by as much as 10°C;
3) as ocean temperature rises, the amount of dissolved oxygen decreases. Warm waters dissolve less oxygen than cold waters;
4) this will destabilize the chemocline or equilibrium zone between O_2 and H_2S ;
5) the hydrogen released into the water will rise;
6) This will lead to a proliferation of sulfur bacteria;
7) hydrogen released into the atmosphere devastates the continental environment and destroys the ozone layer;
8) UV rays are no longer filtered out, destroying the remaining life.

E. Transgression with dysoxia

At the base of the Triassic, a sudden and considerable transgression took place. In just a few thousand years, the water level rises by 210 meters, thanks to the creation of new expansion zones.

The incoming water is warm and laden with CO_2, which reduces the solubility of O_2 in water; this is poorly oxygenated (dysoxic) water that will transgress onto the continents through the anoxia of surface waters; these conditions are unfavorable for marine life.

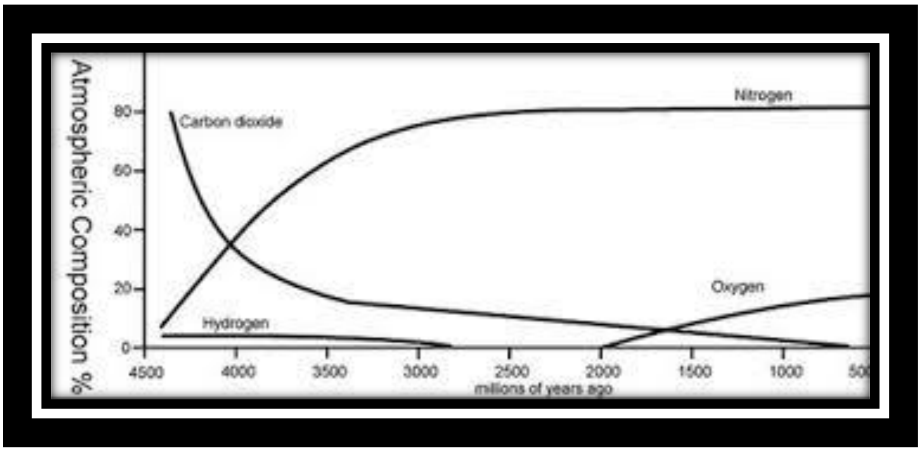

Fig. 24: Evolution of the percentage of oxygen in the atmosphere (Berner, 2003)

- **Causes**

❖ Transgression

- Resumption of dorsal swelling: positive tecto-eustatism;
- General warming: positive thermo-eustatism.

❖ Dysoxia

- advancing shores filmy seas with still waters;
- The high temperature prevents O2 from dissolving in abundance;
- The water at high latitudes is warm, and deep circulation slows down, thus slowing down the entire marine circulation system.

III.3.1 Conclusion

The Upper Permian saw the development of conditions unfavorable to life, with climatic changes, marine regression, a shrinking marine environment and falling salinity.

At the Permian-Triassic boundary, a new unfavorable condition is added by intense volcanism that disrupts vegetation, and a new ordeal befalls this weakened biosphere: at the base of the Triassic, a transgression of poorly oxygenated waters. The Basal Triassic was a time of brutal asphyxiation of the last remaining diverse communities (corals).

The lack of water oxygenation throughout the Lower Triassic is surely the main reason for the delay in recovery. Slow post-event recovery is one of the hallmarks of the Permian-Triassic crisis.

None of these factors alone could have caused such a major extinction. It was the combination of all these factors that brought about this great biological crisis. In this crisis, the Earth's internal dynamics played a major role.

The dynamics of the solar system, and the variation in Earth's orbit, could have influenced the climate.

This permian-triassic mass extinction occurred progressively over 200,000 years to 1Ma, with high mortality concentrated over 20,000 years. The biosphere was devastated: coniferous forests, tree ferns, giant amphibians, sea scorpions, trilobites... were all decimated. We speak of ecocide (the systematic and total destruction of an ecosystem, whether natural or man-made).

Numerous sedimentary and geochemical records attest to major environmental disturbances throughout the Lower Triassic (the five million years following the mass extinction): anomalous carbon cycle, acidic oceans, depleted of oxygen and enriched in carbon dioxide and sulfides.

For 20 million years, the Earth remained virtually barren and toxic: the oceans were practically devoid of oxygen, as was the atmosphere. A few species survived, including small, hardy reptiles known as diapsids: they replaced the therapsids (mammalian reptiles) and formed the lineage of the famous dinosaurs.

It would be 30 million years before biodiversity returned to pre-crisis levels. Although life almost became extinct, this extinction enabled the new life forms that followed to diversify in an unprecedented way.

Summary of the Permian-Triassic crisis

Crisis	**Permian - Triassic**
Age (Ma)	-251
Number of phases	1
Duration	200,000 to 1 Ma
Groups showing disappearances	Trilobites Fusulines Corals Ostracode
Affected groups	Cephalopod s Brachiopods Echinoderms Bryozoans Plankton Gastropods
Causes	Climate change Regression and formation of Pangea Lower salinity Volcanism Gas release Dysoxic transgression

THE TRIASSIC-JURASSIC CRISIS

IV. THE TRIASSIC-JURASSIC (T-J) CRISIS

IV.1 Introduction

The Triassic-Jurassic extinction, which took place worldwide around 200 Ma ago, is one of five major mass extinctions over the last 500 Ma. This long crisis spanned almost 20 Ma, beginning in the Upper Triassic and ending at the Triassic-Jurassic boundary.

In the Triassic, the globe's paleogeography (fig. 25) was still close to that of the Permian: Pangea remained undivided and had reached its maximum extension; the central Atlantic had not yet begun to expand, and the Tethys only incompletely separated Gondwana and Laurasia to the east.

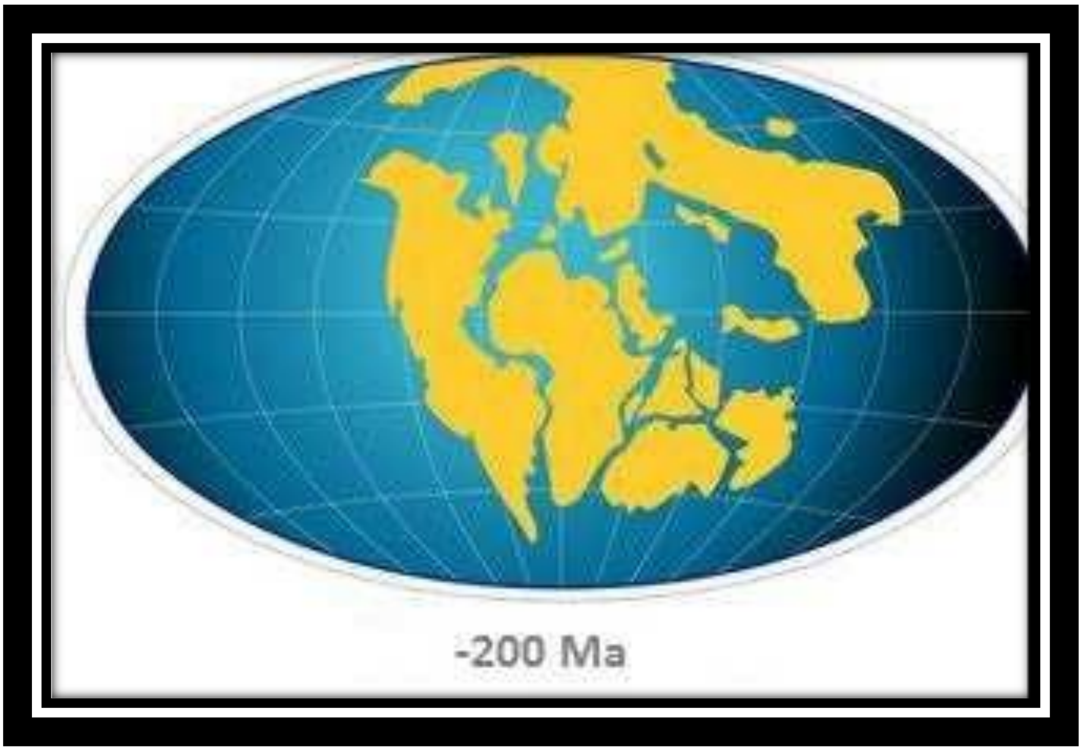

Fig. 25: Paleogeographic map of the globe at the end of the Triassic period.

Early Jurassic (fig. 26): Pangea, the only supercontinent to emerge from Paleozoic and Triassic history, begins to be fragmented by rifting mechanisms as early as the Liassic, particularly at the site of the future Central Atlantic.

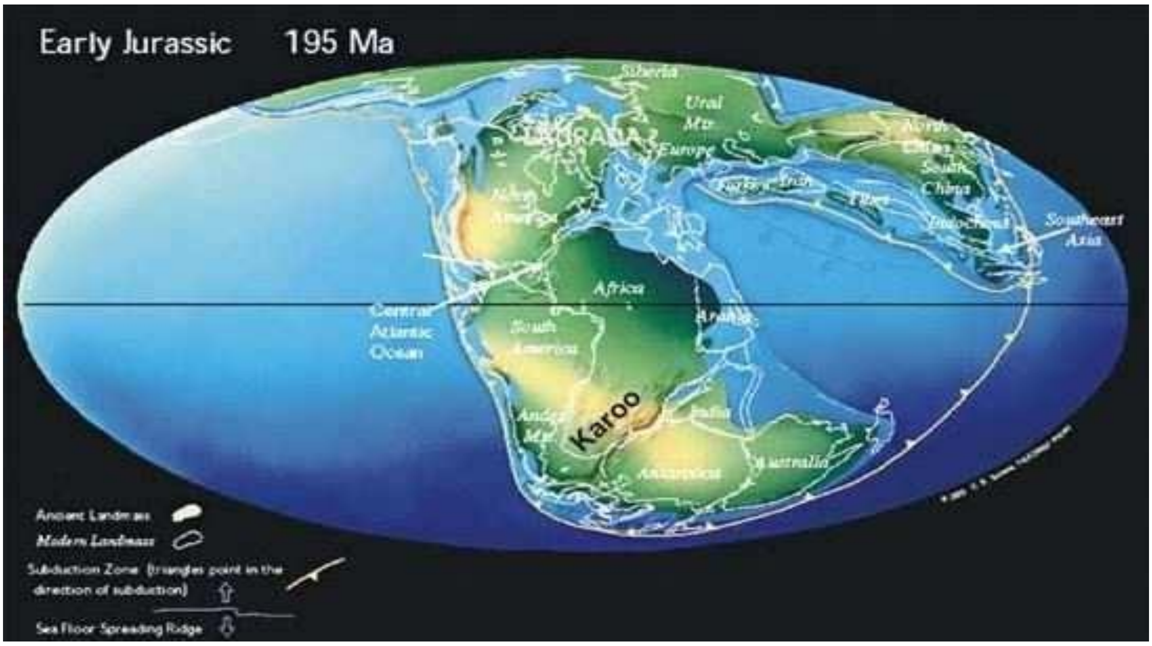

Fig. 26: Paleogeographic map of the globe at the beginning of Jurassic (Scotesse, 1997).. Biological events

IV.1.1 Biological events in the marine environment

It is estimated that three-quarters (3/4) of marine species became extinct at the Triassic-Jurassic boundary.

1. Invertebrates

Important groups desappeared, such as the conodonts, ceratites and Orthocerida.

These last two groups belong to the Ammonoid family, which were represented only by Phylloceratida lineage (ammonites), and crosses the T-J boundary with low diversity. The other groups (lamellibranchs, gastropods, brachiopods, echinoderms, bryozoans) are also affected in different ways.

- Many ammonite species disappeared but not to point of total extinction, which only occurred at the end of the Cretaceous.
- Almost total disappearance of the reef environment.

On the platforms, lamellibranchs dominate over the brachiopods that had previously dominated until then, thin-shelled lamellibranchs characterize pelagic environments.

2. The vertebrates

Concerning vertebrates, different groups of marine reptiles diversified during the Lower and Middle Triassic. Sauropterygians and ichthyosaurs are known from the end of the Lower Triassic. Most reptiles were adapted to a coastal lifestyle. This is why, during the regression of the Upper Triassic, only those forms particularly adapted to life on the open sea (ichthyosaurs and plesiosaurs) were able to survive.

- Ichthyosaur reptiles passed through this period without any damage before diversifying.
- Other marine reptiles (placodonts and nothosaurs) have also been badly affected.
- Extinction of placodont fish.

Green algae (dasycladales) proliferate and phytoplankton begin to develop.

IV.1.2 Biological events in continental environments

1. The Fauna

The transition from the Triassic to the Jurassic is marked by a major change in vertebrate fauna. The end of the Triassic saw the decline of terrestrial faunas: Dicynodonts (herbivorous mammalian reptiles), Rhynchosaurs (herbivores) and pseudosuchians (carnivores) disappeared, while Cynodonts (carnivorous mammalian reptiles) and Thecodonts became rarer. This crisis marked the second decline of the Therapsids, whose last representatives died out in the Middle Jurassic. The ecological niches freed up were rapidly invaded by the surviving species.

In particular, dinosaurs were minorities that spread and diversified into carnivores and herbivores species of all scales

At this time, bipedal dinosaurs were well known. carnivores and the first herbivorous dinosaurs, precursors of sauropods such as the prosauropod, *Plateosaurus* (Terminal Triassic of Europe) (fig. 27).

Fig. 27: Herbivor sauropod.

At the same time, small primitive mammals developed (Late Triassic, Early Jurassic), followed by multituberculates and marsupials, which became numerous during the Cretaceous.

A parallel evolution also exists in avian forms. *Archaeopteryx* (intermediate between birds and reptiles) (fig. 28) lived at the Jurassic (- 140 Ma). The aerial environment then saw the development of toothed birds (-80 Ma).

Fig. 28: *Archaeopteryx* or toothed bird.

2. Flora

The Jurassic flora is dominated by gymnosperms, which reach their apogee. Calcareous nannofossils (coccolithophorids, unicellular green algae), which appeared at the end of the Triassic, developped considerably during the Lias.

IV.2 Geological events

The scientific community recognizes two proven events that may be responsible for this extinction. These are :

- a meteorite impact;
- active volcanism: Central Atlantic Magmatic Province (CAMP).

A. Meteorite impact

- Towards the end of the Triassic or the beginning of the Jurassic (-201 MA), a meteorite 0.8 to 1.5 km in diameter, with a mass of 1 to 6 billion tonnes, struck the ground of our planet, around 4 km west of the present-day town of Rochechouart in France (fig. 29). Its pre-impact speed is between 20 and 50 km/s.
- The energy released is colossal: 1.2 x 10^{21} joules, a thousand times the energy dissipated by the most violent earthquakes recorded by man, the equivalent of 300,000 megatons of TNT, 14 million times the Hiroshima bomb! Around 13 km^3 of immediately underlying rock was vaporized. A volume of 66 km^3 of the basement was melted, enriched by the meteorite and ejected. Colossal quantities of rock are broken up and ejected.
- The basement is transformed, and deeply fractured. A crater, some 23 km in diameter, is formed in about a minute. Meteoritic metallic vapors condense, generating fine particles that fall back, mixing with terrestrial ejecta.
- All traces of life are eliminated within a 500 km radius by the blast effect, the fiery

cloud and the emission of toxic fumes.

- Very deep, hot, highly mineralized water rushes through the deep fissures and up through the fractures to the midnight-blue clayey microbreccia horizon, formed by melting under the impact, and which now forms the floor of the crater.
- Rock debris consolidates, and fallout forms further breccias. The maximum thickness of all these breccias reaches 300 m.
- The final fall out of debris and dust forms kinerites on the crater's surface but the sea very quickly overlies the astrobleme (set of rocks the consequences of an impact, the crater is just one of the components of the astrobleme).
- Since ancient times, people in the region have opened quarries to extract minerals. Magnificent building materials. Now it's time to make some specific observations, in all three dimensions, from the crater itself to its base. Everything can be observed in place, and in breaches, floor, but cutting. Everything can be seen in three dimensions: cinerites, too, base transformed by the formation of bechic veins, by formation of the glassy-looking mylonites known as pseudotachylites, by simple fracturing, and finally the basement that withstood the phenomenal impact.

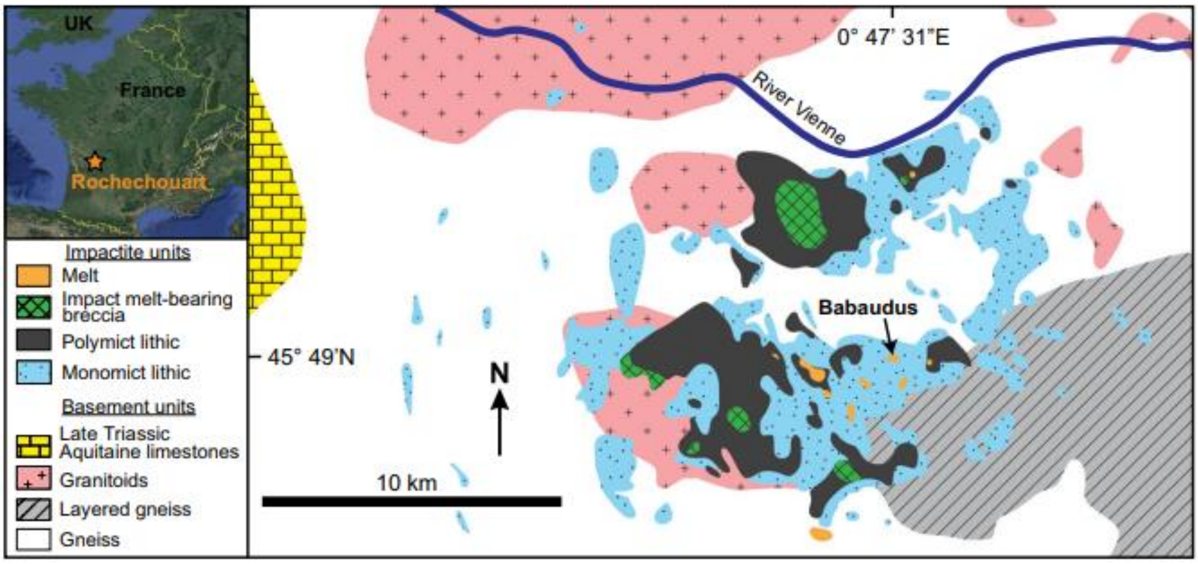

Fig. 29: Map of Rochechouart impact structure (Cohen et al., 2017).

B. Volcanism active: Central Atlantic Magmatic Province (CAMP)

Significant magmatic activity accompanied the initial fragmentation of Pangea, leading to the opening of the Central Atlantic at the beginning of the Jurassic. This activity is at the origin of the largest continental magmatic province, covering more than seven million square kilometers, known as the Central Atlantic Magmatic Province (CAMP). As a result of continental break-up and the opening of the Atlantic Ocean, the remnants of the CAMP are now scattered over four continents: North America, South America, Africa and Europe. However, the geographical limits of the province are still poorly understood, particularly on the African plate, where magmatic rocks were emplaced more than 1,000 km from the Atlantic margin. 40Ar/39Ar dating of CAMP in Algeria (Chabou et al., 2007; fig. 30), Guinea and Mali shows ages between 190 and 202 Ma, with a peak in magmatic activity around 199 Ma.

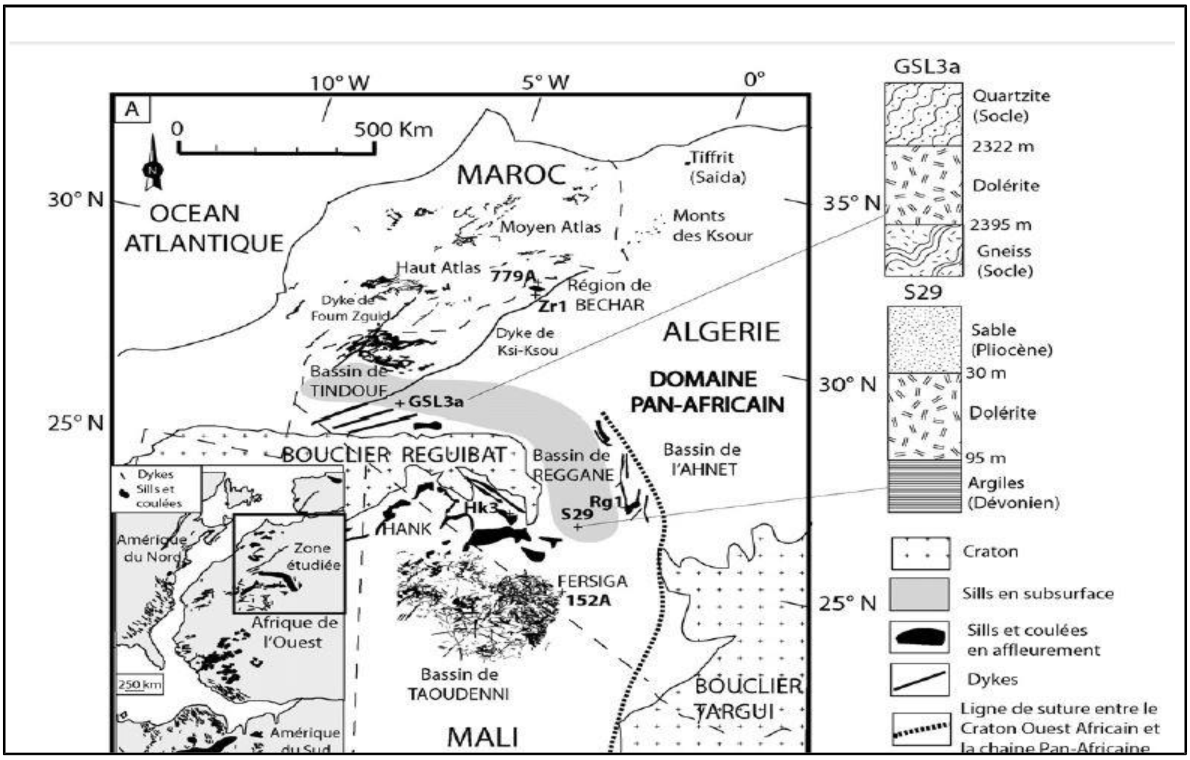

Fig. 30: Map showing CAMP magmatic formations in northwest Africa and location of 40Ar/39Ar- dated samples(Chabou et al., 2007)

The Triassic-Jurassic crisis was therefore mainly caused by volcanism linked to the break-up of Pangea, with a possible aggravating factor: meteorite impact.

IV.3 Conclusion

The Triassic-Jurassic extinction, occurring just 50 Ma after a major event, the Permian-Triassic extinction, around 250 Ma ago, is often seen as paving the way for dinosaur dominance. Indeed, before this mass extinction, dinosaurs represented only around 1-2% of the Earth's fauna, but afterward, as they took over the niches of extinct species, they made up around 50-90% of terrestrial fauna.

Some paleontologists call the Triassic-Jurassic extinction the second-largest mass extinction.

Synthesis of the Triassic-Jurassic crisis

Crisis	**Triassic-Jurassic**
Age (Ma)	-200
Level importance /5	2
Number of phases	1
Duration	1 to 2 Ma
Groups showing disappearances	Conodonts Ceratites Orthocerida Placodont fishes Dicynodonts Rhynchosaurs Pseudosuchians
Affected groups	Lamellibranchs Gastropods Brachiopods Echinoderms Bryozoa
Causes	Meteoric impact Intense volcanism

THE CRETACEOUS-TERTIARY CRISIS

V. THE CRETACEOUS-TERTIARY (K-T) CRISIS

V.1 Introduction

65 Ma ago, in the Late Cretaceous, life on Earth was diverse, as favorable conditions prevailed on its surface. However, the end of the Upper Cretaceous was marked by a sudden mass extinction of part of the biosphere, as evidenced by paleontological data: the Cretaceous-Tertiary K-T crisis.

It's one of the most widely recognized biological crises in history, creating an end to the reign of the dinosaurs. With them disappeared part of the marine plankton, ammonites and almost all deep see inhabitants. Surprisingly, most mammals, birds, turtles, crocodiles, lizards, snakes, fish, some corals and amphibians were only slightly affected.

Numerous causes have been proposed forward to explain the K-T crisis, which saw the spectacular extinction of the dinosaurs. Some examples include an explanation given by creationists.

The catastrophist explanation of a mega-meteorite impact has been revived (Alvarez et al; 1980) new data have been acquired and it is no longer possible to doubt the reality of this impact. However, opinions differ as to whether this impact was responsible for the mass extinction of the K-T boundary.

V.2 BIOLOGICAL EVENTS

The climate from the Jurassic to the Cretaceous is mild, and therefore favorable to the development of the biosphere in both continental and aquatic environments:

- Foraminifera and Coccolithophoridae are very abundant and make up the plankton, the first link in the trophic chain;
- real forests are formed by the proliferation of Ferns, Bennettitales and Gymnosperms (Conifers);
- Invertebrates are very numerous, with corals, sea urchins, molluscs, especially Rudists (bivalves) and above all Ammonites and Belemnites, cephalopods characteristic of pelagic and deep-sea environments, crustaceans and insects;
- Vertebrates also flourished: in particular, Archosaurians and their Dinosaurs, who dominated all ecological niches with their omnipresence: phytophagous and zoophagous terrestrial dinosaurs, and aerial Pterosaurs. Indeed, the secondary era is also known as the "Age of Reptiles", such is their dominance.

A. Biological events in the marine environment

The K-T boundary is associated with a particularly high rate of species extinction and appearance. This was particularly true of the nanoplankton that formed the basis of the Cretaceous limestone deposits. Many extinct species have been replaced by new ones. Statistical analysis of marine species extinctions suggests that the decline in diversity has been caused more by a sharp increase in extinctions than by a decrease in the appearance of new species, through the natural and permanent mechanism of speciation (Bambach et al.; 2004).

1. Marine invertebrates

- Ostracods, which were very common during the Upper Maastrichtian, have left fossil traces in a large number of locations (Hawramy et al., 2023). An examination of these fossils shows that ostracod diversity was lower during the Paleocene than at any other time in the Tertiary.

- Among Late Cretaceous corals, around 60% of genera belonging to the order of Scleractinia failed to cross the K-T boundary and reach the Paleocene. In-depth analysis of coral extinctions during this period shows that around 98% of colonial species that inhabited warm, shallow tropical waters became extinct. Solitary corals, which generally do not form reefs and inhabit colder, deeper regions of the ocean (below the aphotic zone), were less affected.

- Numbers of cephalopod, echinoderm and bivalve genera declined significantly after the K-T boundary; most brachiopod species survived and diversified in the early Paleocene.

    - ✓ Apart from the subclass *Nautiloidea*, all the other cephalopod species became extinct at the K-T boundary. Among these were the species of the superorder Belemnoidea and the ammonites, a subclass of univalve-shelled cephalopods, highly diverse, with numerous specimens and a wide distribution.
    - ✓ Around 35% of echinoderm genera became extinct at the K-T boundary.

Other groups of marine invertebrates, notably bivalves such as rudists and Inocera, also became extinct at the K-T limit (Macleod et al. 1997).

2. Marine vertebrates

Among fishes, approximately of the chondrichthyan families of sharks, rays and other cartilaginous fishes survived the extinction event. On the other hand, less than 10% of bony fish families, i.e. teleosts, became extinct. However, on Seymour Island, off the Antarctic Peninsula, a fossil site from the period immediately before the event shows evidence of a mass extinction of bony fish. It is thought that fish underwent environmental stress before the K-T boundary event and that this must have precipitated the mass extinction. However, it appears that marine and freshwater environments mitigated the effect of extinction on fish (Robertson et al.; 2004).

B. Biological events in continental environments

1. Terrestrial plants

There is dominant evidence for a global break-up of plant groups at the K-T boundary. However, there were significant regional disparities in plant succession.

In North America, the data suggest massive plant devastation at the K-T limit, although there were also substantial megafloral changes before the limit.

In the high latitudes of the southern hemisphere, such as New Zealand and Antarctica, the mass decay of the flora has caused no significant turnover in species, but dramatic short-term changes in the relative abundance of plant groups.

Due to the mass destruction of plants at the K-T boundary, there was a proliferation of detritivorous organisms such as fungi, which do not need photosynthesis and use the

nutrients from decomposing vegetation. The dominance of fungal species lasted only a few years as the atmosphere cleared and organic matter abounded. Once the atmosphere had cleared, photosynthetic organisms such as ferns and other plants returned (Peter et al., 2002).

2. Terrestrial vertebrates

a. Amphibians

There is no evidence mass extinction of amphibians at the K-T boundary, and most survived the event. Extensive studies salamander genera in Montana fossil beds show that of seven genera, six were unchanged after the event.

Amphibious survival resulted from the group's ability to seek shelter in the water or build burrows in sediment, soil, wood or under rocks (Bryant et al.1990).

b. Non-archosaur reptiles

The two living non-archosaur reptile taxa, testudines (turtles) and lepidosaurians (snakes, lizards and green lizards), as well as choristodera (semi-aquatic archosauromorphs that became extinct in the early Miocene) survived the K-T boundary.

Over 80% of Cretaceous turtle species crossed the K-T boundary. What's more, all six turtle families that existed at the end of the Cretaceous survived into the Tertiary and are represented by present-day species.

Living lepidosaurians include rhynchocephalia and squamates. The

Rhynchocephalia, which today include only Tuataras, were a widespread and relatively prosperous group of lepidosaurians in the early Mesozoic, but began to decline from the mid-Cretaceous onwards. Today, they are represented by a single genus found exclusively in New Zealand.

The squamate order, represented today by lizards, snakes and amphisbenes, radiated out into various ecological niches during the Jurassic and made it through the Cretaceous. They survived the K-T boundary and are currently the most successful and diverse group of living reptiles, with over 6,000 extant species. No known family of terrestrial squamates became extinct at the K-T boundary, and the fossil record indicates that they suffered no significant decline in numbers. Their small size, and their ability to change habitat to find more favorable conditions, were key factors in their survival during the late Cretaceous and early Paleocene (Brochu, 2004).

c. Archosaur reptiles

c.1. Crocodilians

Ten families of crocodilians or their close relatives are already represented in Maastrichtian fossils. While five became extinct before the K-T boundary, five other families have fossil representatives as far back as the Paleocene.

All surviving crocodilian families inhabited both freshwater and terrestrial environments, except for the Dyrosauridae, which were both marine and freshwater. The survival of crocodilians to these events may simply have resulted from the persistence of their aquatic niche and their ability to burrow, which reduced their susceptibility to the negative environmental effects of the K-T boundary (Brochu; 2004).

c.2. Pterosaurs

The only pterosaur family whose presence in the Maastrichtian period is certain, the Azhdarchidae, became extinct at the K-T boundary (Slack et al., 2006).

c.3. Non-avian dinosaurs

The extinction of the dinosaurs at the K-T boundary has generated more publications than any other group of organisms. With the exception of a few controversial claims, it is agreed that all non-avian dinosaurs became extinct at the K-T boundary. Since there is no evidence that late Maastrichtian non-avian dinosaurs could dig, swim or dive, they could not shelter during the worst of the environmental stresses that occurred at the K-T limit. It is possible that the smaller dinosaurs survived, but they would have been deprived of food as herbivorous dinosaurs would have found the plant material scarce, and carnivores would have quickly run out of prey. The growing consensus about the endothermic nature of dinosaurs helps to understand their complete extinction in relation to the survival of their relatives close relatives, the crocodilians. As crocodilians are ectothermic ("cold- blooded" animals), they have very limited food requirements (they can live for several months without eating), whereas similar-sized but endothermic ("warm-blooded") animals need much more food to support their faster metabolism. In the circumstances of the food chain breakdown, non-avian dinosaurs died while some crocodiles survived. In this context, the survival of other endothermic animals, such as some birds and mammals, may have been due, among other reasons, to their smaller food requirements, linked to their small size at the time of extinction.

3. Mammals

The mammal groups that exist today were already present in the Cretaceous, they were egg-laying monotremes, marsupials or placentals, as well as others extinct groups such as the multituberculates.

The mammalian species that existed at the K-T boundary were generally small, comparable in size to rats. In addition, it is thought that some primitive monotremes, marsupials and placentals were semi-aquatic or burrowing, as many mammalian lineages still exist. that have retained such behavior today. Finally, any semi aquatic or digging burrows would have had the additional protection against stress environment of the K-T limit.

V.3 Geological events

Three proven events that may be responsible for boundary extinctions (K-T):

- cosmic impact;
- intense volcanic activity;
- a strong marine regression.

These hypotheses are discuss independently of each other. In this way, one proof can be used to justify several hypotheses.

V.3.1 Cosmic impact

Since its appearance, the Earth has undergone numerous climatic changes. These changes have sometimes been the result of meteorite impacts, such as the one recorded at Chicxulub, Yucatan, Gulf of Mexico. This asteroid measured over 10 km in diameter, left a circular structure 180 km in circumference and penetrated the Earth's surface at a speed of 20 km /s. This asteroid had a number of irreversible consequences on the plant and animal life present on Earth in the K-T era, particularly in the impact zone, where all traces of life were instantly wiped out.

1. Evidence cosmic impact

a. Iridium peak

The first observation that led to the hypothesis of a catastrophe of cosmic origin by Luis and Walter Alvarez is the presence of a peak in iridium (Ir) at the level of the sediments that mark the passage of the KT limit (fig. 31). Iridium is a very rare platinoid in terrestrial materials (content of the order of 0.00005 ppm) but much more abundant in meteorites (content of the order of 0.5 ppm) In the hypothesis of an iridium contribution by a meteorite and taking into account the iridium contents measured in the sediments of the KT limit, we must imagine the fall of a body of about ten kilometers in diameter. Such an impact causing an explosion equivalent to a charge of 100.10^{6} megatons of TNT (i.e. one Hiroshima bomb per inhabitant of the Earth, counting 5 billion individuals), it is easily conceivable that it would be accompanied by a major biological crisis!

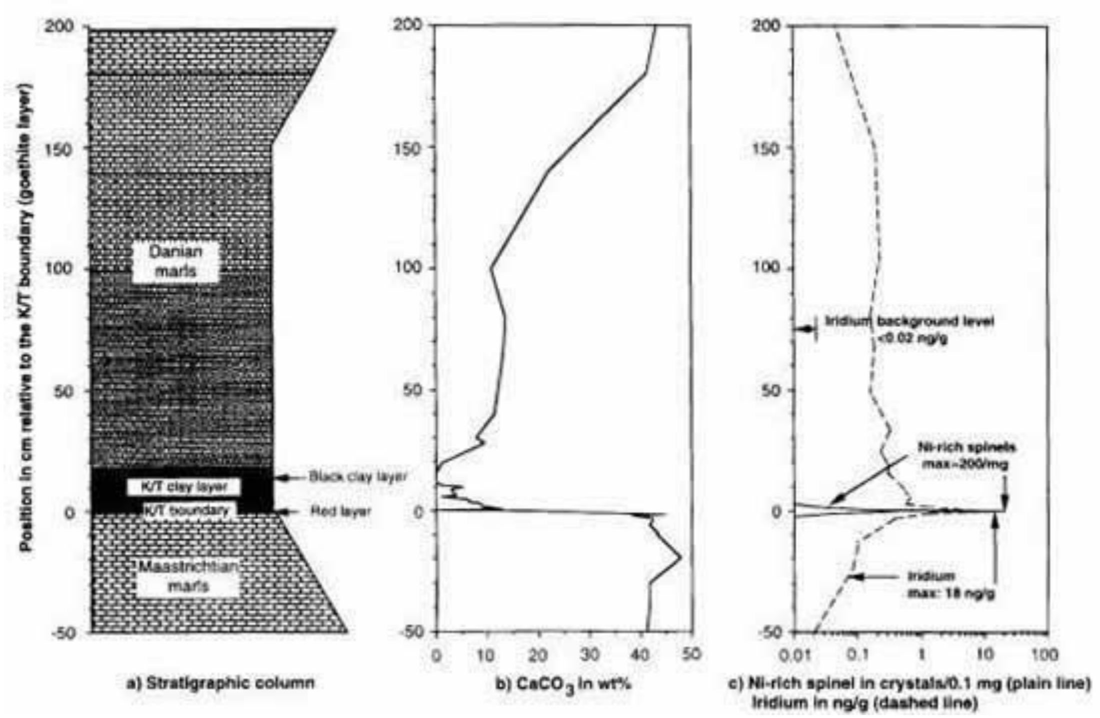

Fig. 31 The Cretaceous-Tertiary passage at the El KEf site (Tunisia): a) Stratigraphic column of the Cretaceous-Tertiary passage at the El Kef site (Tunisia), b) Proportion of carbonates in the rocks, c) Distribution of iridium and nickel-bearing magnetites.

Following the discovery of iridium enrichment in lavas from Kilauea (Hawaii volcano), an alternative hypothesis for explaining the Ir enrichment was proposed: that of extremely active volcanism. However, exceptional volcanism has indeed been demonstrated on the Deccan Plateau (India) at the KT transition. However, it now seems well established that this volcanism alone cannot explain the KT crisis (see below). This event, like the significant drop in sea level that occurred at the KT transition, likely contributed to reinforcing the devastating effects of the meteorite impact.

The hypothesis of a mainly volcanic origin to explain the KT crisis and its manifestations is undermined by the following facts.

- The release of iridium from volcanoes remains modest and does not allow the 500,000 t of Ir present at the KT boundary to be brought to the surface. In addition, the Ir content of the Deccan Trap lavas is low.
- The iridium/palladium ratio of the KT boundary sediments is close to that of meteorites and very different from that of the Deccan lavas (fig. 31).
- The high-Ir event was found between two Deccan flows.
- The presence of nickel-bearing magnetites, tektites (drops of molten rock) and shocked minerals symptomatic of the involvement of a meteorite in the KT boundary catastrophe is proven at many sites.

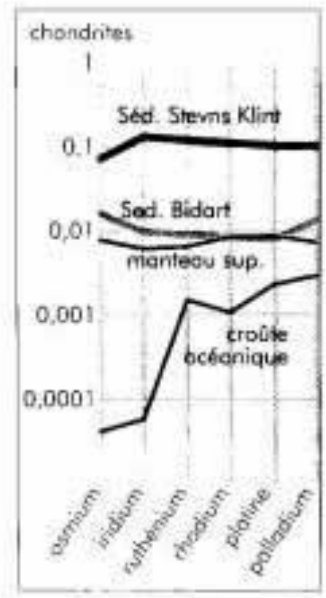

Fig. 31. Distribution of platinoids in KT boundary sediments, in the mantle and oceanic crust. The horizontal distributions correspond to relative abundances comparable to those of chondrites (value equal to 1).

b. Presence of nickel-bearing magnetite

Nickel-bearing magnetite occurs as small, microscopic octahedral or dendritic minerals (Fig. 32). These minerals originate from the melting of a nickel-rich rock in an oxidizing environment. In fact, these minerals cannot originate from terrestrial igneous rocks that are too poor in Ni. Furthermore, these minerals are not found in meteoritic rocks that are rich in Ni, but condensed in a reducing environment. These minerals are symptomatic of the passage of a meteorite through the Earth's atmosphere (oxidizing environment) and form in the melting crust of the meteorite.

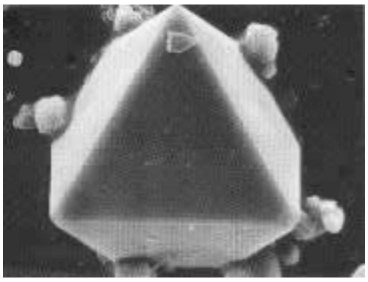

Fig. 32. Nickel-bearing magnetite (or nickel-bearing spinel) crystals extracted from the sediments of the K-T boundary.

The observation of nickel-bearing magnetites in the sediments of the KT boundary provides clear evidence of the involvement of a meteorite in the catastrophe. Nickel-bearing magnetites are found only in a few millimeters of sediments of the KT boundary, which attests to the brevity of the event.

Compared to the peak of nickel-bearing magnetites, the peak of iridium is much more spread out (see Figure 31). Abnormal Ir contents are measured over several tens or even several hundred centimeters on either side of the peak in nickel-bearing magnetites. However, iridium can pass into solution in water. Calculations show that Ir has a transit time of the order of 1000 to 10,000 years, which explains the spread of high values above the peak. The entrainment of iridium by pore waters within the sediments would explain the high contents measured below the peak.

c. Shocked minerals

Quartz is a mineral typical of continental rocks. The abundance of shocked quartz (fig.33) found in K-T layers indicates the location of the meteorite impact, in continental environments (Frankel, 1996). This factor was instrumental in finding the meteorite impact site we know today. In recognized meteorite impact craters, minerals (quartz, zircon, augite) with lamellar defects have been found. The presence of shocked minerals is recognized in many sites where the K-T limit is recorded. When these minerals are magnified under the microscope, a network of characteristic lamellae can be seen on their crystalline structures. This modification is achieved when the minerals are subjected to high pressure and very rapidly. They are the result of an overall movement of atoms under the effect of high stress. Numerous researchers and experiments, including (Frankel, 1996), have shown that only the very high pressures a meteorite impact could, by their sheer brutality, cause this kind of deformation.

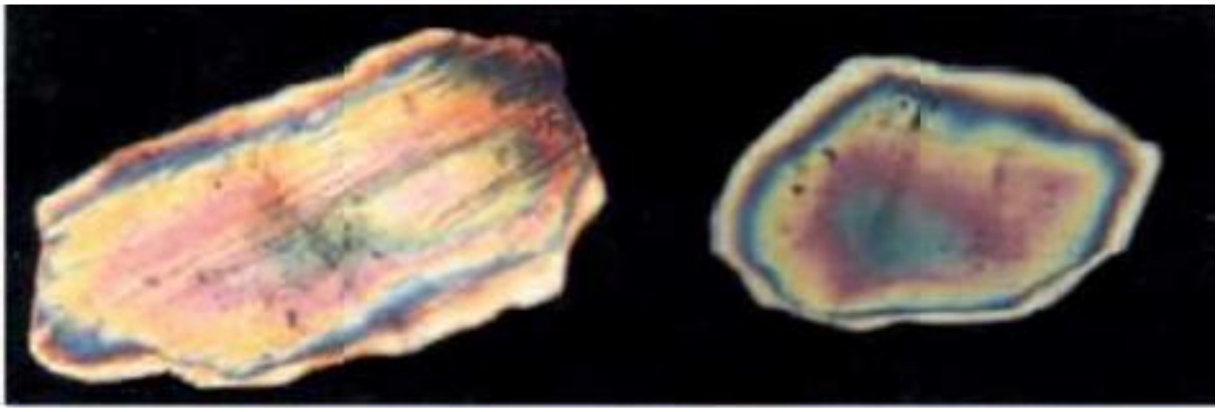

Fig. 33: shocked quartz.

2. Impact site

While the presence of so much iridium (Ir), shocked quartz and spinel in such a short space of time convinced most scientists of the existence of an impact at the K-T boundary, one important confirmation was missing: the crater that the impact should have left somewhere on Earth. The fact that shocked quartz was particularly abundant in North America led to a focus on this region. In 1991, American geophysicists discovered at the tip of the Yucatan peninsula, a large circular structure that may correspond to the impact crater 200 km in diameter, which seemed to have all the characteristics of the famous crater. It was given the name Chicxulub, taken from a nearby Mayan site meaning "gateway to hell". Covered by more than 1,000 m of carbonates, this circular structure does not outcrop. Gravimetric anomalies revealed its presence. This geophysical anomaly had already been detected over 30 years ago by Mexican petroleum geologists and interpreted as a structure of volcanic origin.

V.3.2 Intense volcanic activity: The Deccan traps

Throughout the Mesozoic, plate tectonics transformed the face of the Earth. The supercontinent Pangea broke up as the oceans gradually opened up.

The Indian microcontinent was located at the level of today's hotspot on Reunion Island. Intense volcanic eruptions occurred during the Maastrichian to form the Deccan basaltic plateau (fig. 34) with an average thickness of 2,400 m. (Frankel, 1996).

Fig. 34: Location of the Deccan traps.

The Deccan Plateau is currently one of the most extensive outpourings on Earth, with 500,000 km^2 of lava, about the size of France (Frankel, 1996). The current volume of traps is estimated at 10^6 km^3 of basaltic rock.

At the Cretaceous-Tertiary boundary, the Earth's magnetic field reversed (29R inversion). Paleomagnetic measurements of Deccan traps lava have shown that the basaltic plateau was built during the reversal of the Earth's magnetic field over a surprisingly short period, estimated at less than a million years, around 600,000 years. The magnetic inversion of the poles follows an external disturbance, such as a cosmic impact, or an internal disturbance, such as plate tectonics and the upwelling of magmatic material, of the Earth's magnetic field.

The strong correlation between the age of the Deccan traps and the K-T boundary has led to the volcanic hypothesis being proposed as the origin of the extinction of several species, including large reptiles, 65 Ma ago.

V.3.3 Eustatism hypothesis

- **Eustatic causes**

In the Paris Basin in particular, traces of marine regression have been noted. Thus, the gaps at the base of the Danian and the development of a karst surface (emergence) in the Campanian chalk are evidence of the fall in sea level. More generally, the changes in paleogeography in North America and Europe observed at the end of the Cretaceous demonstrate the extent of sea level regression.

- **Global cooling**

At the El Kef section, the measurement of variations in $\delta^{18}O$ tends to show that a generally cold climate had set in just before the KT limit. Such measurements carried out on Pyrenean sites also suggest that the climatic conditions were then favorable to the installation of an ice cap.

V.4 Conclusion

The expulsion of dust and aerosol into the stratosphere, in sufficient quantity to opacify and prevent the sun's rays from reaching the earth's surface. This phenomenon implies total darkness until the particles fall to the ground and the bottom of the ocean. These sediments then form the clay that identifies the K-T boundary in stratigraphic successions.

We also know where the meteorite impact landed, on the continental crust near Atlantic Ocean. This leads us to strongly believe in the creation of a tsunami.

The gigantic impact wiped out all vegetation and species in its path. Following the impact, some researchers estimate that the Earth's surface froze for 8 to 13 years, followed by 30 to 40 years of warming due to CO_2. Frost would have been a particularly harmful factor for dinosaurs, which were unable to adapt to a cold climate, as they were evolving in a tropical climate at the time.

The Deccan Traps began to form at the end of the Secondary Period, before the cosmic impact. This suggests that the species were already affected by the environment in which they lived. The subsequent asteroid and all its effects were the "fatal blow" that ended the dinosaurs still present at the time.

Moreover, the mass extinction at the end of K-T period was not as sudden as impacts would have us believe. On the contrary, recordings and analyses have revealed the gradual nature of this crisis (Koeberl et al., 2002).

We can therefore affirm that it was not a single event, but a conjunction of three: meteorite impact, volcanism in the Deccan traps, and eustatism and climatic variations, each at their own level, led to the destruction of a significant part of the fauna and the disappearance of many species at the K-T boundary.

It's not just the dinosaurs that have disappeared, but with them 75% of the species on the planet's surface:

- almost all plankton;
- almost all seabed inhabitants, including Rudists;
- many nekton (swimming) organisms such as Ammonites, and other nektonic molluscs;
- a large part of the earth's vegetation. The only ones to survive the crisis:
- small terrestrial mammals, insects ;

- a few reptiles such as turtles, lizards, snakes and crocodiles;
- freshwater, brackish and deepwater fish species, as well as some corals.

Birds, the first Primates, Foraminifera (Globigerinae) and Whales appeared and proliferated in the ecological niches freed up.

Synthesis of the Cretaceous-Tertiary crisis

Crisis	**Cretaceous-Tertiary**
Age (Ma)	-65
Level importance /5	5
Number of phases	1 à 3
Duration	Instantaneous at 2 Ma
Groups showing disappearances	Bivalves; rudists Chnodrichthyes Bony fishes Amphibians Chelonts Crocodillians inocerames multitubercules
Affected groups	marsupial monotremes; pterosaurians placental
Causes	Meteoric impact Intense volcanism Eustatism

The impact of the big five extinction events on Earth's biodiversity

VI. The impact of the big five extinction events on Earth's biodiversity

Analysis of the five major biological crises shows that they can be linked to any or all of three main events:

- asteroid fall(s) (=extra-terrestrial event) ;
- volcanic activity ;
- climatic and/or eustatic variations.

In this section, we'll look at the effects that any or all of these events could have had on the fauna and flora of the earth's surface.

VI.1 The effects cosmic impact

A meteor shower can have a number of consequences, such as :

- the absence of photosynthesis;
- falling temperatures ;
- the release large quantities of radioactive elements and CO_2 ;
- the devastation caused by the burning of many hectares of forest.

A. Darkness

The impact of an asteroid can release an enormous quantity of dust into the stratosphere. This dust can then create an opaque veil obscuring the entire surface of the Earth, plunging it into total darkness for varying lengths of time.

The first consequence of this darkness was to make photosynthesis impossible in continental and marine environments, for the entire period during which the Earth was plunged into total darkness.

The absence of light also had repercussions for the entire food chain. The dust cloud intercepted sunlight and blocked photosynthesis in plants and plankton (Ocampo et al. 2006). This phenomenon had different consequences depending on the species' diet. Animals requiring substantial food resources disappeared without exception (Frankel, 1996).

For example, during the K-T crisis, phytoplankton, a species entirely dependent on photosynthesis, went through a phase of devastating extinction. The depletion of phytoplankton could only have had serious consequences for zooplankton. The food pyramid collapsed, leading to major extinctions for all species dependent on phytoplankton and zooplankton. This was the case for marine invertebrates, fish and even some marine reptiles.

In addition, the herbivorous species died of starvation due to impossibility of feeding on the unregenerated water of the flora. The starvation of herbivores had a direct impact on the starvation of carnivores, which fed mainly on herbivores.

In addition, the darkness generated by the dust caused the temperature to drop by four to five degrees (Frankel, 1996). This drop in temperature is proven by the analysis of calcareous skeletons of planktonic fossils that survived the K-T crisis.

B. Forest fires

On each impact, the projected debris ignited as it rubbed against the air. The incandescent debris then spread across the globe, causing devastating forest fires. Evidence of these fires can be found in the large quantities of carbon found in rocks at the K-T boundary. These fires progressively pumped oxygen from the atmosphere as the forests burned. In addition, the large quantities of soot produced reinforced the planet's darkening.

C. Acid rain

Following each impact, the globe also experienced devastating acid rain. In effect, the great thicknesses of calcium sulfate, the post-impact atmosphere, the shock waves, the fireballs from the impact and the friction of the ejecta with the air heated the air. The factors that cause acid rain were thus brought together for a further effect (Buffetaut, 2003).

In the air we breathe, there is roughly 20% O_2 and the rest is mainly nitrogen N_2. Nitrogen is made up of stable, interrelated molecules. However, when these molecules are in a hot environment, as was the case at the time of and following the impacts, they dissociate. This dissociation allows nitrogen to combine with O_2 to nitrous oxide N_2O. The conditions resulting from the cosmic impact created large quantities of N_2O, which reacted O_2 and water vapour to nitric acid HNO_3 (Alvarez, 1998). This acid rain was not without consequences for the environment, resulting in the loss of mineral nutrients essential for the survival of flora and fauna.

VI.2 The effects of volcanic activity

During volcanic eruptions, aerosols, fine dust and gases such as carbon dioxide and nitrogen dioxide are released into the troposphere and stratosphere (fig. 35).

Gases such as hydrogen sulfide H_2S and sulfur dioxide SO_2 reach the stratosphere and chemically react to form sulfuric acid H_2SO_4. Winds displace the cloud of aerosols and fine dust that traps the Sun's rays in the stratosphere. As a result, the stratosphere warms while the troposphere cools (Foucault, 2009).

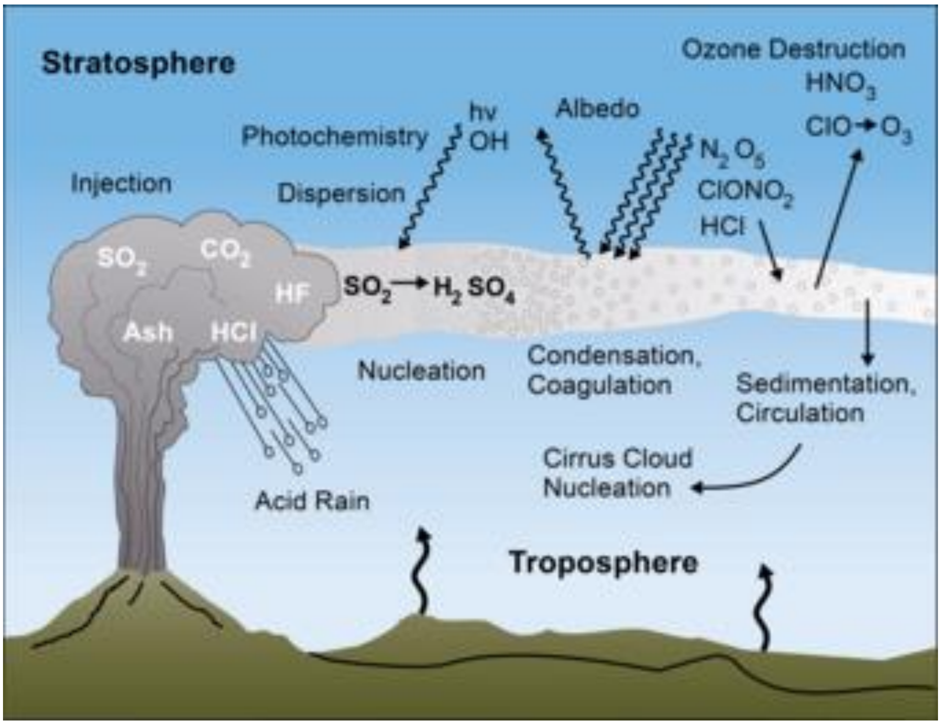

Fig. 35: Impact of a volcanic eruption on the atmosphere (Foucault, 2009).

In addition, lava flowing down the slopes of volcanoes releases the gases mentioned above, and sulfuric acid is formed. Sulfuric acid is the source of the acid rain that then befalls the planet.

The consequences of volcanic eruptions are manifold:

- climate change ;
- release of toxic gases ;
- acid rain.

The effects on climate depend in part on the concentration of the greenhouse gas CO_2 in the atmosphere. Researchers have therefore been studying the CO_2 cycle through geological time. While volcanism produces CO_2, the weathering of silicate rocks consumes it. During and after intense volcanic activity (Siberian traps for the P-T crisis; Central Atlantic Magmatic Province (CAMP) for the T-J crisis; Deccan traps for the K-T crisis), CO_2 levels in the atmosphere are maintained at equilibrium by continental weathering (Dessert et al. 2001).

For example, the Deccan plateau is made up of basaltic rocks. Basalts are silicate rocks that weather easily. What's more, the initial volume of the traps is estimated to be three times the current volume, i.e. 318 km^3. From the time they were built to the present day, trapps have lost two-thirds of their volume. In this way, the basaltic rocks of the Deccan plateau have regulated the concentration of carbon dioxide in the atmosphere (Dessert et al. 2001). The construction of these Deccan traps would have released 1.6×10^{18} moles of CO_2 into the atmosphere.

VI.3 The effects of climatic variations and eustatism

Eustatism characterizes the variation of sea levels. It is generally impossible to determine the short-term effects of eustatism, as the phenomenon is so difficult to assess. However, eustatic causes are well known. These include :

- plate tectonics involving submarine volcanism at ocean ridges;
- climate change involving the melting of ice or the formation of glaciers;
- marine regression is associated with climatic cooling and glacier formation, while global warming increases ocean volumes and sea levels.

- **Consequences of eustatism**

If we relate the evolution of eustatism to the great extinction , we can see a clear correlation between these two phenomena. Indeed, each marine regression has resulted in the disappearance of a large number of genera. This is true for all crises, and seems to be a cyclical phenomenon.

In the event of a transgression, warm waters laden with CO_2 cause a reduction in O_2 solubility, resulting in anoxic waters unfavorable to marine life.

GENERAL CONCLUSION

The examination of extinction events throughout Earth's history reveals a complex interplay between biotic and abiotic factors influencing biodiversity. The foundational work of (Newman, 1996) introduces the dual mechanisms of extinction, suggesting that both sudden catastrophic events—such as meteor impacts and volcanic activity—and gradual biotic changes, like competitive displacement, can lead to significant biodiversity loss. This duality is crucial for understanding the fossil record, which encompasses a vast array of species and provides a statistically significant basis for inferring extinction patterns.

Building on this, (Bailer-Jones, 2009) critically evaluates astronomical impacts on climate change and their potential role in mass extinctions. By analyzing geological and biological records for periodicities, the author highlights the importance of extraterrestrial mechanisms in shaping life on Earth, suggesting that solar variations and cosmic events may act as triggers for extinction events. This perspective emphasizes the need for a multifaceted approach to understanding how external forces can disrupt established ecosystems.

The dynamics of biodiversity through the lens of mass extinctions (Melott and Bambach, 2010), emphasizing the delayed recovery of ecosystems following these events. Their analysis points to a recurring ~62 million-year cycle in marine diversity, suggesting that periodic fluctuations in biodiversity may be a fundamental characteristic of Earth's biological history. This insight invites a reevaluation of the mechanisms driving both extinction and recovery, underscoring the significance of ecological resilience and adaptation.

The end-Permian mass extinction, as discussed by (Irmis and Whiteside, 2012), marks a pivotal moment in Earth's biodiversity, characterized by profound restructuring of ecosystems. Their findings indicate that recovery from this event was protracted, taking millions of years, and highlight the environmental stresses that contributed to the extinction of both marine and terrestrial life. This underscores the intricate relationship between extinction events and the carbon cycle, suggesting that the impacts of such crises are far-reaching and long-lasting.

(Darroch and Wagner, 2014) shift the focus to beta diversity, revealing that extinction events have differential impacts on alpha and beta diversity. Their findings suggest that the extinction of taxa with varying geographic ranges may lead to significant shifts in community composition, further complicating our understanding of biodiversity loss during mass extinctions. This research emphasizes the importance of spatial dynamics in ecological responses to extinction events.

(Stollmeier et al., 2014) contribute to the discussion by proposing a model that interlinks endogenous and exogenous factors influencing biodiversity. Their analysis suggests that while marine life has historically shown exponential growth, its dynamics are influenced by mass extinctions, which disrupt equilibrium and reset ecological processes. This model provides a framework for understanding the complex interactions that govern biodiversity over geological timescales.

The investigateions of (Botha-Brink et al., 2016) on the role of life history traits in survival during mass extinctions, focusing on the Permo-Triassic transition. Their research indicates that changes in developmental strategies may have influenced the resilience of certain species, revealing that not all taxa are equally affected by environmental stressors. This highlights the need to consider biological traits alongside ecological factors when assessing extinction risks.

(Vakulenko et al., 2017) examine the relationship between climatic fluctuations and extinction in a conceptual ecosystem model. Their findings assert that major environmental changes often accompany mass extinctions, reinforcing the idea that ecosystems can be pushed beyond their resilience limits. This work emphasizes the importance of understanding stability thresholds in the context of biodiversity loss.

The modeling study by (Thomas and Oberle, 2019) delves into the biological impacts of ozone depletion during the end-Permian. Their analysis underscores the multi-faceted nature of extinction events, where atmospheric changes and climate simulations reveal critical insights into the mechanisms driving mass extinctions. This research adds depth to the understanding of how environmental changes can precipitate widespread biodiversity loss.

(Huang et al., 2021) explore the ecological dynamics across three mid-Phanerozoic mass extinctions, identifying commonalities in the responses of terrestrial and freshwater ecosystems to severe perturbations. Their work emphasizes the need for a regional perspective to analyze community dynamics and the cascading effects of extinction events, providing a framework for future research on ecological resilience.

Lastly, (García-Girón et al., 2022) investigate the end-Cretaceous mass extinction, emphasizing the shifts in food webs and niche stability that shaped survival and extinction. Their analysis of trophic interactions provides critical insights into why certain groups thrived post-extinction while others perished, underscoring the complexity of ecological interactions during times of crisis.

In summary, the mass extinctions are multifaceted phenomena influenced by a variety of ecological, environmental, and evolutionary factors. The diverse perspectives presented across these studies contribute to a deeper understanding of the mechanisms driving extinction and recovery, as well as the implications for current biodiversity crises.

REFERENCES

Ahlberg, P., Clack, J. & Blom, H. 2005. The axial skeleton of the Devonian tetrapod Ichthyostega. Nature 437, 137–140. https://doi.org/10.1038/nature03893.

Alvarez L.W, Asaro F., Michel H. 1980. Extraterrestrial cause for the Cretaceous–Tertiary extinction. Science; 208, p. 1095–1108.

Bailer-Jones A. L., 2009. The evidence for and against astronomical impacts on climate change and mass extinctions: A review.

Bambach R.K., Knoll A.H., Wang S.C. 2004. Origination, extinction, and mass

Berner R.A. 2003. Overview The long-term carbon cycle, fossil fuels and atmospheric composition, Nature; N° 10, p. 426.

Botha-Brink, J., Codron, D., K. Huttenlocker, A., D. Angielczyk, K., & Ruta, M., 2016. Breeding Young as a Survival Strategy during Earth's Greatest Mass Extinction.

Brochu C.A. 2004. Calibration age and quartet divergence date estimation. Evolution. vol. 58, no 6,.p1382– 1375.

Buffetaut E. 2003. La fin des dinosaures : comment les grandes extinctions ont façonné le monde vivant. Paris, *Fayard*. p. 200-213.

Buntsandstein des Vosges méridionales (Trias inférieur et moyen continental), Sciences de

Chabou M.C., Sebai A., Feraud G., Bertrand H. 2007. Datation 40Ar/39Ar de la province magmatique de l'Atlantique central dans le Sud-ouest algérien. *Comptes Rendus Geosciences*, *Elsevier* ; 339, p. 970–978.

Clack J. 2006. *Tiktaalikroseae* – a missing link?, *Palaeogeography, Palaeoclimatology, PalaeoecologY;* 232, p. 167-189.

Cohen, Benjamin E.; Mark, Darren F.; Lee, Martin R.; Simpson, Sarah L. 2017. "A new high-precision 40Ar/39Ar age for the Rochechouart impact structure: At least 5 Ma older than the Triassic–Jurassic boundary". Meteoritics & Planetary Science. 52 (8): 1600–1611.

Darroch A.F., S. & J. Wagner, P., 2014. Response of beta diversity to pulses of Ordovician-Silurian mass extinction.

depletions of marine diversity, Paleobiology; vol. 30, No 4 , p. 522–542.

Dessert C., Dupre B., Francoise L. M., Scott J., Gaillardet J., Chakrapani G., BAJPAI S. 2001. Erosion of Deccan Traps determined by river geochemistry. Impact on the global climate and the 87Sr/86Sr ratio of seawater, Earth. Plan. Sci; 188, p. 459-474.

Durand M. 1978. Paléocourants et reconstitution paléogéographique - L'exemple du

References

García-Girón, J., Alessandro Chiarenza, A., Alahuhta, J., G. DeMar, D., Heino, J., D. Mannion, P., E. Williamson, T., P. Wilson Mantilla, G., & L. Brusatte, S., 2022. Shifts in food webs and niche stability shaped survivorship and extinction at the end-Cretaceous.

Huang, Y., Chen, Z. Q., D. Roopnarine, P., J. Benton, M., Yang, W., Liu, J., Zhao, L., Li, Z., & Guo, Z., 2021. Ecological dynamics of terrestrial and freshwater ecosystems across three mid-Phanerozoic mass extinctions from northwest China.

Irmis B., R. & H. Whiteside, J., 2012. Delayed recovery of non-marine tetrapods after the end-Permian mass extinction tracks global carbon cycle. La Terre, Nancy ; 22, p. 301-390.

Lethiers F. 1998. Evolution de la biosphère et événements géologiques, *Gordon and Breach Science Publishers*, Paris.

Melott L., A. & K. Bambach, R., 2010. A ubiquitous ~62 Myr periodic fluctuation superimposed on general trends in fossil biodiversity: II, Evolutionary dynamics associated with periodic fluctuation in marine diversity.

Newman E. J., M., 1996. Self-organized criticality, evolution and the fossil extinction record.

Paterson J.R., G.D. Edgecombe, & M.S.Y. 2019. Lee, Trilobite evolutionary rates constrain the duration of the Cambrian explosion, Proc. Natl. Acad. Sci. U.S.A. 116 (10) 4394-4399, https://doi.org/10.1073/pnas.1819366116.

Scotese C. 1997. *Palaeogeographic Atlas*, PALEOMAP Progress, Department of Geology, University of Texas at Arlington, Texas.

Sepkoski J J Jr, Raup DM (1986) Periodicity in marine mass extinctions. In: Dynamics of extinction, ed Elliott D. New York: Wiley, pp 3–36

Slack K.E., Fjones C.M., Ando T., Harrison G.L., Fordyce R.E., Arnason U., Penny D. 2006. Early Penguin Fossils, Plus Mitochondrial Genomes, Calibrate Avian Evolution , Molecular Biology and Evolution; vol. 23, no 6,p. 1155–1144 .

Stewart T.A.,J.B. Lemberg,E.J. Hillan,I. Magallanes,E.B. Daeschler,& N.H. Shubin (2024). The axial skeleton of Tiktaalik roseae, Proc. Natl. Acad. Sci. U.S.A. 121 (15).

Stollmeier, F., Geisel, T., & Nagler, J., 2014. Possible Origin of Stagnation and Variability of Earth's Biodiversity.

Thomas, B C.. & M. Oberle, J., 2019. Biological Impact of Ozone Depletion at the End-Permian: A modeling study.

Vakulenko A., S., Sudakov, I., & Mander, L., 2017. Minor climatic fluctuations lead to species extinction in a conceptual ecosystem model.

Zolotukhin V. et Mukhamedov A.I, 1988, Traps of the Sibirian Platform, Continental Flood Basalts. Kluwer Academic, Amsterdam; p. 273-310.