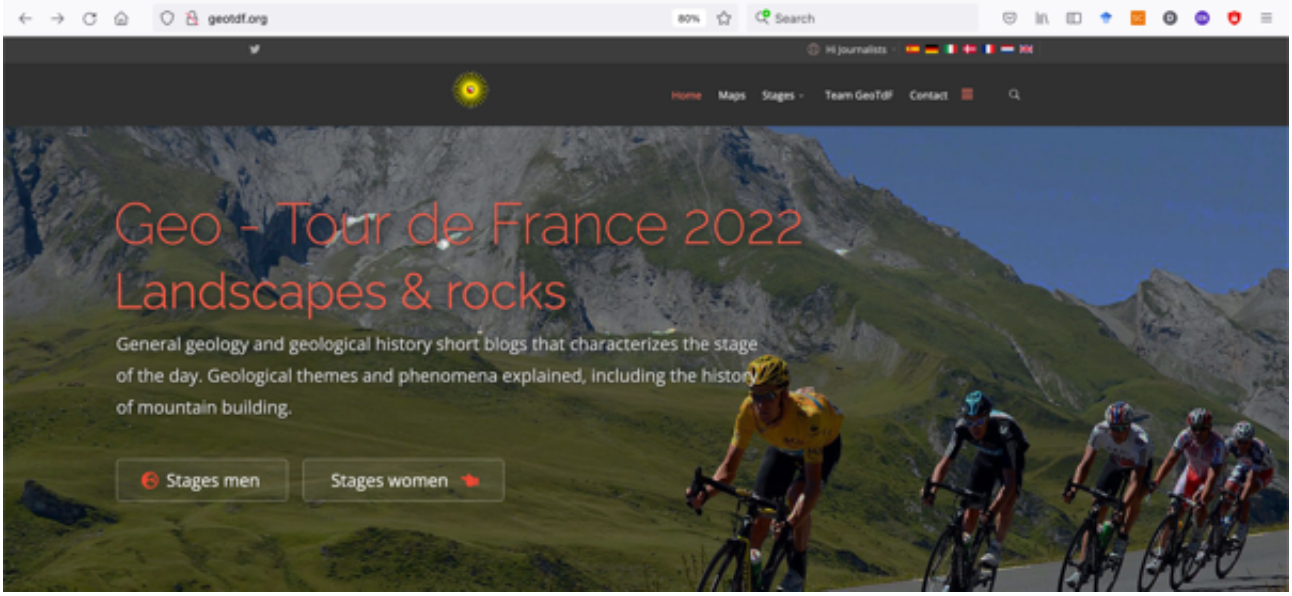


The idea

Background

The idea for blogs of the Geology of the Tour de France was born out of combining two passions: geology and cycling.

Geoscientists tend to love the outdoors, and are a talkative bunch who can't stop explaining about their rocks, fossils, landscapes, and natural processes, and the field expeditions they undertook. At some point I realized that viewers of live coverages of cycling races like the Tour de France watch hours and hours of geological excursions. Surely, we couldn't let the opportunity pass to geo-monologue! And these races are covered by commentators that explain just about everything that passes the camera. All we had to do is help the commentators to explain a few things about the landscape and underlying hidden treasures. As it turns out, there are quite a few geoscientists who love cycling and watching the race, and quite a few cyclists with a keen interest in the environment. GeoTdF was born.

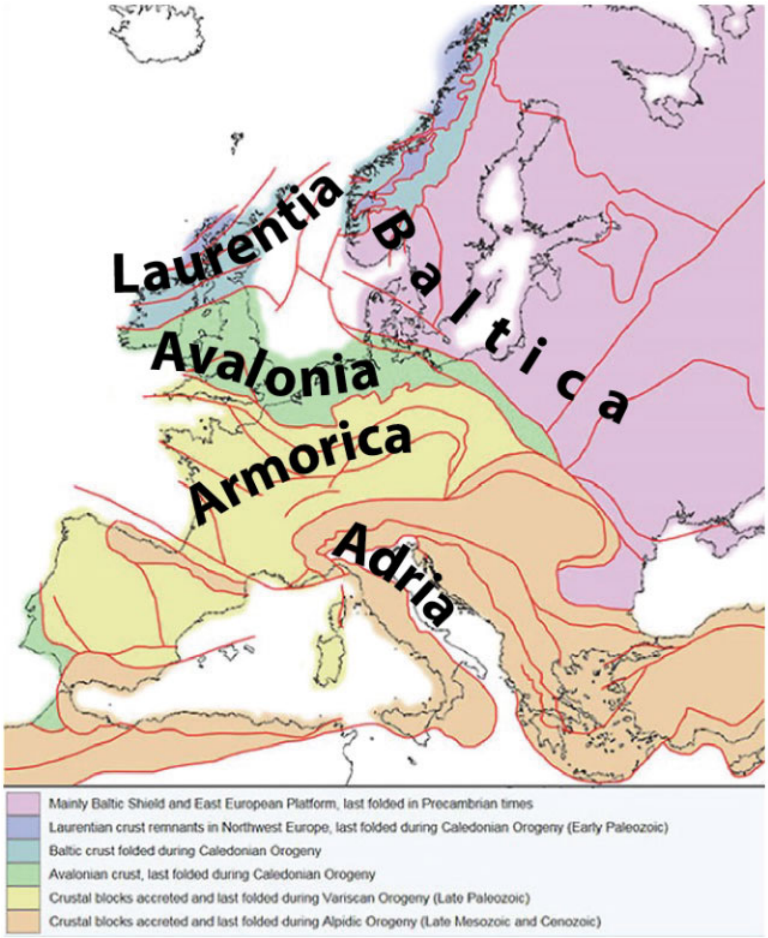
This web page is dedicated to the Geology of the Tour de France. But on the Twitter account @geotdf, we can't help ourselves and tweet about the geology of just about every race where we find something to tell you. So if you want your regular geo-fun fact, follow us, and drop your questions should you have any! We hope you enjoy, and we'll see you on the road!

REFERENCES TO IMAGES. All images in the blogs below come from internet pages. On the GeoTdF website, each figure is linked to the source.

Stage 1 | Copenhague - Copenhague / A ride over a prehistoric continent

[Men]

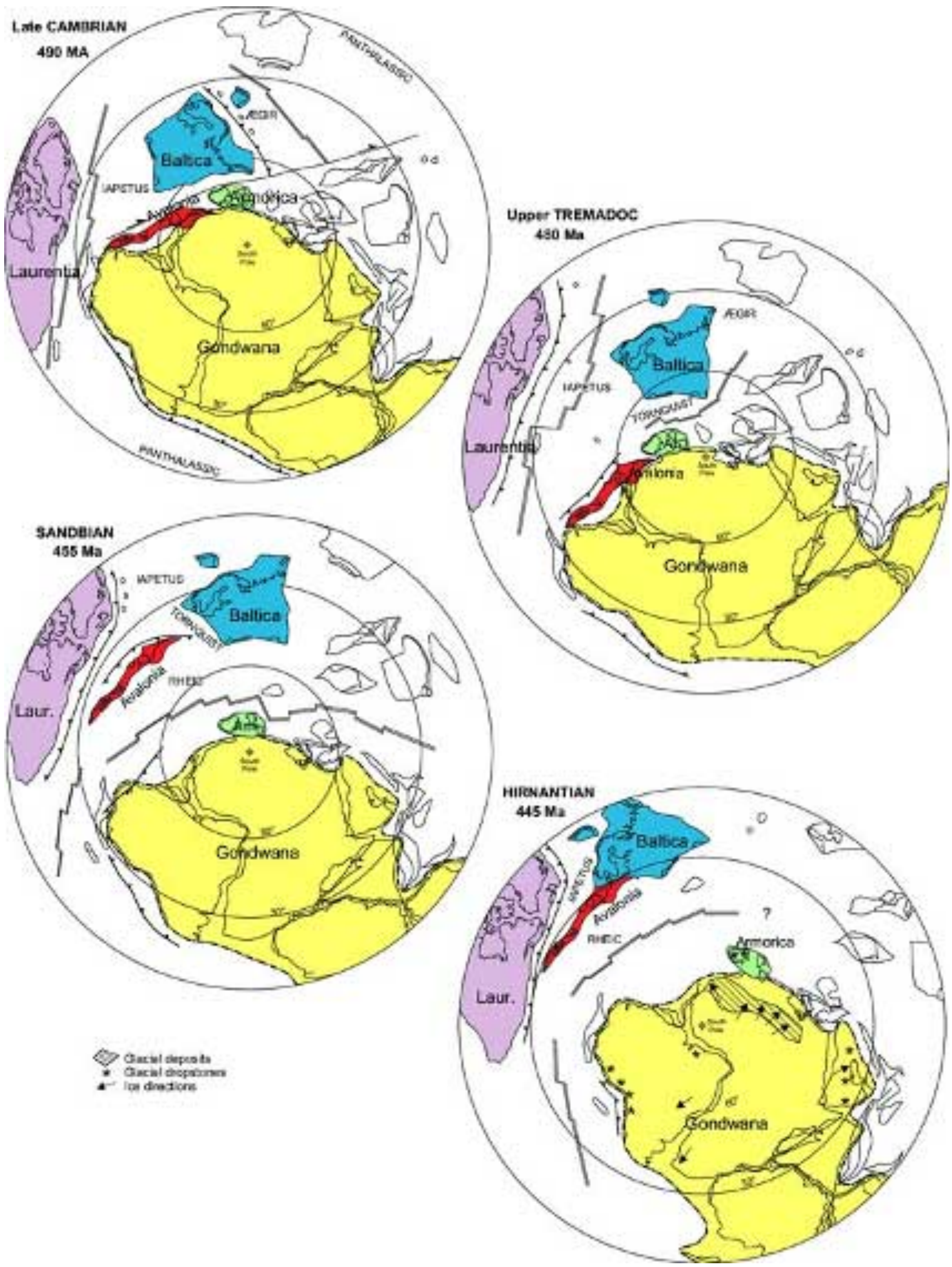
13 km		Individual Time Trial		Prehistoric continent Baltica



Prehistoric continent Baltica hides below the Danish subsurface, that contains as much as 12 kilometers of sedimentary rocks, formed in the last 450 million years. Baltica is now part of the Eurasian continent, and stretches from the Atlantic coast of Norway to the Ural Mountains, and from the Arctic Ocean to the Black Sea.

What is a prehistoric continent?

What is a prehistoric continent? They are packages of 30 km thick crust that mostly consists of magmatic rocks that formed above subduction zones. Like below that volcano in Tonga that exploded last winter. These types of rocks are more buoyant than the underlying mantle rocks. When the plate of which they form part arrives in a subduction zone, these rocks are offscraped to form mountain belts, or they even stop subduction. So continents can move along the Earth's surface together with the plates of which they are part, but they will not disappear. They break off one continent and merge with the next in an endless plate tectonic dance. Baltica too.



Avalonia

About 500 million years ago, Baltica was on the southern hemisphere together with the supercontinent Gondwanaland (which included South America, Africa, India, Australia, and Antarctica), around the South Pole. Baltica moved northward, together with another continent, **Avalonia** (consisting of parts or Ireland, Wales, and England, Belgium, the Netherlands, and northern Germany). About 450-400 million years ago, Baltica and Avalonia collided with Laurentia (Greenland and North America). Baltica and Avalonia also collided with east other, and the fault along which this happened is located around the Danish-German border. But hidden below an enormous pole of sedimentary rocks that were brought in from Scandinavia and Germany.

Armorica

And **France**? Most of France is part of yet another continent: **Armorica**. Armorica collided with Avalonia around 300 million years ago. And the last part of Europe, Adria, arrived in the last 50 million years ago, and the faults along which that happened now form the Alps. So Denmark-France is a day's drive today, but during Baltica's heydays, they were separated by a hemisphere and an ocean!

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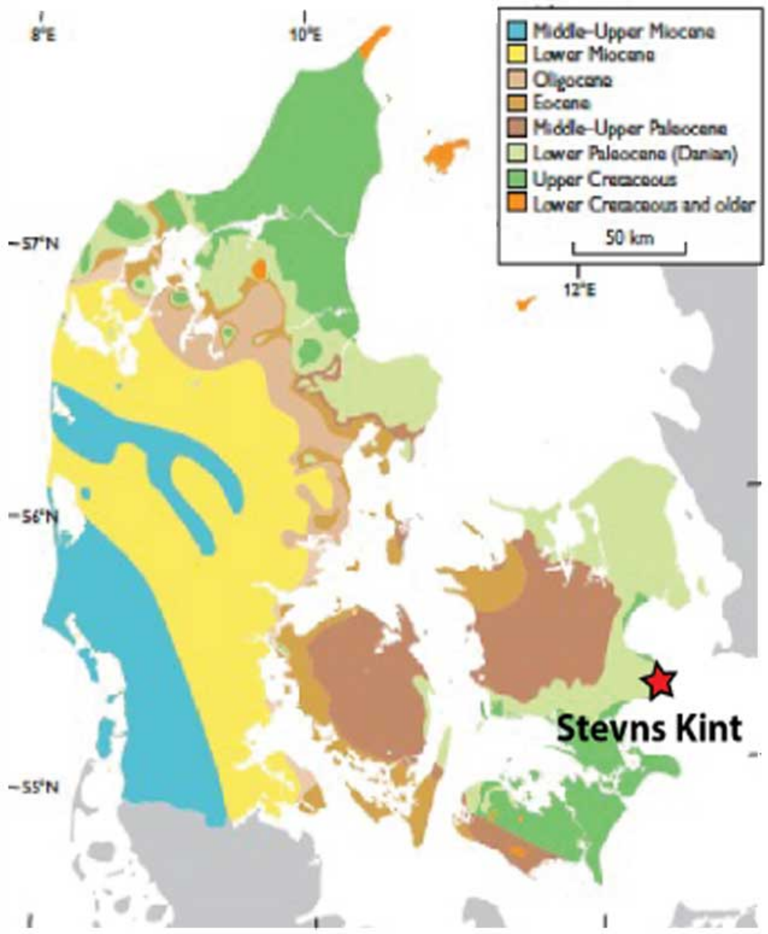
Douwe van Hinsbergen

Stage 2 | Roskilde - Nyborg / From the age of the dinosaurs to the age of the mammals

[Men](#)

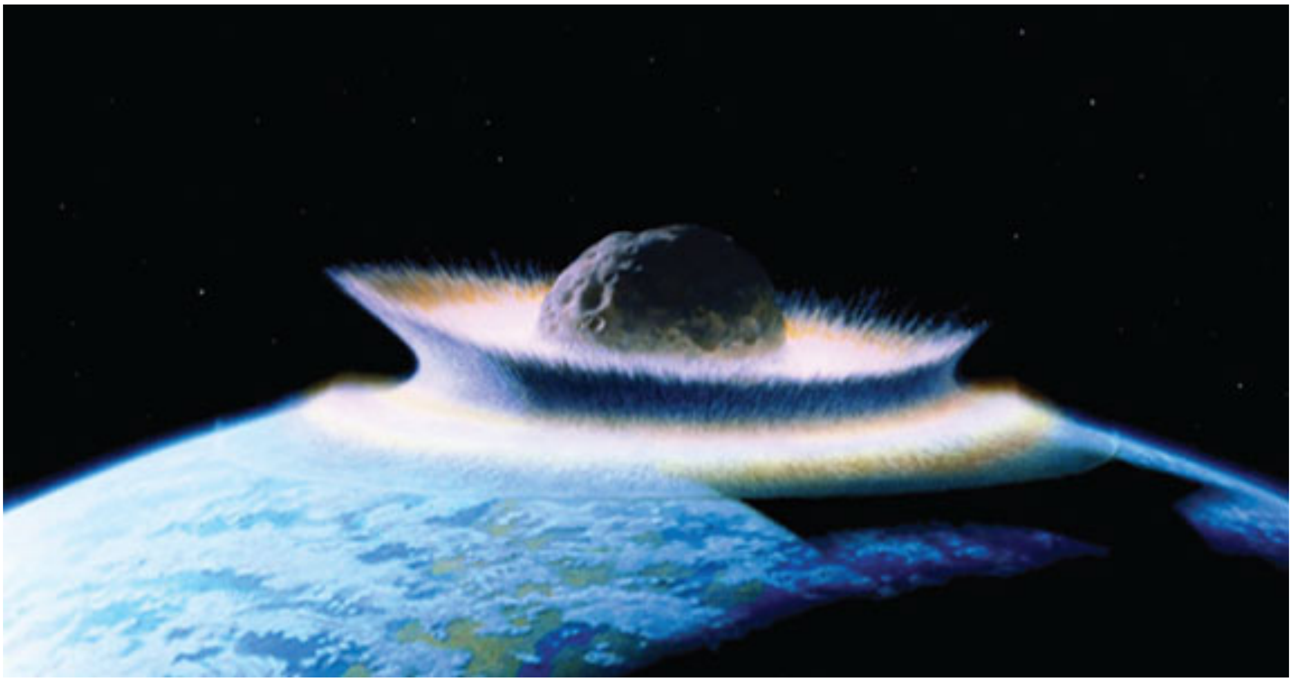
199 km		Hills		Danian



The largest part of the more than 12 km thick pile of sedimentary rocks that forms the Danish subsurface can only be reached by deep drillings. But sediments that formed in the last ~100 million years can occasionally also be seen at the Danish surface. The geological map of Denmark (see figure below), on which the 'young' sediments and soils of the last 1 million year or so are not shown, reveals that the sedimentary rocks that are close to the surface in Denmark becomes younger from north and east to southwest. On these geological maps is a broad band indicated with a 'Danian' age. And the Danian contains a special story.

Early Danian: the extinction of the dinosaurs

allows to date sedimentary rocks. The ‘Danian’ is named after Denmark and is the first time interval of the Cenozoic, which followed directly upon the last interval of the Cretaceous period known as the ‘Maastrichtian’, named after Maastricht in the south of the Netherlands. And the transition from the Maastrichtian to the Danian, 66 million years ago was one of the biggest changes in the history of life: the extinction of the dinosaurs and the impact of the Chicxulub meteorite in the Gulf of Mexico.



During today’s stage, the riders will start in the Cretaceous, in the world of Mosasaurs, T-Rexes, and Triceratopses, but also ammonites. During the day, they will pass catastrophic mass-extinction and enter the barren, almost inhabitable world of the early Danian. After the Chicxulub meteorite impact, an ‘impact winter’ followed, during which the earth was dark and cold, plants had difficulty growing, and 75% of life perished. In the same period, but unrelated to the impact, there were enormous volcanic eruptions that covered 20% of India below a thick pile of lava, which made life even harder. The dinosaurs did not survive this hell, but from their decedents, the birds developed. And mammals saw their opportunity and started to flourish.

The white cliffs of Denmark

This Earth catastrophe is extensively studied in rocks at the Danish coast, not far from the start of today's stage. The white cliffs of Stevns Klint (see figure) contain the famous transition of limestones that are rich in fossils, through a thin clay layer rich in the metal iridium that is not common on earth but abundant in meteorites and that is recognized across the globa as a trace of the meteorite impact. And what follows are limestones poor in fossils and poor in fossil diversity. These days, the Danian is extensively studied to learn how life recovers from a catastrophe…because humanity's influence on earth is threatening to cause another one.

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Douwe van Hinsbergen

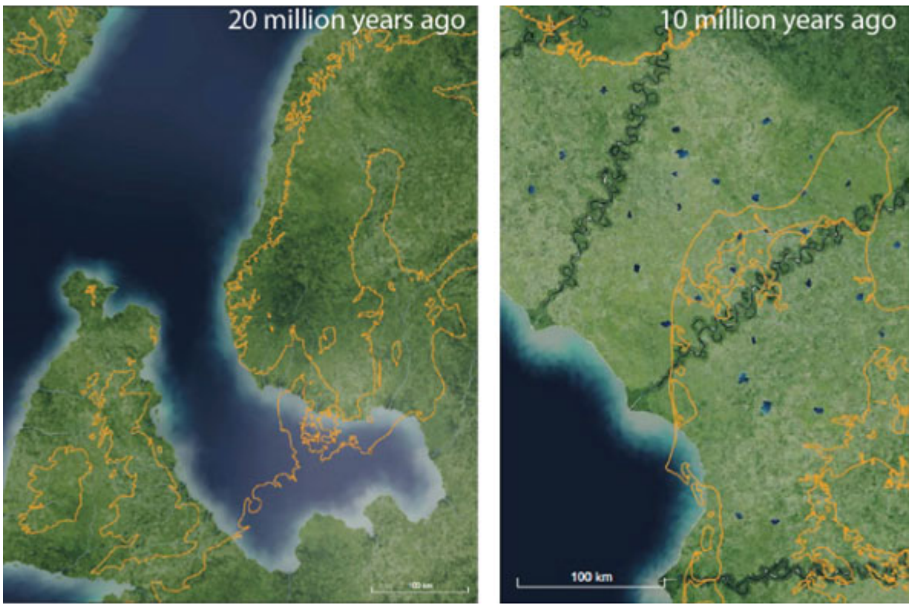
Stage 3 | Vejle – Sønderborg / Borrowed land from the Scandinavian highlands

Men

182		Fl		Denmark youngest rocks - borrowed land: sediments from

The last stage on Danish soil takes us over the youngest rocks in the Danish subsurface, which are Miocene in age, about 20-10 million years old. When these sediments were deposited, the North Sea was an embayment that ran between Norway and Scotland to Denmark, but not to northern France (see figure). And during this period, this shallow sea was filled up with sand and clay that was eroded from the highlands of Scandinavia; borrowed land.

Borrowed land



These sediments from Scandinavia's highlands were transported via large rivers and deposited in deltas, causing the land to grow slowly, turning the shallow sea into swamps and sandbars. And even a few meters of sea level rise, resulting from changes in the volume of ice at the poles, was enough to flood the newly claimed land. Much of northwestern Europe, including the Netherlands, Flanders, and northwestern France, still consists of such 'borrowed land'. But unlike Denmark in the Miocene, we are now able to keep rising seawater away from this borrowed land (for now at least) by building dikes. One danger, however, is that the soils and sediments behind the dikes will compact and subside and it is no longer receiving new sediments – we don't want to flood the cities and fields every few years to bring in new silt. So there are concerns about the future of the borrowed land.

Denmark under an icecap

The last hundreds of thousands of years of Danish geological history were dominated by the ice ages. During several episodes, Denmark was completely

or partially covered by a pack of ice several hundred meters thick, which in their heydays extended to central Germany, the Netherlands and southern England. When the Danish lands were not covered by ice, they formed dry tundras and steppes, home to the famous Pleistocene Ice Age inhabitants such as mammoths. In the last 10,000 years we have gone from a "glacial" to an "interglacial" and the ice has retreated. One of the effects of the disappearance of the enormous mass of a kilometer or more of land ice is that the earth's crust slowly rebounds. And to this day, the borrowed land of Denmark is also still slowly rising, at a rate of one millimeter per year.

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Douwe van Hinsbergen

Stage 4 | Dunkerque - Calais / Michaelangelo’s hills & white marls

Men

172 km		Hills		Plankton skeletons

Anyone who has ever crossed the channel by boat knows the cliffs of Calais. Today's stage leads through the limestone and marl area of west Flanders and northwest France. Over the hills and along the cliffs. These rocks are from the Late Cretaceous, between 90 and 66 million years old.

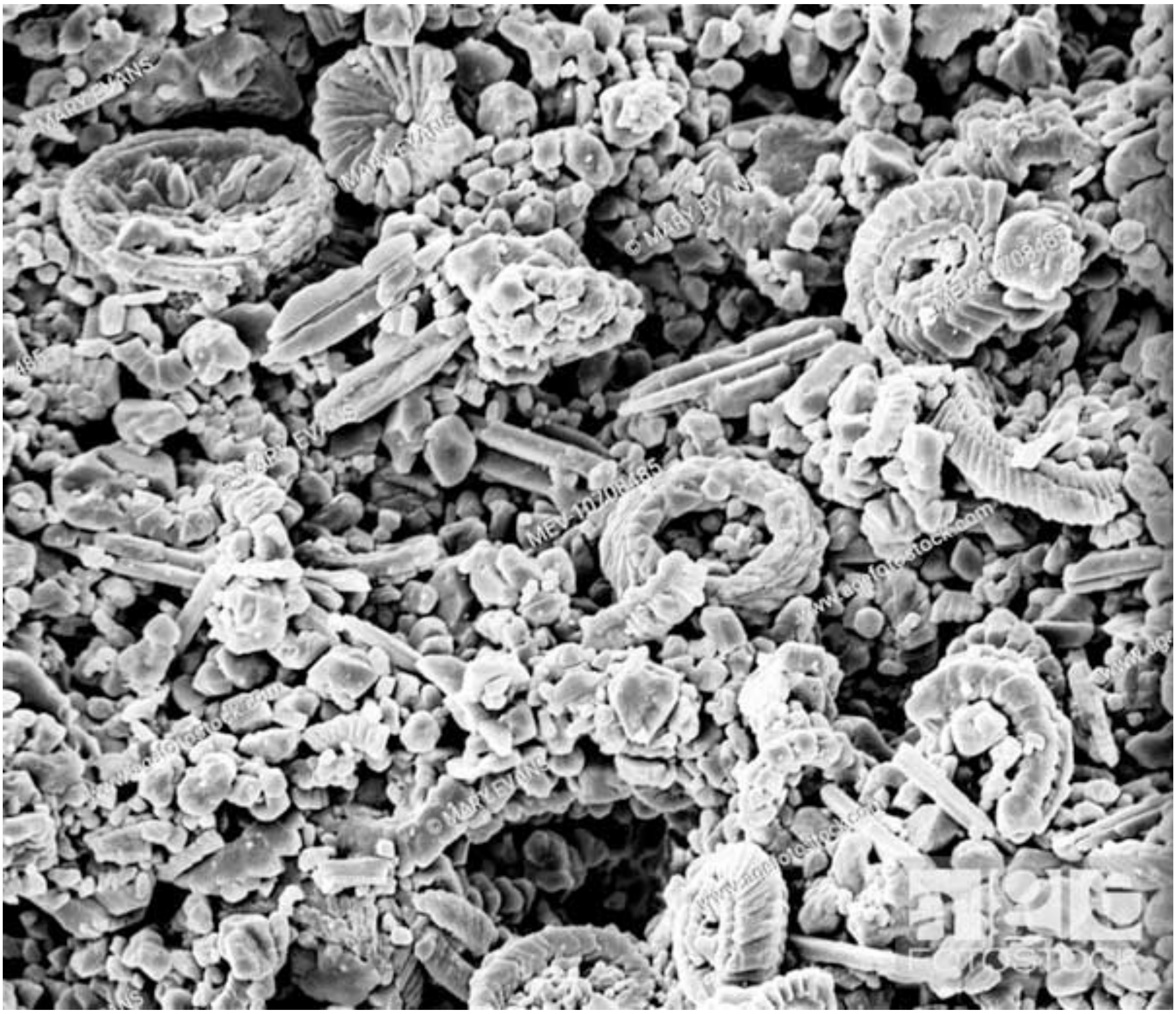
Forming of plankton skeletons during period of ice-free Earth

The Late Cretaceous was a super warm geological period. At that time, the sea level was 80 meters higher than today, because the climate on Earth was so warm that all

the ice that is stored in polar ice caps today was in the sea. The Earth was ice-free. Moreover, Europe then was much more southerly, in a drier climate zone, where today the Mediterranean Sea is located. In fact, the cliffs of Calais were formed in a kind of subtropical shallow sea, in which plankton and other marine life had a very good time. The cliffs consist almost entirely of microscopic fossil plankton skeletons. Of calcium carbonate, which is why the cliffs are so bright white.

Spectacular coastel cliffs easy to erode

These coastal limestone cliffs look quite spectacular: they loom vertically. With such vertical cliffs you quickly think of rock hard rock, but nothing could be further from the truth. Actually, the mergels of the chalk cliffs near Calais are quite easy to erode: by slightly acidic rainwater,



and by rivers that cut into the chalks. This is also the reason that todays stage goes up and down a lot: the heavy annual rainfall in this area have cut out valleys from the soft chalk. And here comes another fun fact. Where normally mountains are formed because tectonic plates collide with each other, and a crumple zone of those 2 plates is created (for example, the Alps, more on this when the TdF gets there), in this area we see relief because rivers have cut into the landscape. The rock layers of the Cretaceous are almost horizontal in this area, and therefore not folded as in the Alps, but the relief is caused by erosion. This can sometimes cause viciously steep ascents, as we also know from the Limburg landscape, where this phenomenon also occurs.

Witness Hill: The Kassel Mountain

There is 1 more funny geological phenomenon that is visited in this stage: the Kassel Mountain, is a special kind of hill. The Dutch word for it would translate to "witness hill". It is the first climb of the stage, after 28 km of racing. A witness hill is actually an anti-mountain. It could have been made by Michaelangelo: his credo was that you have to free sculptures from the block by removing the excess rock. That is what nature thought when forming the witness hill near Kassel. The mountain lies in the landscape because nature has cleared away the excess rock, through erosion processes. And Kassel Mountain was witness to that erosion, hence the name. Apparently the rock under Kassel was slightly harder than the surrounding stone, and because rivers choose the path of least resistance, the surrounding rock was eroded, and the Kassel Mountain remained.

I study climate and ocean conditions on and around Antarctica, during the Earths most recent 100 million years. Specifically, I study sediment cores to reconstruct the onset and development of the Antarctic circumpolar current around, and the ice sheet on Antarctica. Check the TdF-team.

Peter Bijl

Stage 5 | Lille - Arenberg / The Flemish Basin and ice age loess

Men

155		Cobblestones		Rocks from the Flemish basin and the Paris

- In cooperation with Patrick de Wever -

The peloton will ride through northern France, a wide open landscape of meadows and agriculture that hide sedimentary rocks from the Paris Basin and the Flemish Basin. These consist mostly of sandstones and shales (compresses claystone), chalk, and below that the older rocks of Avalonia such as diorites - a type of granite but

without quartz, which forms in big magma chambers - that stem from the Silurian period (440 million years ago). And these rocks have been covered by packages of loess: wind-blown, very fine-grained, and very fertile sediments that formed in the steppen south of the giant glaciers of the ice ages. In northern France, there are not many rocks visible at the surface, but they are quite shallow: they are excavated in quarries.

Construction geology

In almost all areas in the world, you can get a good impression of the geology of the surrounding subsurface by studying the walls of buildings. In ‘poorly-exposed’ areas - which in geological terms means that the rocks close to the Earth’s surface are only rarely visible - you can get a pretty good impression of the composition of the shallow subsurface by looking at the walls of the buildings. Even if it may look a little strange when you’re not looking through the display windows of shops, but at the facade next to it. But make sure you use ‘old’ buildings, say, from before 1950. The rocks in buildings of the last decades come from all over the world. For instance, the sand that was used for the artificial ‘palm island’ in the United Arab Emirates was shipped in from Australia. It’s not going to be easy to be a geologist in 10 million years from now….

Blue-grey loess makes for red bricks

The geology of Northern France is clearly visible in the buildings along the route of today’s stage. A well-known feature is the ‘rouges-barres’, the red-white banded walls. These consist of a row of the bright white chalk limestone that we saw yesterday in the cliffs of Calais. On top are then three rows of red bricks that are made from the loess of the ice ages. By the way, did you know that red brick is not necessarily made from red clay? Moet loess and clay is bluegrey in color, but when it is heated to more than about 700°C, iron minerals in the clay oxidize. And when they do, they color the brick red. And in addition to the rouges-barre, the walls often contain bluegrey sandstones (which when weathered turn brown). The roofs consist of shales, or tiles: that’s basically the same stuff, but the first was geologically baked, and the second was baked by us.

The cobble road of Paris-Roubaix

But today will mostly be about the nightmare of the mechanics that have to prepare and fix the bikes: the famous cobbled roads of northern France. These roads, or ‘drèves’, a word derived from Dutch and that also underlies the word ‘drive’, was made by farmers in the region who did

not want to get stuck in the mud. They used hard sandstones, and even harder diorite from the Silurian of Avalonia: the ‘Henegouwen porphyry’ that is mined in a quarry across the Belgian border. ‘Porphyry’ means that there are ‘chunks’ in the rock, which in this case consist of plagioclase minerals. These started to crystallize the first when the magma cooled - so-called ‘phenocrysts’. But also the roads of northern France cannot withstand the progress of society: for repairs today, rocks are used that come from Scandinavia. And they are protected: in several cases the local population cannot use them anymore. Only the riders in the peloton can, who come from all over the world to France, to race.

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Douwe van Hinsbergen

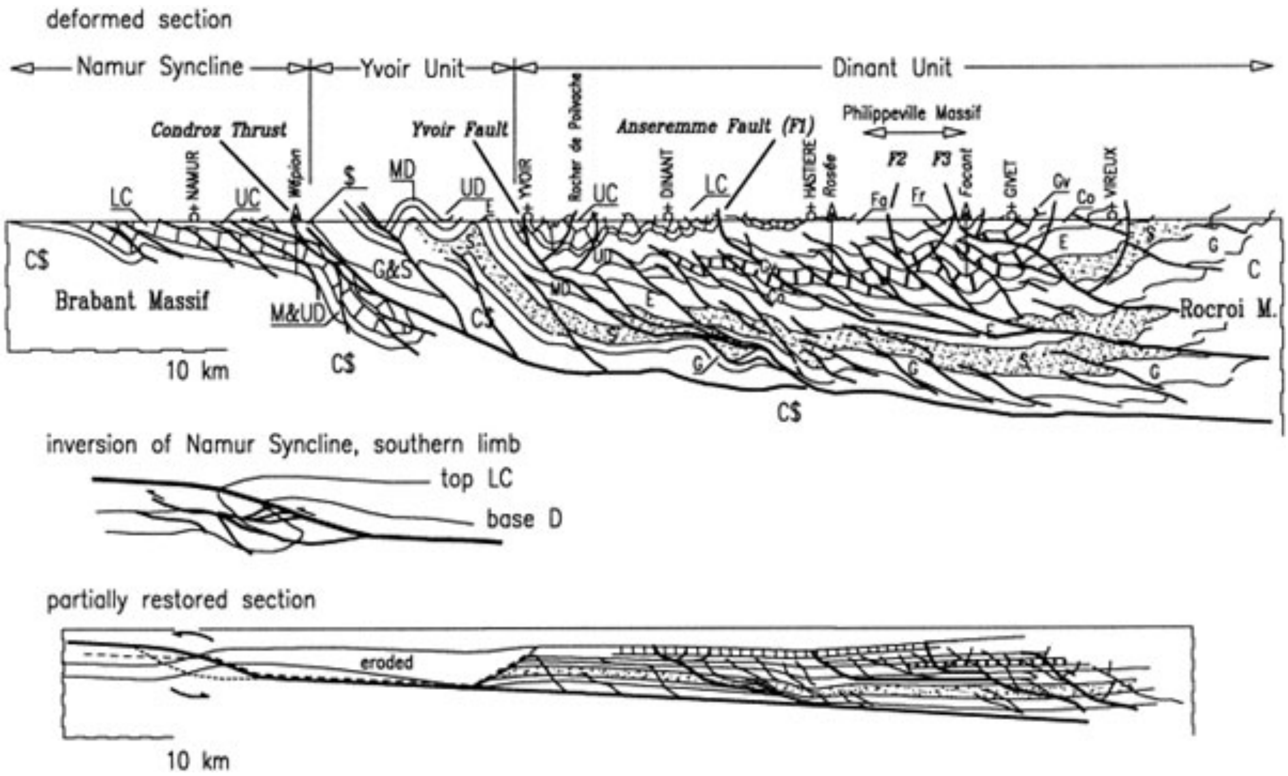
Stage 6 | Binche - Longwy / A 'pushed-up sleeve' landscape

Men

220 km		Hills		The Himalayas of Europe

In the first half of stage 6, we find ourselves on the shores of the Paris Basin, in the Ardennes Mountains. These mountains today have elevations of no more than a few hundred meters, and the terrain where breakaway groups and attackers may be successful.

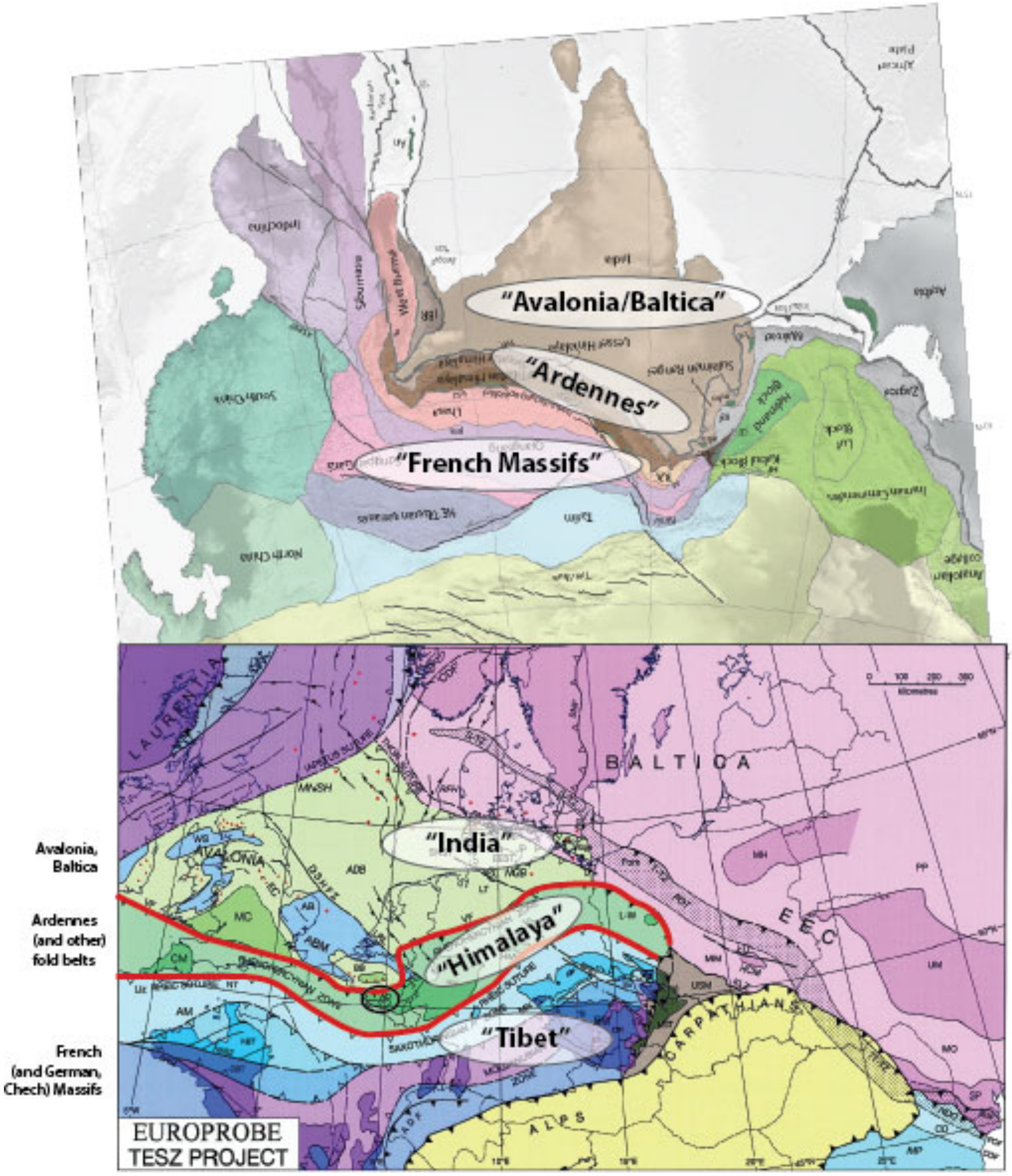
A mountain belt across Europe



When the Ardennes formed, about 335-300 million years ago, it was part of a spectacular 'Rheno-Hercynian' mountain belt, from Poland, through Germany to the Ardennes, and from there to southern England, to continue at the other side of the Atlantic Ocean (which didn't exist yet) to the Appalachians of the eastern United States. This mountain belt formed because an oceanic basin (the 'Rheic Ocean') closed due to subduction between a continent in the (present-day) north (Laurasia, that included Baltica and Avalonia) and a deformed belt of small continents that formed Armorica (read more about Armorica: stage 1) in the south (including the French crystalline massifs of the Vosges, Massif Central, Morvan, and the Armoricaine Massif of Bretagne).

Pushed-up sleeve: folded sedimentary rocks

The subduction zone that existed between Armorica (France) and the Baltica-Avalonia continent (Belgium, the Netherlands, England, northern Germany, Denmark) was diving southward into the Earth's mantle. As a result, when all the oceanic crust was consumed, Avalonia was shoved down below Armorica, and Armorica started bulldozering over Avalonia. At the southern shores of Avalonia, thick packages of



sandstones, clays, and limestones had formed in the course of tens of millions of years, in shallow seas, a bit like the Great Barrier Reef of Australia today. Those sedimentary rock packages were scraped off the rest of the plate that went down below Armorica, a bit like a pushed-up sleeve on your arm. That folded 'sleeve', you can now see in the Ardennes. But the sedimentary 'sleeve' of Avalonia was not a few millimeters thick, as on your arm, but a few kilometers, so you can imagine that the forces and time required to fold and break those rocks and push them together over a few hundred kilometers into a high, wide mountain belt (see Figure cross-section).

A bit like the Himalaya

We can find a modern-day example that is comparable to Avalonia/Baltica, the Ardennes, and the French Massifs in present-day Asia (see Figure maps). There, the Indian continent (which also contains older continental fragments and subduction zones) is being shoved below Asia. The sandstones, clays, and limestones that existed on India's northern shores have been, and are being, offscraped and folded up like a sleeve, forming the Himalaya Mountains. The southern parts of Asia, in the Tibetan Plateau, are similar to the French Massifs, but we will see more of that in tomorrow's stage, when we leave the Ardennes and go to the Vosges! Many in the peloton will be happy that there has been 300 million years of erosion in northern France…otherwise they'd have to climb up to the Tibetan Plateau today!

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Douwe van Hinsbergen

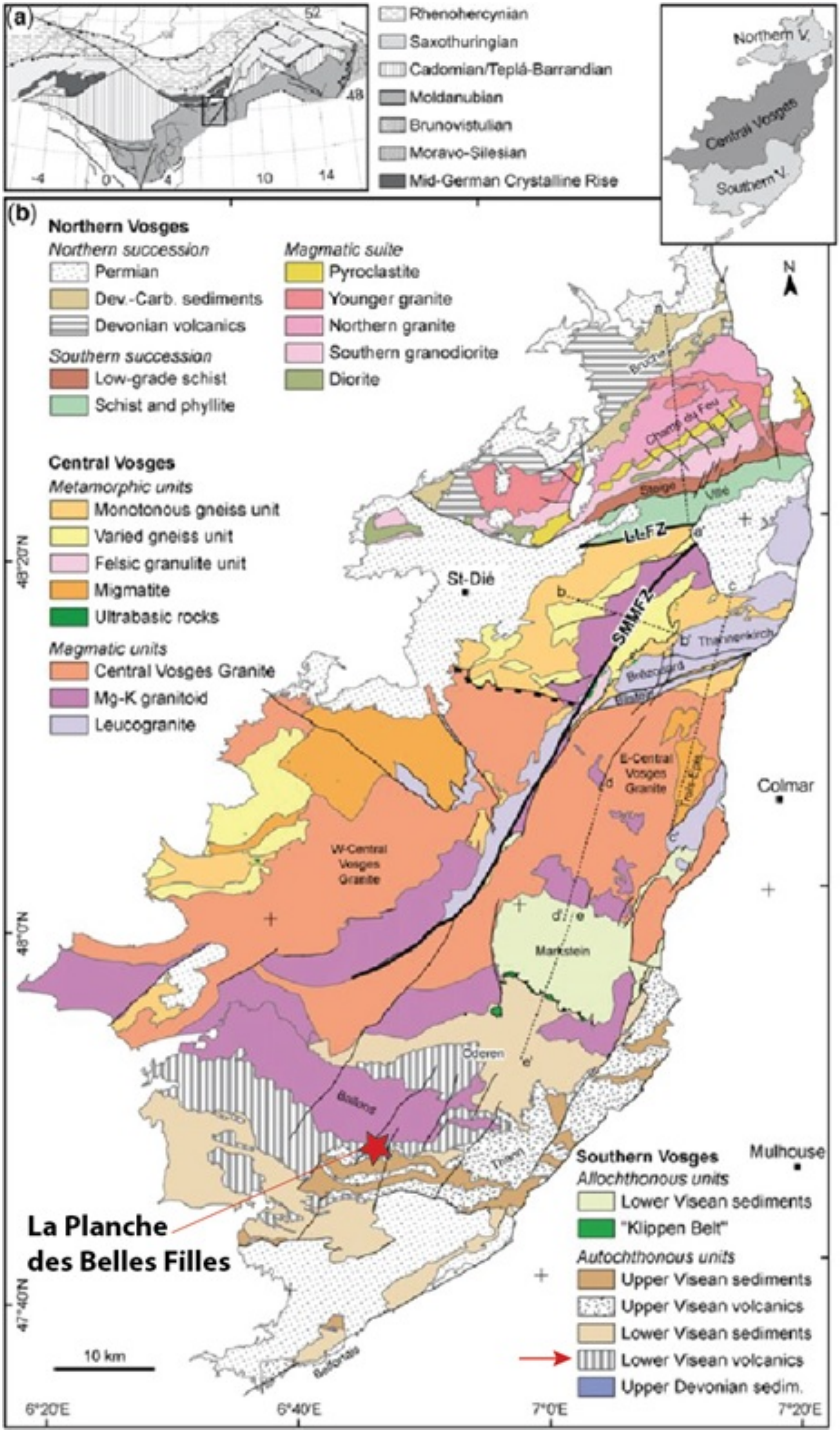
Stage 7 | Tomblaine - La Super Planche des Belles Filles / The Ring of Fire

Men

176 km		Mountain		The Vosges a part of the Ring of Fire

This year's Tour de France brings the peloton back to the Vosges, one of the main crystalline massifs of France. These massifs formed the upper 'Armorican' plate above the subduction zone that eventually closed the Rheic ocean and that eventually led to the formation of the Ardennes mountain belt, between 335 and 300 million years ago (see yesterday's blog). But during the oceanic subduction stage, the Vosges massif was located above a subducting oceanic plate, or 'slab' as we call them. And those locations are famous for their volcanism, as we see in the Ring of Fire, around the Pacific Ocean.

The Ring of Fire: How volcanoes form due to subduction


(a)
Rhenohercynian
Saxothuringian
Cadomian/Teplá-Barrandian
Moldanubian
Brunovistulian
Moravo-Silesian
Mid-German Crystalline Rise
52
48
-4
0
4
10
14
Northern V.
Central Vosges
Southern V.
(b)
Northern Vosges
Northern succession
Permian
Dev.-Carb. sediments
Devonian volcanics
Southern succession
Low-grade schist
Schist and phyllite
Magmatic suite
Pyroclastite
Younger granite
Northern granite
Southern granodiorite
Diorite
Central Vosges
Metamorphic units
Monotonous gneiss unit
Varied gneiss unit
Felsic granulite unit
Migmatite
Ultrabasic rocks
Magmatic units
Central Vosges Granite
Mg-K granitoid
Leucogranite
N
LLFZ
SMMFZ
St-Dié
Colmar
Mulhouse
Thannenkirch
W-Central Vosges Granite
E-Central Vosges Granite
Markstein
Oderen
Ballons
Thann
La Planche des Belles Filles
Southern Vosges
Allochthonous units
Lower Visean sediments
"Klippen Belt"
Autochthonous units
Upper Visean sediments
Upper Visean volcanics
Lower Visean sediments
Lower Visean volcanics
Upper Devonian sedim.
10 km
48°20'N
48°0'N
47°40'N
6°20'E
6°40'E
7°0'E
7°20'E

Oceanic crust forms at mid-oceanic ridges, where two plate spread apart, the Earth's mantle below the plates rises up, melts (in part, about 20%), and the melt percolates upward to fill the gap forming new crust. During that process, the magmas interact with sea water, and that sea water gets incorporated in the minerals of the crust. Moreover during its lifetime, sediments that contain water form on the ocean floor above the crust. But over time, oceanic crust becomes denser than the underlying mantle, and sooner or later, it will sink back into the Earth's mantle - the process we call subduction. During its descend into the mantle, the sediments and the magmatic rocks of the oceanic crust transform into denser minerals, and the water they contained is released into the mantle (a process called 'dehydration') above the downgoing 'slab'.

When this happens at a depth of about 100 km or more, that water leads to (partial) melting of the mantle above the slab. At a depth of about 150 km, the last water-containing minerals release their water, and as a result, magma forms in a narrow zone where the downgoing slab is about 100-150 km deep. Those magmas arise up and form large magma chambers in the upper plate (so-called plutons, with 1-10 km diameter, and a lot of plutons together form a batholith of 10's-100's km dimension), and an array of volcanoes. Those volcanoes are known as a 'volcanic arc', and these are typically located about 150-300 km (depending on the angle at which the downgoing plate dips into the mantle) from a subduction trench, on the upper plate. Take your Atlas and have a look at the volcanoes around the Pacific, or in the Lesser Antilles, and you'll see that these rules of thumb work pretty well.

Similar to the Andes

The Vosges are part of such a batholith, with plenty of plutons of ~350-330 million years old. Much of the Vosges contains crystallized magma chambers, which cooled slowly,

allowing for large (cm-scale) crystals to grow, together forming granite rocks. The famous 'Ballons' of the Vosges are in those granites. The Planche de Belles Filles, however, is located in volcanic rocks: the volcanoes that formed the 'Ring of Fire' during the subduction of oceanic crust just before Avalonia collided and the Ardennes formed. Volcanoes and plutons are important sources of metal ores, and mining in the Vosges dates back as far as the Bronze Age! (Figure). Plutons and volcanoes like in the Vosges are well-known from similar settings like southern Tibet (see yesterday's blog), and are actively formed today in places like the Andes! The Colombian and Ecuadorian riders in the peloton may feel right at home today!

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Douwe van Hinsbergen

Stage 8 | Dole - Lausanne / France’s youngest mountain range

Men

186.5		Mountains		France’s youngest mountain range

After the crystalline massif and the ancient volcanoes of the Vosges, the peloton will cross the youngest mountain belt of France today: the Jura Mountains. In the Jura, the peloton will be surrounded by, below the lush vegetation, white rocks: limestones. These limestones were deposited in a shallow sea, just like in the Paris Basin in the northwest and in the Aquitaine Basin in the southwest of the country. And a considerable part of these limestones date from…the Jurassic, which was named after the Jura. The Jurassic formed the heydays of the ammonites, between 201 and 145 million years ago.

An isolated mountain range?

But why are these Jurassic rocks visible at the surface? We are close to the Alps, and the foreland of the Alps are covered by a thick pile of debris from the mountains. Why not the Jura? The answer lies in the subsurface. The Jura is half-moon shaped and lies parallel to the northwestern Alps, but is separated from the Alps by a wide vallei in Switzerland that hosts the Geneva Lake and the Neuchâtel Lake. In this valley there is a lot of debris from the - this formation is known as the ‘Molasse’ that was mostly deposited since about 25 million years ago. And this Molasse has also covered the sediments of the Jura mountains, but between 20 and 7 million years ago, the sequence of limestones and overlying sediments was squeezed, shortened, folded, and thrusted. Just like that?

The little, younger brother of the Alps

No, not just like that. The Alps foldbelt formed because Europe was diving below the African plate - we will explain more about that later during the Tour. In the process, the rock sequences of the European plate were offscraped and piles up, just like in de Ardennes 250 million years prior, and this process formed the Alps. The northern and western rocks in the Alps were the youngest to be added, to the bottom of the pile (foldbelts grow at the base). In the northwest, the sediment sequences of Europe were deposited on a thick pile of 'evaporites' (rock salt and gypsum that formed by evaporation of seawater) from the Triassic. These evaporites formed about 220 million years ago in a shallow sea under the desert climates in central Pangea. Rock salt and gypsum is very weak. So when the sequence of limestones that were resting on the gypsum started to be pushed below the Alps, the evaporites started to slide, like a banana skin. The limestones above the evaporites became part of the Alps, whereas the crust below the evaporites stated part of Europe and moved below the Alps. This process occurred below the valley between the Jura and Alps. But in the northwest, where the gypsum layer was thinner or stronger, the limestones did not slide any further, but were shortened, folded, and thrusted: the Jura mountains. In total, the Jura mountains were shortened by about 30 km and this amount decreases to zero to the northern and southern tips.

Modeling in the laboratory

To illustrate how this process of 'detachment' on a weak horizon works, and how one process can produce two mountain belts, we modeled the process in the 'Tectonics' laboratory in Utrecht (the TecLab) - especially for GeoTdF! In the movie below you can see how layer by layer a model was built that represents the limestones and the other sediments of the Jura. And how the shortening of this sequence can make two foldbelts separated by a valley. The non-climbers of the peloton would probably have preferred to do today's stage also in our sand-box model!

I am a geophysics student who likes to be outside and to be physically active. I aim to use knowledge of geophysical tools to investigate shallow-subsurface structures, especially those with immediate societal or technological relevance. In the Tectonics Laboratory, we study plate tectonic processes such as mountain building or earthquakes. Check the Geo-TdF team.

Sjaak van Meulebrouck

As geologist I investigate processes that lead to deformation of the Earth's crust and lithosphere leading to the formation of mountain belts or sedimentary basins. I do that by describing geological structures through field observations and by explaining these observations through building and running physical scale models.

Ernst Willingshofer

I am a geologist and I study plate tectonics and the driving mechanisms in the Earth’s mantle, mountain building processes, and the geography of the geological past. I enjoy geological fieldworks all over the world, and translating the results to science and a broad public.

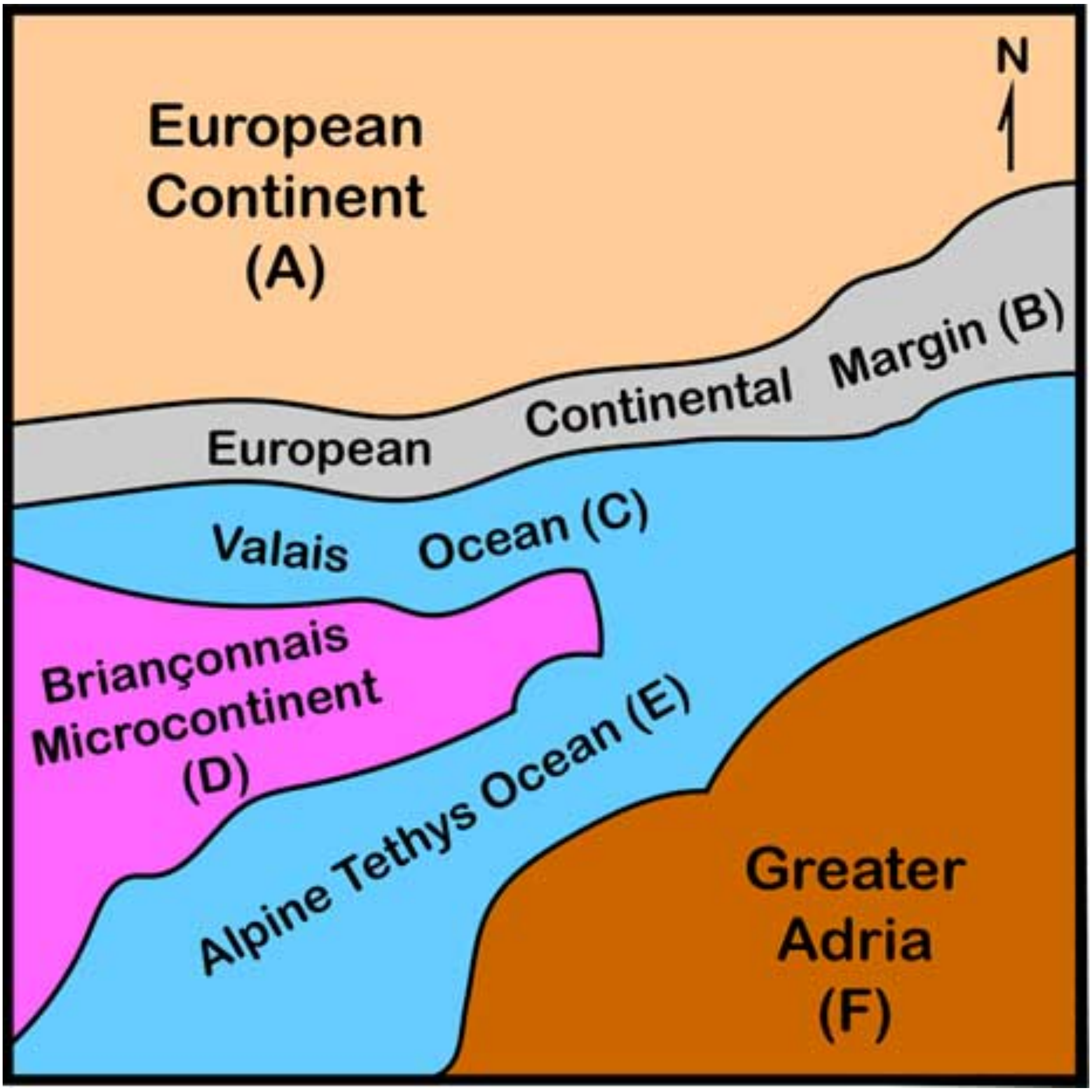
Douwe van Hinsbergen

Stage 9 | Aigle - Châtel / Microcontinent Island Hopping by Bike

Men

193		Mountains		Microcontinent Island Hopping by Bike

Today's stage from Aigle to Châtel les Portes du Soleil takes the riders through many of the main geological units of the Western Alps, but the road will not be easy for either the riders or the geocurious. Expect a mix-up, with the riders testing their legs on the biggest climbing day so far in this year's Tour, and with slivers of continents



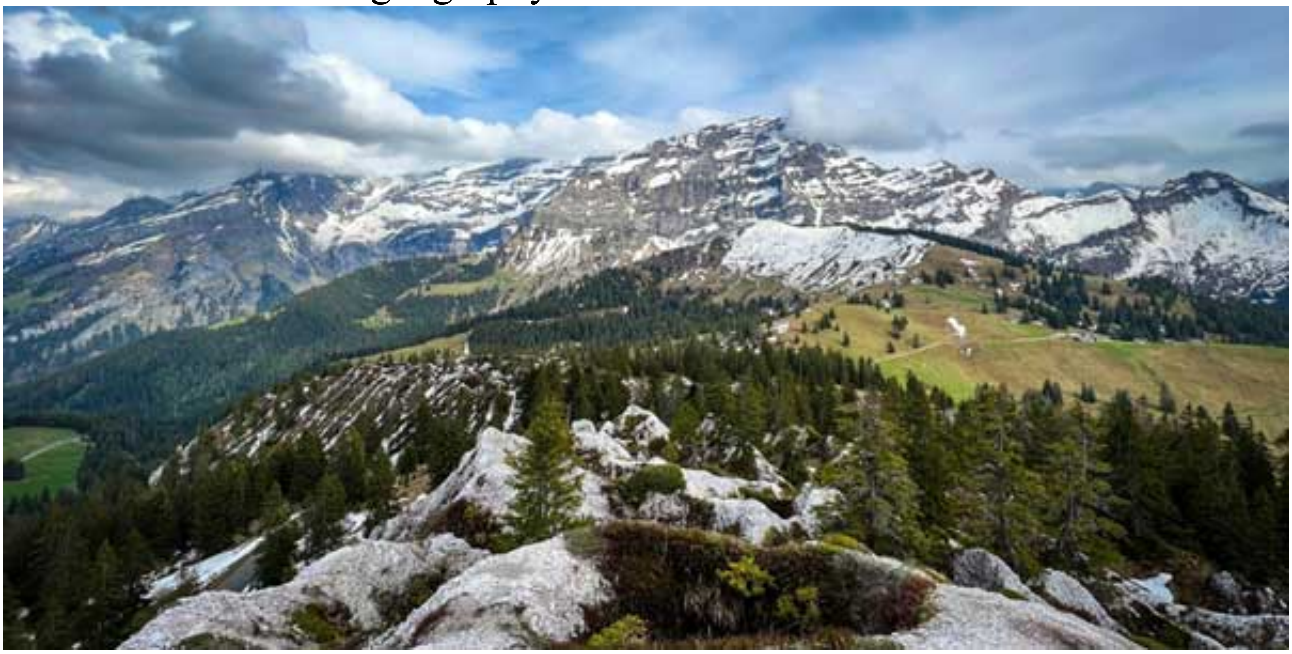
and microcontinents, continental margins, and deep oceans appearing and reappearing in anything but an orderly fashion. The riders will spend most of the day riding uphill into deep ocean basins and will come up for air only a few times on rocks from ancient shallow seas or isolated pieces of continental crust.

Microcontinent - The simple story

If we restore the last 50 million years of deformation in this region of the Alps, then we find a fairly simple geography that includes two continents (Europe & Africa (Greater Adria)), two marine continental margins, two oceans, and a microcontinent (Briançonnais) in the middle of it all. The subduction of the European Plate beneath the African Plate that led to the collision of these two continents brought all of the intervening units together, deformed them into spectacular sheets (nappes) of fault-bounded folded rock, and moved them into new configurations and locations. If this deformation was straight-forward, like a scrunched up sleeve of a shirt described in Stage 6, then it would be much easier to piece together these units: starting in the north and moving south, we'd encounter

- A. rocks of the European continent, including younger sedimentary rocks comprising the eroded and transported sand and cobbles of the Alps (the Molasse described in yesterday's post, as well as moraines and outwash from once far-more extensive Alpine glaciers and ice sheets);
- B. marine sediments deposited on the southern continental margin of Europe (referred to as the Helvetic nappes);
- C. deep marine sediments and ocean crust of the ancient Valais Ocean (referred to as the Lower Penninic nappes);
- D. crystalline rocks of the crust of the Briançonnais microcontinent (referred to as the Middle Penninic nappes);
- E. deep marine sediments and oceanic crust and uppermost mantle of the Alpine Tethys Ocean (see Stage 11 for more information about these rocks, link) (referred to as the Upper Penninic nappes); and finally
- F. rocks comprising the northern margin of Greater Adria.

These units and their geography are shown in the cartoon below.



The story is rarely simple

In today's stage, the riders visit all of the units described above, except for rocks from the African plate that lie in the southern Alps and Dolomites. But as the Tour travels south from Bülle to Aigle and up to Châtel, the riders don’t simply ride from Unit A to B to C to D and finish on E. Instead, they will pilot their bikes from Unit A to B to E to B to D to E to C to D to B to A to B and finally to Unit D. They’ll spend much of the day riding through deep, ancient oceans and only occasionally come up for air on islands of dismembered microcontinent. Will the neat and tidy order of the GC from the first week of racing also get mixed up by this mélange of continental collision?

Why so complicated?

How is it that these tectonic units are so mixed up and so seemingly disordered? When trying to reconstruct the structure and history of the Alps (and most ancient and modern mountain belts), it’s important to remember that erosion by rivers and glaciers has removed much of the record of Alpine deformation, and that many key features are hidden beneath the surface. Geological reconstructions of mountain belts are guided by geometrical rules and our understanding of rocks’ material properties during deformation, as well as observations made and understanding gained from studying other mountain belts. Analog models of thrust belts and rock deformation (like those

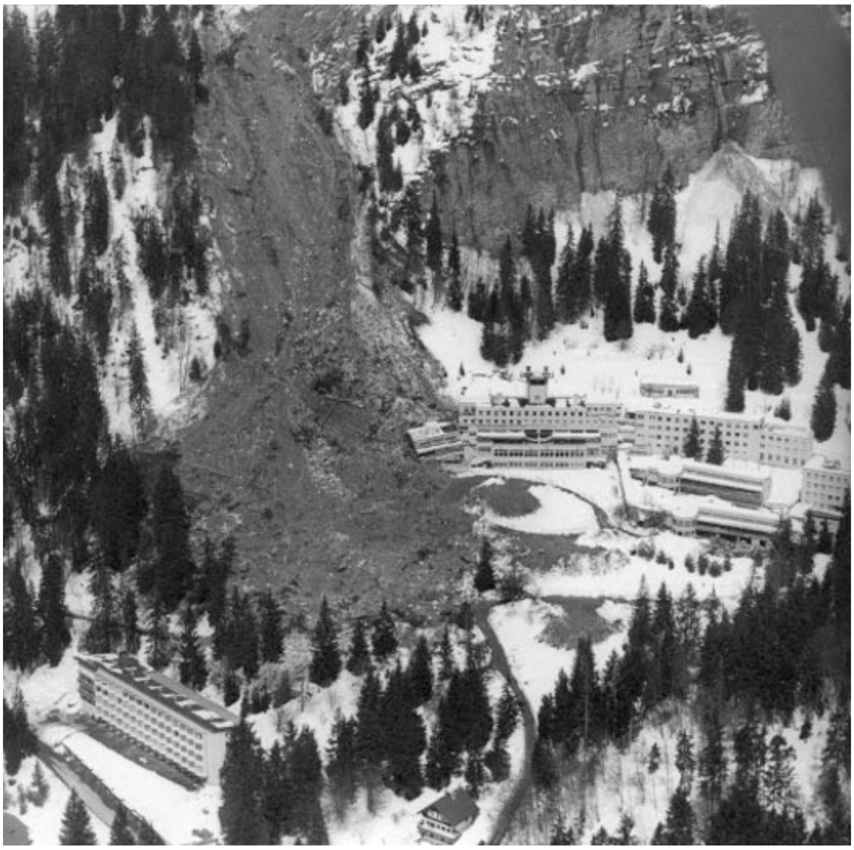
described in Stage 8, as well as computer models and subsurface imaging by geophysical techniques help us test and refine these rules and interpretations. Remember from the description of Stage 8 that nappes and fold belts typically grow at their base, such that material accreted to a plate early in a continental collision (such as the Units C, D, and E) can be far transported, refolded, and even dismembered by units, folds, and faults added to the plate more recently, and closer to the plate (such as Units A and B). Erosion often removes the continuous trace of units or faults on the surface and can even create ‘islands’ (klippe) of exotic rocks at the tops of mountains and ‘windows’ through one nappe into another. In this way, a once continuous nappe of microcontinental crust appears on the surface as isolated slivers of rock amongst a sea of earlier and later accreted oceanic sediments. With all of this riding across oceans, perhaps Le Tour should add a pedal boat stage!

I am an Earth Scientist who harnesses the unique information encoded in the magnetic properties of geological materials to study tectonic, climate, ecological, and environmental processes.
Pete Lippert

Stage 10 | Morzine les Portes du Soleil - Megève / Landslides and the Tour

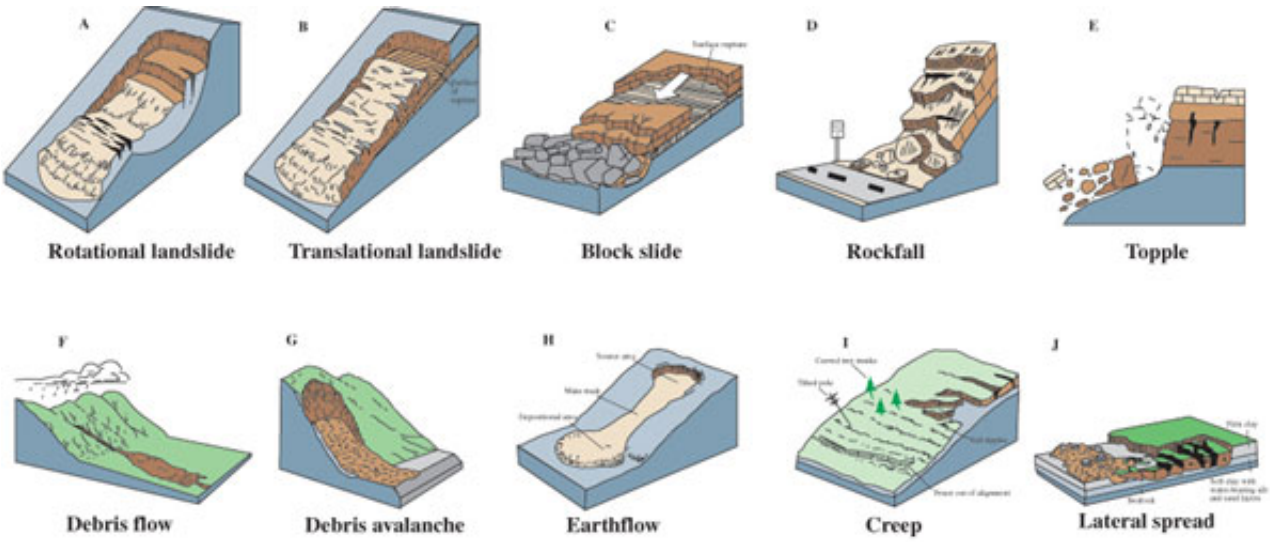
Men

148 km		Hills		Landslides



On the steep hillsides of mountainous regions, large packages of rock and loose debris can slide down in slow or catastrophic events: so-called landslides. The remains of landslides are visible in many places along the Tour de France route, especially on the sides of the large cols during mountain stages. Landslides are common in all mountainous regions on Earth. It comprises the movement of rocks and soil along a slope, and may include falling, sliding, or flowing (see Figure). Especially the last form, of flowing, will be remembered by many a Tour de France viewer after stage 19 in the Tour of 2019. That stage was canceled just below the top of the Col de l'Iseran after a mud flow blocked the road in front of race leader Egan Bernal.

The mechanisms that lead to landslides



A landslide forms when the forces, especially gravity, that pull slopes down exceed the strength of rock and soil on a slope. Landslides may occur on slopes that were already on the edge of collapsing after the subsurface is weakened due to rain, melting snow, changes in water level, erosion due to streams, changes in groundwater supply, earthquakes, volcanic activity, human activities, or a combination of these. Landslides are very hard to predict and we therefore cannot prevent all landslides. Slopes with a high landslide risk can be stabilized through a number of methods, amongst others lowering of the slopes, increasing drainage to avoid soil saturation and loss of strength, and increasing the slope strength by for example a combination of concrete and earth anchors (as sometimes observed along road cuts).

The deadly landslide in Passy

Today, the Tour family will pass one of the most devastating landslides in French history, in the village of Passy, close to Mont Blanc and at the start of the final climb of

today. During the night of 15 to 16 april 1970, Passy was struck by a catastrophic landslide (Figure). This slide was likely caused by the melting of the thickest snow cover in years. The melt water then infiltrated the soil leading to a decrease in soil strength. A slide plane formed at the transition between soil and bedrock, and the upper part of the hillside collapsed and slid down. The Passy landslide claimed 71 lives, mostly children, when it destroyed part of the Roc des Fiz sanatorium. Ironically, this sanatorium was intended for children between 4 and 16 years to recover from tuberculosis in the healthy mountain air. In 2019, a memorial was raised at the location of the former sanatorium (Figure).

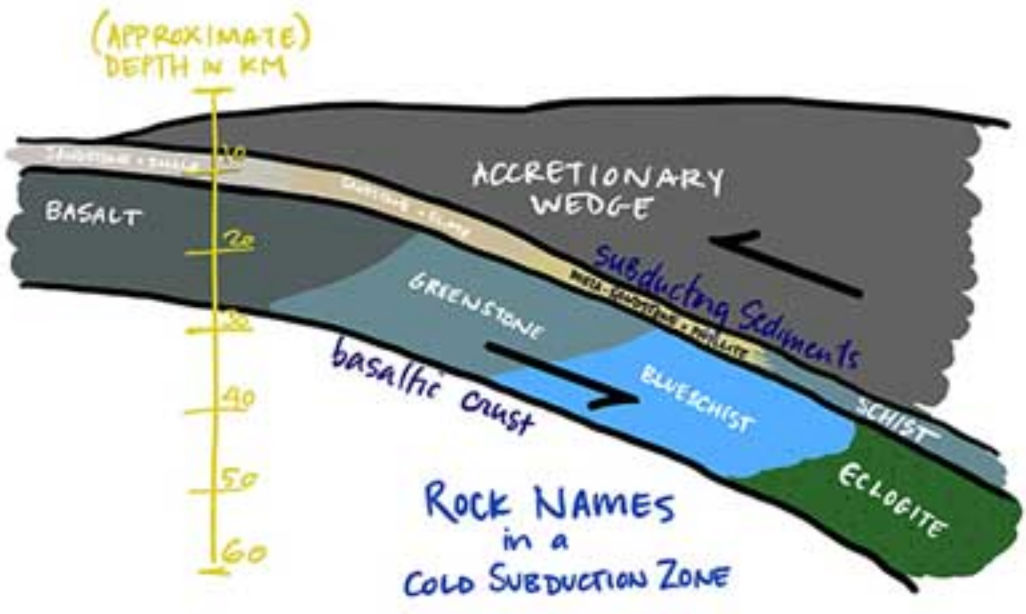
I am a geomorphologist specialized in high-mountain processes on Earth and Mars. My main goal is to minimize landslide and debris-flow hazards, by understanding and recognizing their triggers, flow dynamics, erosion processes, and deposits. This quest has taken me from mountain ranges all over the globe all the way to the mountains of Mars.

Tjalling de Haas

Stage 11 | Albertville - Col du Granon / A ride through a former subduction zone

[Men](#)

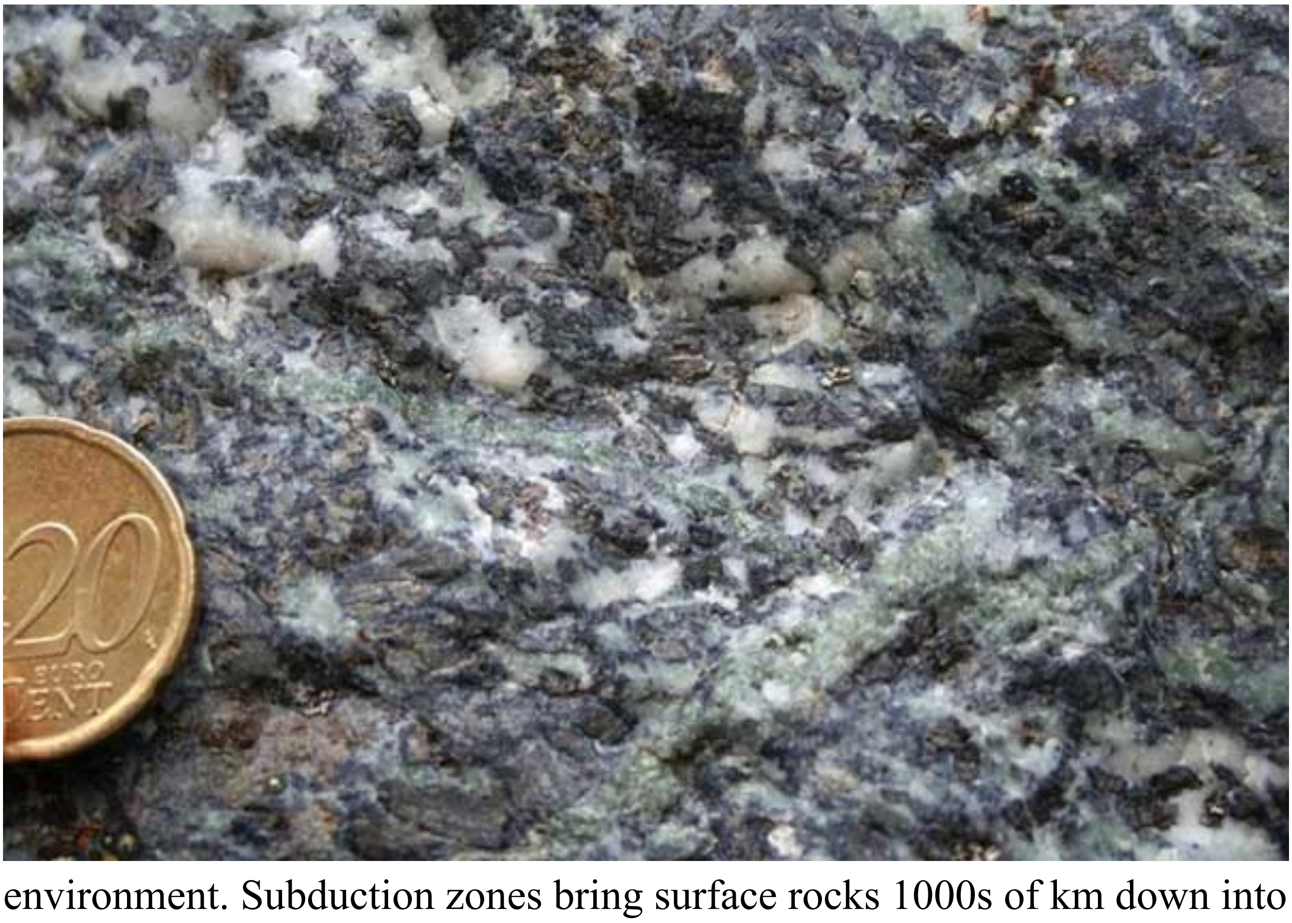
152		Mountains		A ride through a former subduction zone



Today's ride is both! Journey with the riders as they traverse what used to be the edge of Europe, pass over a collisional zone where fragments of oceanic crust are caught up in the wreckage, and then enter a terrane of rocks that were dragged deep into Earth's interior, 45 million years ago. However, over the years, they've made their way back up to the surface. Rocks like these ones comprise large parts of the incredible topography of the Alps. To see these deeply buried rocks, the peloton will battle a series of rolling hills that caps out at ~2600 m at Souvenir Henri Desgrange. Marking roughly two-thirds through today's trek, this peak is situated at the boundary between French provinces Savoie and Hautes-Alpes and is aptly deemed the heart of the French Alps. Today's climb is a small price to pay to reach the rare rocks that formed 70 km beneath the Earth's surface!

The Earth is a pressure cooker, and rocks are the ingredients

As the riders close the first ~45 km of today's 149 km, the peloton approaches the foothills of the Alps. If the weather allows, keep an eye out for rocks with sparkling flecks that shine in the sunlight. These sparkling minerals are sheet-like crystals of mica which testify to the rocks' high-pressure history. When rocks are buried deep in the Earth due to tectonic forces, the chemical constituents reorganize and mineral structures change to equilibrate with the higher pressures and temperatures during a process called metamorphism. When cold, dense oceanic crust plunges beneath less-dense continental rocks, high-pressure metamorphism occurs in a subduction zone



environment. Subduction zones bring surface rocks 1000s of km down into the mantle, but sometimes subducted rocks come back to the surface, even from depths of more than 100 km, where they can make diamonds! Even though the shiny minerals on today's route are not diamonds, metamorphic petrologists think they're even more special. This is because each metamorphic mineral is a direct witness of the depths, temperatures, and chemical environments in which they formed. By measuring the chemistry and structure of metamorphic minerals, geologists can reconstruct tectonic conditions of the past. Therefore, we know that there was a subduction zone that made these rocks and it was plunging towards the south about 45 million years ago. As the riders crest their climbs at Col du Telegraphe and then at Souvenir Henri Desgrange, they are traversing deeper and deeper into the ancient subduction zone that consumed a small ocean that separated Europe from the microcontinent called Brianconnais.

A subduction zone today

If these rocks in the Alps formed in a subduction zone 45 million years ago, why do we care about them at all? As with any geoscience field, looking at rocks from ancient systems teaches us about processes that occur today. Subduction zones make up over 55,000 km of the Earth's plate tectonic boundaries, for example along the western edge of South America, up around the Pacific ring from the Aleutians to Japan and Sumatra. Subduction zones continuously recycle oceanic crust back into Earth's interior, generate the largest and most destructive earthquakes on the planet (Magnitude 8 or 9 quake? That was a subduction zone!) and host the most explosive volcanic eruptions (like the recent one in Tonga). Studying subduction zones in the rock record can give us clearer insights into why earthquakes occur, what triggers volcanic eruptions, and how often these destructive events occur. Although these events are some of the most devastating natural hazards to our human perceptions, they are barely blinks of an eye in geologic time. Nevertheless, they show us that our Earth is a living, breathing system and its pulse persists over the eons. And the temporary end product of all this raw tectonic power makes for spectacular bike races!

My goal is to figure out how subduction zones get started, and after they start, how they change through time. I combine structural geology in the field and mineral and isotope chemistry in the lab (metamorphic petrology and geochronology) to reconstruct plate tectonic histories from ancient subduction zones. I've studied rocks from Greece, Oman, and Quebec, and I'm adding to the list!

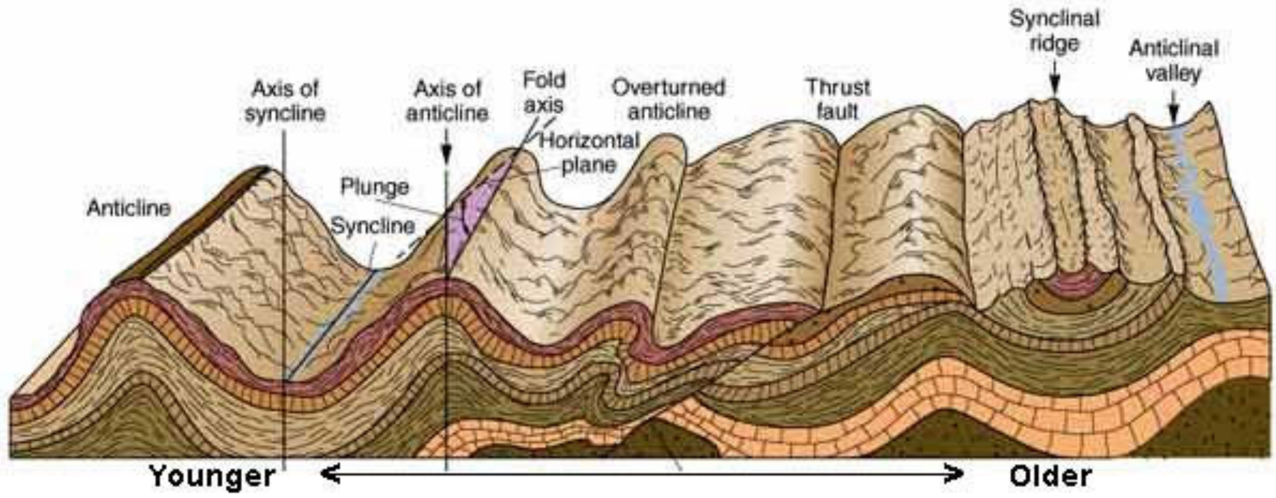
Alissa Kotowski

Stage 12 | Briançon – Alpe d’Huez / Bending, or failure and breaking on Alpe d’Huez

Men

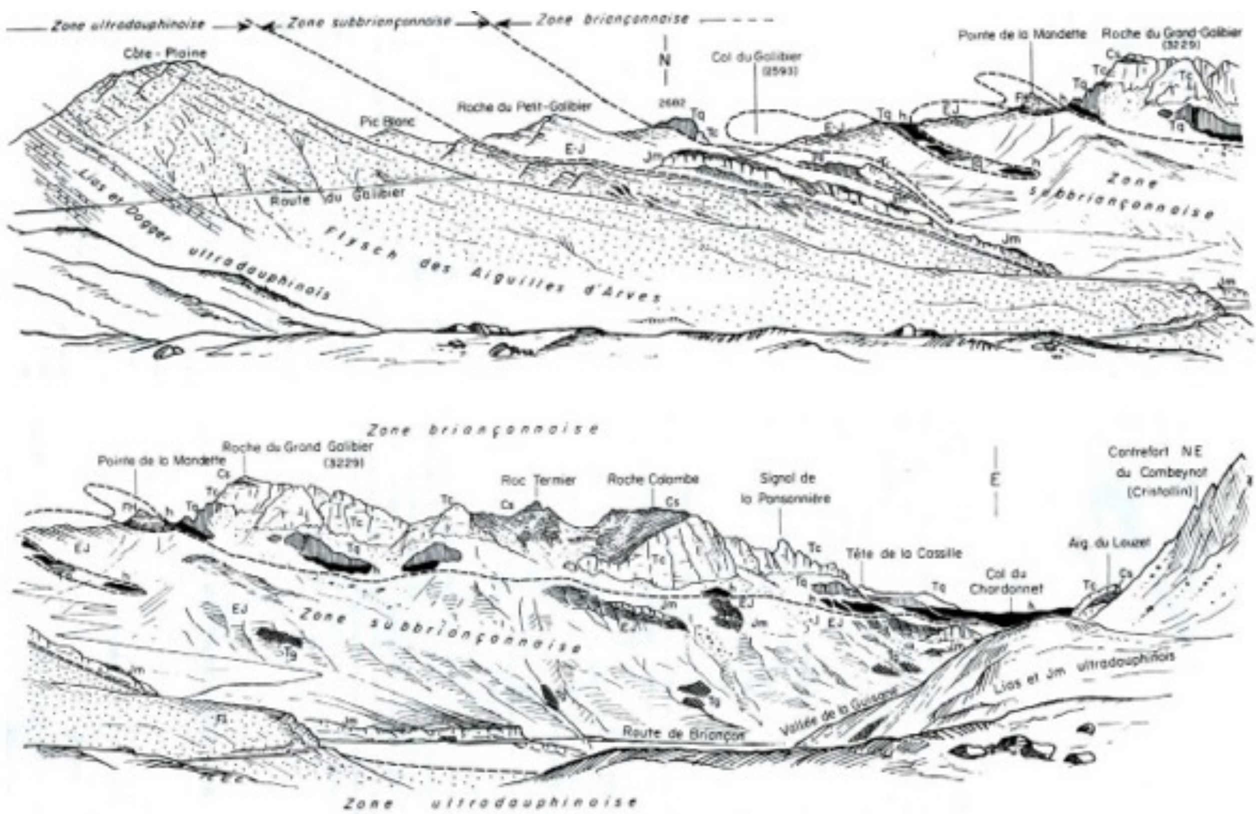
165		Mountains		Brittle deformation, fold, fail and bend

Today is the last stage through the Alps, and promises fireworks on the flanks of the Galibier, the Croix de Fer, and Alpe d’Huez. The riders will start the ride in the nappes of the Alps that were derived from the Valais Ocean and Briançonnais microcontinent (see stage 9 and stage 11) and will ride through the deformed margin of Europe that



contains de Croix de Fer and Alpe d’Huez. Throughout the stage, the peloton will cross rocks that have undergone the two different mechanisms in which rocks and rock packages can deform, on millimeter-scale, or on scale of entire mountain belts: rock packages along the route are in places broken – for instance where ‘nappes’ were pushed (thrust-faulted) over each other (see stage 9), or where crust is pulled apart and crustal blocks slide off each other. This kind of behavior is known as brittle deformation and occurs when the stress on a rock overcomes its strength: the rock will fail and break. When rocks fail, break, and suddenly slide, this causes earthquakes.

On the other hand, rocks may fold, and make for pretty wrinkles that can be centimeter-scale, or kilometers wide. This is known as ductile deformation and occurs when the stress of a rock makes it flow. Ductile deformation is gradual, does not produce earthquakes, and is the common mechanism of deformation in the Earth's mantle. But at the surface, depending on the properties of the rock and the rate and amount of displacement, rock packages may experience both types of deformation. And this is what happened along the route of today's stage.

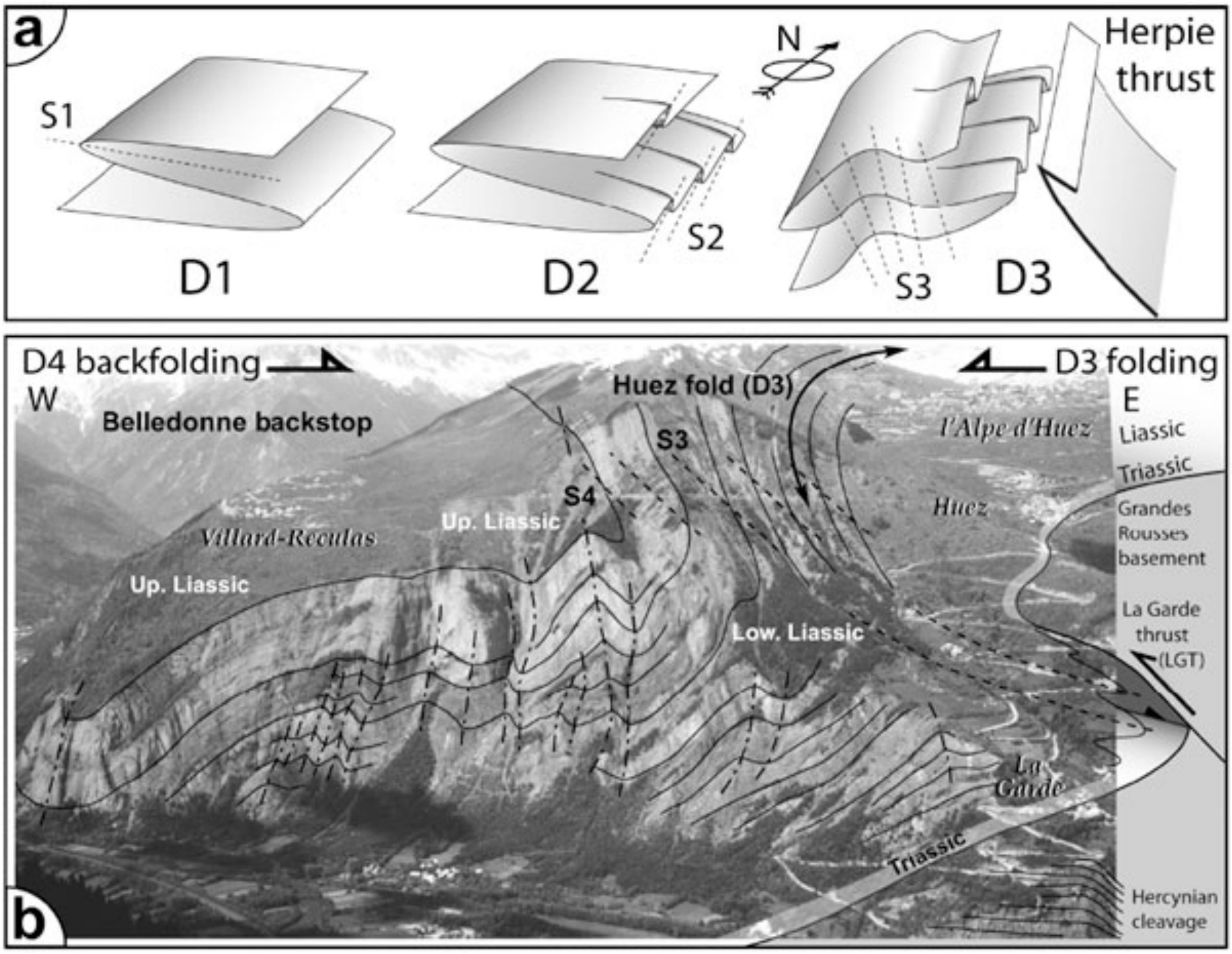


Galibier – an enormous fold above a fault

The Galibier is a mountain that is part of the Briançonnais nappe – the thick rock slice that was derived from the microcontinent (see stage 9) and that was buried to great depth (stage 11). This nappe is separated by faults from underlying and overlying units, but internally, it has been folded in enormous, flat-lying folds. In the sketch in the Figure, you can see where the Col de Galibier is located in major, flat-lying folds. The Alps are known for such enormous structures and these illustrate the enormity of wreckage that occurs when continents collides. Deformation like this requires that the km-thick rock slices behave like chewing gum accommodating tens of kilometers of deformation.

Folding on Alpe d'Huez

The famous Alpe d'Huez is probably the best-known col in the Tour de France, and one of the most heroic climbs of the race. The image of Alpe d'Huez that is shown here, you may not have seen before. French geologist Thierry Dumont and his colleagues showed that Alpe d'Huez is part of a major fold that is larger than the entire



mountain. Rock layers of Jurassic (Liassic) age similar to the ones that we saw in the Jura Mountains, are folded to vertical along most of the route. And this fold is not a simple one: the detailed work of the French geologists has shown that folding occurred in at least four different phases and directions. The rocks look like a towel that you threw in the corner after using it. On the scale of the entire Alps, the fold of Alpe d'Huez looks like no more than a detail. But it is a detail that the fastest climber on the flanks of Alpe d'Huez (Marco Pantani) took almost 37 minutes to climb up on. And he was only halfway the fold! Let's see what todays climb will bring us: who will fold, who will fail, and who will bend without breaking?

I am a geoscientist specializing in paleomagnetism, geochronology, and stratigraphy. I develop palaeogeographic, paleoenvironmental, and paleolandscape reconstructions. My current projects focus on: - ocean and marine connectivity, the evolution of ocean passages and sea-straits; - connectivity-driven environmental changes, in deep oceans and epicontinental seas; - landlocked basins - paleoenvironmental evolution and reconnections with the global ocean.

Dan Palcu

I am a geologist and I study plate tectonics and the driving mechanisms in the Earth's mantle, mountain building processes, and the geography of the geological past. I enjoy geological fieldworks all over the world, and translating the results to science and a broad public.

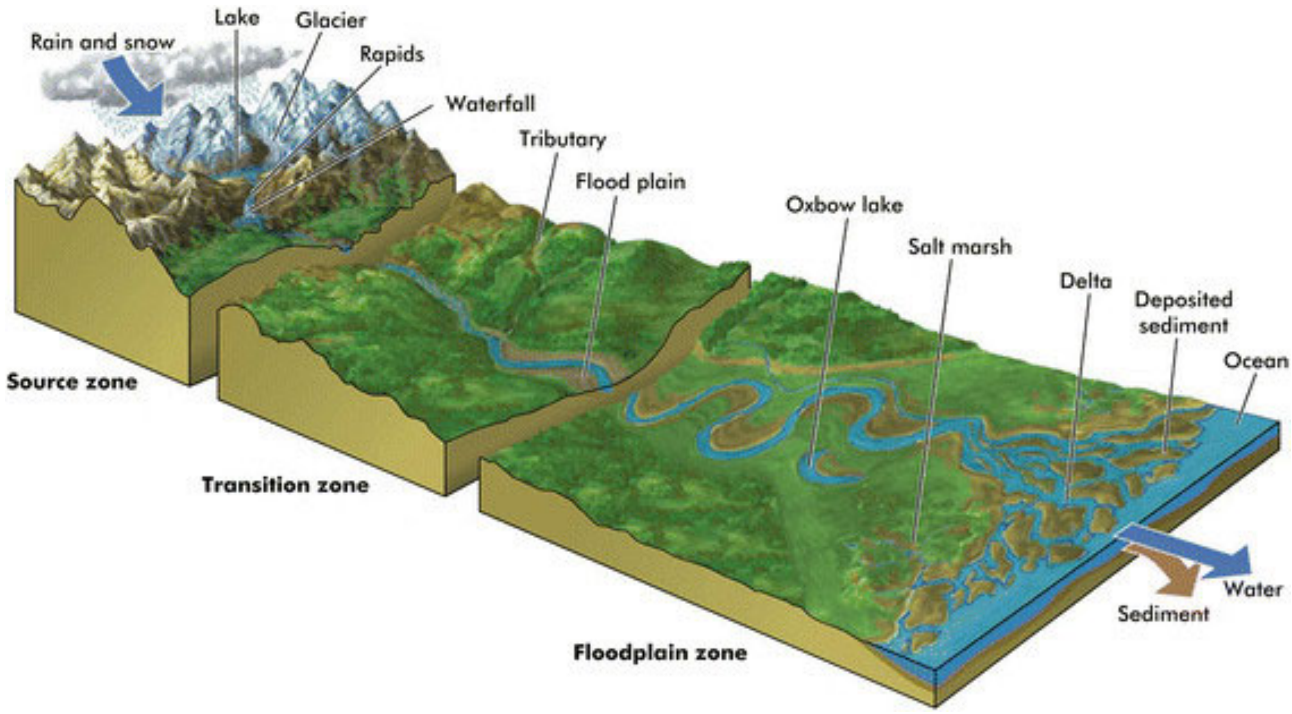
Douwe van Hinsbergen

Stage 13 | Le Bourg d'Oisans - Saint-Étienne / Messinian Salinity Crisis

Men

195 km		Hills		Messinian Salinity Crisis

The stage from Le Bourg d’Oisans to Saint Etienne brings the peloton from the foreland of the Alps to the crystalline massif of the Central Massif, and thereby crosses the Rhône Valley. The valley of today will not particularly impress the rides, but that would have been quite different in the geological past! The Rhône valley lies in the foreland of the Alps and is mostly fed by water and sediment that comes mostly from the Alps, but also from the Central Massif. At first sight, this makes the Rhône a river like many, draining a mountain range and transporting its sediment to the nearest sea, in this



case the Mediterranean Sea. But the Rhône underwent a spectacular history in the geologically speaking, recent past, of the last 6 million years. And this led to a subsurface that is pretty popular among wine-lovers!

The ideal profile of a river

Rivers like the Rhône typically originate as a wide network of streams in mountain ranges that one by one merge to eventually form a large river, heading for the sea. And in the process, rivers attempt at developing an ideal profile that looks a bit like a giant ski-jump: close to the source, rivers flow steeply down-hill and cut into the underlying bedrock. But as the river approaches its mouth, the bedding becomes shallower. Down-stream, rivers flow slower, become wider and transfer from mountain streams, to braided rivers full of pebbles, to meandering rivers that slowly progress through flat lands, to eventually reach the delta (Figure). If the river bed is not steep enough, a river will cut down to steepen the profile. If a river bed is too steep, the river will deposit sediments to make it

shallower. Changes in sea level at the river mouth thus have an important effect on an entire river: if sea level rises, the mouth of the river will migrate inland and the old bedding will become too steep: the river will respond by depositing sand and clay on land. But if sea level drops, the river will respond by cutting down along its length.

The Messinian Salinity Crisis - The desiccation of the Mediterranean Sea

The ideal profile of the Rhône river is influenced by the sea level changes of the Mediterranean Sea. The Mediterranean Sea is in many places underlain by oceanic crust, and in those places, water depths reach 4-5 km or more. But the connection to the Atlantic ocean is a very narrow and shallow bottleneck: the Straits of

Gibraltar. And approximately 5 and a half million years ago, during the Messinian period, tectonic motions between Morocco and Spain closed the connection of the Mediterranean Sea to the world's oceans.
Because the rivers that feed water to the Mediterranean Sea, like the Rhône and the Nile, are unable to supply enough water to balance the water lost by evaporation, sea level in the Mediterranean Sea started to drop. This process is currently active in the Dead Sea, where today's sea level is 427 m below global sea level (!!), and which in the process became incredibly salty. Sea level of the Mediterranean Sea during the Messinian thus dropped and dropped, and

thick packages of gypsum and rock salt were deposited in this period. This period is known as the Messinian Salinity Crisis which are visible in the hills,some of which have been uplifted by tectonic processes and are now visible in countries surrounding the Mediterranean Sea like Greece, Italy, and Spain (see photo). Many geologists believe that the water level of the Mediterranean Sea dropped a kilometer or more (see theTwitter video's embedded in this article).

The Grand Canyon of the Rhône

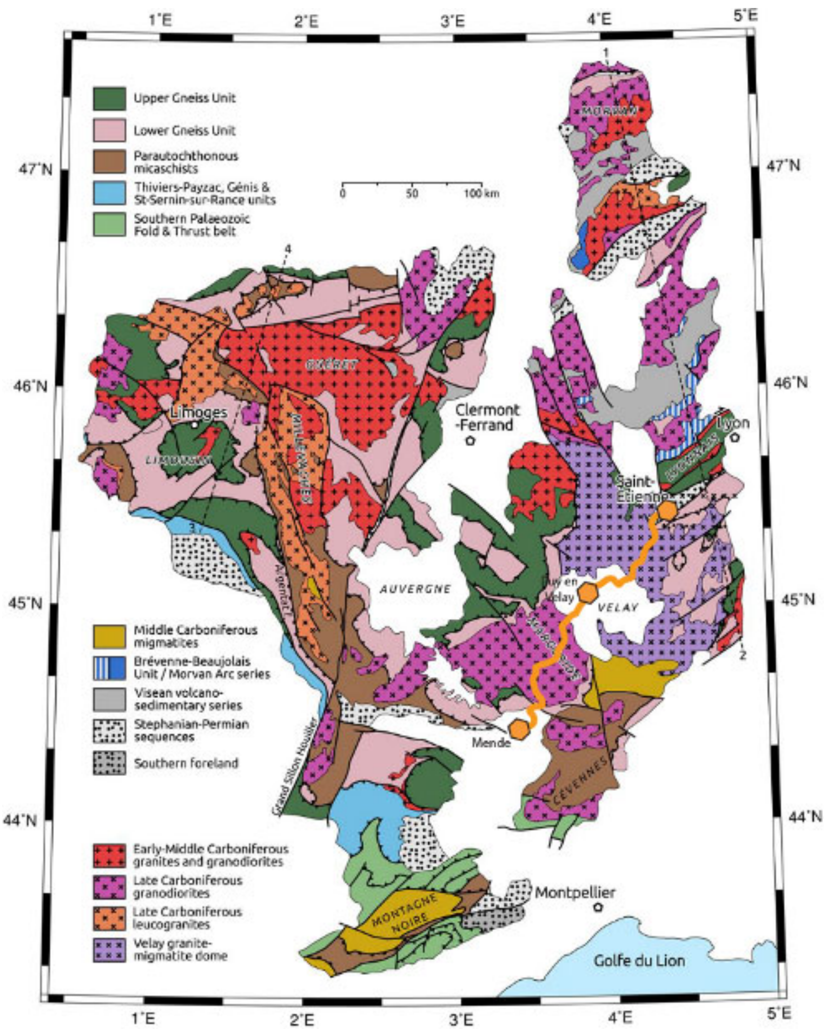
The Rhône and its tributaries, like the Ardèche, responded to this extreme sea level drop by cutting down kind of a ‘Grand Canyon’ that became more than 500 m deep. Geologically speaking, this occurred very fast, within about a hundred thousand years. Approximately 5.3 million years ago, the modern Gibraltar Straits opened and refilled the Mediterranean Sea with sea water (see the Twitter videos). The deeply incised Rhône canyon was filled with sea water, and in the millions of years that followed, this canyon was filled with gravel, rich in quartz from the Alps and the Central Massif, that was carried by the Rhône River. These quartz-rich gravels are fertile ground for grapes such as the Châteauneuf-du-Pape! If the Tour de France would have been organized during the Messinian salinity crisis, today’s stage would have been considerably more mountainous than today’s stage!

I am a geologist and I study plate tectonics and the driving mechanisms in the Earth’s mantle, mountain building processes, and the geography of the geological past. I enjoy geological fieldworks all over the world, and translating the results to science and a broad public.
Douwe van Hinsbergen

Stage 14 | St. Etienne - Mende / Volcanism of the Massif Central

[Men]

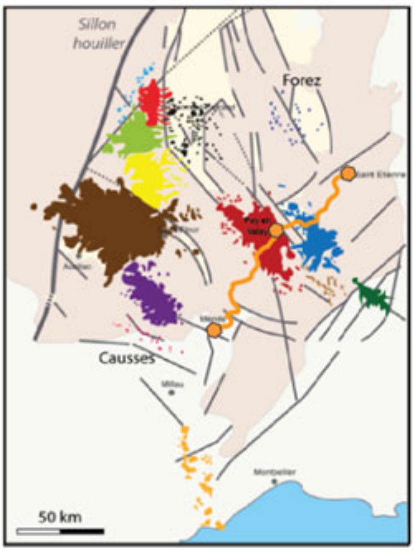
195		Hills		Volcanism of the Massif Central

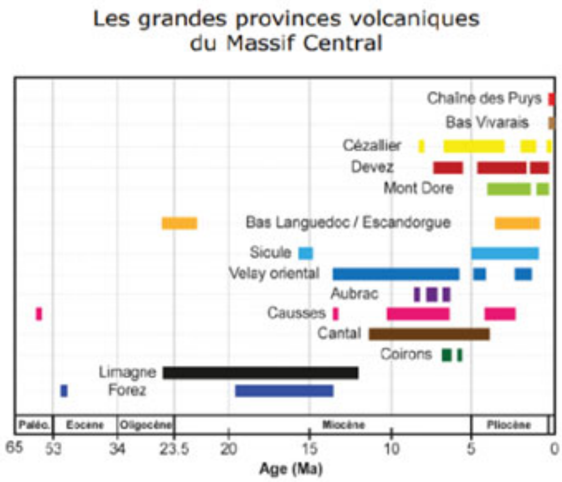


Stage 14 will lead the peloton through the eastern part of the old Massif-Central crystalline massif. But not all rocks are old: parts of today's stage will come through volcanoes that are young (for a geologist)! The rocks of the Massif Central crystalline massif were formed during the collision of the Armorica and Laurasia continents during the Hercynian mountain building event between 335 and 300 million years ago. These crystalline rocks, many of granitic composition, were formed by cooling of large magma chambers related subduction of tectonic plates and the collision of continents. The granites used to be buried deep within the mountain range that was as high as the Himalayas today. These rocks are now exposed, because of ~300 million years of erosion. The start and the end of stage 14 will lead over the root of this old mountain belt (see Figure).

Young volcanism

After nearly 300 million years of erosion the area experienced a new phase of volcanism. Scientists do not entirely understand why this volcanism occurred: some think that it was associated to stretching of Central France (also making the Rhone rift), others think there was a plume of hot mantle material rising up below the Massif Central, like below for the Canary Islands making last year's La Palma eruption. In any case, the rocks of the in the mantle below the crust were partially molten, and the molten rock rose to the surface as magma. The magmatic activity on the surface of the Massif Central started in the early Miocene at around 23 million years ago and continued until very recently with the youngest volcano erupting around 1000 BC. There are more than 400 volcanoes in seven main volcanic provinces of which the Chaîne de 'Puys' is most famous with its "Puy de Dôme" followed by the Mont-Dore, Cézallier, Cantal, Aubrac, Devez and Velay Oriental (see Figure). The Puy de Dôme is a Hors Categorie climb, where the likes of Coppi, Bahamontes, Gimondi, van Impe, and Zoetemelk won stages.





Volcanoes in the landscape

The volcanism throughout the Mio-, Plio and Pleistocene was highly variable in character varying from highly explosive to effusive (calm) resulting in a very different style of volcanoes now visible in the landscape. Explosive volcanism is associated with magma that is viscous (i.e., it is too syrupy to flow very well). These viscous magmas form steeper volcanoes built of dome structures, or when the magma interacts with water, enormous volcanic explosions can form deep round craters in the ground called calderas (like in Tonga last winter). Effusive eruptions are associated with more fluid magma resulting in less steep volcanoes built of lava flows and spatter (scoria) cones (like in La Palma and Iceland). The volcanic areas of the Massif Central are thus composed of large Etna style volcanoes (the Cantal volcano was at least twice the size of Etna), volcanic plateaus, volcanic domes, small cones structures, but also explosive 'maar' calderas. Halfway stage 14, the peloton passes through Puy en Velay which is built on an old volcano. Two eroded volcanic necks, remnants of the volcano magma pipes, stand out in the landscape to the west of the D103: the 'St Michel de Aiguille' with its Chapel on top and the "Rocher Corneille' with the 'Notre-Dame de Puy' Cathedral. Will today's stage yield an explosive (Mathieu van der Poel, Wout van Aert) or an effusive (Thomas de Gendt, Nance Peters) winner?

I am a deep Earth geochemist using the composition of volcanic rocks to understand large-scale tectonic processes that control deep elemental cycles. I am specalised in analysing compositions of very small (<1mg) samples using advanced mass-spectrometry techniques. I analyse magmatic minerals, but also dust in ice-cores, precious archaeological artefacts and/or famous paintings. Check the Geo-TdF-team-2022.

Janne Koornneef

Stage 15 | Rodez – Carcassonne / Hard rock with element Lithium

Men

205		Flat		Hard rock with in high demand element

Today's stage is mostly flat, but the riders are crossing a region that was once a big mountain belt. The peloton will start in Rodez that is half built on crystalline rocks (mainly granite, old magma chambers, the ones that exist below explosive volcanoes). The other half is built on sedimentary

rocks that were deposited in the Permian (299-252 million years ago) on top of the old Massif Central. From there, the Tour will find its way through the sediments of the Aquitaine and Carcassonne Basins that were deposited in shallow seas and rivers during the last 200 million years. But between these two basins, the riders first have to cross a narrow zone known as “la Montagne Noire”, where we see the southernmost edge of the Massif Central. And this “Black Mountain" hides a resource that is in high demand these days.

Recharge your batteries in the Black Mountain

The Massif Central, and the Black Mountain, corresponds to a large area of rocks that were once so hot that they partly started to melt between 320 and 300 million years ago, during the ‘Variscan’ mountain building stage that formed the supercontinent Pangea. The Black Mountain rocks were then buried to a depth to ~20 km where they suffered temperatures of ~700°C, and under those conditions, certain minerals in the rock started to melt. Out of such partially molten rocks (that we call migmatite, see stage 17) comes granitic magma that is full of the elements that like it best to be molten (so-called ‘incompatible elements’). When that magma cools and

solidifies they often form rocks with enormous crystals (sometimes tens of cm across) that we call pegmatites. And those pegmatites, which are present in Montagne Noire, are enriched in incompatible elements that can form ores.

Hard rock Lithium

Some pegmatites in the Montagne Noire contain mineral deposits that are rich in elements that we need for economic purposes that they are ores. That is the case with the Brassac pegmatite. It contains quartz, feldspar, muscovite, and tourmaline that are common minerals of pegmatite. More special is that this pegmatite also contains lepidolite and elbaite. These two last minerals do not only have uncommon names that most of us have never heard of before, they host a chemical element that is in high demand nowadays: Lithium. When a pegmatite is rich in Lithium, it is often also rich in other chemical elements such as Niobium, Tantalum, Cesium, or Tin. These elements belong to the list of critical substances defined by the European Union commission. Also other granites and pegmatites in the Massif Central are Lithium ores, such as the Beauvoir Granite and the Monts d'Ambazac pegmatites.

Lithium and the green technologies

Findings of ore deposits often give mixed feelings. On the one hand, Lithium is critical for industry, where it is used to strengthen ceramics or glasses, but it is also an important constituent of batteries. The green energy revolution has thus increased the demand for lithium, and many other elements that are needed in electric devices, solar panels, or windmills. On the other hand, winning these minerals requires mining, which is straining local environments. The debate between the cost and demand will likely only rise in the future. The riders will only climb Montagne Noir today, but perhaps they can recharge their batteries on the top for the final sprint to Carcassonne!

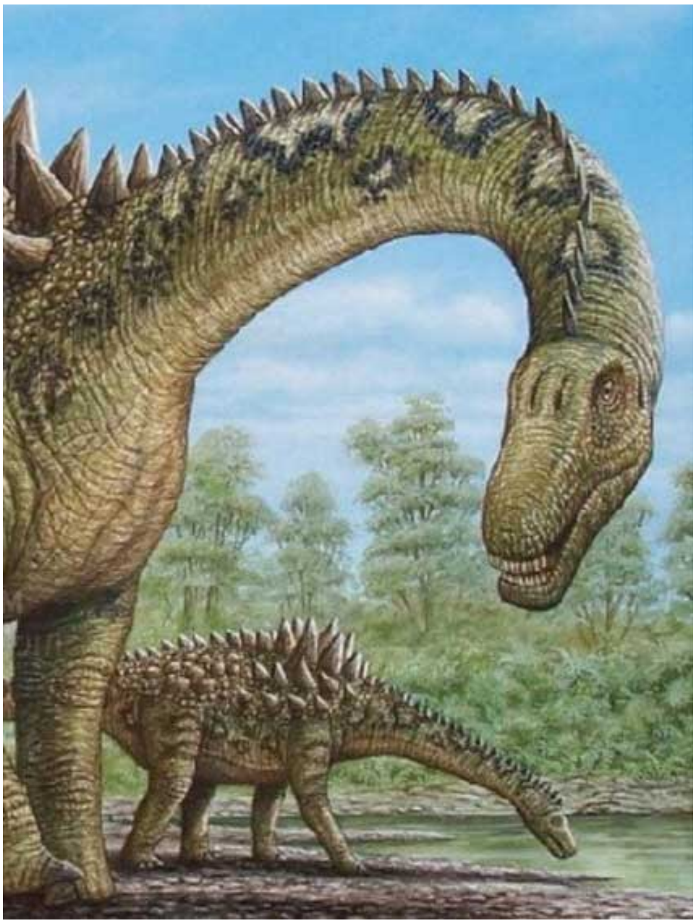
I am a metamorphic petrologist and a field geologist. I have training in numerical modeling of geodynamics processes. I love to be outside hammering rocks before preparing them for EPMA analysis. For a few years I have now specialized in the behavior of metal elements during the melting of rocks. Check the Geo-TdF-team-2022.

Alexis Plunder

Stage 16 | Carcassonne – Foix / The vineyard dinosaur

Men

179		Hills		The vineyard-saur of te Aude



During the stage from Carcassonne to the south, the first part will come through the valley of the Aude. Close to Limoux, the route heads west, and as they progress, the first foothills of the Pyrenees come into sight. The Pyrenees form the crumple zone that formed because Iberia shoved below Europe. Because of erosion of the uplifted southern margin of Europe in the south of France, rocks that formed tens of millions of years ago are now exposed at the surface, and these tell us a story of the Cretaceous and the vineyard dinosaur.

Forming of the Pyrenees

The precursors of what we now call the Pyrenees already started to form at the end of the era of the dinosaurs, so at the end of the Cretaceous. Sea level was a lot higher than today because there was no ice on the poles. As a result, much of Europe was covered in shallow, tropical seas. The islands that rose up from these seas, like the crystalline massifs of central France, were the territory of plenty of dinosaurs. When the Pyrenees started to be pushed up, rivers dumped thick packages of sandy and muddy sediments. Sometimes, also a dinosaur bone, or even an entire skeleton, became covered by these sediments. Todays stage will pass through these red-orange deposits, now often covered by vineyards - including those of the Blanquette de Limoux, a sweet bubbly wine.

The vineyard dinosaur

Not far south of Limoux, around Espéraza, countless remains of dinosaurs have been recovered from these red-orange deposits. One species has even been named after the vineyards: the titanosaur Ampelosaurus atacis, a middle-large long-neck dino that wore a special jacket of armor plates and that is well known from the excavation of Campargne-sur-Aude. “The vineyard-saur of te Aude’, is the literal translation of the name. These fossils can be visited in the dinosaur museum of Espéraza. We place our bets on the tallest rider of the peloton, especially when he rides with a titanium frame!

My research focuses mainly on tetrapods from the Age of Dinosaurs; I have a particular interest in dinosaurs, mosasaurs and fossil trackways. I currently work on T. rex and Triceratops from North America, and on mosasaurs from Angola. Check the Geo-TdF team.

Anne Schulp

Stage 17 | Saint Gaudens - Peyragudes / A tour in the earth's molten crust

Men

130		Mountains		The Pyrenees: A tour in the earth's molten

This mountain stage brings the riders close to the center of the Pyrenees.

Young rocks in the foothills of the Pyrenees

In an east-west direction we call it the Central Pyrenees, in a north-south direction it is the Axial Zone. It is also the area with the highest peaks, above 3000 m. The riders go westwards from Saint-Gaudens along the border between the Pyrenean foothills (~100 million year old rocks) in the south and the younger products of erosion of the High Pyrenees, which are still being deposited to the north. After about 40 km they turn southwards and start riding through ever older rocks.

Into the older and hotter rocks of the Pyrenees

After Arreau, the riders take a detour to the west, following a half circle that brings them close to the Néouvielle granite (granodiorite), a very large 300 million years' old magma chamber. The stage ends with several climbs through the even older sediments of the Axial Zone to Peyragudes. This part of the Pyrenees shows spectacular evidence for two mountain-building cycles: the Hercynian mountains around 300 million years ago,

when the supercontinent Pangea was formed, and the recent Alpine cycle that is best seen in the Gavarnie area. During the Hercynian cycle old sediments, derived mainly from the erosion of the southern continent Gondwana, were brought to 10-20 km depth where they were heated to temperatures between 300 and 700 °C. The rocks changed appearance (metamorphism) and various minerals were formed that can be seen with the naked eye, for example andalusite, staurolite, and sillimanite.

Melting the deep domains of the Pyrenees

At the highest temperatures, the rocks underwent a special process that we call "partial melting". It has been known since at least the bronze age that rocks do not melt completely.

Instead, some metals and minerals melt at lower temperatures than others. For example, tin and lead melt at much lower temperatures than copper. Apart from these metals (or metal sulfides), most minerals are silicates. Some combinations of silicate minerals melt at 650-700 °C. When the melt escapes, it can collect upwards and form large granite (or granodiorite) bodies that we see all over the Pyrenees. Minerals with higher melting temperatures stay behind in the source rock, which we call restite. In many places, some melt also stays behind, and the rock then shows layers or patches of restite and melt. This rock type we call a migmatite. Some of the best areas to see this are in Gavarnie and some valleys south of the finish line. And in nicely polished kitchen worktops!

I am a geologist who specializes in high-temperature processes in the deep continental crust. My motto in research and teaching is that knowing the history of our planet will help making reasonable predictions about our future. Main professional passions are fieldwork, microscopy of rocks, and teaching. Check the Geo-TdF-team-2022.

Leo Kriegsman

Stage 18 | Lourdes – Hautacam / The 2006 Hautacam seismic crisis

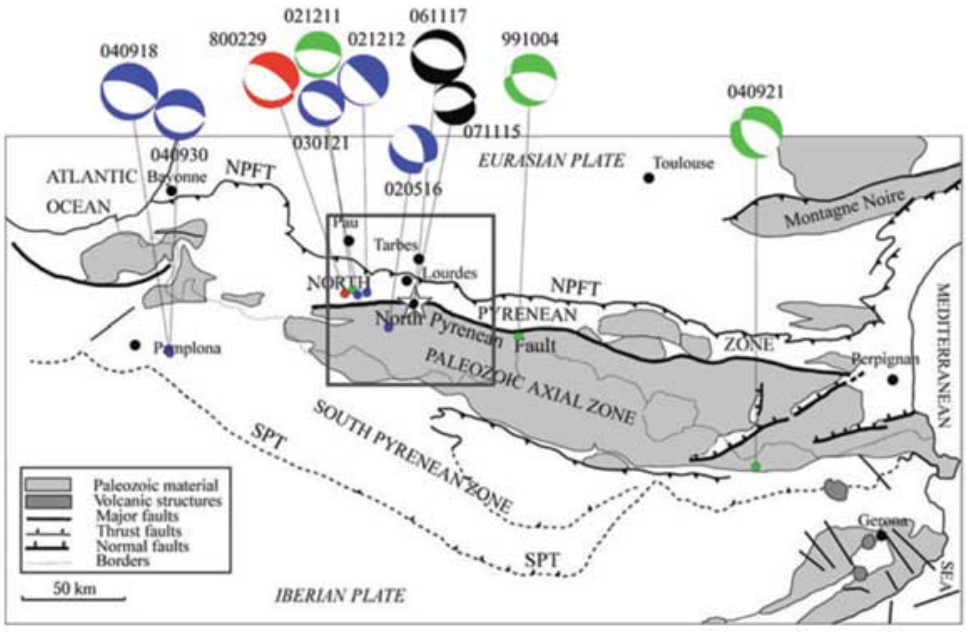
Men

143.5		Mountains		Lourdes earthquake: The Hautacam seismic

On November 17th, 2006, the departure city of today's stage, Lourdes, was rattled by a ML 5.0 earthquake that was widely felt, but did not cause significant damage. The earthquake occurred about 10 km south of Lourdes (Figure 1) at a depth of 9.7 km and was felt from Bordeaux to Barcelona. It was followed by over 250 aftershocks, smaller earthquakes that highlight a source region with an area equivalent to the area of about 1250 football pitches.

The Hautacam seismic crisis explained

The earthquake occurred along a so-called 'normal fault', which is a fault that accommodates stretching, with an upper block that slides down from a lower block. In this case, the normal fault was dipping to the north, and shows that the Pyrenees are being stretched in a north-south direction. This seems a bit strange,



since the Pyrenean mountain belt formed because of north-south shortening. However, this shortening stopped about 20 million years ago, and the mountain belt is slowly collapsing, like a pudding. This is probably the cause of the Hautacam seismic crisis.

Cause of earthquakes

Earthquakes are the results of rapid motion between large masses of rocks which is accompanied by a release of energy, some of which is radiated as seismic (elastic) waves which cause the ground to shake. A simple representation of this is shown in the video: the elastic strain stored in the spring is released suddenly when the block slips. That slip generates seismic waves that we then feel as an earthquake.

Earthquake size

The amount of shaking that is experienced at the surface depends on several factors, such as the depth at which motion occurred and the size of the ruptured area. The total energy of an earthquake can be determined from the seismic waves and is presented on a logarithmic scale. Since this represents the increase in the amplitude of the seismic waves and the energy scales as amplitude to the power 1.5, this means that a magnitude 6 earthquake has 32 times more energy than a magnitude 5.0 earthquake.

Historical seismicity in the Lourdes region - the Hautacam seismic crisis

Earthquakes are not uncommon in the Pyrenees and particularly in the Lourdes region. Historical records show an earthquake occurred close to Lourdes on June 21st 1660 which caused significant damage. The magnitude of this earthquake is estimated to be 6.1, so with more than 32 times more energy than the one in 2006. Unfortunately, we currently don’t have sufficient knowledge and tools to predict whether or when such an event is likely to occur. Let’s hope the ground shaking action is restricted to the race of today!

I am a geologist with expertise in earthquake and fault mechanics. I attempt to decipher how earthquakes start and stop by torturing rocks in the laboratory at high pressures and temperature. Occasionally, I spend time investigating exhumed faults in remote (e.g. New Zealand) and not so remote locations (e.g. U.K.). Check the Geo-TdF-team-2022.

André Niemeijer

Stage 19 | Castelnau-Magnoac – Cahors / The Aquitaine Basin and the Wilson Cycle

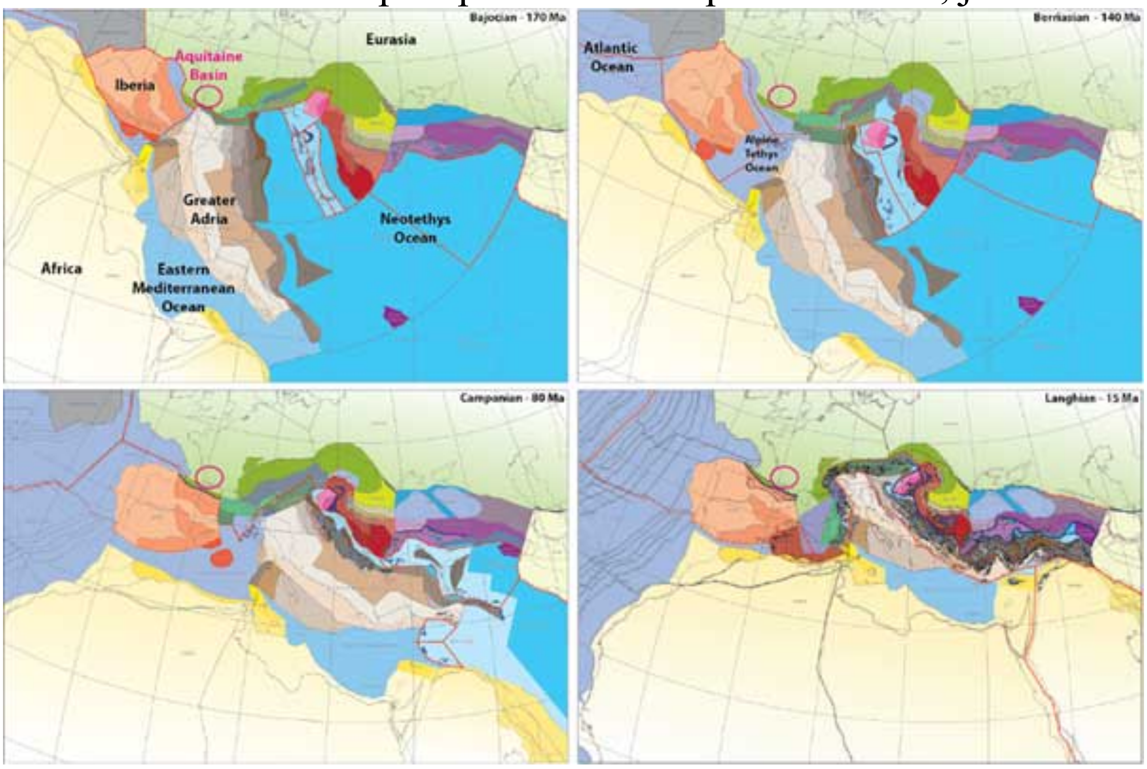
Men

189		Flat		The Aquitaine Basin and the Wilson Cycle

With the Pyrenees left behind, today's stage will lead the peloton through the rolling hills of southern France. This region is known as the Aquitaine Basin and is today drained by the river Garonne and its tributaries. The landscape of southern France may be gentle, but the topography in the subsurface is much more spectacular.

Aquitaine Basin: as deep as the Marianas Trough

Along the northern perimeter of the Aquitaine basin are coral reefs from the tropical seas of the Jurassic, approximately 180 million years old, that overlie the crystalline massifs of the Central Massif and the Armorican Massif. But in the deepest point of the Aquitaine Basin, just north of the



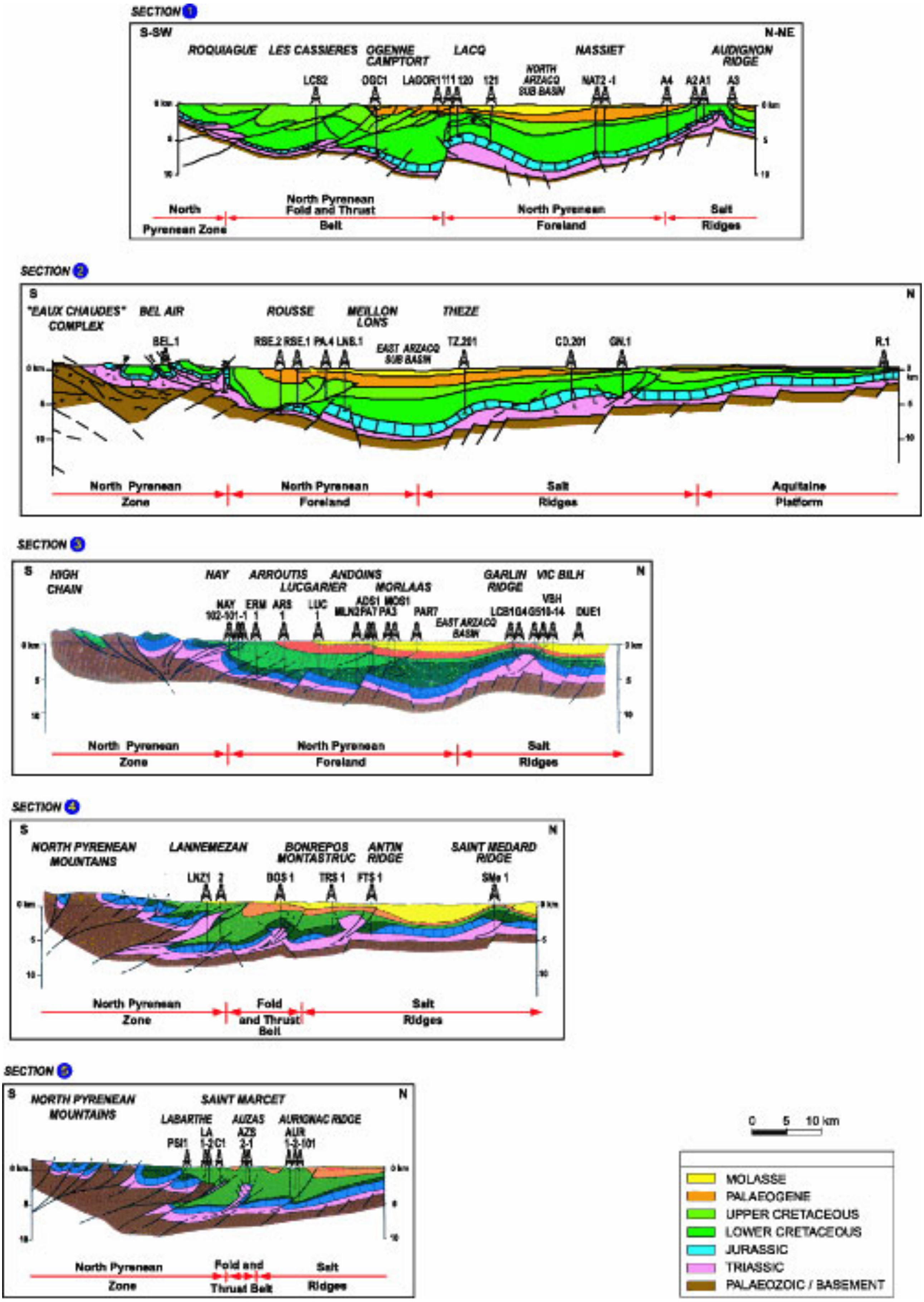
Pyrenees, that transition from crystalline massif to the Jurassic limestones, or Triassic sediments that lie underneath, is at a depth of 11 km. And at the top of the Pyrenees, we find those same crystalline rocks at an elevation of 3 km: a vertical difference of 14 km. For comparison: The Aquitaine Basin at its deepest point is as deep as the Mariana Trough, the deepest point of the Earth's surface. Mt. Everest is not even 9 km high.

The Wilson Cycle, part 1: continental breakup

The Aquitaine Basin is actually a series of basins stacked on top that had different causes, and tell a story from the breakup and re-unification of continents: the so-called Wilson cycle. The oldest rocks of the Aquitaine Basin that we can see at the surface, the 180-million-year-old limestones on the northern and eastern margin, were deposited in calm-water, shallow-marine environments. But this calm environment is deceptive: seismic lines across the Aquitaine Basin show that during this period, a series of steep faults formed along which the crust was broken into large blocks that slid down, each next one deeper than the previous, with the deepest point in the south. Such a process of extension breaking continental crust is known as 'rifting', and is currently active for instance in the East African Rift Valley. These so-called 'normal faults' formed in a time that Pangea started to break up, which first led to the formation of the Central Atlantic Ocean that separated Africa from North America. To the north, the Central Atlantic Ocean developed two branches, one between Iberia and North America, which also connected to the Bay of Biscay, and the other went into the western Mediterranean region, between Africa and Iberia, separating Adria (to which the modern Po Plain of northern Italy belongs) from Europe at the location of the southern Aquitaine basin. When a mid-oceanic ridge formed in that new ocean that we call the 'Alpine Tethys' Ocean, extension in the Aquitaine basin ceased and the basin became filled by limestones and sandstones that were derived from the lands of Europe that formed a 'passive' margin of the ocean.

The Wilson Cycle, part 2: continental collision

Aging oceanic lithosphere becomes denser than the Earth's mantle and will eventually subduct, and the subduction process will continue, in one or more phases, until a continent on the subducting plate collides with a continent in the overriding plate, and subduction eventually comes to a halt. In the case of the Pyrenees, this closure



history was a bit less simple than in textbook models, and the closure and opening of basins occurred twice. How that occurred exactly is still heavily discussed in the scientific community that studies the Pyrenees, but normal faulting and extension occurred again in the Aquitaine Basin around 100 million years ago. But the oceanic basin that formed between Iberia, southern France, and Adria (Italy) in the Jurassic has now disappeared because of subduction. This subduction eventually led to the formation of the Alps, the Apennines, and, when the continental margin of Iberia was shoved below France, the Pyrenees. During the formation of the Pyrenees, the Aquitaine basin became a so-called ‘foreland basin’. The weight of the Pyrenees makes the crust around the mountain belt bend down, and the resulting depression is filled with debris eroded from the mountain belt. The products of erosion of the Pyrenees form a 2 km thick succession of rocks with a total volume of more than 50 thousand cubic kilometers. An increase in the rates of deposition of these materials took place some 25 million years ago, around which time the shortening in the Pyrenees stopped. The rocks of this age are exposed at the surface in the southern part of France next to the Pyrenees, and they have given their name to the interval in Earth history during which they were deposited, the Aquitanian (23-20 million years ago). And another Wilson Cycle closed its circle.

At the moment of writing of this blog, the start list of the Tour de France 2022 is not known yet. But it would be wise to bring a cyclist named Wilson for this stage: that must be today’s winner.

I am a geologist and I study plate tectonics and the driving mechanisms in the Earth’s mantle, mountain building processes, and the geography of the geological past. I enjoy geological fieldworks all over the world, and translating the results to science and a broad public. Check the TdF-team.
Douwe van Hinsbergen

Stage 20 | Lacapelle-Marival – Rocamadour / Karst, fossils & evolution

Men

40 km		Individual		Karst, caves, underground rivers, fossils &

This time trial will lead the riders individually over a limestone plateau where geologically recent (since 3.5 million years ago) erosion formed steep canyons creating the exciting end of today's stage. Most of the limestone rocks found in the geopark 'Causses du Quercy' were formed during the Jurassic between 200 and 145 million years ago; a time when the Young Atlantic Ocean was growing and expanding.

Carbonate limestone plateau

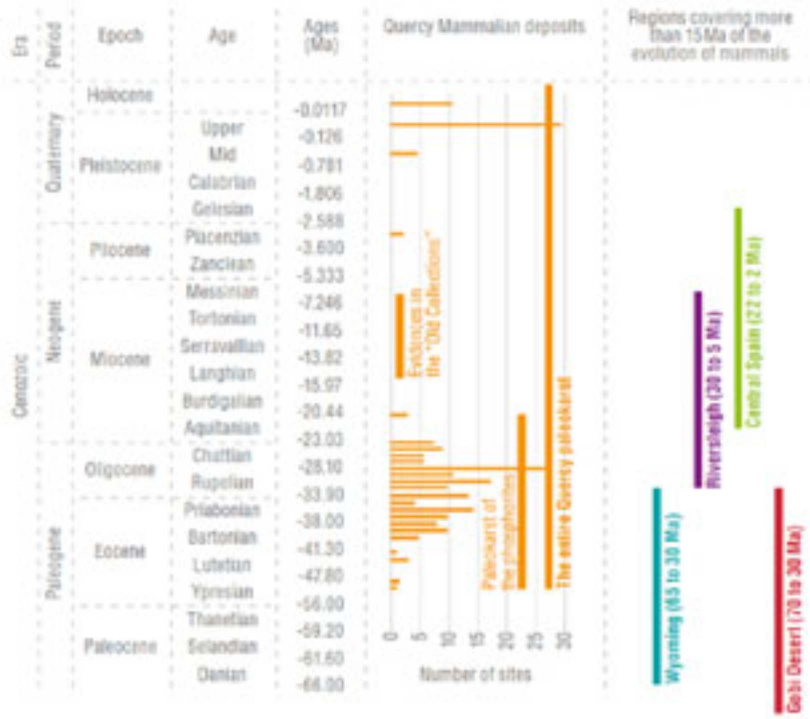
Racing forward to 70 million years ago, the thick deposits of carbonate limestones were hefted above the sea surface and became subject to erosion and the formation of karst. At this time, the climate was very different, and resembled a tropical rainforest, with rivers and strong erosion, not dissimilar to those found in South America today.

Forming karst and rivers

Karstification is a process which regularly occurs in carbonate limestones as water dissolves minerals and in doing so forms cracks in the rock through chemical weathering. Cracks can grow into caves and through time these caves (like the Padirac Chasm, figure 1) can link to form huge interconnected cave systems containing stalagmites and even underground rivers. One of those partly underground rivers is the Ouysse river, its source in Lacapelle-Marival (the stage start), disappearing near Thémines before it resurfaces ~20 km further northwest near Rocamadour (the stage finish). Fortunately, the peloton can take a more direct route!

Fossils and evolution

Karst landscape features (such as caves) make ideal sites for animals to shelter or hibernate. Occasionally, the cave dwellers were unfortunate enough to be engulfed in floods, and the caves refilled by sediments leading to the burial and preservation of animal remains in the caves. Due



to long continuous karst formation here (extending to 70 million years), the geopark is famous for its fossils, with more than 30 million years of evolution in bats, rats, bears and many more mammals uncovered by paleontologists (figure 2). This unique preservation enables scientists a valuable insight into such events as the Eocene-Oligocene extinction event (34 million years ago) in which the Earth experienced a major cooling climate change, where Antarctica started growing its ice-sheet.

The word karst is named after the Slovenian Karst Plateau (Kras), so the Slovenian riders might feel at home today and have a good chance for the victory!

I study geodynamics, more specifically the interaction between the mantle and plate tectonic processes on the surface and on a very large scale. As we can not go into the mantle, my computer models are based on data from rocks all around the world that tell the story of plate tectonics. Check the Geo-TdF-team-2022.

Erik van der Wiel

Stage 21 | Thoiry - Paris / The Lutetian age

Men

112 km		Flat		Origin of the paving stones of the

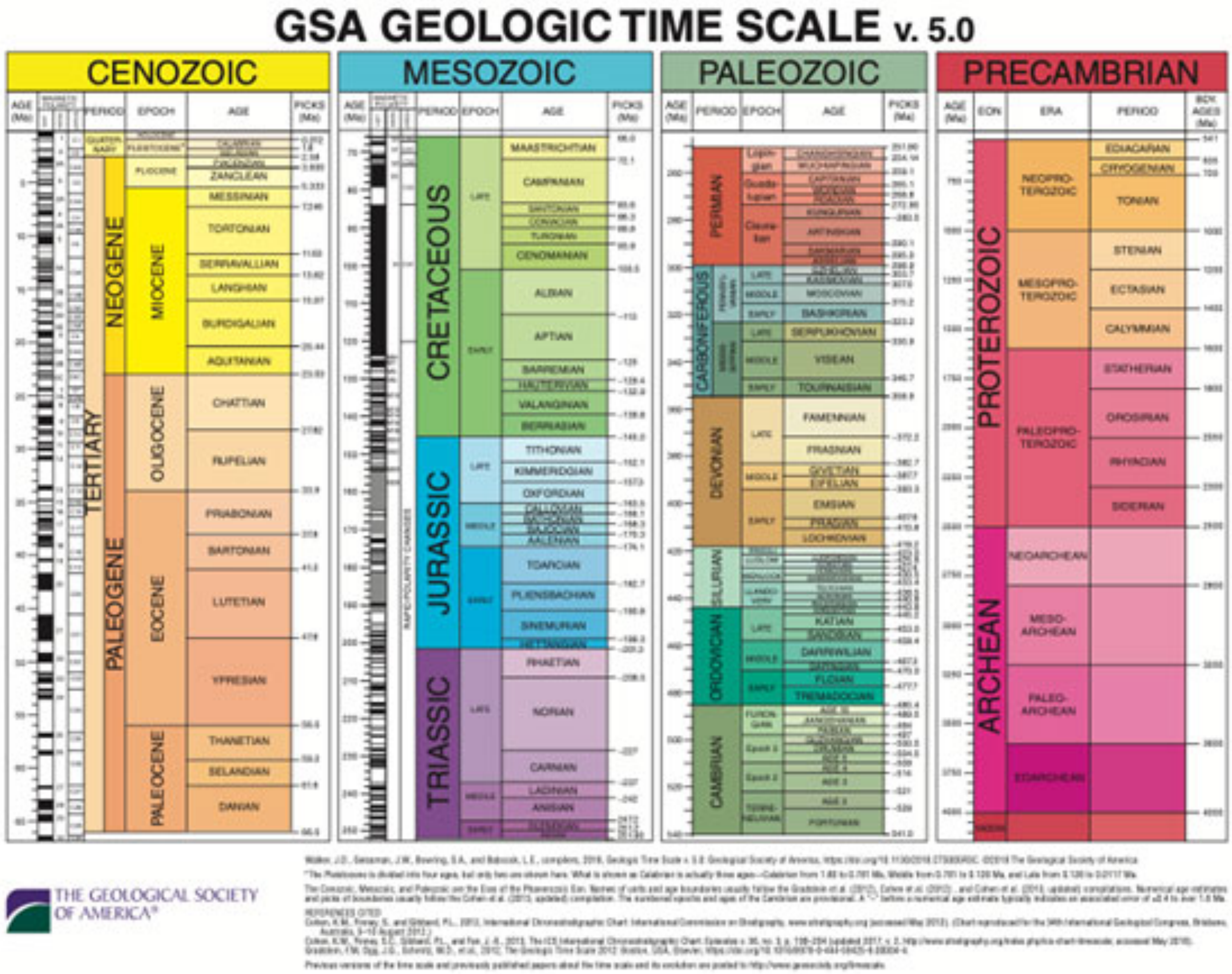
The last stage of this Tour de France brings us back to the Paris Basin. Paris itself is built on the youngest rock formation that were deposited in this basin. These rocks, with an age of approximately 45 million years old formed during a period known as the ‘Lutetian Age’, are dominated by limestones that were deposited in shallow, warm seas, like a tropical version of the North Sea, and contain enormous fossils, such as 70 cm long gastropods (spiral-shapes shells) (see figure).

The Lutetian Age, named after Lutetia (the Roman name for Paris)

As explained before, sedimentary rocks can be dated based on fossils that existed during a period of geological time, and that are so abundant that they are easily found and recognized.

Those are often microfossils, since they occur in great abundances, but also ammonites are useful fossils for dating. On basis of the presence of charactertistic fossils, the geological timescale is subdivided into intervals that are named after type localites where these rocks are particularly abundant, or where they were first described. The Lutetian is such a time interval, and this is named after Paris that was known in Roman times as 'Lutetia'. (Remember, in the blog of stage 2, we explained two earlier Epochs: the Maastrichtian named after the Dutch city of Maastricht and the Danian, named after Denmark, separated by the meteorite impact that led to the extinction of the dinosaurs, 66 million years ago).

So the time intervals in the geological timescale are largely based on fossils, and originally, we only knew the relative occurrence of these time intervals: a series of rock in which a certain fossil existed is followed by a series in which it didn't, marking that the fossil species probably went extinct. The



geological timescale was built this way in the course of 200 years of painstaking research. Only in the second half of the last century did we really start to piece together how old these intervals were in millions of years. Through measuring the radioactive elements in minerals, we can determine the absolute age of these time intervals. This showed that the Lutetian Age started at 48.6 million years ago, and ended at 40.4 million years ago.

The paving rocks of the Champs Élisées

And in case you wondered whether the iconic paving rocks of the Champs Élisées consist of limestones from the Lutetian: no, they do not. These are pieces of Brown Najran granite from a rock quarry in Beer Askar and Aakefah in Saudi Arabia. Goodness knows why: granite is not exactly in short supply in France…

I am a geologist and I study plate tectonics and the driving mechanisms in the Earth's mantle, mountain building processes, and the geography of the geological past. I enjoy geological fieldworks all over the world, and translating the results to science and a broad public.

Douwe van Hinsbergen

Geoscience?

Background

The first association you may have with geoscience are the landscapes - from high mountains and steep cliffs of the Alps to the wide open flatlands of NW France. These landscapes, their evolution, the rivers and glaciers that flow through them, the nature of the soils, and the hazards that they contain, such as landslides, are studied by a field of geoscience known as physical geography. Processes that shaped the modern landscapes are typically on the order of hundreds of thousands of years or less.

The realm below these landscapes contains a record of a much longer history, of millions to billions of years. Geological processes such as sedimentation and volcanism make kilometers-thick piles of rock. These piles contain an archive of the geography of the past, but also life and climate, in the form of fossils and the chemical compounds they contain. At the edges of tectonic plates, these rocks become folded and broken, uplifted and eroded. They are buried and change their mineralogy, they may melt in places, fluids move through them, ore deposits form, earthquakes happen, volcanoes erupt. And the study of the rock record and the long-term reconstruction of the history of the Earth's geography, climate, life, deformation, and mineralization is covered by the field of geology. And even deeper parts of the Earth, beyond tens of kilometers, is the realm of which the only abundant records come from lavas brought up from the deep studied by geochemistry, or where we use waves or magnetic fields to image Earth's interior and its processes, studied by geophysics.

Each blog will briefly explain a geo-process that is related to that day's stage. If you want to know more, find us on Twitter. And if you want to know more about a study in geoscience, check out the institutes where the blog writers work, all over Europe. And maybe we will see you in the field!