CARBON RESERVOIRS

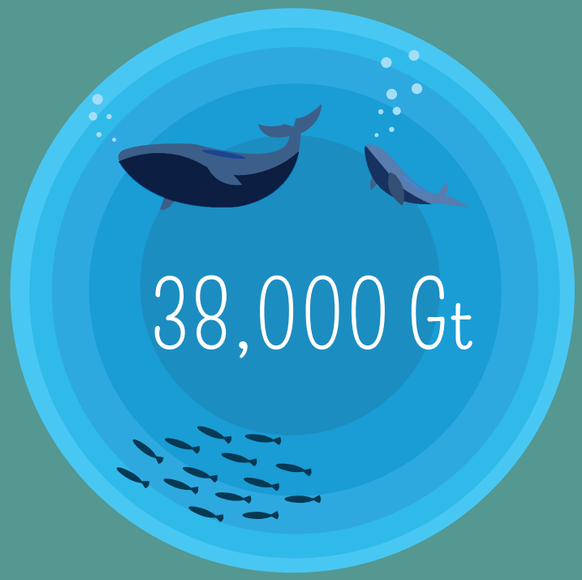
LITHOSPHERE

CRUST

UPPER MANTLE

100,000,000 Gt

OCEANS



38,000 Gt

TERRESTRIAL BIOSPHERE & SOIL

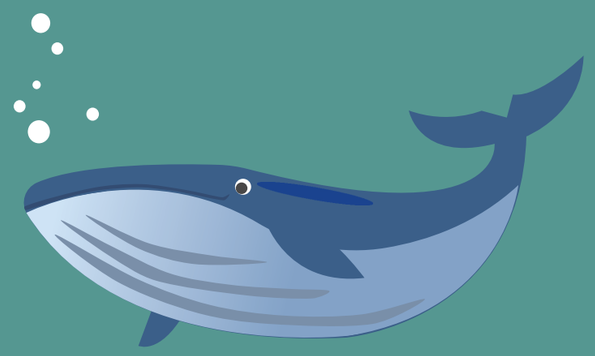
2,400 Gt

ATMOSPHERE

average increase 4 Gt year^{-1}

830 Gt

1 Gt =



X 6 MILLION

Data from: 2013: Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

CARBON IN THE OCEAN

CO_2 = CARBON DIOXIDE
H_2CO_3 = CARBONIC ACID
$CaCO_3$ = CALCIUM CARBONATE
$C_6H_{12}O_6$ = GLUCOSE
HCO_3^- = BICARBONATE ION

CO_2 IN ATMOSPHERE

CO_2 EXCHANGE

PHOTIC ZONE

~200m

PHYTOPLANKTON GROWTH

$6CO_2 + 6H_2O \rightleftharpoons C_6H_{12}O_6 + 6O_2$

CO_2 IN OCEAN

$CO_2 + H_2O \rightleftharpoons H_2CO_3$ (ACID)

$H_2CO_3 \rightleftharpoons HCO_3^- + H^+$

$H^+ + CO_3^{2-} \rightleftharpoons HCO_3^-$

ORGANISMS BUILD $CaCO_3$ SHELLS

$Ca^{2+} + 2HCO_3^- \rightleftharpoons CO_2 + H_2O + CaCO_3$

UPWELLING

DEEPWATER CIRCULATION

DECOMPOSITION

NUTRIENTS $+CO_2$

SEDIMENTATION

ORGANIC SEDIMENTS

DISSOLUTION OF CARBON IN DEEP OCEAN

CARBONATE SEDIMENTS

SEDIMENTATION

CARBON IN THE TERRESTRIAL BIOSPHERE

CO_2 IN ATMOSPHERE

ATMOSPHERE HOLDS 830 Gt CARBON
NET ANNUAL INCREASE ~4 Gt

120 Gt

9 Gt

120 Gt

BURNING FOSSIL FUELS, LARGE SCALE DEFORESTATION & CEMENT MANUFACTURE RELEASES CO_2 INTO THE ATMOSPHERE

AUTOTROPHS EXTRACT CO_2 FROM THE ATMOSPHERE DURING PHOTOSYNTHESIS & CONVERT IT INTO ORGANIC MATTER

PHOTOSYNTHESIS

$$6H_2O + 6CO_2 \rightleftharpoons C_6H_{12}O_6 + 6O_2$$

RESPIRATION

RESPIRATION BY PLANTS, ANIMALS & SOIL MICROBES USES THE ENERGY STORED IN CARBOHYDRATES & RELEASES CO_2 BACK INTO THE ATMOSPHERE

CARBON CARRIED BY RIVERS TO OCEAN

VEGETATION HOLDS 450-650 Gt CARBON

SOIL MICROBES DECOMPOSE DEAD ORGANISMS AND WASTE PRODUCTS

SOIL HOLDS 1500 - 2400 Gt ORGANIC CARBON

Data from: 2013: Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

CARBONATE COMPENSATION DEPTH

CO_2 IN THE OCEAN REACTS WITH H_2O TO FORM H_2CO_3 WHICH DISSOLVES $CaCO_3$. THE MORE CO_2 IN THE WATER, THE MORE $CaCO_3$ DISSOLVES

INCREASING CO_2 IN WATER

CO_2 HELD IN WATER INCREASES WITH DECREASING TEMPERATURE

INCREASING CO_2 IN WATER

ARCTIC

ANTARCTIC

ORGANISMS BUILD $CaCO_3$ SHELLS

ABOVE CCD $CaCO_3$ ACCUMULATES

MARINE SNOW

BELOW CCD $CaCO_3$ DISSOLVES

INCREASING SOLUBILITY OF $CaCO_3$

INCREASING CO_2 IN WATER

CARBONATE COMPENSATION DEPTH (CCD)

~4500m

$CaCO_3$ SOLUBILITY INCREASES WITH DEPTH DUE TO INCREASING PRESSURE & DECREASING TEMPERATURE. DECOMPOSITION OF SINKING ORGANIC MATTER CAUSES CO_2 CONCENTRATION TO INCREASE WITH DEPTH.

CO_2 = CARBON DIOXIDE
H_2CO_3 = CARBONIC ACID
$CaCO_3$ = CALCIUM CARBONATE

REALLY OLD!

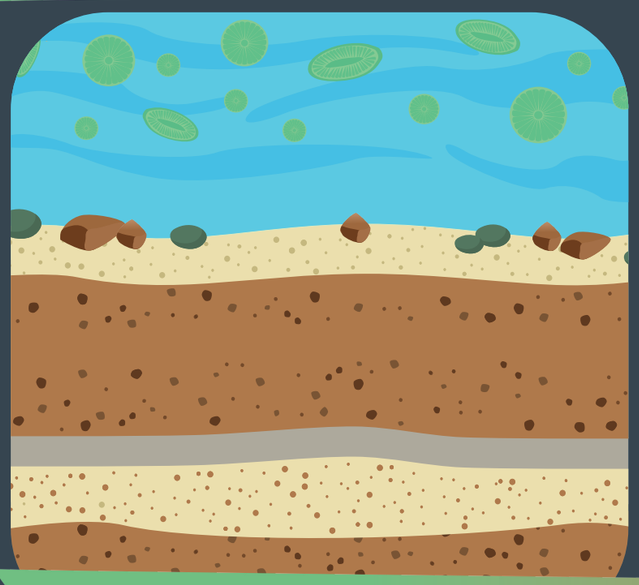
OLD

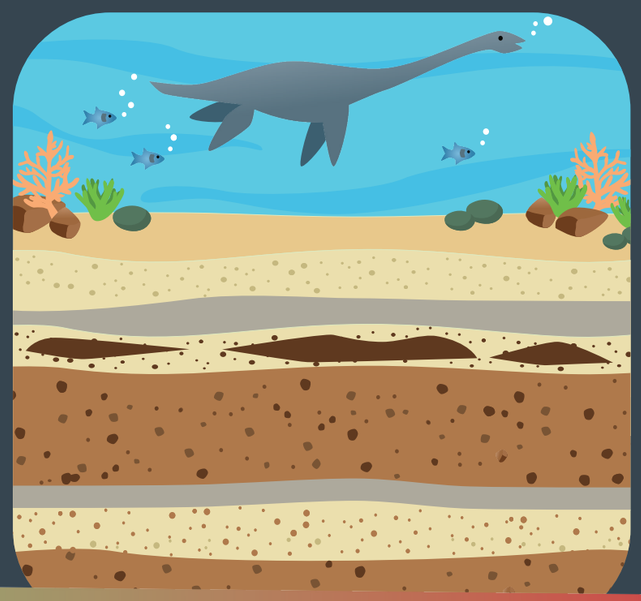
PRESENT DAY

DECAYING VEGETATION FORMS PEAT

LIGNITE

COAL





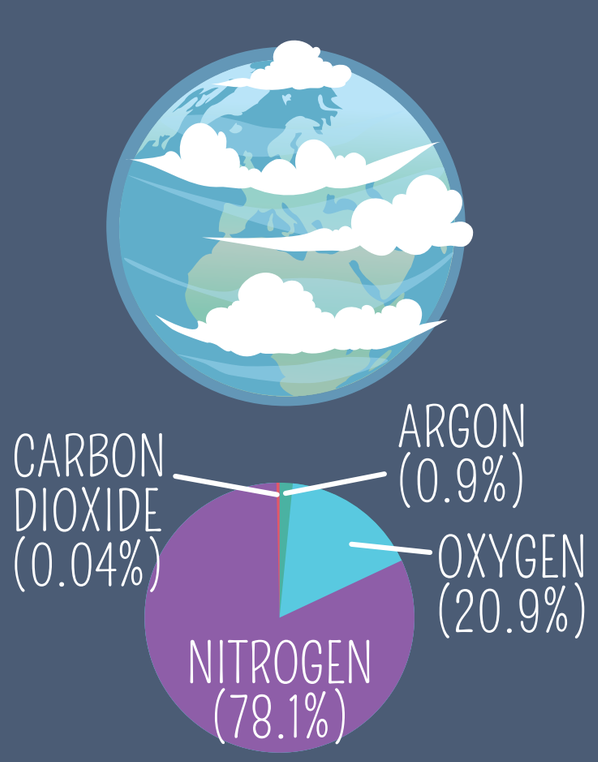
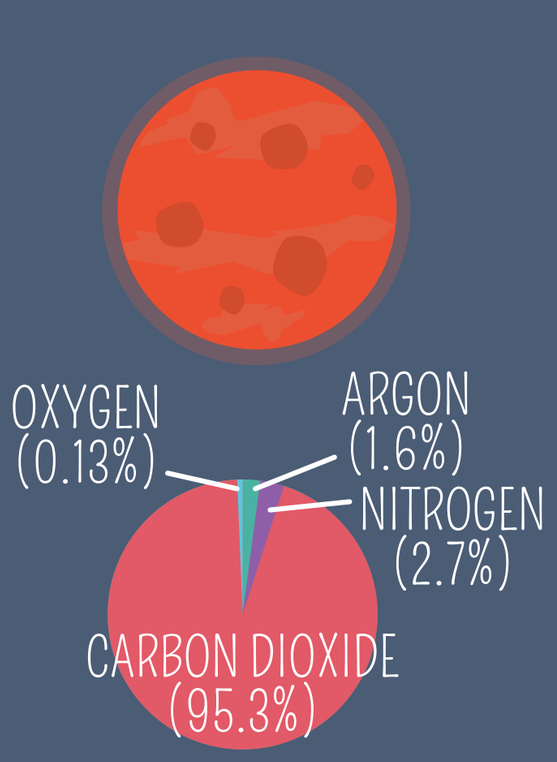
ORGANIC MATTER FORMS ORGANIC RICH SEDIMENTS

KEROGENS

OIL & GAS

HYDROCARBON FORMATION

CARBON IN PLANETARY ATMOSPHERES

PLANET	VENUS	EARTH	MARS
ATMOSPHERIC COMPOSITION	 TRACE AMOUNTS OF: Ar, He, CO, H_2O, HCl, HF	 TRACE AMOUNTS OF: Ne, He, CH_4	 TRACE AMOUNTS OF: CO
SURFACE TEMPERATURE & PRESSURE	92.1 atm 462°C	1 atm 14°C	0.006 atm -63°C

WHY IS VENUS SO HOT?

EARTH AND VENUS ARE SIMILAR SIZED PLANETS AND WHILST VENUS IS CLOSER TO THE SUN, ITS THICK CLOUD COVER REFLECTS MOST OF THE SUNLIGHT THAT HITS IT. VENUS'S ATMOSPHERE HOWEVER IS 96.5% CARBON DIOXIDE (CO_2) AND IT IS MUCH DENSER THAN EARTH'S. THIS AMOUNT OF CO_2 CREATES A STRONG GREENHOUSE EFFECT, RAISING VENUS'S SURFACE TEMPERATURE TO AROUND 462 °C, HOTTER THAN ANY OTHER PLANET IN THE SOLAR SYSTEM.

CARBON & THE GREENHOUSE EFFECT

SOLAR RADIATION (LIGHT) 340 Wm^{-2}

SOLAR RADIATION REFLECTED BY ATMOSPHERE, CLOUDS & SURFACE 100 Wm^{-2}

SOLAR RADIATION ABSORBED BY ATMOSPHERE

SOLAR RADIATION ABSORBED BY LAND & OCEAN*

TOTAL INFRARED RADIATION EMITTED TO SPACE 240 Wm^{-2}

CLOUDS EMIT INFRARED RADIATION

GHGs IN ATMOSPHERE ABSORB & RE-EMIT INFRARED RADIATION

EARTH EMITS INFRARED RADIATION (HEAT)*

INFRARED RADIATION EMITTED BACK DOWN TO SURFACE

INCREASED GHGs CAUSED BY HUMAN ACTIVITIES TRAP MORE INFRARED RADIATION & WARM THE PLANET

EARTH AVERAGE SURFACE TEMPERATURE

15°C WITH GHGs

-18°C WITHOUT GHGs

GREENHOUSE GASES (GHGs)

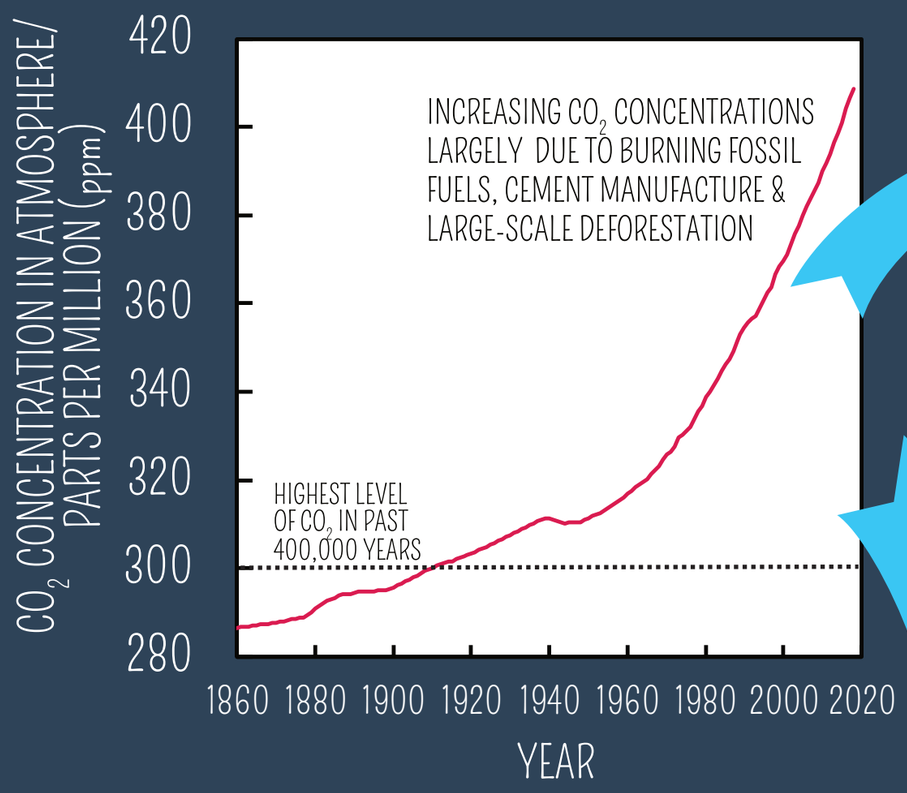
CO_2 CH_4 NO_2 H_2O

* The Earth intercepts solar radiation as a 2D disc but radiates infrared radiation in all directions as a 3D sphere

Data: NASA Earth Observatory

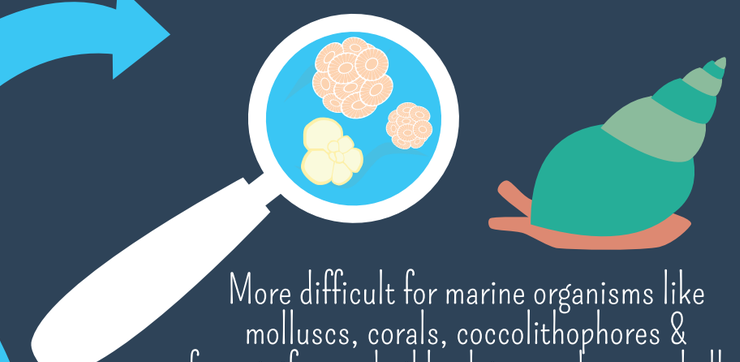
CARBON & CLIMATE CHANGE

INCREASING CO_2 CONCENTRATION IN THE ATMOSPHERE ENHANCES THE GREENHOUSE EFFECT AND HAS A POSITIVE FEEDBACK ON GLOBAL WARMING. THIS HAS SEVERAL SIGNIFICANT AND POTENTIALLY IRREVERSIBLE KNOCK-ON EFFECTS...



OCEAN pH

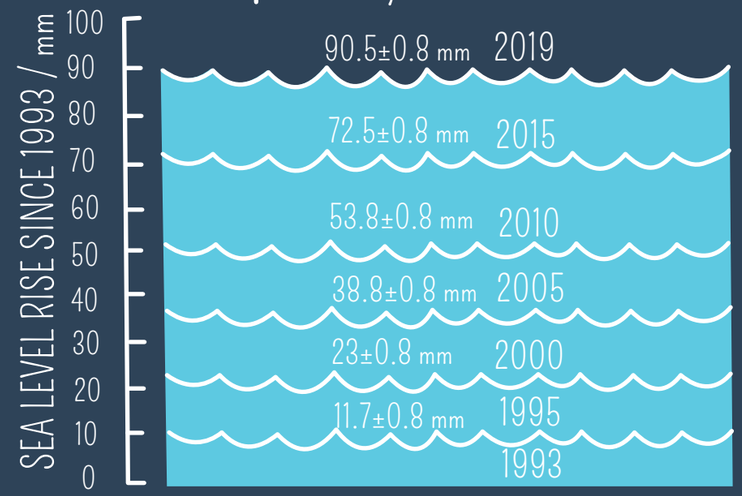
↓0.1 pH in surface water (since 1860)
equivalent to 26% increase in concentration of H^+ ions

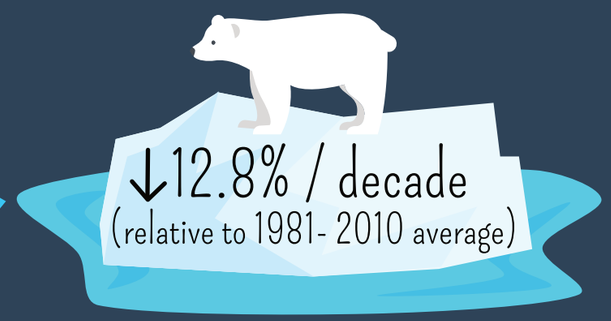


More difficult for marine organisms like molluscs, corals, coccolithophores & foraminifera to build calcium carbonate shells.

GLOBAL SEA LEVEL

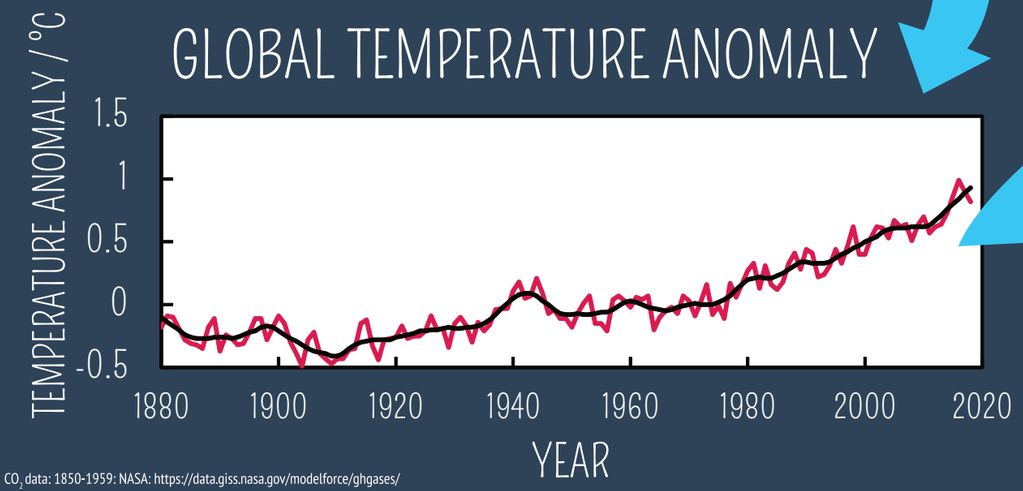
↑3 mm/year (since 1993)



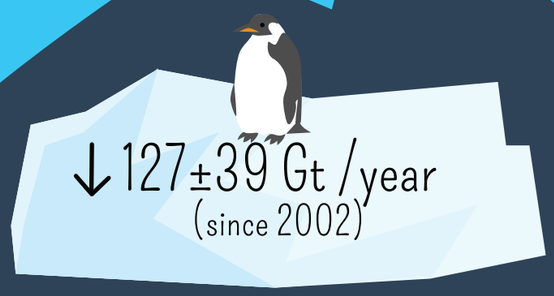


↓12.8% / decade
(relative to 1981- 2010 average)

ARCTIC SEA ICE



GLOBAL TEMPERATURE ANOMALY



↓127±39 Gt /year
(since 2002)

ANTARCTIC ICE MASS

↓286±21 Gt /year
(since 2002)

GREENLAND ICE MASS

CO_2 data: 1850-1959: NASA: https://data.giss.nasa.gov/modelforce/ghgases/

CO_2 data: 1959-2018: National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division.Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/).

Global Temperature Anomaly data: Land-Ocean Temperature Index NASA's Goddard Institute for Space Studies (GISS).

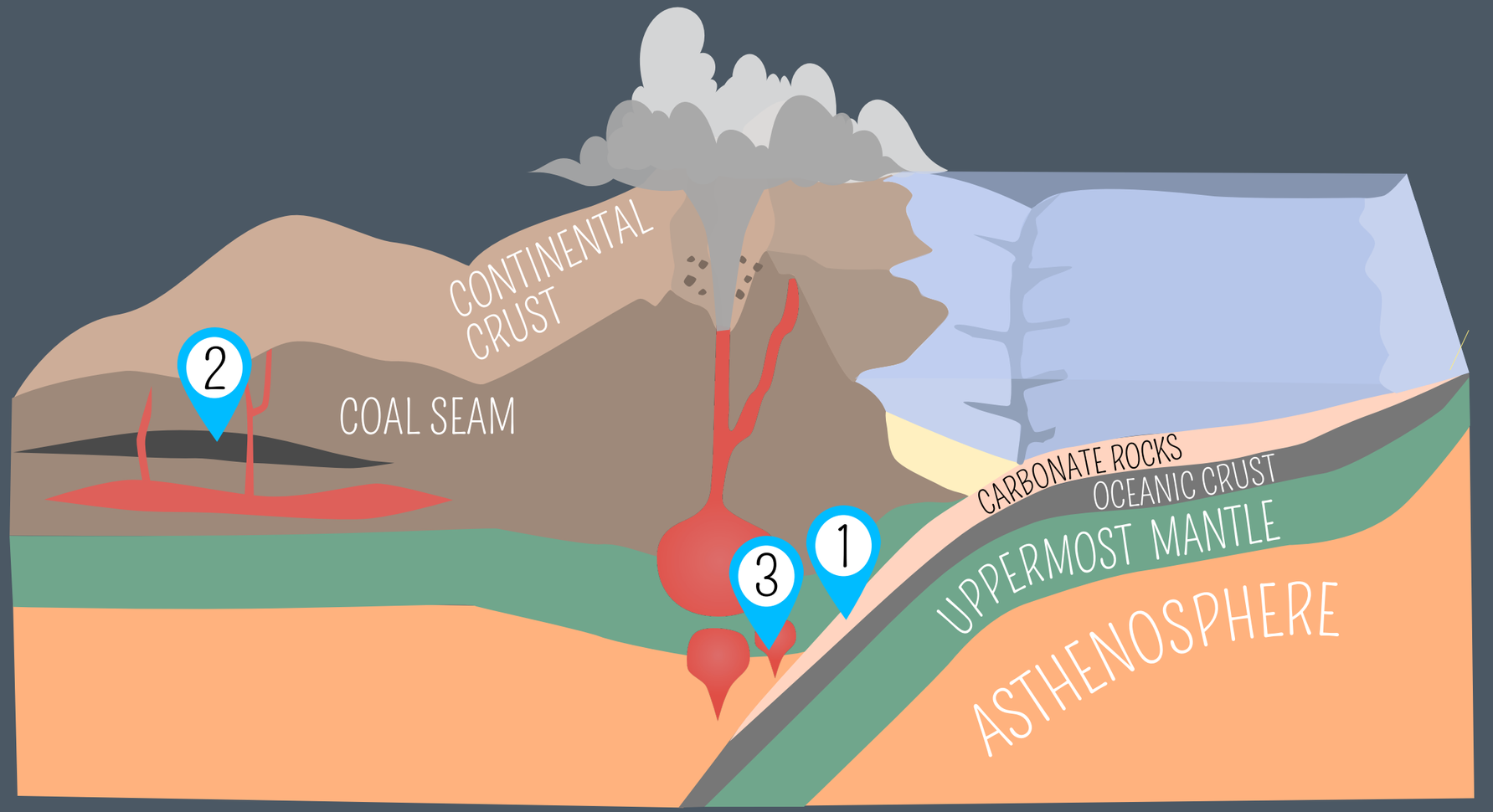
Greenland& Antarctica Ice mass data: Wiese, D. N., D-N. Yuan, C. Boening, F. W. Landerer, and M. M. Watkins (2016) JPL GRACE Mascon Ocean, Ice, and Hydrology Equivalent HDR Water Height RL05M.1 CRI Filtered Version 2., Ver. 2., PO.DAAC, CA, USA. Dataset accessed [2019-04-07] at http://dx.doi.org/10.5067/TEMSC-2LCR5.

Global sea level data: GSFC. 2017. Global Mean Sea Level Trend from Integrated Multi-Mission Ocean Altimeters TOPEX/Poseidon, Jason-1, OSTM/Jason-2 Version 4.2 Ver. 4.2 PO.DAAC, CA, USA. Dataset accessed [2019-04-07] at http://dx.doi.org/10.5067/GMSLM-TJ42.

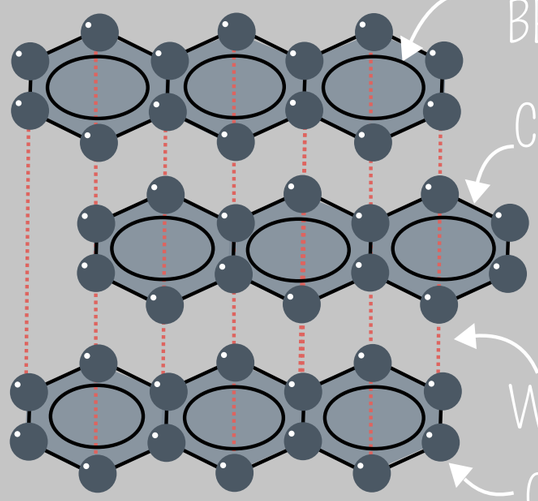
Ocean Acidification data: Pörtner, H.-O., D.M. Karl, P.W. Boyd, W.W.L. Cheung, S.E. Lluch-Cota, Y. Nojiri, D.N. Schmidt, and P.O. Zavialov, 2014: Ocean systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.

GRAPHITE
FORMATION

1. SUBDUCTION & REGIONAL METAMORPHISM OF CARBON-RICH SEDIMENTARY ROCKS
2. CONTACT METAMORPHISM WITH COAL SEAM
3. IGNEOUS ROCKS ASSOCIATED WITH METAMORPHOSED GRAPHITE-BEARING SEDIMENTARY ROCKS



STRUCTURE



PROPERTIES

- HIGH MELTING POINT
- CONDUCTOR OF HEAT & ELECTRICITY
- LUBRICANT
- OPAQUE
- SOFT

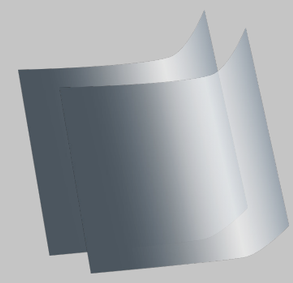
USES

PENCILS

LUBRICANT

ANODE IN LITHIUM ION BATTERIES

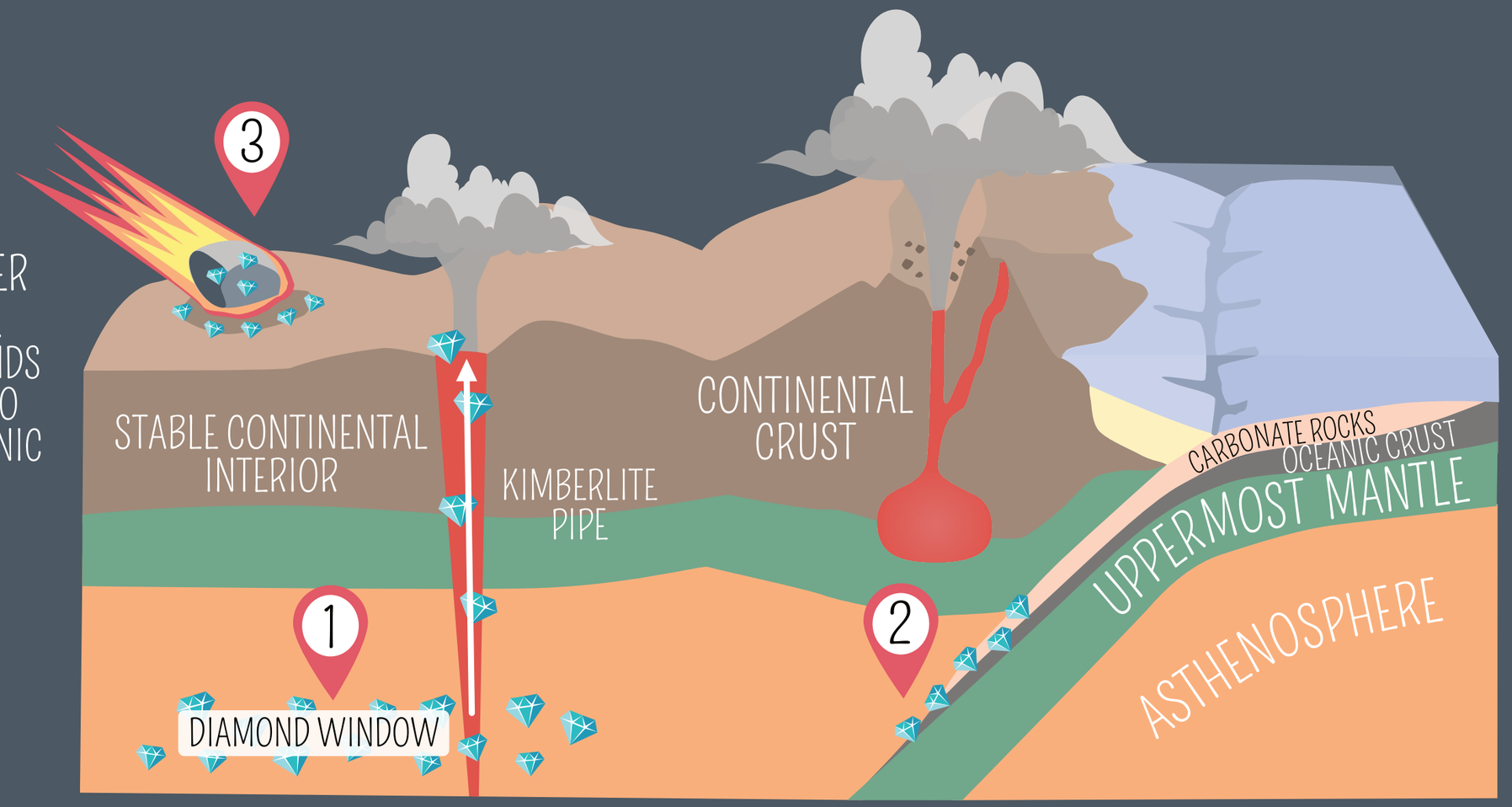
REFRACTORY APPLICATIONS e.g. CRUCIBLE



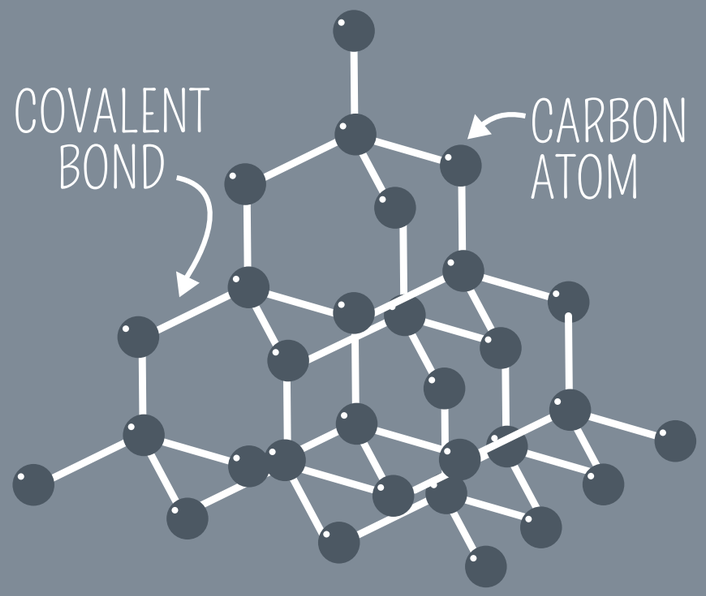
GRAPHENE SHEETS

DIAMOND
FORMATION

1. DIAMOND WINDOW - ZONE UNDER STABLE CONTINENTAL INTERIORS. MAJORITY OF MACROSCOPIC DIAMONDS FORM HERE & CAN BE TRANSPORTED TO THE SURFACE IN DEEP SOURCE VOLCANIC ERUPTIONS
2. ULTRA HIGH PRESSURE METAMORPHISM OF CARBONATE SEDIMENTS
3. METEORITE IMPACT (NANO DIAMONDS)



STRUCTURE



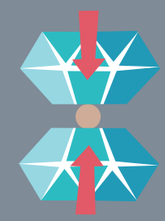
PROPERTIES

- HIGH MELTING POINT
- HIGHEST THERMAL CONDUCTIVITY OF ANY NATURAL MATERIAL
- TRANSPARENT
- HARDEST NATURAL MATERIAL

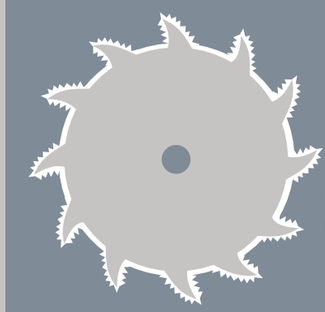
USES*

DIAMOND WINDOWS IN LASERS & X-RAYS

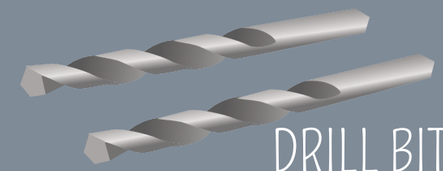
JEWELLERY



ANVILS IN HIGH PRESSURE EXPERIMENTS



SAWS



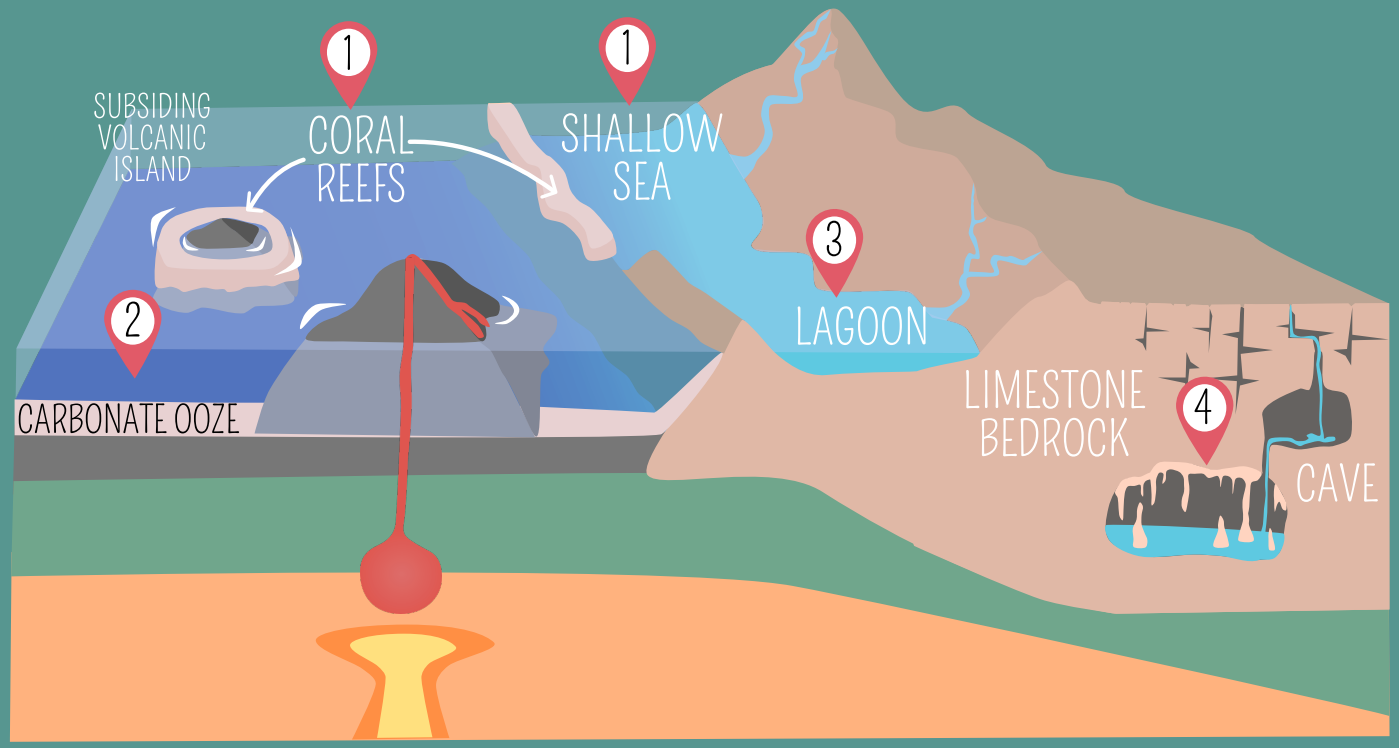
DRILL BITS

*high tech applications of diamond use synthetic rather than natural diamond

LIMESTONE

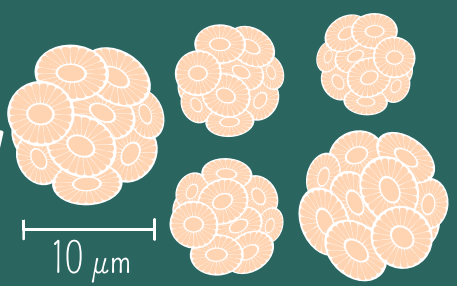
FORMATION

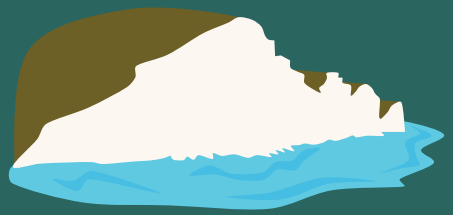
1. ACCUMULATION OF $CaCO_3$ FROM ALGAE, CORAL, SHELLS & FAECAL MATTER IN WARM SHALLOW SEAS
2. ACCUMULATION OF $CaCO_3$ IN DEEPER WATER (<4500m) FROM CALCIFYING PLANKTON
3. PRECIPITATION OF $CaCO_3$ IN SATURATED WATERS E.G. IN LAGOONS & HOT SPRINGS
4. EVAPORATION OF WATER LEAVES BEHIND $CaCO_3$ DEPOSITS



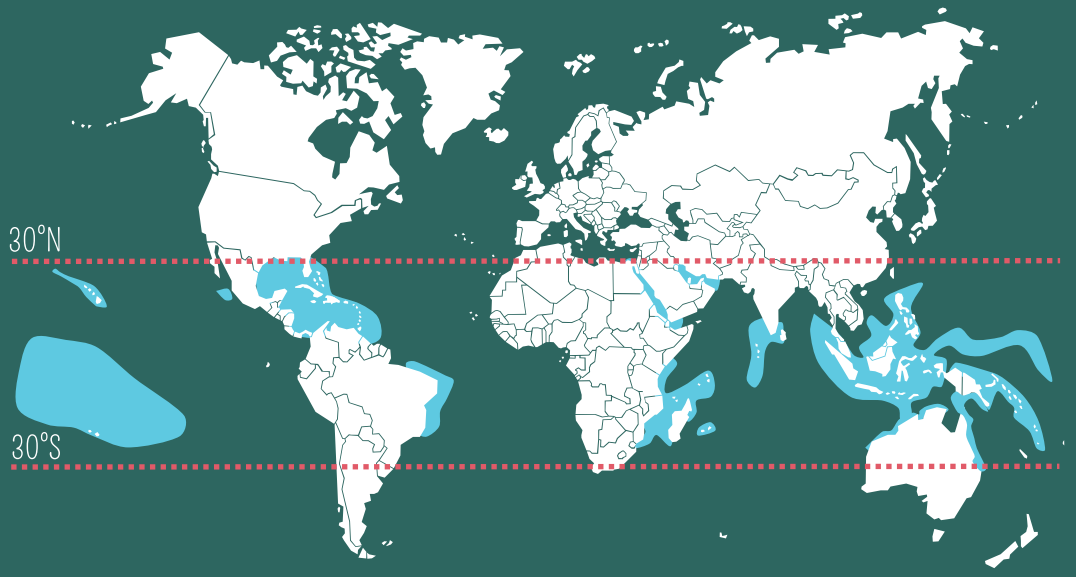
CHALK

- LIMESTONE FORMED PREDOMINANTLY FROM NANOPLANKTON CALLED COCCOLITHOPHORES
- CHALK DEPOSITED IN THE LATE CRETACEOUS PERIOD ~89-85 Ma FORMS THE FAMOUS WHITE CLIFFS OF DOVER & THE NEEDLES ON THE ISLE OF WIGHT
- THE UK CHALK ACTS AS AN AQUIFER - A PERMEABLE ROCK THAT HOLDS GROUND WATER





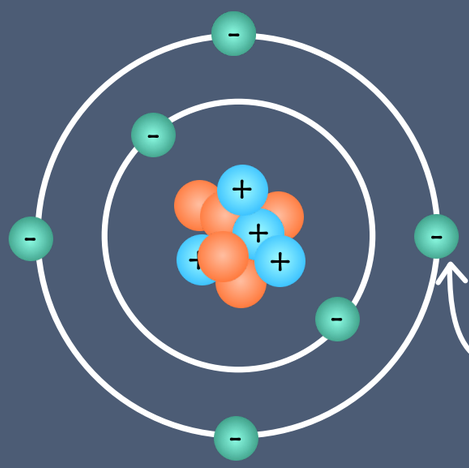
MODERN MARINE LIMESTONE FORMING ENVIRONMENTS



CARBON

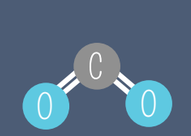
C_6

ATOMIC NUMBER 6

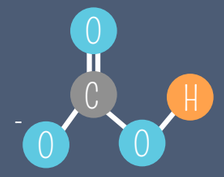


- 6 ELECTRONS
- 6 PROTONS
- 6 NEUTRONS

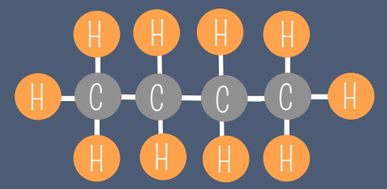
4 VALENCE ELECTRONS ABLE TO FORM COVALENT BONDS WITH OTHER ATOMS



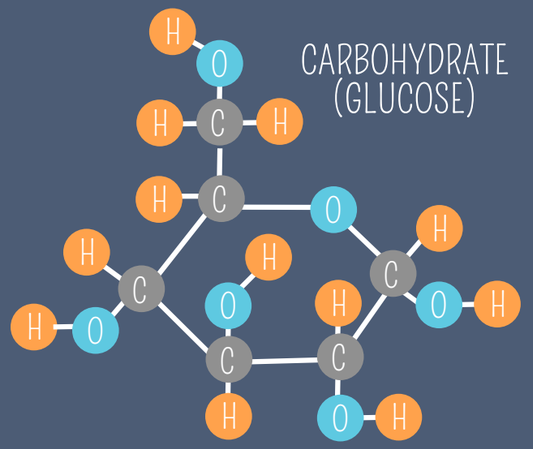
CARBON DIOXIDE



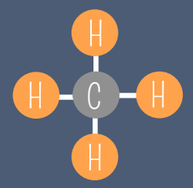
BICARBONATE



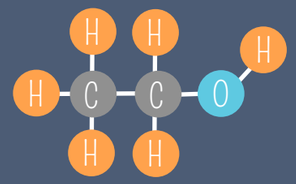
BUTANE



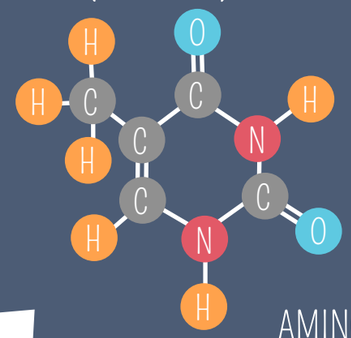
CARBOHYDRATE (GLUCOSE)



METHANE

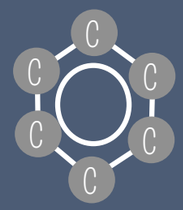


ETHANOL

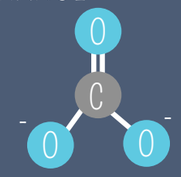


NUCLEOBASES (THYMINE)

→ DNA



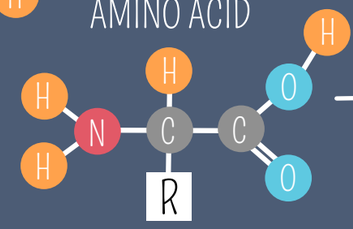
BENZENE RING



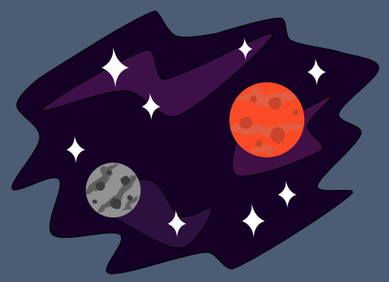
CARBONATE

CARBON CAN FORM OVER 10 MILLION COMPOUNDS

AMINO ACID



→ PROTEINS

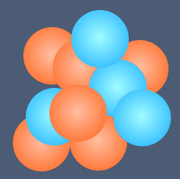
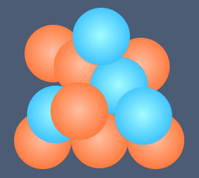


4th MOST ABUNDANT ELEMENT IN THE UNIVERSE

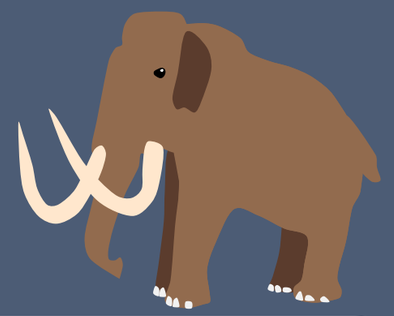
15th MOST ABUNDANT ELEMENT ON EARTH

NATURAL ALLOTROPES (PHYSICAL FORMS): GRAPHITE, DIAMOND & AMORPHOUS CARBON

ISOTOPES

C^{12}	C^{13}	C^{14}
98.9%	1.1%	TRACE
		
STABLE	STABLE	RADIOACTIVE HALF LIFE 5730 YEARS

RADIOCARBON DATING



LIVING ORGANISMS EXCHANGE CARBON WITH THE ATMOSPHERE/OCEAN AND INCORPORATE IT INTO THEIR TISSUES. DURING LIFE, ORGANISMS HAVE THE SAME PROPORTION OF C^{14} AS THE ATMOSPHERE (1 ppt). WHEN ORGANISMS DIE THEY NO LONGER EXCHANGE CARBON SO THE RADIOACTIVE C^{14} IN THEIR TISSUES STARTS TO DECAY. WITH TIME, THE RATIO OF C^{12}:C^{14} DECREASES AT A KNOWN RATE. THIS CAN BE USED TO DETERMINE HOW LONG AN ORGANISM HAS BEEN DEAD FOR, RELIABLY UP TO ~50,000 YEARS.