

Radiocarbon Dating

How & why?



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पुराना



कितना पुराना?

Carbon Dating Gyanvapi Not As Easy As It Sounds

A technique best used for plant and animal remains, not stones like this

Mobile News/Thinkgroup.com



Eventual complex

A Varanasi High Court's decision to order a "scientific survey" of the Gyanvapi complex has raised a flurry of questions about how this will be done. The court's order, which came in the form of a judgment, was issued on the basis of a petition filed by a group of people who claim to be the rightful owners of the complex.

What is carbon dating and can it be used at the Gyanvapi complex?
Carbon dating is a widely used tool to establish the age of organic materials. It is based on the decay of a radioactive isotope of carbon, called carbon-14, which is present in all living organisms. When an organism dies, the carbon-14 begins to decay at a known rate, and by measuring the amount of carbon-14 left, scientists can determine how long ago the organism died.

Is it correct that the court's order to conduct a scientific survey of the Gyanvapi complex will involve carbon dating of the 'shiling'?
The court's order is not clear on this point. It only mentions a "scientific survey" and does not specify the methods to be used.

What are the other ways to verify such a site may be studied?
There are several other methods that can be used to verify the age of a site. These include dendrochronology (tree-ring dating), stratigraphy (studying the layers of a site), and radiocarbon dating of organic materials found at the site.

How long does the process of radiocarbon dating typically take?
The process of radiocarbon dating can take anywhere from a few weeks to several months, depending on the complexity of the sample and the methods used.

Even if radiocarbon dating is used, it can only provide a rough estimate of the age of a site. How can this be improved?
Radiocarbon dating is most accurate when used on organic materials that are well-preserved. For stone structures, other methods like stratigraphy and dendrochronology may provide more reliable information.

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Radiocarbon dating is conducted by scientists at the IITR, Lucknow.

C-14 concentration in the atmosphere is relatively constant, but it is not constant in the ground. It is affected by the amount of carbon-14 that is taken up by plants and animals.

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OTHER WAYS TO DATE A FIND

Radiocarbon Dating

- C-14 is a radioactive isotope of carbon that is found in all living organisms.
- When an organism dies, the C-14 begins to decay at a known rate.
- By measuring the amount of C-14 left, scientists can determine how long ago the organism died.
- This method is most accurate for organic materials that are well-preserved.

Stratigraphy

- Stratigraphy is the study of the layers of a site.
- By studying the layers, scientists can determine the relative age of different parts of the site.
- This method is most accurate when used on well-preserved sites.

Dendrochronology

- Dendrochronology is the study of tree rings.
- By counting the rings, scientists can determine the age of a tree.
- This method is most accurate when used on well-preserved trees.

Thermoluminescence

- Thermoluminescence is a method of dating ceramics.
- It is based on the amount of light that is emitted from a ceramic when it is heated.
- This method is most accurate when used on well-preserved ceramics.

Optically Stimulated Luminescence

- Optically Stimulated Luminescence is a method of dating sediments.
- It is based on the amount of light that is emitted from a sediment when it is heated.
- This method is most accurate when used on well-preserved sediments.

A NOBEL-WINNING TECHNOLOGY

Carbon dating was pioneered by Willard Libby in the late 1940s at the University of Chicago. He received the Nobel Prize for his work in 1960.

How is carbon dating used?
Carbon dating is used to determine the age of organic materials that are up to 50,000 years old. It is most accurate when used on well-preserved materials.

What are the limitations of carbon dating?
Carbon dating is not accurate for materials that are older than 50,000 years. It is also not accurate for materials that are not well-preserved.

How is carbon dating used in archaeology?
Carbon dating is used in archaeology to determine the age of organic materials found at archaeological sites. It is most accurate when used on well-preserved materials.

What are the other methods used in archaeology?
Other methods used in archaeology include stratigraphy, dendrochronology, and thermoluminescence. Each method has its own strengths and limitations.

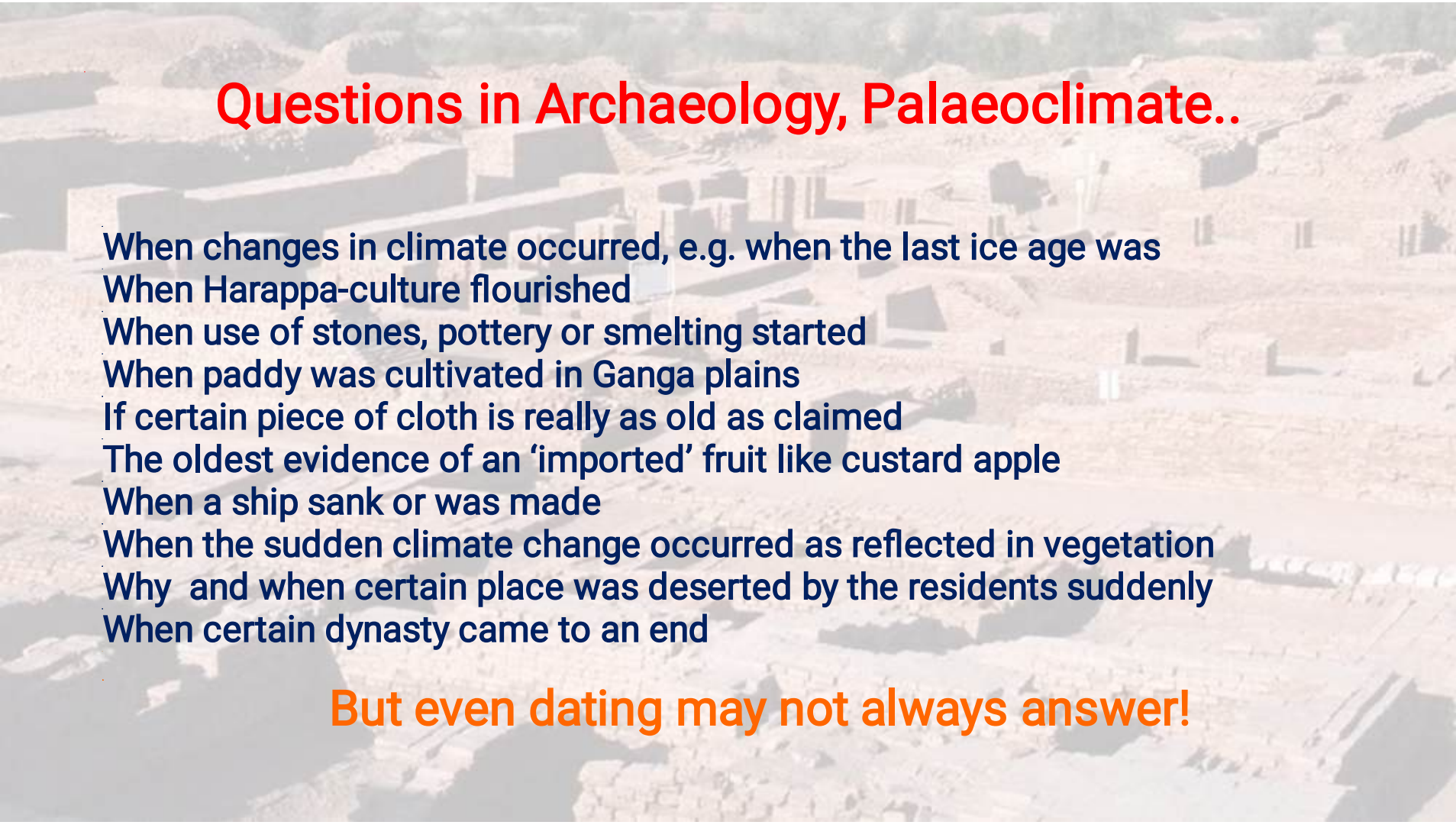
Answered by
Discovery of Radiocarbon (C^{14}) Dating by
Willard F Libby



- Seldom has a single discovery in Chemistry had such an impact on the thinking in so many fields of human endeavour. Seldom has a single discovery generated such wide public interest-

-NOBEL COMMITTEE (1960)

Actually, the evolution of C14 method is a set of several inter-woven stories



Questions in Archaeology, Palaeoclimate..

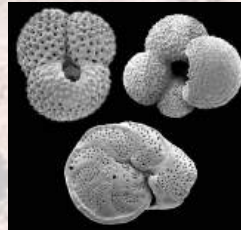
When changes in climate occurred, e.g. when the last ice age was
When Harappa-culture flourished
When use of stones, pottery or smelting started
When paddy was cultivated in Ganga plains
If certain piece of cloth is really as old as claimed
The oldest evidence of an 'imported' fruit like custard apple
When a ship sank or was made
When the sudden climate change occurred as reflected in vegetation
Why and when certain place was deserted by the residents suddenly
When certain dynasty came to an end

But even dating may not always answer!

Where do you see radiocarbon on Earth?

Radiocarbon is seen

- In the air
- In water
- In plants
- In soil
- In the bodies of all animals, in their bones
- In bio-precipitates like coral, foraminifera,...
- May be even in iron products,
- In pottery, bricks, clay items like seals



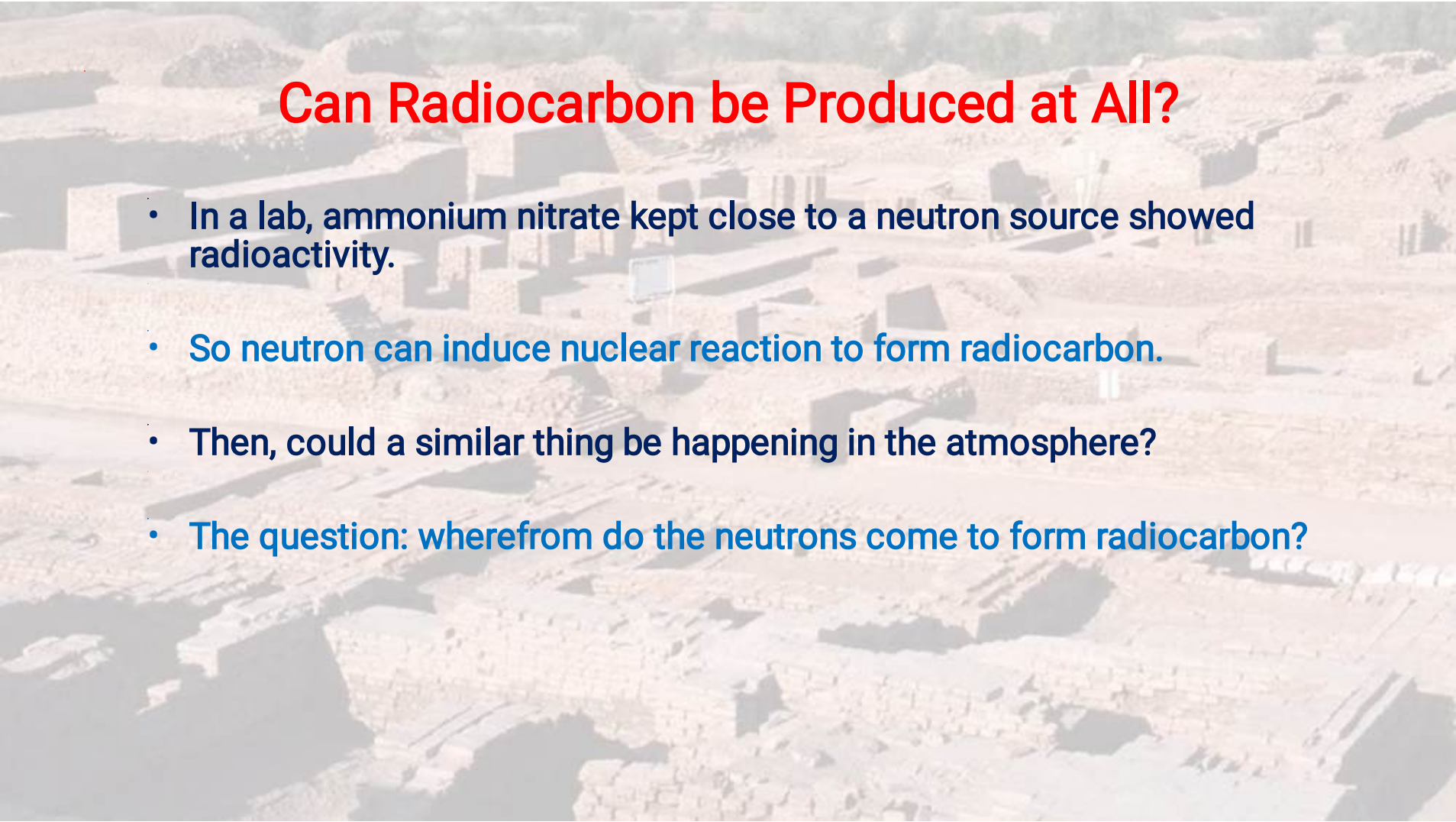
But where does this radiocarbon come from?

A Detective-Like Approach:☒ The Source of C¹⁴

Can not be from the Sun

- No C¹⁴ production inside the Sun (only helium)
- No old Radiocarbon inside the Sun as no remnants from 4.6 Ga ago possible (C¹⁴ has a half life of 5730 years)



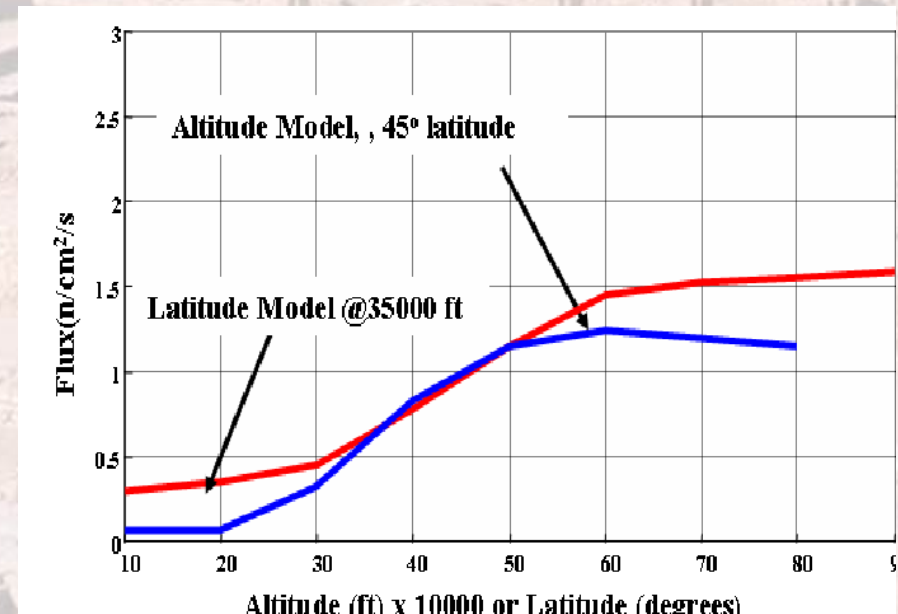
An aerial photograph of ancient stone ruins, possibly Mayan or Aztec, with various rectangular and circular structures. The image is faded and serves as a background for the text.

Can Radiocarbon be Produced at All?

- In a lab, ammonium nitrate kept close to a neutron source showed radioactivity.
- So neutron can induce nuclear reaction to form radiocarbon.
- Then, could a similar thing be happening in the atmosphere?
- The question: wherefrom do the neutrons come to form radiocarbon?

Parallely, Research on Neutrons was Proceeding

- Could cosmic rays be doing it? But they have no neutrons!
- Balloon observations were being made. They showed that as we go up in the atmosphere, neutrons increase. So can't be coming from Earth.
- This increasing trend is up to about 20 kms but then decreases. So can't be coming from space.
- So C14 is being produced in the atmosphere. Reaction of neutrons on atmospheric nitrogen possibility.



Production Reactions for C14



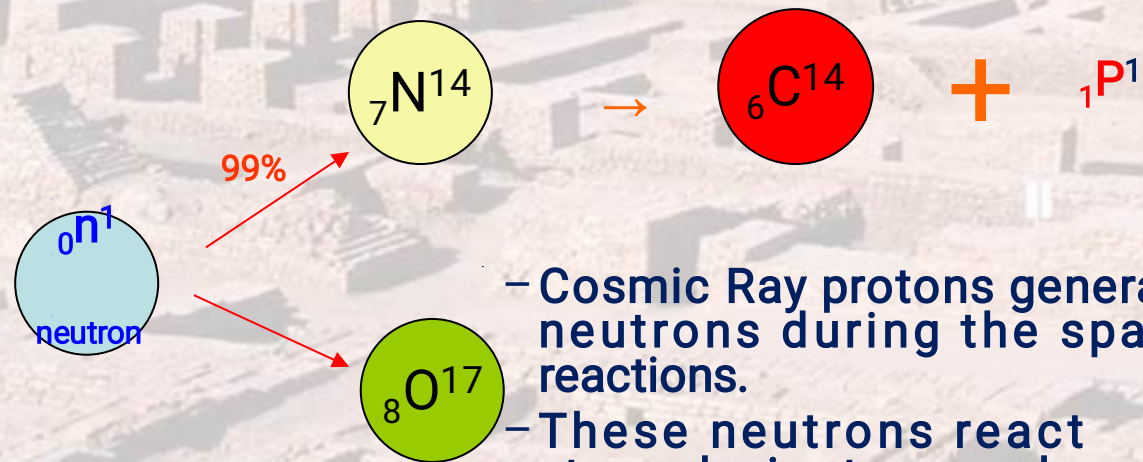
{cross section= $1.7 \times 10^{-24} \text{ cm}^2$ }

Other reactions



- Clearly, neutrons can be produced in the atmosphere

Production of Carbon- 14



– Cosmic Ray protons generate thermal neutrons during the spallation reactions.

– These neutrons react with the atmospheric atoms such as nitrogen and oxygen to yield radiocarbon (C^{14}) which forms CO_2 , which then mixes in the atmosphere

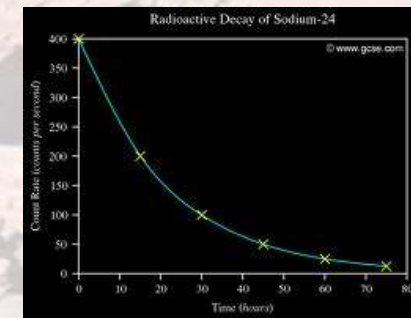
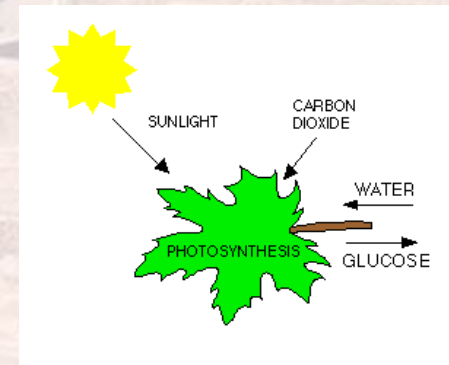
$\text{B}^{11} + \text{He}^4 = \text{C}^{14} + \text{H}^1$
(v. low cross section)

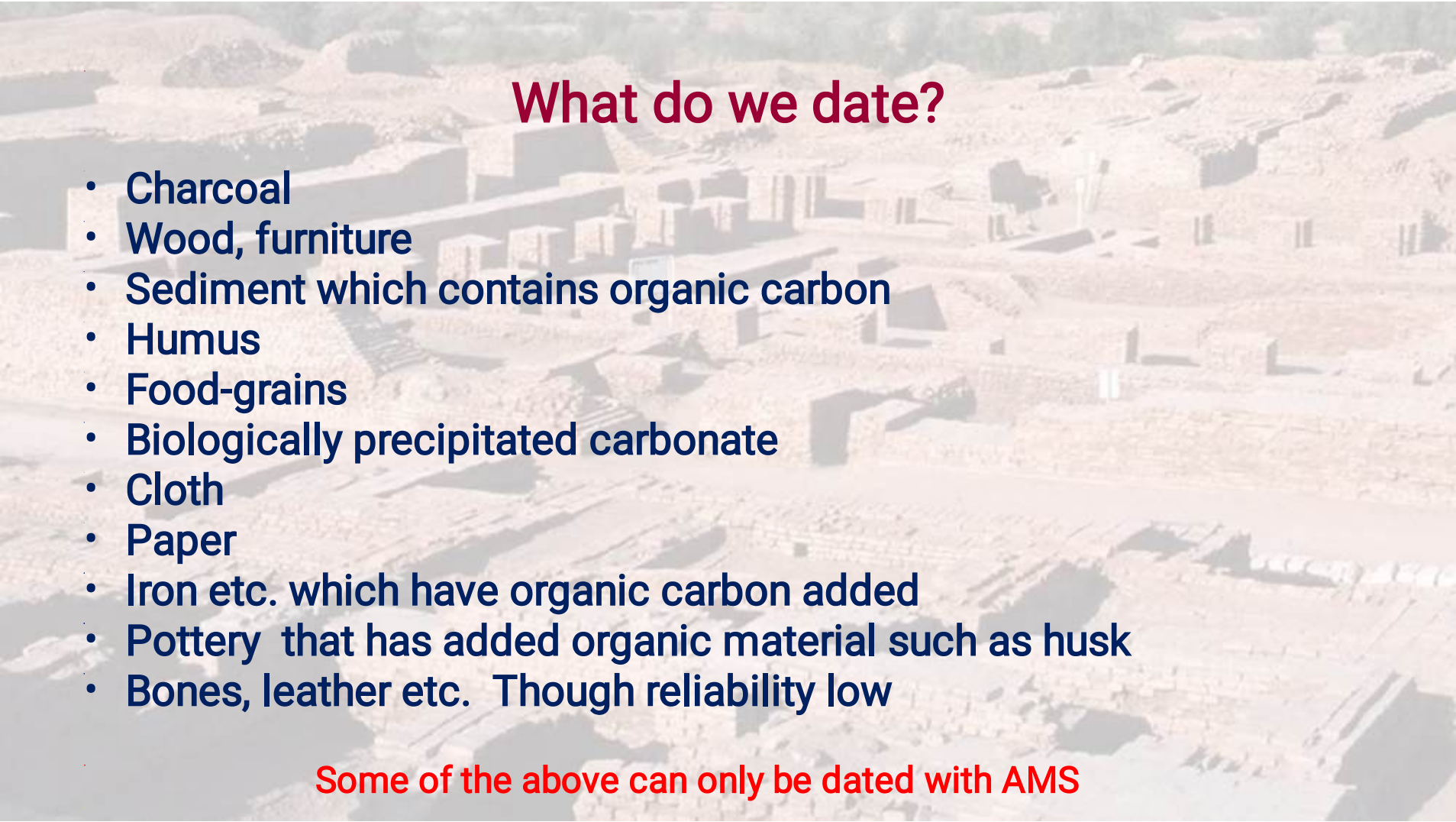
How is Radiocarbon Measurement Applied to Dating?

- We know the level of C^{14} (radiocarbon) in the modern atmosphere
- This level of radiocarbon is maintained when the plant is alive. The minor changes due to fractionation between isotopes can be corrected for.



- Carbon is assimilated into plants during photosynthesis. So plants contain radiocarbon at the same level as the atmosphere. The living, herbivores or carnivores, acquire it from plants.
- With passing time, C^{14} concentration decreases at a definite rate. The amount of change is a measure of time lapsed



The background of the slide is a faded, high-angle photograph of ancient stone ruins, possibly a city or temple complex, with various walls, columns, and structures visible. The image is semi-transparent, allowing the text to be overlaid clearly.

What do we date?

- Charcoal
- Wood, furniture
- Sediment which contains organic carbon
- Humus
- Food-grains
- Biologically precipitated carbonate
- Cloth
- Paper
- Iron etc. which have organic carbon added
- Pottery that has added organic material such as husk
- Bones, leather etc. Though reliability low

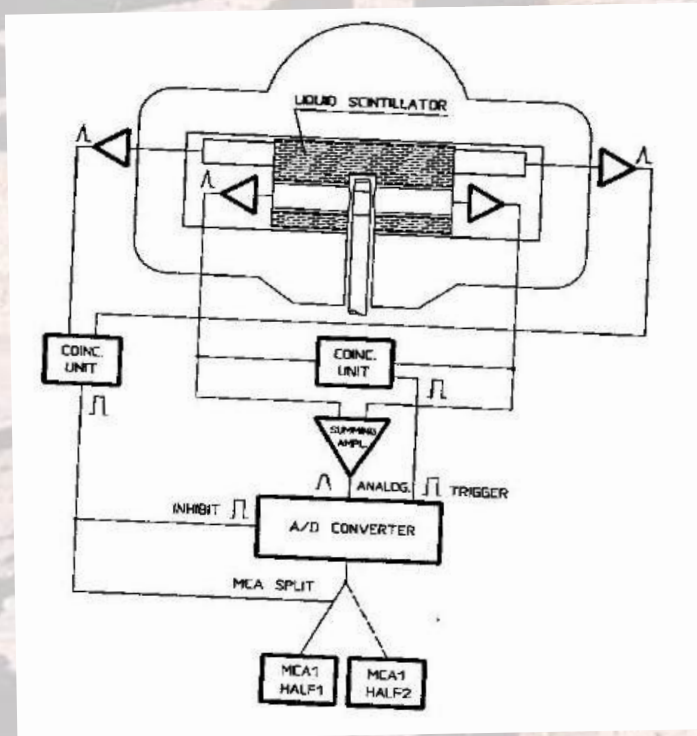
Some of the above can only be dated with AMS

Sample- processing system (CO₂ - side)

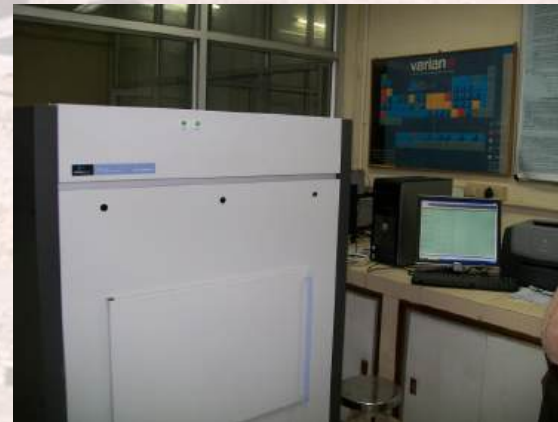


BSIP

The Radioactivity Counter



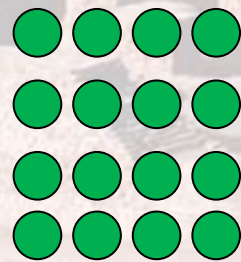
$$dN/dT \propto -N$$



The benzene is weighed & placed in a vial. After adding scintillator, the vial is placed in a Liquid Scintillation Counter to determine C^{14} atoms decay/ min. NOW AMS.

For C^{14} the value half life is 5730 years.

$$\text{Age } t = 1/\lambda (\ln A_0 - \ln A)$$

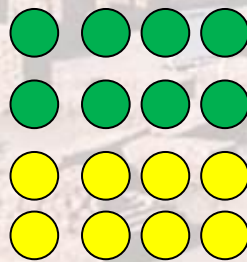


0 Day

16 raw

0 ripe

Initial

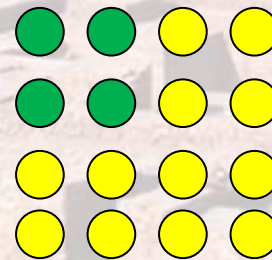


1st day

8 raw

8 ripe

After one
half life,
halved

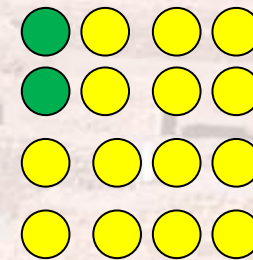


2nd day

4 raw

12 ripe

After 2
half lives,
quartered



3rd Day

2 raw

14 ripe

After 3 half
lives,
1/8 th left

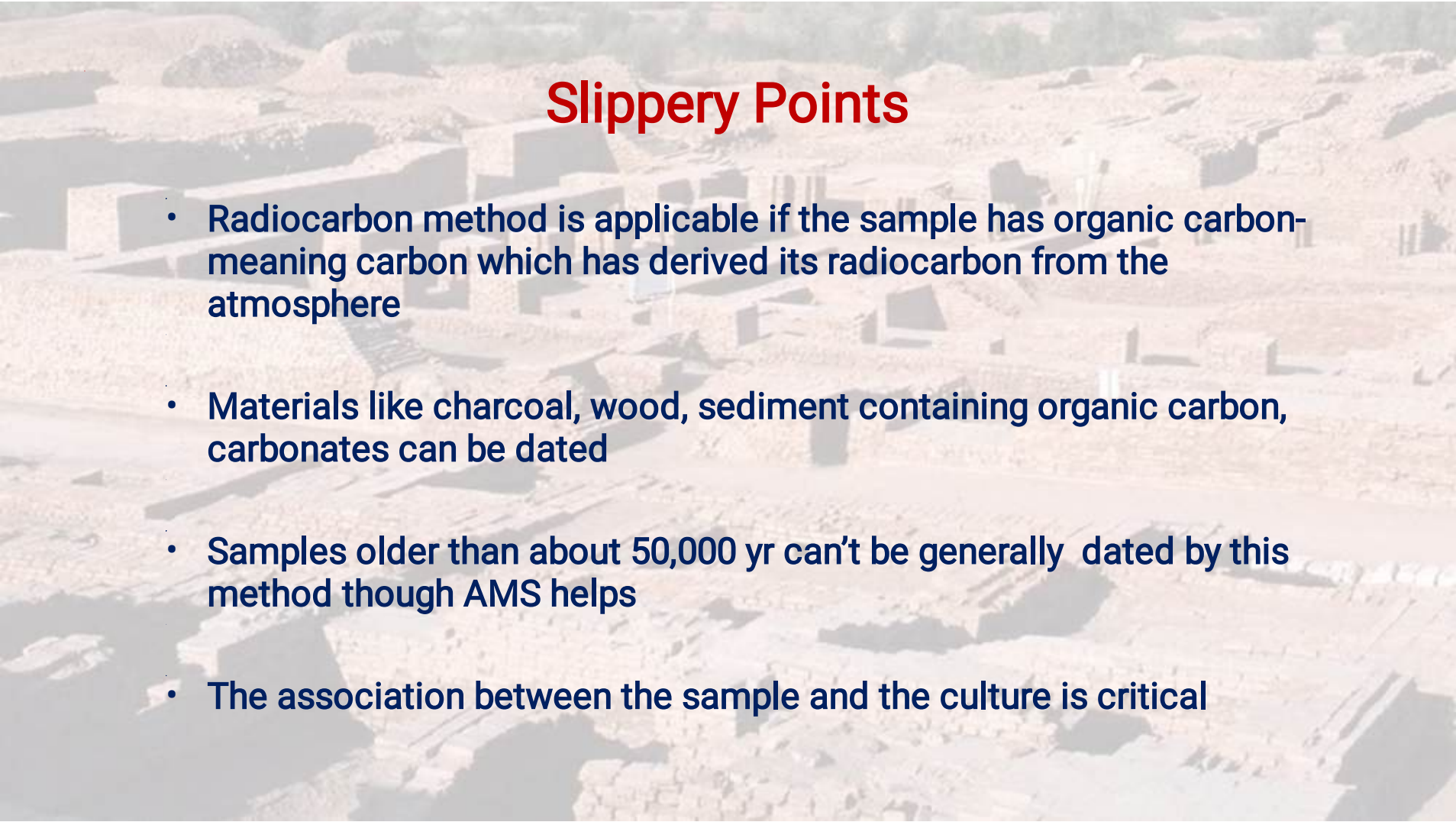
Meaning of Radiocarbon Age

- We measure the time lapsed since the moment the radiocarbon started decreasing as no more assimilation of radiocarbon.
-
- For vegetation it is the point of cessation of the photo synthesis which is caused by the uprooting, cutting or death of a plant.
-
- If we are dating sediment, furniture, door or anything that contains that radiocarbon (as part of organic carbon), even then we are dating the point of photosynthesis cessation.

A Constant Production rate of C^{14} ?



- 1. Dendrochronology (German oak: 9147 cal BP , New Pine Chronologies from Switz. & Eastern Germany: 12,410 cal yrs BP)
- 2. Coral dating
- 3. Spleothemes, varves also though not very accurate
- 4. Correction for location

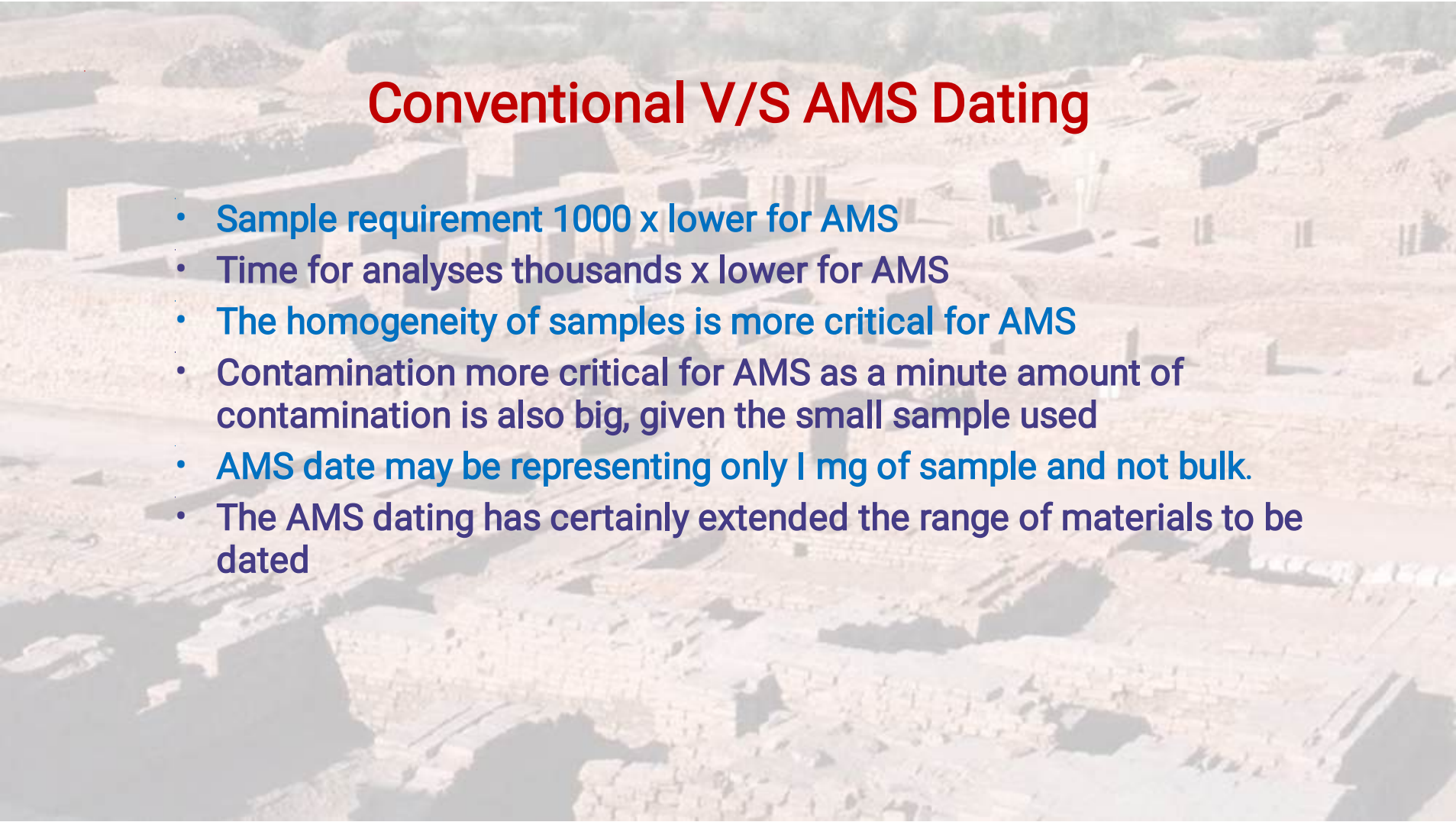
The background of the slide is a faded, high-angle photograph of ancient stone ruins, possibly Mayan or Aztec, with various rectangular and stepped structures. The title "Slippery Points" is centered in the upper half of the image in a bold, red, sans-serif font.

Slippery Points

- Radiocarbon method is applicable if the sample has organic carbon-meaning carbon which has derived its radiocarbon from the atmosphere
- Materials like charcoal, wood, sediment containing organic carbon, carbonates can be dated
- Samples older than about 50,000 yr can't be generally dated by this method though AMS helps
- The association between the sample and the culture is critical

Limitations of Radiocarbon Dating

- The farthest back in time: About 50,000 years
- The youngest is about 300 years
- If older material has been used in a later structure, the date is not for structure but for the material
- Certain minimum amount of radiocarbon needed which is a few grams for Conventional methods but just a few mg for AMS

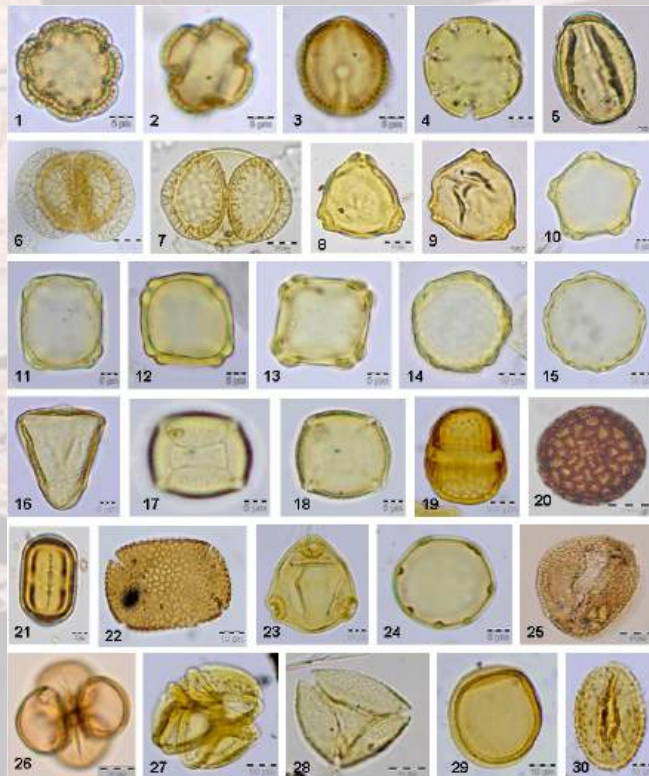
The background of the slide is a faded, high-angle photograph of ancient stone ruins, possibly a city or temple complex, with various walls, foundations, and structures visible in a dry, hilly landscape.

Conventional V/S AMS Dating

- Sample requirement 1000 x lower for AMS
- Time for analyses thousands x lower for AMS
- The homogeneity of samples is more critical for AMS
- Contamination more critical for AMS as a minute amount of contamination is also big, given the small sample used
- AMS date may be representing only 1 mg of sample and not bulk.
- The AMS dating has certainly extended the range of materials to be dated

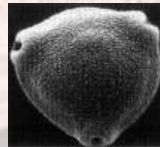
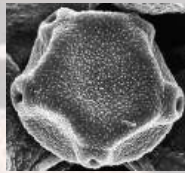
An aerial photograph of an ancient archaeological site, likely a city or fortress, featuring numerous stone walls, rectangular buildings, and a central courtyard. The ruins are made of light-colored stone and are surrounded by a dry, hilly landscape. The text is overlaid on the center of the image.

☒
Applications to ☒
Palaeoclimatology, Palaeobotany, ☒
History and Archaeology



1. Euphorbiaceae, 2. & 3. *Oldenlandia gracilis*, 4. *Chrozophora prostrata*, 5. *Quercus* sp., 6. & 7. *Pinus khasiana*, 8. & 9. *Betula* sp., 10-13. *Alnus* sp., 14. *Ulmus* sp., 15. Juglandaceae, 16. Cyperaceae, 17. & 18. Ranunculaceae, 19. *Polygala chinensis*, 20. *Polygonum serrulatum*, 21. *Polygonum plebeium*, 22. *Impatiens balsamina*, 23. *Ludwigia octavalvis*, 24. *Myriophyllum indicum*, 25. *Potamogeton pectinatus*, 26. *Typha latifolia*, 27. *Trapa bispinosa*, 28. *Nymphoides indica*, 29. *Nymphaea nouchali*, 30. *Eichhornia crassipes*.

Dating Sediments of the Loktak Lake



History of Settlements in Khajnavar



Fig.3

Khajnawar

Biharigarh (Saharanpur)

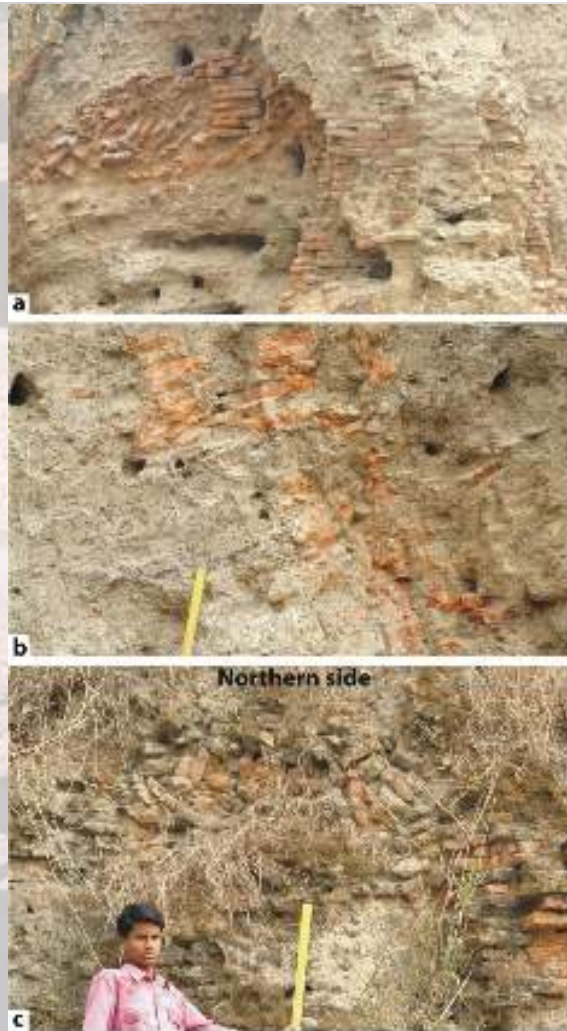
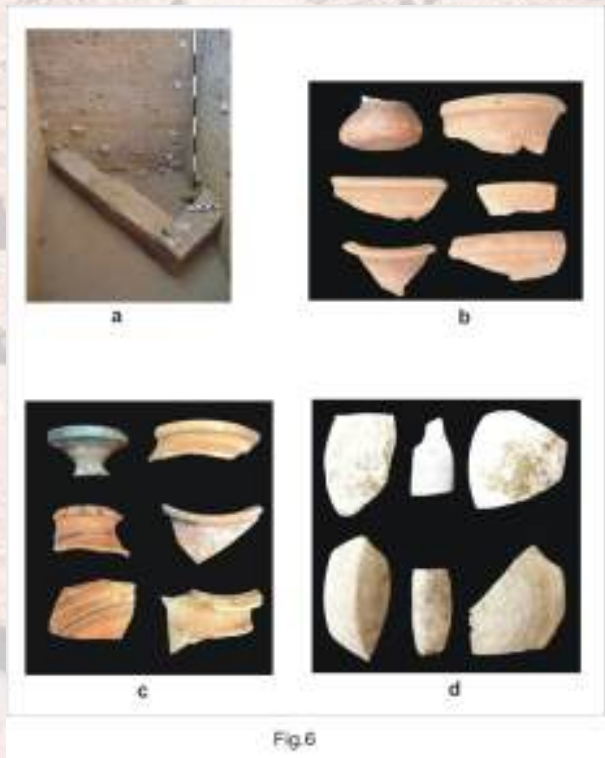


Fig.8



2500 yr BP, 1400 yr BP, 800 yr BP,
350 yr BP (Habitation in bold)

Khajnawar

An archaeological site in Saharanpur

- Concluded to have been affected by 2 earthquakes separated by 1Kyr & perhaps a climate change. Hence a hiatus of about 550 yr between 2 successive settlements.
- Phase-I: 2650- 1400 yr BP, Magadh empire (Large bricks, potsherds, painted greyware, iron nails, copper rod, coins, wheel....)
- Phase-II: 850 - 350 yr BP, Mughal empire (Red, black vases, jars, haandi, lamps, glass, lac items, iron nails, spindle, hook,...)
- The 2650 yr BP was a wet phase and 1500-1300 BP of bad SW monsoon



Thakur, Pandey, Nautiyal...
Curr. Sci. (April 25, 2010)

Kanmer (Kachchh, Gujarat)

The Harappan Culture had several phases during 2600- 1900 CA BP period.

- **KNM-I:** This is early Harappan Terracota cakes, potsherds, red ware, & pottery like bulbous jars
- **KNM-II:** This is Mature Urban Phase. painted red ware, planned town, fortification, Harappan pottery, seals, seal impressions.
- **KNM-III:** Remains of late Harappan. This is overlain by 1600 years of dark grayish sandy soil

Thakur,...Nautiyal (2014)

Kanmer: Rabi & Kharif Crops

Winter crop (Rabi) in Kanmer

Cereal: Barley, bread wheat, dwarf wheat

Oil seed: Lin seed Sesame

Leguminous: Field pea, grass pea, fenugreek

Fruit: Jubebe (*Ber*) which is actually common all through.

Summer crop (Kharif):

Rice (*Oryza sativa*), Jowar
Green black gram cotton, sesame

However, barley dominates the crops and the rest are a meager 10%.

	Barley (<i>Hordium vulgare</i>)	Rice (<i>Oryza sativa</i>)	Jowar (<i>Sorghum bicolour</i>)
KMR-I	93%		
KMR-II	49%	5%	
KMR-III	2%	24%	18%

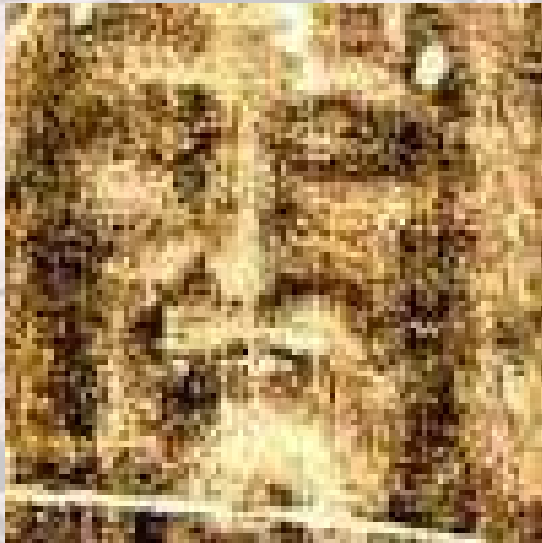
The Shroud of Turin

In Turkey a piece of cloth of the size 4.4 x 1.1 m (14.3 x 3.7 feet) was found.

The marks on cloth suggested that it covered a person who had been crucified.

It soon came to be known as Shroud of Turin till AMS Radiocarbon dating in 1988 busted the myth (1260 AD).

A stamp- sized piece was dated in 1988 to be about 700 year old! Obviously it couldn't be Shroud of Christ's time.



Application of LSC & AMS C14 Dating Yield Similar Results



Grains of domesticated rice from Lahuradeva, 7000 BC

Dating Facing Rhinos (Chauvet-Pont d'Arc, France)



Clottes et al. (1995)

AMS Radiocarbon dates on the figures:

About

30,940+- 720 Ca Yr

Burial Practices in Kanam (HP)

- At an altitude of 2699 meters above sea level, Kanam is accessed by a side road from Spillo and is sixty kilometers from Kalpa.
- 'Ka' of the sacred texts, the Kangyur and 'nam', or place – and thus, 'a place of sacred books'. This indicated possibilities of material of archaeological interest there.
- Human burial reported from Leh, Cave burial in Malari (~200 BC), Mustang (W Nepal): 1200 BC,



Dates for charcoal

BS-3421 LPA-I Cist burial
Charcoal 1420 ± 170 Cal BC

BS-3327 KNM-I Gravel, pottery, bones.
Charcoal: 540 ± 70 Cal BC

Kanam (Kinnaur, HP)



Kanam ($31^{\circ}0'39.51''\text{N}$, $78^{\circ}0'23.57''\text{E}$). Also found at site: Gravel, red ware pottery, bones. A full human (50 yr) skeleton, horns of ruminant and iron tools were found. The skeleton's forearms had copper bangles.

BS-3327 KNM-I, Charcoal: **540 $\pm$ 70 Cal BC**. The OSL date for pottery: **2.3 $\pm$ 0.2 Ka**.

The burial culture in Kinnaur trans-Himalaya developed around the sixth century BC though more dates are required to establish a firm chronology.

Look into the Past..

The significant features of the Koti Banal architecture :

- (i). Simple layout, construction on elaborate, solid and raised platform (2- 4m),
- (ii). Judicious use of locally available building material, incorporation of wooden beams all through the height of the building at regular intervals,
- (iii). Small openings and shear walls.

The old surviving buildings are of interest to historians. Finding their age is important to understand the progress of architecture during different regimes.



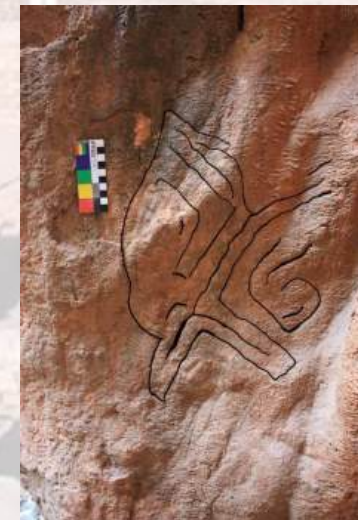
Rautela et al., Curr. Sci

880 +/- 90 year
old

5- storied house

Billasurgam, Kurnool

- The cave complex has been investigated archaeologically since the late 1800s, it was not until 2008 that a large petroglyph, consisting of the remains of three nested diamond designs on a stalactite, was noted.
- The flintstone was sampled from on top of and below the engraving petroglyph
- Radiocarbon dating revealed a mid-Holocene age of about 5000 cal BP for the petroglyph. However, cannot rule out the possibility that the engraving is several centuries younger.
- *Tacon et al. 2013*



The Antiquity of *Sharifa*

It was generally believed that Custard Apple (*Sharifa*) reached India through the Portuguese during the 16th century

The findings of custard apple seeds at Tokwa & Nal-ka Tila (Mirzapur & Sonbhadra resp.) and coat at Sanghol (Panjab) in India speak otherwise.

Raja Nal-ka-Tila (Sonbhadra) The age turned out to be 2690±70 yr BP

Emerging Scope: Rock Art

Earlier, the efforts were limited to finding a relative chronology using evolution of style or trends such as use of charcoal to that of colours.

Efforts for dating of such paintings received a boost with advent of Accelerator Mass Spectrometry (AMS) in eighty's in the last century and developments in mass spectrometry.

The conservation of such sites has been now initiated in India in recognition of their significance for understanding the evolution of art and culture but there have been little effort to date them quantitatively.

Baghmanwa, Sonbhadra

Rock ART

Based on dates , it's clear that the rock art is about 40 Ka old in Europe, or may be 65 Ky old.

This demolishes the notion of progressive evolution and implies that a radical change human evolution occurred.

Considering the evidence for cultivated rice in Gangetic plain about 8 Ka ago, we should expect older rock art in India too.

Baghmanwa,
Sonbhadra



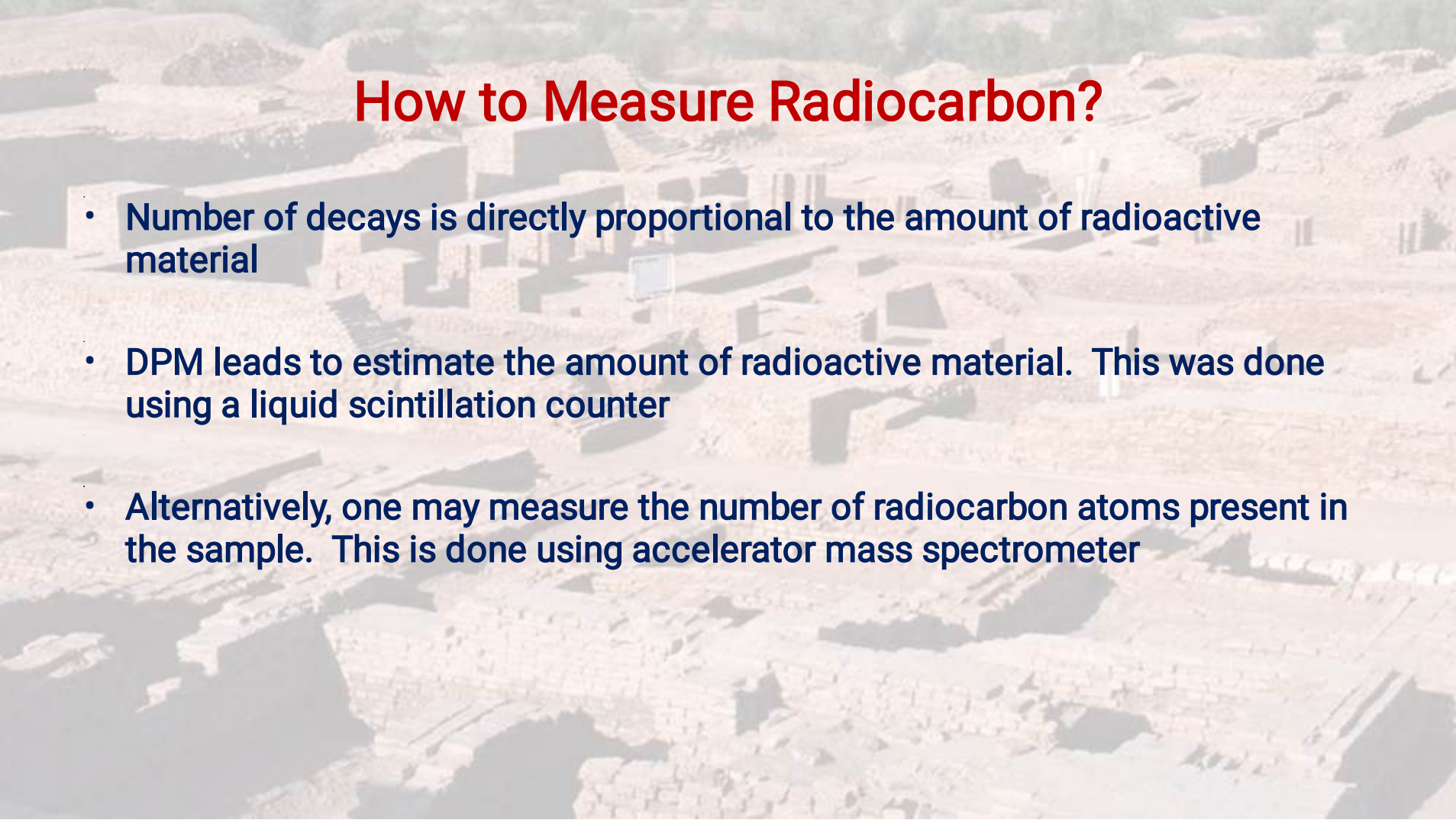
Dating of Rock Art

- The vegetal colours used in painting can be dated
- The charcoal used in drawing may be scraped and used for dating
- The carbonate on which the painting is done, may be dated by U-series dating
- The carbonate underlying the painting may be dated
- The calcite deposited in the engravings may be dated as that may also contain radiocarbon

Summary

1. Radiocarbon is produced in atmosphere by reaction of slow neutrons on N, O etc. It changes into CO_2 and gets homogenised in air.
2. Through photosynthesis it enters plants; attains equilibrium
3. Through food chain, it enters living beings
4. Once detached from plant, its C^{14} component decays at known rate (Half Life: 5730 yr)
5. So residual C^{14} is measured to back calculate how much time it should have taken to decay to this level
6. Initial level is known from measurements on plants
7. During the past 200 and 70 years, disturbance by fossil fuel burning and nuclear testing respectively resp. . Upper limit: 70 Kyr (AMS)
8. Datable: Food grains, wood, charcoal, leather, bones, bricks, Rock art ,apply to changes in climate, vegetation, ...
9. Applications extend beyond imagination

- 
- An aerial photograph of ancient ruins, likely Mayan or Aztec, showing a complex of stone buildings with flat roofs and courtyards. The ruins are surrounded by dense tropical vegetation. The image is slightly faded and serves as a background for the text.
- Neutrons in air <https://www.scirp.org/journal/paperinformation?paperid=36700>
 - <https://ui.adsabs.harvard.edu/abs/2020EGUGA..2217774B/abstract>

The background of the slide is a faded, sepia-toned photograph of ancient stone ruins, possibly Mayan or Aztec, with various rectangular and circular structures. The title is centered over the upper part of this image.

How to Measure Radiocarbon?

- Number of decays is directly proportional to the amount of radioactive material
- DPM leads to estimate the amount of radioactive material. This was done using a liquid scintillation counter
- Alternatively, one may measure the number of radiocarbon atoms present in the sample. This is done using accelerator mass spectrometer

Conversion of the Material into CO_2 , C_2H_2 and C_6H_6

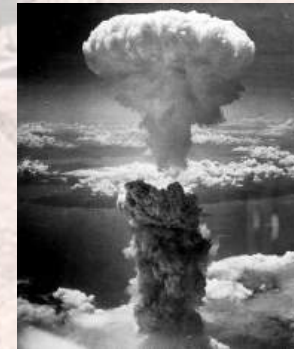
- The wood/sediment/humus/peat samples are cleaned of roots, pebbles etc.
- They are chemically treated (sediment with dilute HCl if suspected to have calcium carbonate followed by alkaline and again acid treatment and rinsing), wood pre-burnt and charcoal just washed
- The cleaned sample is combusted in a furnace at 750 degree C
- The carbon dioxide so released is purified, dried and made to react with trickling water in presence of molten Li to form acetylene (C_2H_2)
- The C_2H_2 is trimerized in presence of a catalyst to get benzene (C_6H_6)

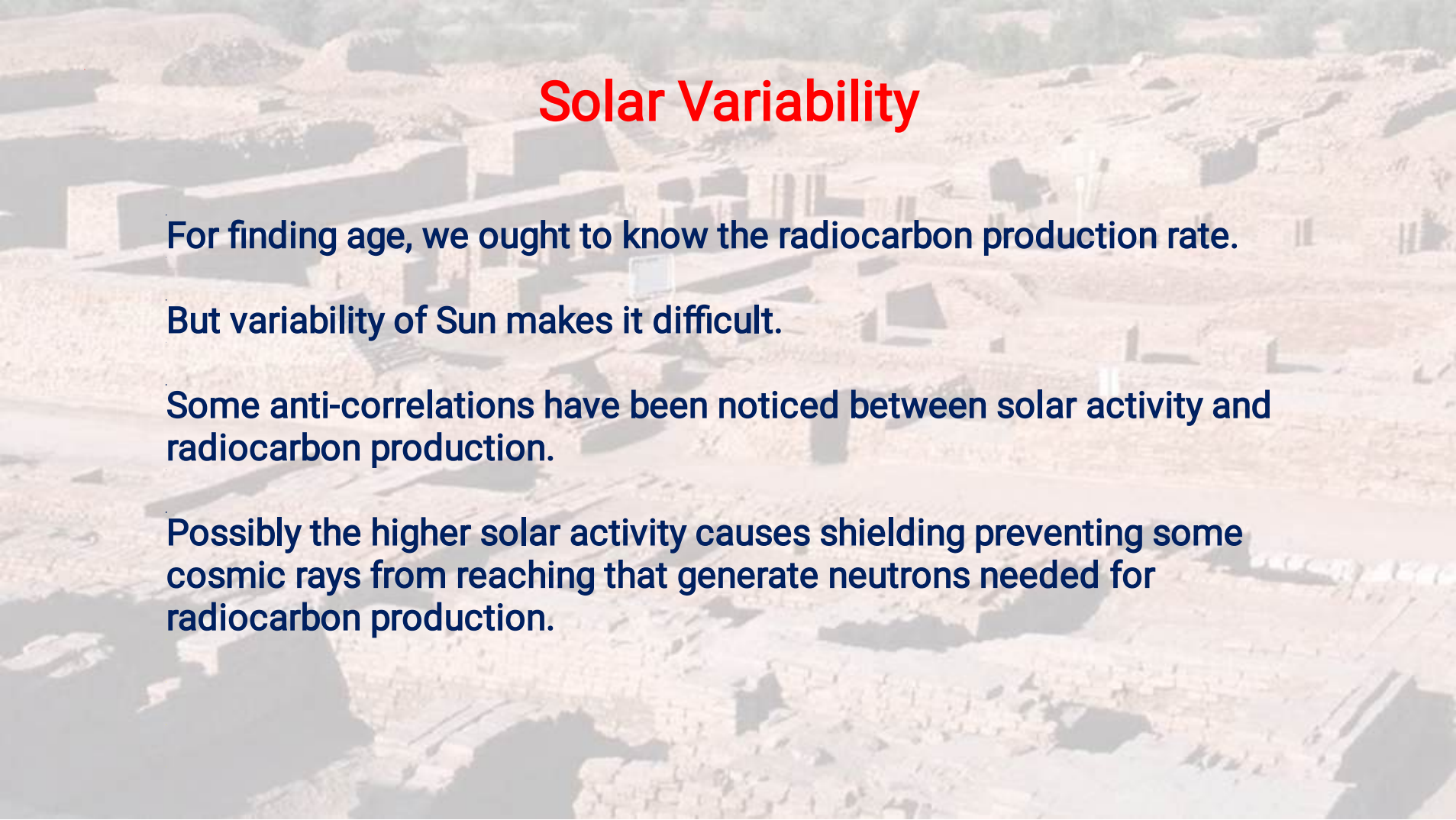
Wish It Were So Simple!

- Radiocarbon level of the atmosphere depends on its production which is a consequence of 'cosmic' ray flux and spectrum, reaction cross section, target in the atmosphere (N, O). During the past, the cosmic ray flux has not been constant. The flux is also dependent on the earth's magnetic field which too is variable and is modulated by solar activity.
2. Since the nineteenth century, the radiocarbon (C^{14}) in the atmosphere has been diluting due to the burning of the fossil fuel which contains no C^{14} .

Bomb Interference

3. Neutrons are produced during Nuclear tests. So since the mid of 20th century, radiocarbon has been added to the neutron reaction-generated radiocarbon in the air. The combined effect of these 2 opposite factors is uncertain.
4. We presume that C^{12} , C^{13} and C^{14} have always maintained their ratio in the air. But fractionation (e.g. isotope exchange) affects the ratio in the samples if, for instance, has been stored in water of a different isotopic composition.



The background of the slide is a faded, high-angle photograph of ancient stone ruins, possibly Mayan or Aztec, with various rectangular and stepped structures. The text is overlaid on this image.

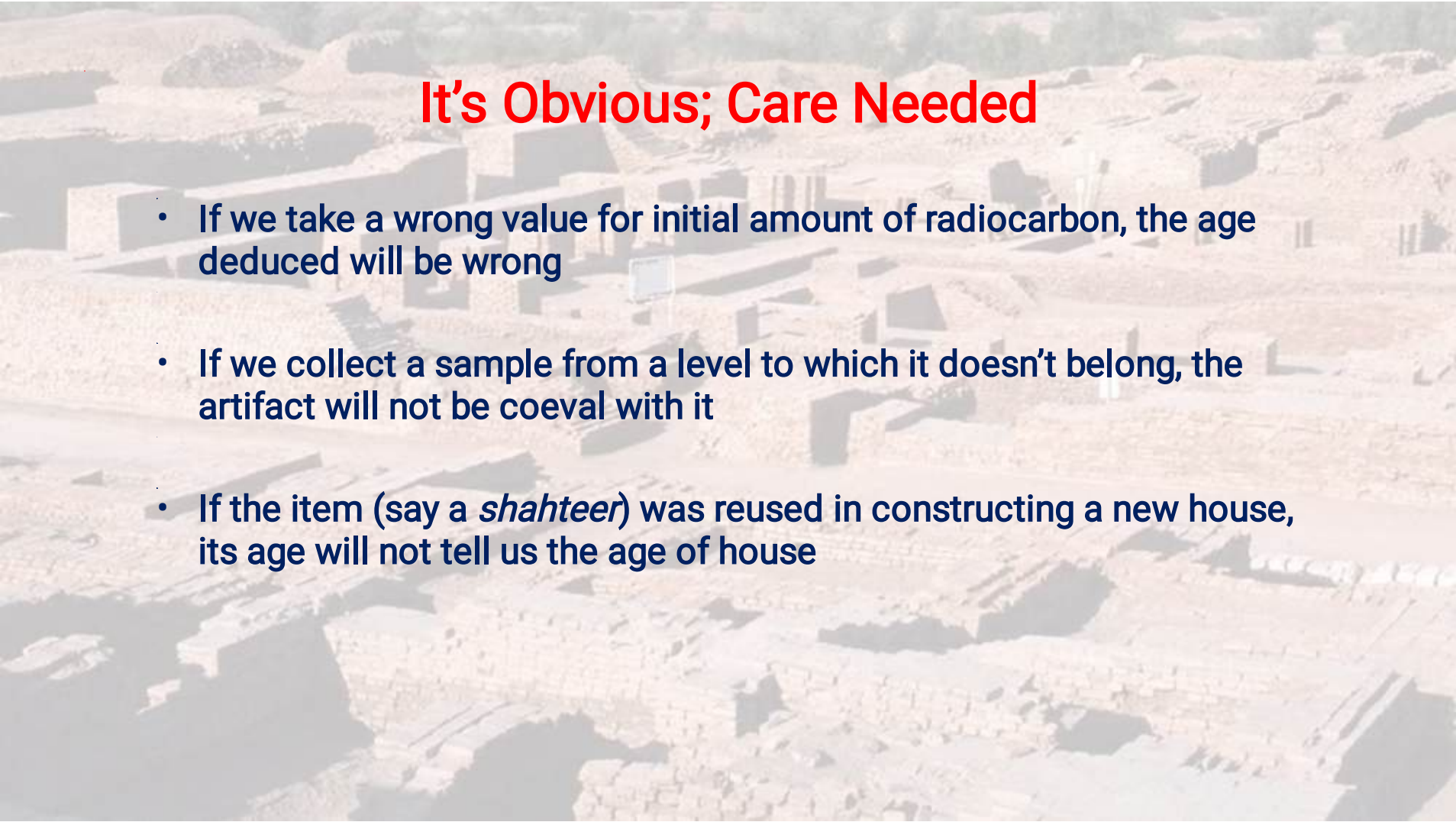
Solar Variability

For finding age, we ought to know the radiocarbon production rate.

But variability of Sun makes it difficult.

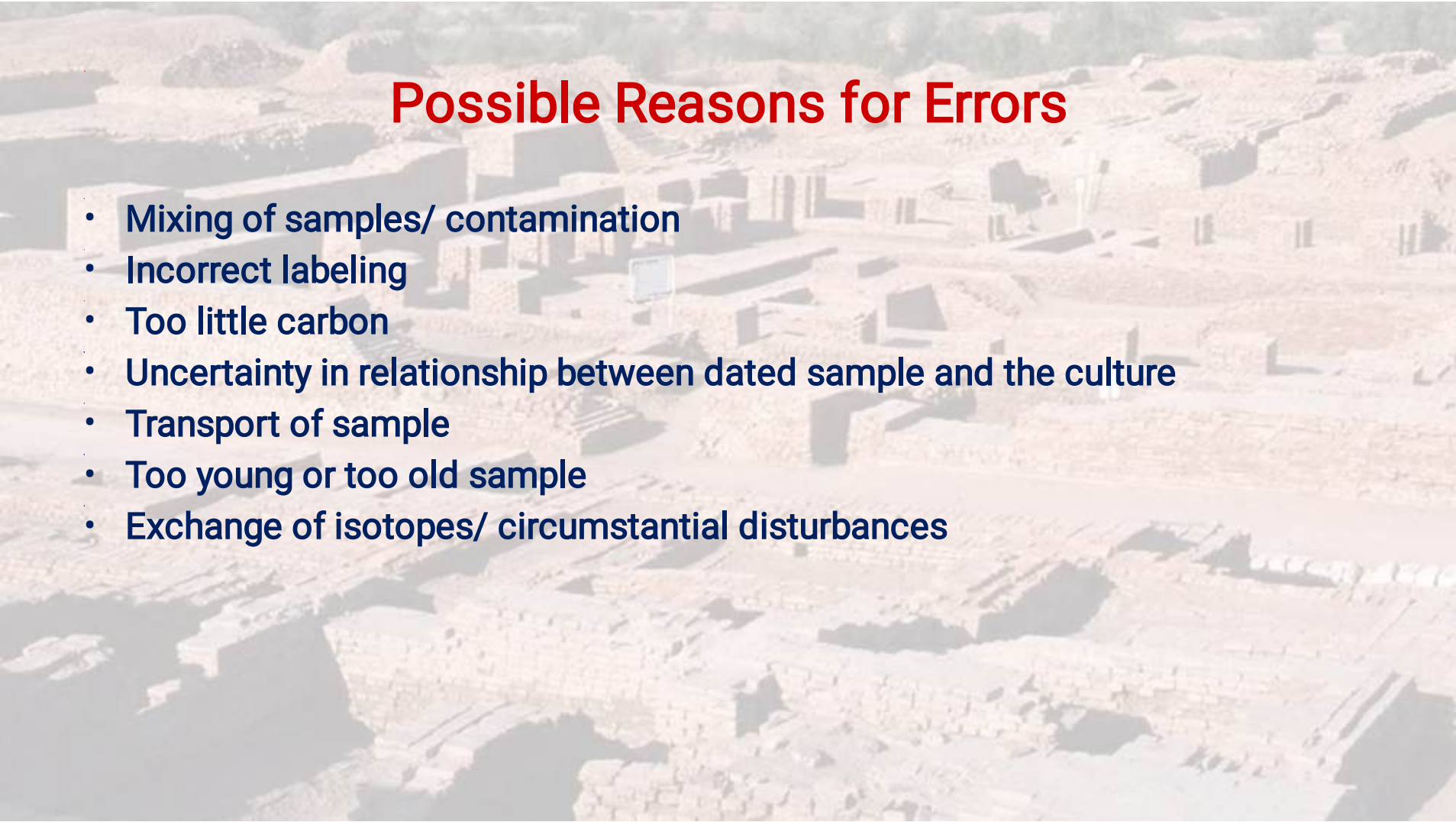
Some anti-correlations have been noticed between solar activity and radiocarbon production.

Possibly the higher solar activity causes shielding preventing some cosmic rays from reaching that generate neutrons needed for radiocarbon production.



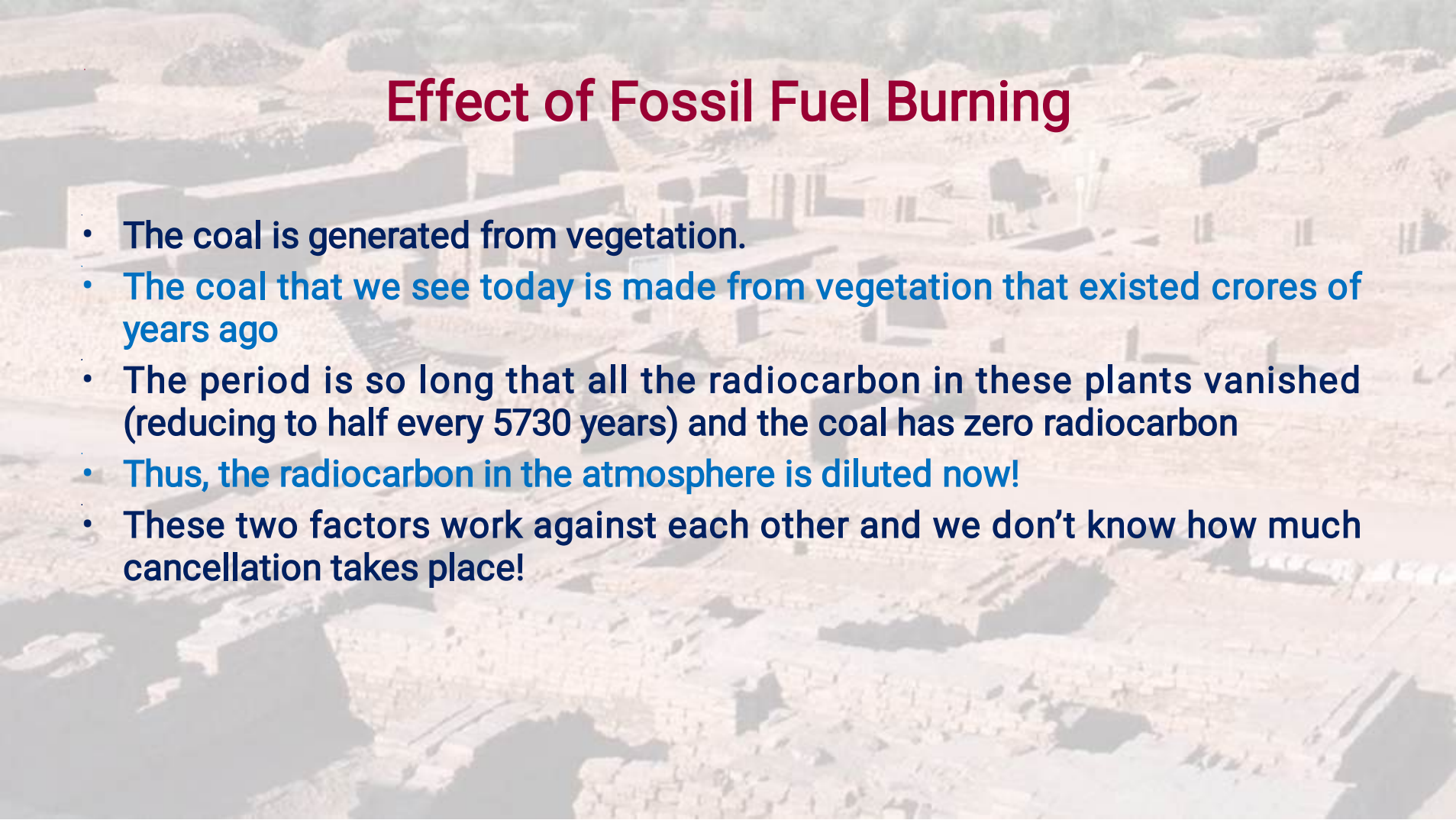
It's Obvious; Care Needed

- If we take a wrong value for initial amount of radiocarbon, the age deduced will be wrong
- If we collect a sample from a level to which it doesn't belong, the artifact will not be coeval with it
- If the item (say a *shahteer*) was reused in constructing a new house, its age will not tell us the age of house

The background of the slide is a faded, high-angle photograph of ancient stone ruins, possibly Mayan or Aztec, with various rectangular and circular structures. The title 'Possible Reasons for Errors' is centered in the upper half of the image in a bold, red, sans-serif font.

Possible Reasons for Errors

- Mixing of samples/ contamination
- Incorrect labeling
- Too little carbon
- Uncertainty in relationship between dated sample and the culture
- Transport of sample
- Too young or too old sample
- Exchange of isotopes/ circumstantial disturbances

An aerial photograph of a vast, arid desert landscape. In the foreground and middle ground, there are numerous ancient stone ruins, including walls, foundations, and some standing structures. The terrain is sandy and rocky, with sparse, low-lying vegetation. The background shows more distant ruins and a hazy horizon under a clear sky.

Effect of Fossil Fuel Burning

- The coal is generated from vegetation.
- The coal that we see today is made from vegetation that existed crores of years ago
- The period is so long that all the radiocarbon in these plants vanished (reducing to half every 5730 years) and the coal has zero radiocarbon
- Thus, the radiocarbon in the atmosphere is diluted now!
- These two factors work against each other and we don't know how much cancellation takes place!

For Sensitivity : Accelerator Mass Spectrometry

- So often we don't get enough sample and so the LSC method doesn't work.
- The question: Why can't we measure C14 with a mass spectrometer? There are problems.
- Nitrogen, which is 99.63% of the mass 14 isotope, will dominate. There may be other isobars too like $C^{13}H$, $C^{12}H_2$
- What if we use negative ion?
- But N does not form stable negative ion, and other isobars can be filtered
- So with negative ion MS, N^{14-} will not appear in the initial ion beam.

AMS Radiocarbon Dating

- AMS is a combination of Accelerator and a mass spectrometer
- This is based on negative ion mass spectrometry unlike the common positive ion mass spectrometry
- Negative ions ensure that there is no interference of negative N^{14} which are not stable! The hydrocarbons also can be removed by stripper foils
- This sample is made into a graphite pellet and put into the AMS for negative ion mass spectrometry and radiocarbon measurement

