Evolution of the Earth and Life
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Radiometric Dating

Welcome to the course, evolution of the earth and life. Today we are going to talk about radiometric dating.

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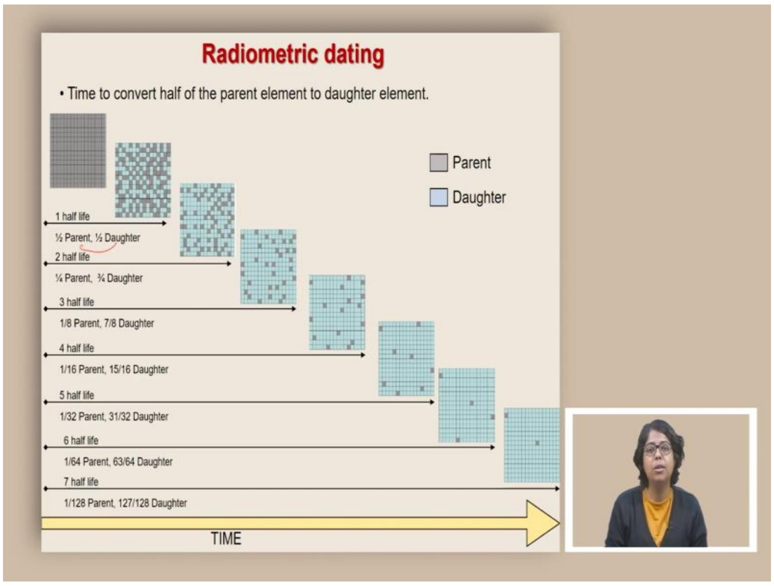

Radiometric dating involves the elements which decay naturally and the time to convert half of the parent elements to daughter element is something which is a marker and we call it a half-life. So, let us take a look at it visually. If we start with some parent elements, after a fixed time, some of them are going to convert, some of them are going to go through radioactive decay and convert to another daughter element and that daughter element can be a stable one or another radioactive element, which will further decay.

For simplicity's sake, we are going to start with systems where the parent element decays, it is unstable, but the daughter element is stable. So therefore, we are looking at a process which only has one step of conversion, where the parent element decays and makes it to daughter element. So what do we actually mean by half life? It means at any given point of time, if we start with some number of elements, there would be a fixed time, after which the number is going to be half.

So half of the parent element would have converted to daughter elements, but it is important to recognize at any given point of time, if you are looking at one particular element, one particular atom, it is not possible to say whether that particular atom is going to decay or not. So therefore, we look at the entire population and say that after specific time, the entire population is going to give us this half parent and half daughter element ratio. So after a single Half Life, half of the parent will remain and half of it has already converted to daughter element.

If we go for another half-life, percentage, or the ratio is going to be one fourth parent and three fourth daughter. If we go even farther, after three half-lives, it is basically going to be one eighth parent and seven eighth daughter, and we can keep on going about it. And eventually we are going to end up with a very low number of a daughter elements. But as I mentioned that it is primarily going to be a ratio and therefore, in theoretical terms, there will not be any number of half-lives after which the number of parent element is going to be zero.

But because we are looking at systems, where there are a finite number of elements, which we are starting from, and also there is an instrumental detection limit, because of which we should stay in a phase where there is some amount of remaining parent as well as daughter ratio, so that we can measure this ratio.

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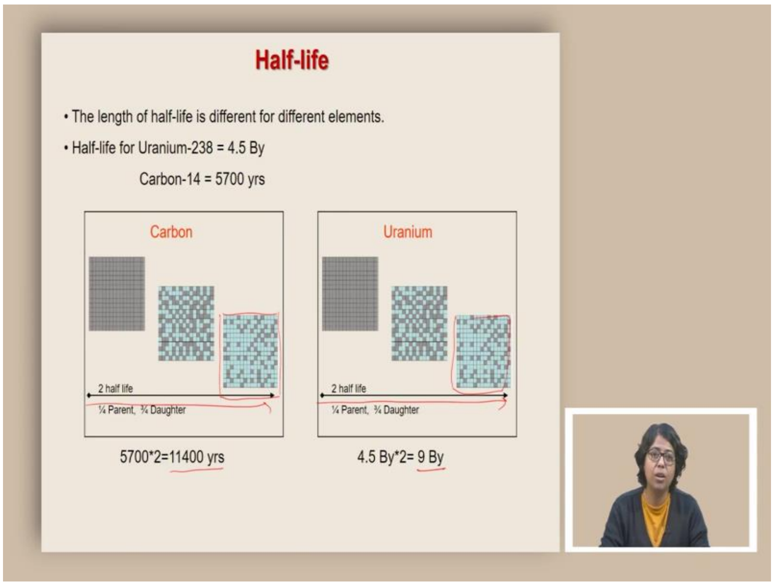

So let us take an example that the half-lives are going to have different duration in terms of the age for different elements. So although it is true that after one half life, it does not matter which kind of elements we are going to start from after one half life, we always going to find half of that parent element, the duration of the half life depends on which element we are looking at. So the length of the half-life is different for different elements.

So if we compare uranium 238, it has a half-life of 4.5 billion years. Whereas if we look at carbon 14 it has a half-life of 5700 years. And what it means that after two half-lives, carbon also will yield this kind of pattern where we are seeing more daughter elements than the parent element and so would uranium but the length of the time for uranium and length of time of carbon would be very different. Here we are talking about 11,400 years, whereas here we are talking about 9 billion years.

So, it is important to recognize that you have to have some understanding of the duration of the half-life before a particular system can be used. And it also depends on what kind of rock we are looking at to date. If the rock is very young, we have to choose a particular system, and it cannot be the same if the rock is very old. So, before going into the radiometric dating scheme, we have to have some understanding of the rough age of the rock.

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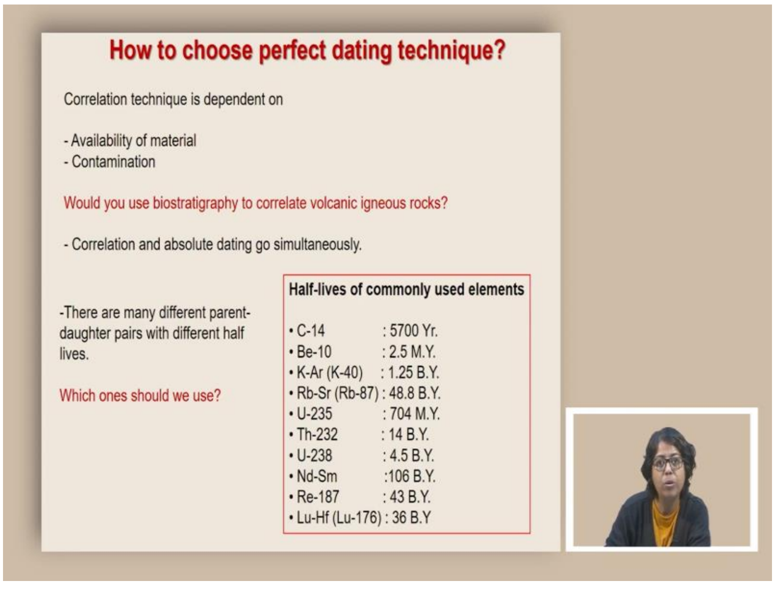

Now, again, how to choose the perfect dating technique, it depends on the availability of the material, and we should avoid contamination. What that means is, when we are choosing a particular rock and a particular mineral to date, we should go for rock dating scheme, which of the element that is present in the mineral. So, if we are going for a mineral which does not have any element that we are planning to use for dating technique, it is not going to yield anything.

The second important point is we should also try to avoid contamination. So, if there are elements which can go in later, they can give you an age which will not going to be a perfect age of those minerals. Now, this bio stratigraphy and the absolute dating, it goes hand in hand, because you can actually look at specific ages of specific strata and then correlate things by looking at the fossils. But directly dating fossils are not always easy. So we are going to concentrate mostly on the igneous rocks and how that can be dated.

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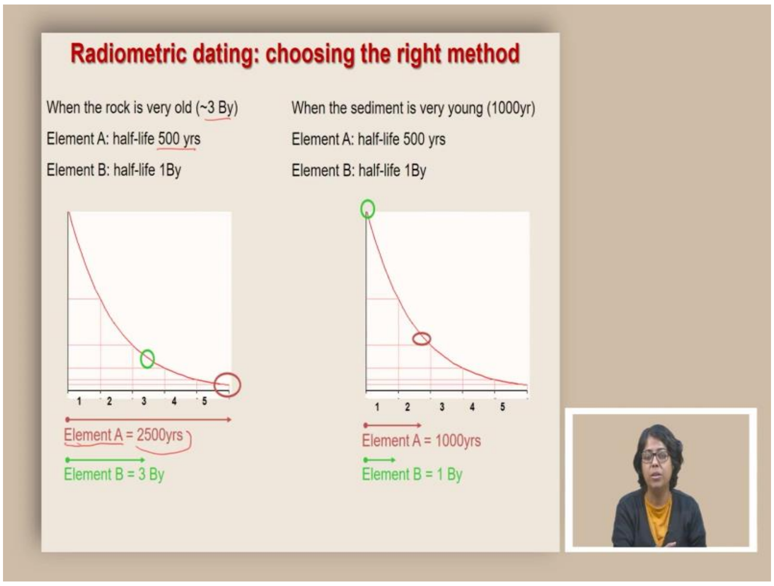

Now again, just to elaborate on the point that it depends on your question and the average age of the rock, that we have to choose a particular scheme. Now let us say that a rock is very old and we have two choices, either to use element A, where the half-life is 500 years, or to choose element B where the half-life is 1 billion year. Now theoretically again, as I am saying that, yes, the elements are continuing to decay and produce daughter elements.

But in reality, what happens is if we are looking at a rock, which is 3 billion year old, and we are trying to date it with element A, what happens is, in element A by the time it reached to this age, because element A has 500 years of half-life, after five half-lives, it already got a very low amount of parent element and if we go on up to 3 billion years, the amount of parent element is going to be so low that it will not be able to be detected and that is one of the reasons that we cannot use things which has short half-lives to date very, very old rocks.

The opposite is also true, to some extent that if it is a very young sediment, and if we are using extremely large half-lives, then also it gives you a problem because there will not be enough production of enough daughter elements to be detected. So, therefore, it is important to recognize that every rock depending on their average age, researchers choose the dating techniques accordingly.

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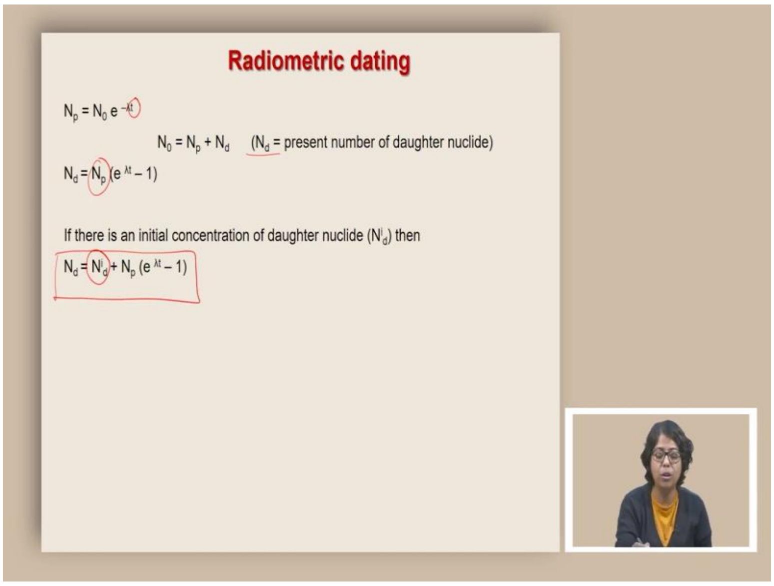

Now, let us look at exactly how this is done. So we know that the general understanding of radiometric dating, already active decay tells us that there would be a number of elements of the parent product would be equal to N 0 e to the power lambda t, where this t designates the time. And we are basically denoting Nd as the present number of the total nuclide. So, N 0 equals to parent nuclide plus the daughter nuclide. And therefore, the daughter nuclide, it can be represented as the parent nuclide times e to the power lambda t minus 1.

So, if there is an initial concentration of the daughter nuclide, which is basically this, then the form takes shape of this. So, basically we have to solve it. Now, we are going to look at first a system where the initial concentration of the daughter nuclide is 0.

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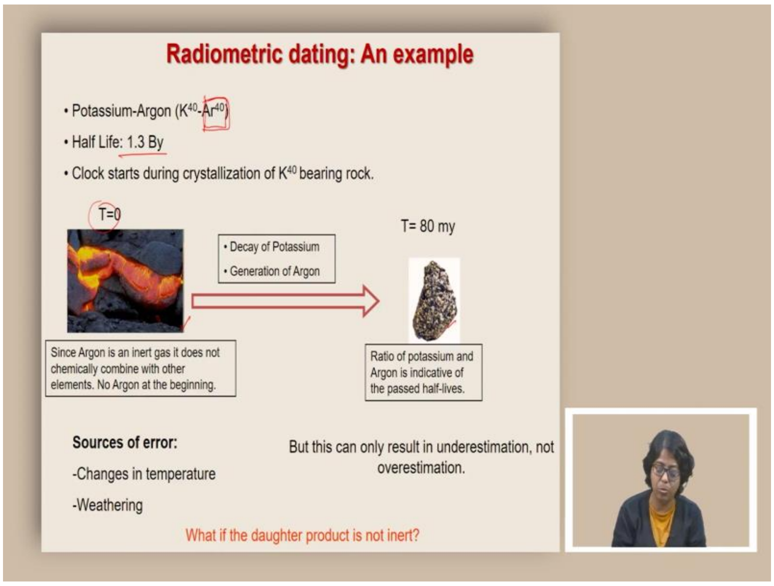

So, let us take a look at such a system. So, when we talk about this particular system, it is potassium argon. If we look at it very simply, it is K 40, which is potassium, which is radioactive. It decays to argon 40. Now, because argon is an inert gas, it really does not react with anything else, and therefore, it does not bind with anything else. And therefore, when we think about the equation, the initial concentration of the daughter element which is Ar 40, should have been 0.

Therefore, if we are looking at a closed system, then whatever Aragon has been produced, must have been produced because of the decay of the potassium. And therefore, if we know the amount of argon, and we also know the half-life of the system being 1.3 billion years, it is possible to use this technique to date. So, the clock, the way the radiometric dating works, the clock starts during the crystallization of K 40 bearing rock. So, when things are in molten stage, we are talking about igneous rocks to when things are in molten state, there are enough nuclides and it is all mixed up.

But the moment there is a formation of the crystal and specific amount of potassium is taken into this crystal, in the mineral crystal, the clock starts because that is the point where it is isolated and then whatever decay produced, argon will be developed, it will be part of this mineral structure. And then, if the mineral structure can be studied, and the volume of these or the amount of this daughter nuclide of argon that has been produced can be counted, it will basically tell us the age of that development.

Now, the same thing has been done here. So, it started with a magma and then finally crystallized rock and therefore, it can be calculated knowing the t 0 and then finally, how long would it take to produce that much of argon gas? How can it be contaminated? Well, one of the major sources of error is because it is in gaseous form, if the crystal is somehow damaged, it gets a fracture, then some of these argon gas can escape and therefore, giving you a lower number than expected.

So, it can give you an underestimation, but it is very hard to put extra argon in that system and therefore, very unlikely that you are going to get an overestimation. But this is a special case where because argon is an inert gas, it gives you this nice balance of this equation, where the initial concentration of the daughter nuclide is 0, but it does not have to be. There can be daughter nuclide. Especially if we are talking about stable forms of daughter nuclides, there can be other concentration which have been there.

So, if let us say argon was not an inert gas, then they could have been situations where such elements could be binding with. So, these are known radiogenically produced daughter nuclides, which could have bound within the crystal structure and they could have been there. So the initial concentration of the daughter nuclide might not be 0. In that case, we have to design the, we have to develop another way to address this question through those equations.

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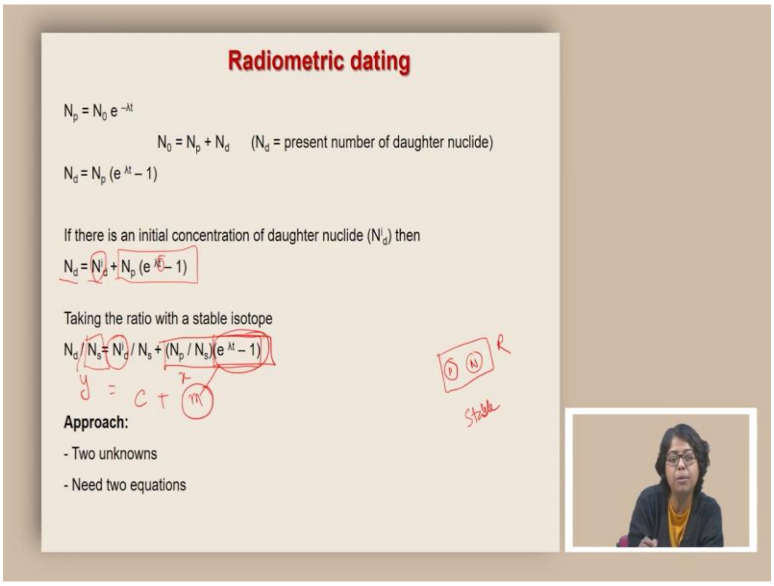

So again, we are taking a look at it. So where we stopped last time was the daughter nuclide was essentially the initial concentration of the daughter nuclide and then the parent nuclide which converted into daughter nuclide because of the radioactive decay. Now, this is a complicated situation, because if we do not know this, and if we do not know this, there are two unknowns, so, which means we will basically need to have two equations to solve it.

One clever way of going around it is to divide it with the stable isotope. So, when we talk about isotopes that basically means that we are talking about the same number of protons, but different number of neutrons. And sometimes this combination, the proton and the neutron can be radioactive, which is not stable. But it could also be a stable form, which basically means, we are simply going to get heavier or lighter version of the same element. And in nature, often we find the same element can be presented in multiple isotopic base.

So there can be two or three different isotopes of the same element, and many of them are stable. So, what we can do to this equation is divide this entire equation with a stable isotope of that daughter nuclide. And then we find an interesting change. What it does, it basically gives you, daughter nuclide divided by the daughter nuclide but stable form. And then it also gives you this initial concentration of the daughter nuclide divided by the nuclide stable form. And, for the rest of the equation, it does the same thing.

And this equation, also the previous equation, it has a form of a straight line, because it is basically y, this is the y equals N. This is the N part, which is the slope, x plus c. So, if we can solve for the slope that is actually going to tell us something about the age because that is what we are going to solve. So now let us see how we can get multiple values for these two parts and then we can create multiple lines, which can either intersect or give us a slope.

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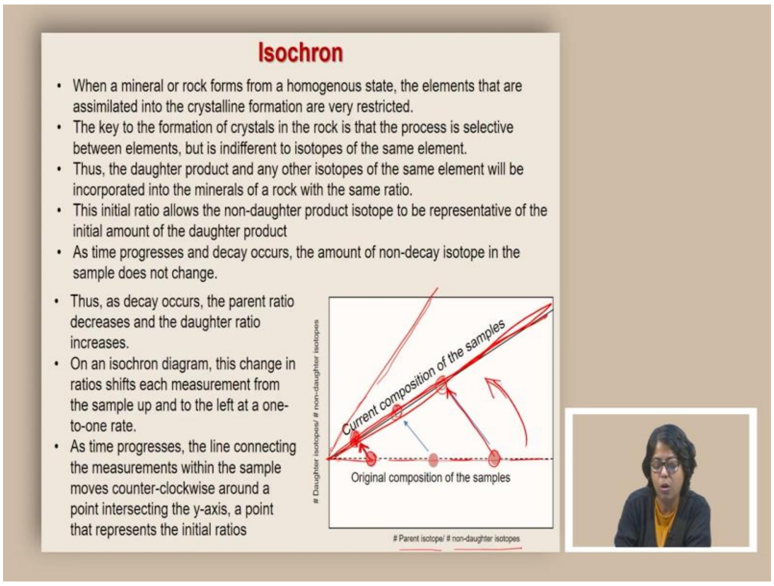

And the way to do it is through using isochron. When a mineral or rock forms from a homogeneous state, the elements that are assimilated into the crystalline formation are very, very restricted. The key to the formation of crystals in the rock is that the process is selective between elements, but is in different to the isotope of the same element. So they will maintain some sort of a balance. Thus, the daughter product and any other isotopes of the same element will be incorporated into the mineral of a rock with the same ratio.

Now, this initial ratio allows the non-daughter product isotope to be representative of the initial amount of the daughter product. And as time progresses, the decay occurs the amount of known decay isotopes in the sample does not change. Thus, as decay occurs, the parent ratio decreases and the daughter ratio increases that is because of the decay. But there is also a part where it was there from the very beginning, and that part stays constant.

So on an isochron diagram, this change in ratios shifts each measurement from the sample up and to the left of one to one rate. So I will show you that let us say this is the original ratio, which we will never I mean, we are not going to observe it. But what we observe is this daughter isotope divided by non-daughter isotopes, but again of the same element, and this is parent isotope divided by non-daughter isotope, we can actually measure those things and this measurement from different minerals are going to give us these patterns.

Now what these patterns represent, it is basically the current composition of the samples. And they have evolved from these original composition because the more it has in terms of the parent element divided by the non-daughter isotope, the farther it is going to move and the less it has, it is going to move slightly less, but maintaining a balance, and therefore this line is the isochron line. On this line, the slope, because it is a straight line, the slope is the same. And that slope is going to tell us about the age because the slope is basically e to the power lambda t minus 1.

And if you solved for this, then it is going to tell us about the age. Now, as the time progresses, the line connecting the measurements within the sample moves counterclockwise. So basically, we are saying that it is going to always move like this. If we are going to find older and older rocks, it is basically going to give us isochron lines like this. So it is going to move in this direction.

And finally, there is an intersection and around the Y axis, and this intersection, a point that represents the initial ratios, again, as I am saying that the initial ratios we could not observe, but we can reconstruct back just by looking at the present day ratios of multiple mineral grades and that is how the isochron works. So, let us take a look at some of the real examples.

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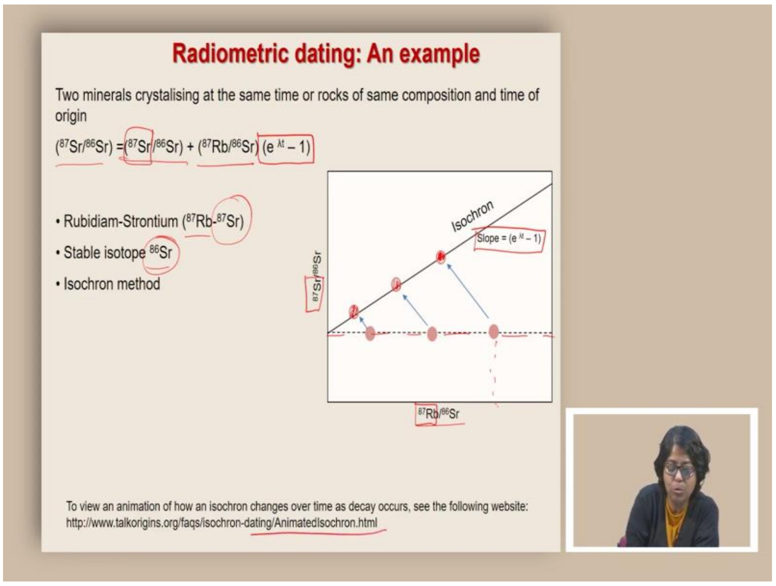

So, we are going to look at a system which is called Rubidium-Strontium system. So, this is dating, white common dating method where the rubidium 87 decays to strontium 87. Now, there is also a stable isotope of strontium which is strontium 86. So, using the previous idea, we are simply going to divide that initial formula of 87 strontium equals to 87 strontium initial concentration plus 87 rubidium times e to the power lambda t minus 1 by 86 strontium.

So, this is the stable form of the strontium which has been generated due to radioactive decay. So, if we do that, then the formula takes the shape of 87 strontium by 86 strontium and this part becomes 87 strontium initial concentration divided by 86 strontium and then this part takes the form of 87 rubidium divided by 86 strontium and then this part remains unchanged. Now, when we plot in our y axis, it becomes 87 strontium divided by 86 strontium, this can be measured 87 rubidium and divided by 86 strontium this ratio can also be measured.

And once we measure these ratios from different minerals, they are going to plot somewhere over here. What again it means is that there were initial concentration and this initial form initial concentrations, things have shifted, because of the increase in the radiogenically produced isotope and in this case, that is going to be this one. And the more it has, the more parent element it has again, this is the part where there is more parent element. They are going to produce more daughter elements, that is the 87 Sr.

But the factor which is 86 Sr, that part is going to stay constant. More importantly, the initial concentration of the part is going to remain the same. And therefore, we can figure out the initial concentration. Not only that this isochron line, the slope of this isochron line is going to tell us about the age and as the slopes change, that is going to tell you the different ages of the rock.

There is a very interesting animation to see how the isochron is produced and how it moves depending on the age of the rock or as the rock ages or as the age of the rock progresses through time in this particular website. So I would encourage you to look at it. This develops or this shows visually how the isochron lines move as we are looking at different aged rocks.

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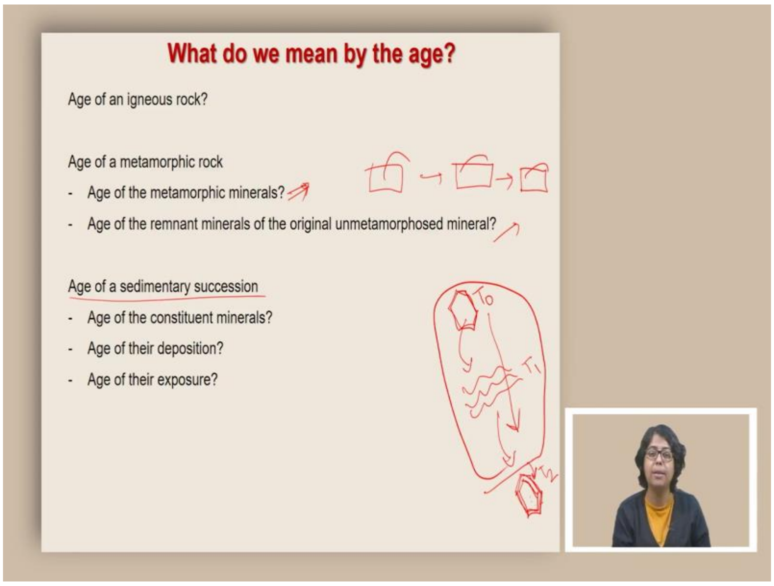

So we have understood how we can use the radiometric dating to get an age but exactly what do we mean by age? So the age of an igneous rock basically means when the crystals were forming out of the magma or lava, and that is where the system got closed up, or locked and that is that times zero. So whenever we get an age of an igneous rock, it means that is the last time it solidified out of a melt.

But let us imagine a scenario where this has gone through multiple cycles of magma, and then again produced some more minerals and so on and so forth. Interestingly, because we are always going to look at the stable system of closed minerals, this will not have the memory of the previous mineralization and melting. So it is only going to give you the date of t2, unless this mineral as the mineral survived these processes.

So, every time we find the mineral age of a mineral that it was produced because of the crystallization out of magma, it is going to tell you the last age during which it precipitated out of the magma or it crystallized out of the magma.

Now, let us come to the age of a metamorphic rock. Now, each of the metamorphic rock can give you different information. For example, if you are targeting some of the minerals, which formed due to metamorphism, metamorphic minerals, in that case, it is going to tell you the age of the metamorphism. But then there can be metamorphic rocks, where some of the old minerals of let us say the original igneous rock is still there. In that case, it is going to tell you the age of the last time it crystallized out of magma.

So this can give you a very old age, compared to the age of the metamorphism. From the same metamorphic rock if it has undergone different phases of metamorphism and produced multiple minerals in multiple phases, we can have different ages of the same metamorphic rock. It basically indicates different metamorphic events. The most complicated part of directly dating rocks is the sedimentary succession. Very rarely do we find development of minerals due to sedimentary processes.

As a result, it becomes complicated to justify the exact age of the sedimentary succession. Do we mean the age of the constituent minerals because a sedimentary rock can have constituent minerals, which are coming from older sedimentary rocks, older metamorphic rocks, or igneous rocks. And there can be situations where the whole rock is much younger compared to the inclusions or compared to the minerals that they are made up of. So therefore, the age of the sedimentary succession is complicated and often it is quite difficult to directly date them.

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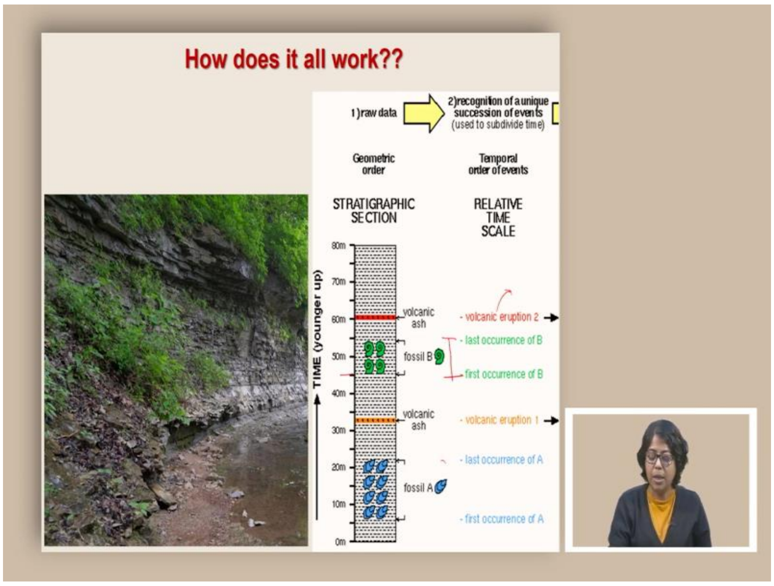

So now that we understand some of the complexities of radioactive dating, let us try to understand how all of these things are put together. So let us say we go to the field and look at these kinds of succession. Using The Law of superposition, we know that the strata which is below is much older, compared to the strata which is at the top. And if we represent it in a stratigraphy section, it will look something like this.

Now, let us imagine right around here, we find some fossils. And somewhere here, there is an ash bed. And we find some more fossils somewhere here, and there is another ash beds right around here. Now, what are these great things about these ash beds? These ash beds when they are created, often they have a very large spatial extent. So they cover a lot of area at the same point of time.

Second point is often these ash beds are developed through very quick cooling and through an igneous process. So they will have these mineral grains, which are a product of igneous process, and they are going to tell you the exact age through absolute dating. So we can employ these volcanic ashes and try to date them using radioactive dating. If we do that, then we can find some age of this volcanic eruptions. But within this, we also have the fossils.

So let us say we find the first appearance of these fossils in this strata. And the last appearance of this fossil in this strata. And the same thing is true for this different type of fossil at a lower strata.

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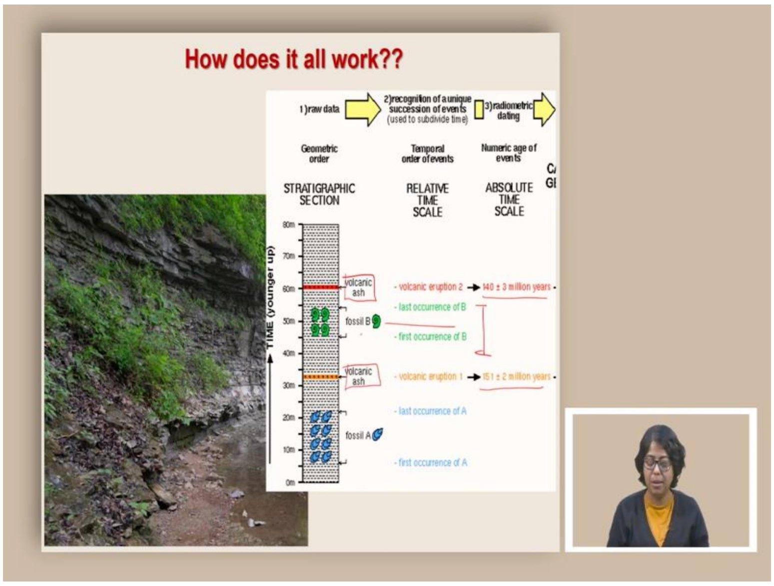

Now, once we have and this is the arrangement of the relative timescale, now we start attaching the absolute age, and the way we do it is by analyzing this volcanic ash, with a suitable radioactive dating method. Using that radioactive dating method, let us say we come up with the age of 140 plus minus 3 million years. And this volcanic ash bed gives us another age, which is 151 plus minus 2 million years.

What it tells us? It tells us that basically, we can see something about the age of the fossil B, we can say that the age of the fossil B must be older than 140 plus minus 3 million years, and must be younger than 151 plus minus 2 million years. Once this is done, and if we can do it globally, then these fossils can be correlated to different strata all over the world. And every time we correlate these strata, we can also attach the time of 151 to 140 plus minus 3 million years. And that gives us a very precise idea of how the strata are correlated spatially. This is the way of reconstructing geologic time and reconstructing geologic timescale.

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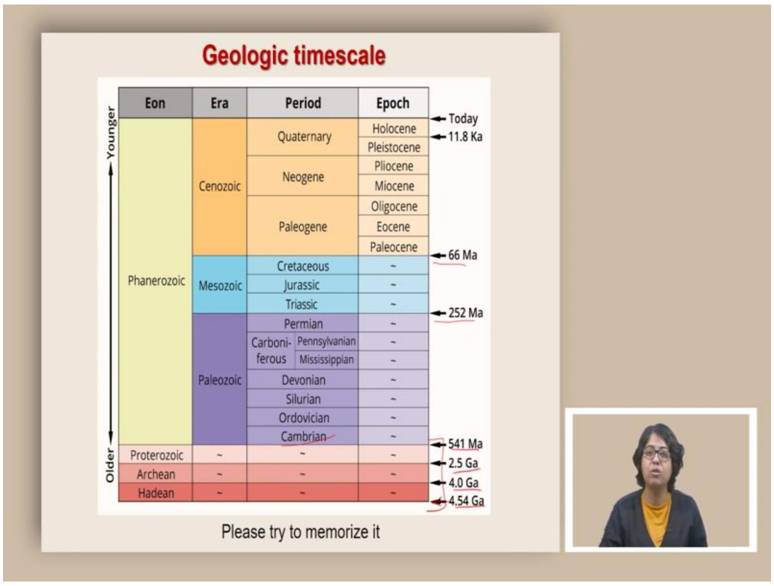

So now if we recall our original geologic timescale, we only had these names. But now, using this method, these numbers were also attached. In some of the parts there are no fossils. So it was primarily done based on only absolute dating. But other parts, there are fossils, and it can be correlated very well. These are the major events and therefore these numbers are extremely important in the context of Earth's history and therefore it is important that this should be remembered.

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In summary, today, we have learned how the radioactive dating scheme works; how to select a particular dating scheme depending on the average age of the rock, whether it is too old or too young of a rock. We also understood something about how it can be used, especially when the initial concentration of the daughter product is not zero. We learnt something about the age, per se. For example, what is the difference between age of an igneous rock versus age of a metamorphic rock.

And finally, we compiled all these relative understanding of the sequences or the strata and attached that absolute time to it and looked at the geologic timescale with the absolute dates. Here are some of the resources that I used to create these slides.

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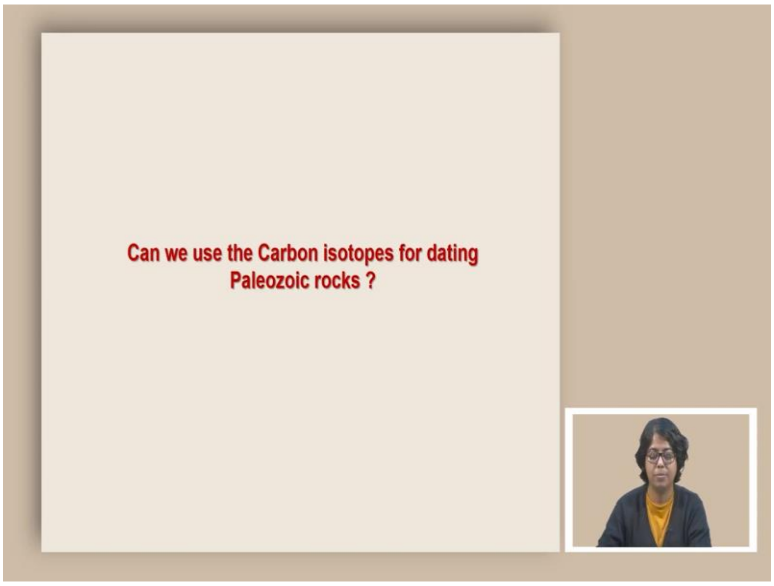

And here is a question for you to think about. Thank you.