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CHEMICAL EVOLUTION

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Melvin Calvin

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ABSTRACT

How did life come to be on the surface of this earth? Darwin himself recognized that his basic idea of evolution by variation and natural selection must be a continuous process extending backward in time through that period in which the first living things arose and into the period of 'chemical evolution' which preceded it. We are approaching the examination of these events by two routes.

One is to seek for evidence in the ancient rocks of the earth which were laid down prior to that time in which animals capable of leaving their skeletons in the rocks to be fossilized were in existence. This period is something prior to approximately 600 million years ago, the earth having been formed approximately 4·7 billion years ago. We have found certain organic molecules in rocks whose age is about one billion years which are closely related to the green pigment of plants, chlorophyll. This seems to establish that green plants were already flourishing prior to that time. We are now examining rocks of still greater age, namely, 2·5 billion years, to determine whether they contain any molecules which could be attributed to the presence of a living organism.

The second approach is to attempt to reproduce in the laboratory chemical processes induced by radiations of various kinds—from the sun, from radioactivity, from electrical storm, etc., which could give rise to molecules and combinations of them, ultimately leading to systems which could be called alive. This has also succeeded along many lines, and many of the present-day biologically important molecules have been constructed in this way, providing laboratory evidence for the hypothetical processes.

Finally we must seek evidence for the same processes in material found elsewhere than on the earth, such as other parts of our solar system, e.g. the moon and Mars. We can expect to know whether such materials exist at all in the rocks of the moon within this decade. We may even know something more definite about the botany of Mars in this same period.

INTRODUCTION

Darwin himself most succinctly stated the case for the continuity of evolution in his most important paper with Wallace: 'On the Tendency of Varieties to Depart Indefinitely from Original Types'.[1] That title contains within it the implication that on backward extrapolation one must arrive at a point at which there was only one variety which could be called alive. This variety, in turn, was only one of several different kinds of organization of matter which took over, so to speak, the organic world of its day. Darwin recognized this continuum back through organic evolution into the time of prebiotic evolution, and he expressed it in a letter written in 1874 in which he said that almost certainly the first living aggregation occurred in a soup of proteinaceous material, but that he himself was not ready to undertake a discussion of that period and deliberately limited himself to organic evolution.[2]

> 'You expressed quite correctly my views where you said that I had intentionally left the question of the Origin of Life uncanvassed as being altogether *ultra vires* in the present state of our knowledge, and that I dealt only with the manner of succession. I have met with no evidence that seems in the least trustworthy, in favour of so-called Spontaneous Generation. I believe that I have somewhere said (but cannot find the passage) that the principle of continuity renders it probable that the principle of life will hereafter be shown to be a part, or consequence, of some general law. . . .'

> It is often said that all the conditions for the first production of a living organism are now present, which could ever have been present. But if (and oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric acid salts, light, heat, electricity, etc. present, that a proteine compound was chemically formed ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which would not have been the case before living creatures were formed.'

Darwin did not deny the continuity of chemical evolution, that is, prebiotic change, into organic evolution, but he was right in denying himself the privilege of speculation at that time because chemical, physical and geological science had not yet developed to a stage where he could fruitfully discuss this question. It is only in the last two or three decades that chemical (biochemical) science has reached a level of sophistication which permits us to undertake both experiment and theory in this direction.[3]

The first requisite for such experiments and speculations is to have some knowledge of the molecular processes which we are trying to understand. Today a good deal is known about the molecular constitution of living things and the dynamics of the interaction of those molecules which give rise to the 'life' of living organisms. Figure 1 shows the most abundant atoms of the solar system

FIG. 1. Schematic representation, in chemical terms, of the set of formations which have to be accomplished from the atoms to produce the structure of the cell.

and the universe, and maps some of the stages through which these atoms must pass, in terms of organization, to arrive at the kinds of molecules which would be required for living things. The most plentiful atoms in the universe are, of course, hydrogen, and following that carbon, oxygen and nitrogen. So it is not surprising that living things are made of these very same atoms. From these atoms we must pass to the simple molecules whch constitute the substrates of living things, i.e. amino acids, sugars, bases, fatty acids, hydroxy acids, and from these to the next level of complexity, the biopolymers, particularly protein and nucleic acid, which are made from these simple constituents. Any process of chemical evolution which we might hypothesize must carry us forward through these structural changes from the simple combinations of atoms to the more complex groups to the large molecules which are required for the functioning of living organisms.

We will speak of living organisms in terms of two functions, namely, the ability to transfer and transform energy in a directed way and the ability, once having learned this process, to remember it and transfer it from one generation to the next. These two properties are primarily contained in the two biopolymers —the protein for the energy conversion process and the nucleic acid for the information transfer process. I have deliberately avoided a definition of 'life'. There are some who will accept a self-replicating molecule as a living organism and there are others who will require a cell with a nucleus. It depends upon the orientation from which the problem is approached.

TERRESTRIAL CHEMICAL EVOLUTION

With the knowledge of today's molecular processes as our base, what approaches do we have to discovering what the series of chemical transformations were (or might have been) which gave rise to this sequence? There are two quite different approaches which can be used, one of which is the classic approach of looking for the record in the rocks. This, of course, carries us back some 500-600 million years. But the record in recognizable morphological residues of living forms gives out approximately 600 million years ago, and we have to turn to other types of evidence.

The time available in which to achieve the entire sequence is best defined in terms of the history of the earth, summarized in Figure 2. We have roughly

FIG. 2. Time scale for total evolution.

4·7 billion years to achieve these transformations, according to the reckoning of geologists. The period of chemical evolution presumably begins at the time the earth took its present form, and I have placed its beginning at about 3·9-4 billion years ago, a purely arbitrary choice. The question of when organic evolution begins is one of the prime questions with which I am sure we will be concerned; when and in what manner. Quite arbitrarily organic evolution was placed on the figure as beginning 2·5 billion years ago, and when we finish with the first part of this discussion, you will see that this was quite a fortuitous accident. As organic evolution took over the organic chemical world, the process of nonbiotic (chemical) change gradually ceased. The pool of organic chemicals upon which the processes of chemical evolution could operate was diminished by organic evolution to insignificance. We are, at the moment, trying to define the starting point of organic evolution. We will then go back from there and start at the other end of the sequence and use what chemicals the astronomers and geologists say were present on the primeval earth together with the energy sources which were available at that time. We will then see how far we can carry forward the changes which might be induced in that prebiotic system until we meet the point at which we have come by backward search from the present time.

Let us now have a look at the historical record. Figure 3 shows an expansion

FIG. 3. Expansion of the time scale, showing the fossil record.

of the time scale, showing the period in which the fossil record exists from the Cambrian period on. In the Precambrian period there are a number of fossil types which have been recognized, particularly the algal stromatolites, but the nature of these is still unknown. Since the morphologically recognizable fossil record gives about 600 million years ago, we must seek a molecular record, and in this search we have about 4·2 billion years in which the beginnings of organic evolution may be localized.

Organic Geochemistry

It was at this point that we began to seek experimental evidence in the rocks. This search has only been possible in the last dozen years because the technical methods of analysis required to find and identify the organic molecules that might be present in the ancient rocks have been developed only recently. The methods which we use are highly developed chromatographic techniques in which we can separate a few micrograms of material and identify the molecules specifically. By this I mean specific molecular structure, specific architectural arrangements of the atoms which can be indicated by chromatographic methods and then further specified by mass spectrometry, infrared spectrometry and similar methods.

In order to check out the methods, we undertook to examine hydrocarbons as a means of identifying biological materials, as distinct from non-biological materials. We tested our methods with a relatively young rock, 50 million years old ~~Wyoming~~ Green River shale. The layering of this material appears very nicely, and eventually we will get to the point where we will examine each of the layers separately. Until now we have taken only the entire section as one piece. We can extract the hydrocarbons from the crust rock without heat or chemical treatment, so that we know we are dealing with the materials as they are in the rock. We then perform an analysis on them. We first separate the nonhydrocarbons from the hydrocarbons and then the hydrocarbons are separated by a

treatment which separates the branched chains from the straight chains. The hydrocarbon molecules thus separated are made up of only carbon and hydrogen and we can now separate the straight chains (with no branches) from all molecules which have even one branch on them. This is done with a molecular sieve, a small bead with the hole of a correct size to let in a single chain of carbon-hydrogen atoms. If there is even one branch on the chain, it cannot get through the hole in the sieve bead, but if there are no branches, the chain can wiggle its way through the hole, get inside the bead, and then it cannot be washed out. In this way we can separate the straight chain hydrocarbons from any others, and we have done this on microgram amounts.

Figure 4 shows the result of such an analysis. The top curve is a record of the

Green River

FIG. 4. Alkanes from ~~Colorado Oil~~ Shale (Miocene). Each peak represents a different hydrocarbon, the heights of the peaks indicating relative quantities. The horizontal scale gives the temperature of extraction from 100° to 300°C at an increase of 6°/min. *A*, total alkanes; *B*, branched, etc.; *C*, normals. Column size: 5 ft. × ⅛ in.; column packing: 3% SE—30.

effluent gas of all the hydrocarbons as it comes through the gas chromatograph; the middle curve is of the branched chain hydrocarbons; the bottom curve is the straight chain hydrocarbons. In the 50-million-year-old rock the straight chain hydrocarbons show the alteration pattern very characteristic of modern hydrocarbons. Fresh leaf wax, in fact, shows the same kind of character, and the dominance of C_{17}, C_{29} and C_{31} is characteristic of modern leaf waxes. The Green River ~~Wyoming~~ shale is a relatively young oil, 50 million years old, and this is the characteristic pattern, then, of a fresh hydrocarbon. The odd numbers dominate the even ones because the even carboxylic acids are dominant over the odd acids in the living plant. They are decarboxylated and reduced in the rock, giving the odd hydrocarbons. In the branched chains of the ~~Wyoming~~ Green River shale there are two peaks which are dominant. We have identified these as phytane and pristane, and in a moment I will discuss the relationship of these to the plant and animal world.

I would like to show now the same kind of analysis, carried out on a rock one billion years old, that is, the Nonesuch shale of the White Pine Mine in Michigan. The shale itself, with the carbonaceous marker bed upon which it lies, is relatively rich in oil, the oil actually oozing out from the junction. We have analysed both the free flowing oil and the material which can be extracted from the rock after it is ground up. The analysis is the same for both, which suggests that the oil is material laid down with the rock. Figure 5 shows the gas chromatographic

FIG. 5. Alkanes from Nonesuch Shale Oil (Precambrian). Each peak represents a different hydrocarbon, the heights of the peaks indicating relative quantities. The horizontal axis is increasing extraction temperature. *A*, total alkanes, 100-282°C at 6°/min.; *B*, branched, cyclic, etc., 100-300°C at °/min.; C, normals, 100-305°C at 8°/min. Column size: 5 ft. × ⅛ in.; column packing: 3% SE—30.

analysis of the one-billion-year-old material. Above is the total hydrocarbon; in the centre is the branched chain and cyclic fraction; and on the bottom the straight chain fraction. One can see that the odd dominant pattern of the fresh hydrocarbon is no longer the principal characteristic of the pattern. It now begins to look almost as though there were a thermodynamic distribution around C_{17}, but it isn't quite. You can still see that the C_{17} peak is a little too high and is not yet completely randomized. Whether this distribution recurred by virtue of the fresh oil being changed or by virtue of mixing a nonbiogenic oil with a biogenic one is still something which can be argued. However, in the branched chains these two dominant peaks occur again, and these have been unequivocally identified as phytane and pristane, thus placing them, or their precursors in the milieu, even one billion years ago.[4]

What are phytane and pristane, and what is their relationship to the biological world? This is shown in Figure 6. Phytol is a branched chain alochol, and one

FIG. 6. A possible source of pristane and phytane.

of the carboxyl groups of chlorophyll is esterified with this phytol alochol. The phytane arises by way of a reduction and dehydration of phytol, and it has the same number of carbon atoms as phytol. Pristane is derived from phytol by a hydrogenation of the double bond and oxidation of the alcohol followed by decarboxylation, giving the pristane which has one carbon atom less. There is little doubt but what these two molecules are related to phytol which, in turn, is very characteristic of the presence of chlorophyll. Although these hydrocarbons (phytane and pristane) are present in certain animal sources, such as wool wax, it appears unlikely that wool wax is the source of the oil. It is more likely that the chlorophyll is the source of the oil, and this would constitute pretty clear evidence that chlorophyllous photosynthesis was in existence at least one billion years ago.[5]

We have in our hands a still older rock, dated at 2·5 billion years from the Soudan iron formation of Minnesota. ~~The figure shows the bed itself and also a graphitic lens taken out of it.~~ As yet we have not had an opportunity to analyse this rock. delete this sentence

Recently Dr. Hoering described his results on an African rock dated at 2·7 billion years in which he measured the C^{13}/C^{12} ratio and found the ratio of C^{13} in the reduced carbon of that rock to be low[6] by a value which is presumed characteristic of the reduction of carbon on photosynthesis, but there are also other possible chemical processes which could do this. Nevertheless, if he is right and if the reduced carbon which is present in this African rock of 2·7 billion years is indeed due to photosynthesis, as indicated by the C^{13} defect, then we have a very short time indeed for chemical evolution. It would mean that the photosynthetic organism, with all of its complexities—all of its complex system of carbon reduction and light energy conversion—was in existence at least 2·7 billion years ago. That leaves us only two billion years to get to that point, the earth having been formed 4·7 billion years ago. Time is getting short, as you can see. The whole process of chemical evolution, then, leading all the way to the complexities of photosynthesis, would have to have taken place in two billion years from the beginning of the earth in its present form to 2·7 billion years ago, if Hoering's interpretation is correct.

Prebiotic Chemistry

We can now approach the problem of chemical evolution from the other end, namely, starting at 4·7 billion years, what kind of chemical processes could induce the transformation of the primeval organic environment of the earth into biologically important material, material which could give rise to the living organism. This is subject to some experimental tests. We accept the geologists' and astronomers' statements that the primeval atmosphere of the earth was a reducing one, and, secondly, that most of the atoms in the atmosphere of the earth were bound to hydrogen. Figure 7 shows the primeval and primitive

FIG. 7. Primeval and primitive organic molecules.

organic molecules: the oxygen bonded to hydrogen, the carbon bonded to hydrogen, the hydrogen bonded to hydrogen and the nitrogen bonded to hydrogen. When these molecules are subjected to the various forms of energy which bombarded the earth, from the sun (solar ultraviolet, as well as more ionizing radiation), terrestial radioactivity, electrical storms in the atmosphere, etc., they are torn apart, the bonds are broken, a recombination occurs and metastable molecules are formed.

When this type of experiment is performed in the laboratory, as we did in 1950, in the absence of ammonia, one gets formic acid, acetic acid, glycolaldehyde, formaldehyde, succinic acid—all of these non-nitrogenous compounds.[7] When ammonia was added to the reaction mixture, which was first done by Stanley Miller, amino acids were obtained, first glycine, then HCN, alanine, aspartic acid.[8] Many others have done this same type of experiment, and all of the molecules which you will recognize as the common metabolites of today's living organisms have been created from prebiotic starting materials. Not only that, they represent the substrates for the construction of the biopolymers as well. To this list we should now add all of the heterocyclic bases which are required for the formation of nucleic acids. Both ribose and desoxyribose are formed in the same types of processes.[9] We now have all of the simple substrate molecules for the metabolic action of living things as we know them today. Beyond that, they also constitute the starting materials for the formation of the biopolymers which we know are required for the activities of today's living organism.

Polymerization

In the course of this nonbiogenic formation of these biologically important structures we have not yet constructed the polymers—protein, nucleic acid, carbohydrate. These polymers are all made in the same kind of reaction, shown in Figure 8, which is a characteristic dehydration reaction. The proteins are

FIG. 8. Dehydration reactions leading to biopolymers.

formed by dehydration of a pair of amino acids (carboxy group and amino group); the polysaccharides by dehydration of the monosaccharides; and the nucleic acids by three kinds of dehydrations, one forming the nucleoside, the second forming the nucleotide, the third forming the phosphate ester (the dinucleotide).

How can these simple dehydration reactions be brought about by the same type of system which gives rise to the amino acids, the heterocyclic bases (adenine, cytosine, etc.) and the sugars? How can these dehydration reactions be brought about in aqueous solution? The chemists usually do these things in nonaqueous media, but these reactions are today carried on by living organisms in an aqueous media; presumably it happened originally also in water. Is there a possible chemical system for bringing about this dehydration reaction in water?

About a year ago we set as our next goal the discovery of such a chemical system, and we were successful. We have found that cyanamide dimer will induce the dehydration condensation in water solution of glucose to cellobiose and will cause the dehydration esterification of glucose and phosphate to glucose-6-phosphate in 0·001 *M* solutions *in water*, as well as induce the formation of the dipeptide, alanylalanine, in 0·01 *M* aqueous alanine.[10] This is a very interesting reaction, and those of you who are chemically oriented will appreciate how exciting this is in terms of chemistry. Recently I have learned that not only does cyanamide dimer induce this type of reaction but also cyanogen can be used. Stanley Miller used cyanogen in a similar experiment. It is now clear that the cyanamide dimer is formed in exactly the same type of process as the other simple molecules.

We have now formed the simple molecules (amino acids, sugars, heterocyclic bases) and we have formed the unsaturated molecules (the cyanogens, the cyanamide dimer) which themselves store the radiation energy and use it in a specific dehydration reaction. With this we are now able to make the polymers by a nonbiogenic process in a dilute aqueous solution. Can we now get to the next level of structure?

We have gone from the simple atoms to the simple molecules, to the biologically important substrates, to the polymers. Now, how do the polymers themselves take on the next level of structural organization which a biologist requires for a living organism?

GENERATION OF ORDER AND NEW INFORMATION

The next level of structure is contained in the polymer. I want to remind you, therefore, that the polypeptide structure which is shown in Figure 9 spontaneously

FIG. 9. Protein structure.

takes up a second degree of order in the form of the helical arrangement because of the particular relation of the nitrogen and hydrogen atoms, and carbonyl bonds to each other. What might have appeared as a random chain, at room temperature and at the right pH will assume a highly ordered second degree of structure—the alpha helical structure. This is a perfectly reversible process, and the structure is stable thermodynamically. One can demonstrate this by melting it: upon heating or a change of the acidity, the polypeptide will come apart, and by reversing the temperature change or the acidity change, it comes back together again. The same kind of thing can be said of the helical structure which is taken up by the polynucleotide, shown in Figure 10. This shows a ribose

FIG. 10. Molecular drawing of components of desoxyribonucleic acid.

phosphate 'tape' on which are strung a couple of the heterocyclic bases, as well as a second 'tape' of ribose phosphate upon which are hung the other two complementary bases. As you all know, these are hydrogen-bonded and complementary to each other, and they form a double helix which is a thermodynamically stable form; one can melt it and reform it, either by temperature or by pH adjustment. The second order of structure, the helical structure which is built into both of these biopolymers, is, therefore, built into them directly by virtue of the nature of the monomers of which they are made and the bond which brings the monomers together.

Is there a third order of structure built into these biopolymers? This can be shown by the reversible formation of collagen fibrils. The top part of Figure 11

FIG. 11. Structure of collagen.

is the disaggregated single collagen molecules, and the bottom part is the reaggregated collagen fibrils, formed by adjusting the salt concentration of the single molecular species. You can see that these reformed, constructed collagen fibrils obviously are stable, and the whole structure of the helix which is present here contains in it the necessary bits of information to give rise to this third order of structure.

There are many other kinds of evidence of higher degrees of order built into the polymers. The multiplicity of the forms of enzymes which is now being described everywhere bears witness to this. One can dissociate and reassociate many complex structures, even to the quaternary degree of structure, in which the helix is the secondary structure, the way the helix is folded is the tertiary structure, and the way in which the folds pack together into almost visible aggregates is the quaternary structure. In many cases we have found that these things are reversible. We can therefore say that the quaternary structure is built right into the atoms of which the material is made.

The atoms give rise to the small molecules, the small molecules give rise to the poylmers, the polymers give rise to the secondary structure, the secondary to the tertiary, the tertiary to the quaternary which is now visible. We have thus come right up into the visible region of cellular structure. Figure 12 shows

FIG. 12. Electron micrographs showing the 'fundamental particles' of biology: ribosomes, electron transport particles of the mitochondria, quantasomes of the chloroplasts and unit lipoprotein membrane.

electron micrographs of several types of structure, showing the fundamental particles of biology (ribosomes, electron transport particles of mitochondria, quantasomes of chloroplasts, unit lipoprotein membrane). This shows the fine structure which we can take apart, but we have not yet been able to put it back together. Recently it has been reported by Dr. David Green that the mitochondrial structures can be dismantled (certain parts of the function can be removed), and when this is done by suitably adjusting the medium, the little knobs in the mitochondria spontaneously go back onto the mitochondrial membrane.[11] This process is built into the structure of the material.

CONCLUSION

We have now traced right from the beginning—from the atoms themselves to visible structures and their functions—a sequence of events for which a number of experimental points of contact have been found. We have been able to check the path at half a dozen different points. There are obviously many points that have not yet been mapped. For example, the construction of a biologically active membrane layer has not yet been successfully accomplished by any means. (This is an area which is very important, and the physicists and chemists are just now reaching the stage where they can attempt to do this.) The map will gradually be filled out, modified and changed as we learn more about it.

One last word about where new information can come from: new information both of the type we are seeking in the ancient rocks and the type we are seeking in experimental prebiotic development may come to us from quite another source. Today we have, of course, no other source of prebiotic materials except the laboratory. There is, however, another possible source and that is material which comes to us from off the earth in the form of meteorites. There has been a good deal of work in this direction in recent years. However, the number of meteorites that are available to us which have organic matter in them, for examination and analysis, is very limited, and what is worse, it is difficult to be sure that the organic matter in them came with the meteorites. This is because you just don't catch the meteorite as it falls—it hits the ground and all of you know what is in and on the ground.

There is really only one way we can be confident that the information which we get by analysis of the organic matter in the ancient rock was there to start with, and that is to get the rock (meteorite) from off the earth and seal it up before it gets back to the earth. I suspect that within this decade this will be done, and there is every reason to expect that we will have nonterrestrial rock samples which have been sterilely sealed and brought back for terrestrial laboratory biological and chemical examination in the not too distant future. Many of us will have the opportunity to examine such materials, brought back to terrestrial laboratories within a decade.

Also, within the next ten years, we can expect at least spectroscopic information to aid in answering the great botanical question as to whether there are lichens on Mars. This should provide, at the least, a most interesting classification problem for the taxonomists.

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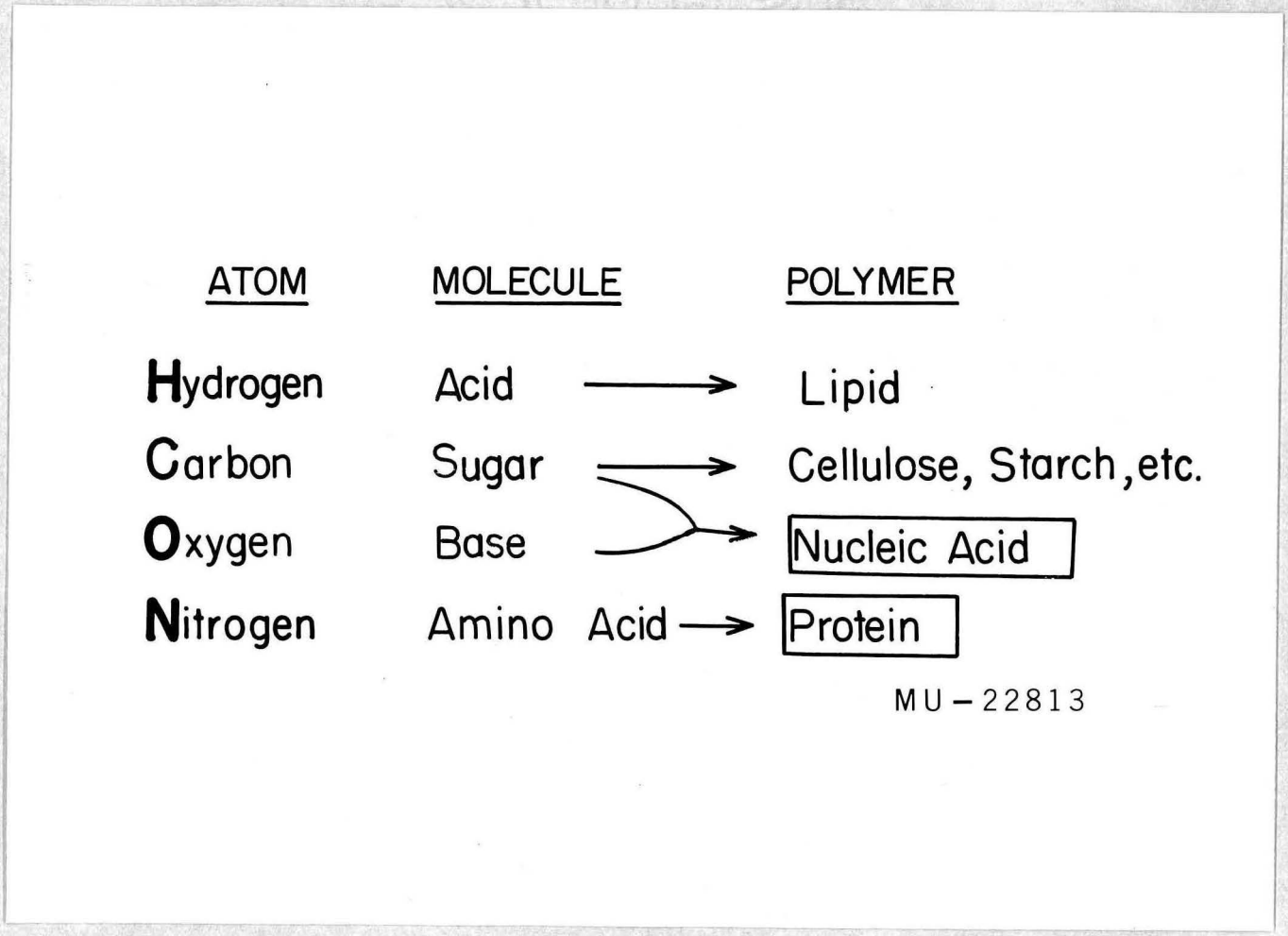
ATOM
MOLECULE
POLYMER
Hydrogen
Acid
Lipid
Carbon
Sugar
Cellulose, Starch, etc.
Oxygen
Base
Nucleic Acid
Nitrogen
Amino Acid
Protein
MU-22813

Fig. 1

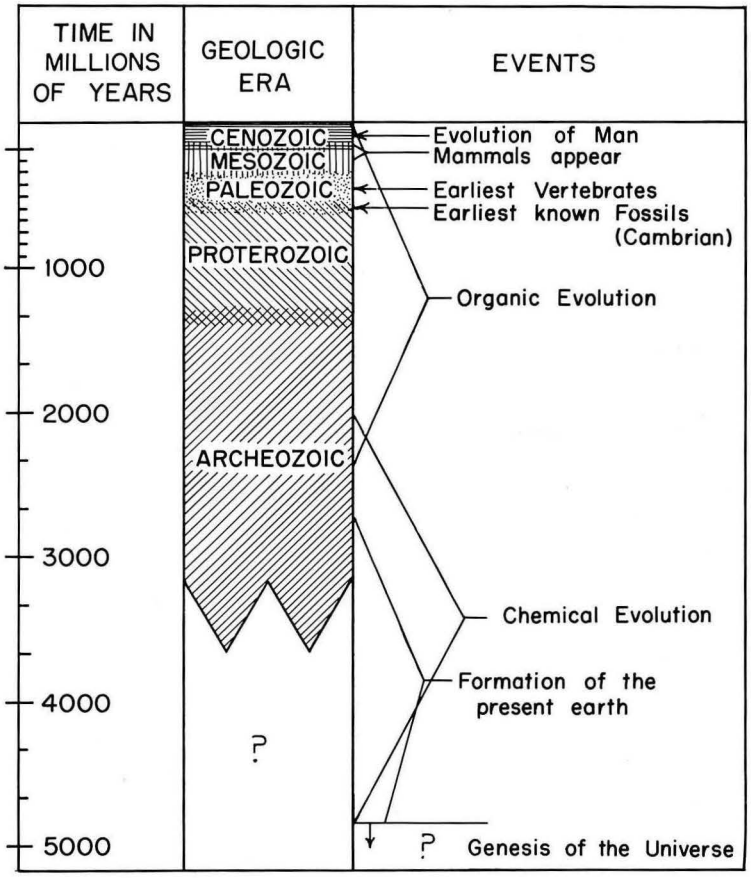

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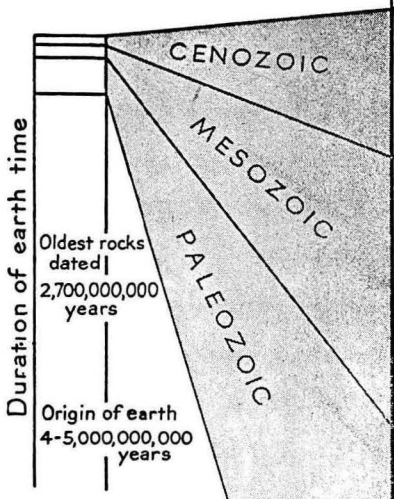
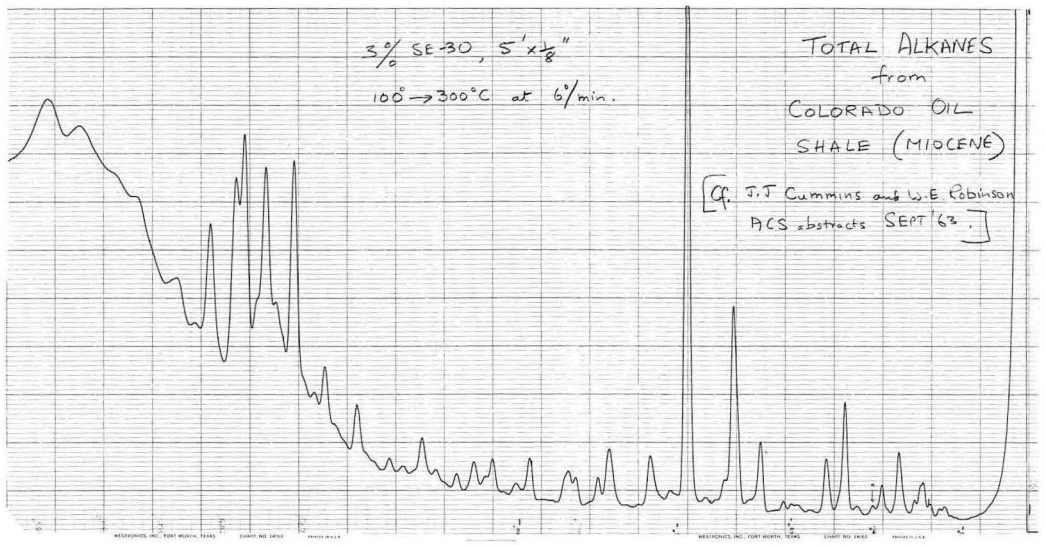
Fig. 2

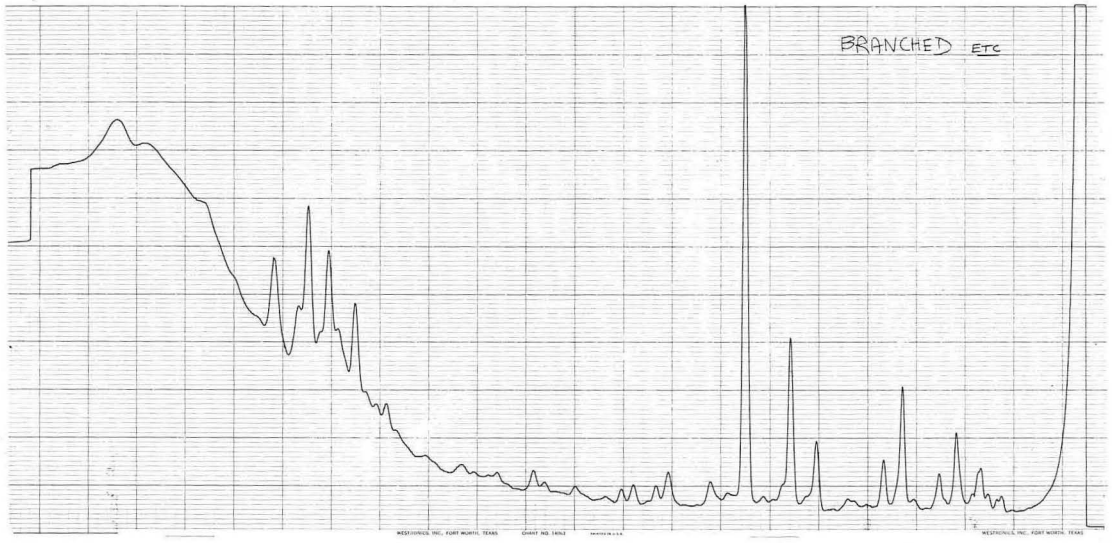


PERIODS	EPOCHS	MILLIONS OF YEARS: DURATION	MILLIONS OF YEARS: BEFORE THE PRESENT
Cenozoic	Pleistocene	1,000,000	
	Pliocene	10,000,000	
	Miocene	15,000,000	
	Oligocene	10,000,000	
	Eocene	20,000,000	
	Paleocene	14,000,000	70,000,000
Cretaceous		55,000,000	
Jurassic		40,000,000	
Triassic		35,000,000	200,000,000
Permian		30,000,000	
Pennsylvanian		30,000,000	
Mississippian		30,000,000	
Devonian		40,000,000	
Silurian		30,000,000	
Ordovician		60,000,000	
Cambrian		80,000,000	500,000,000
Precambrian time			

Fig. 3

MUB-2612





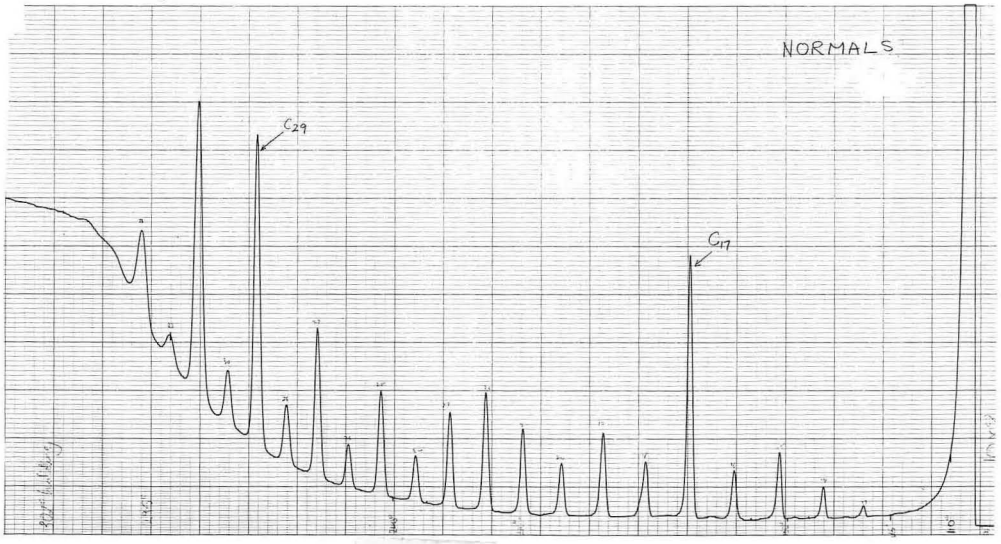


Fig. 4

MUB-2599

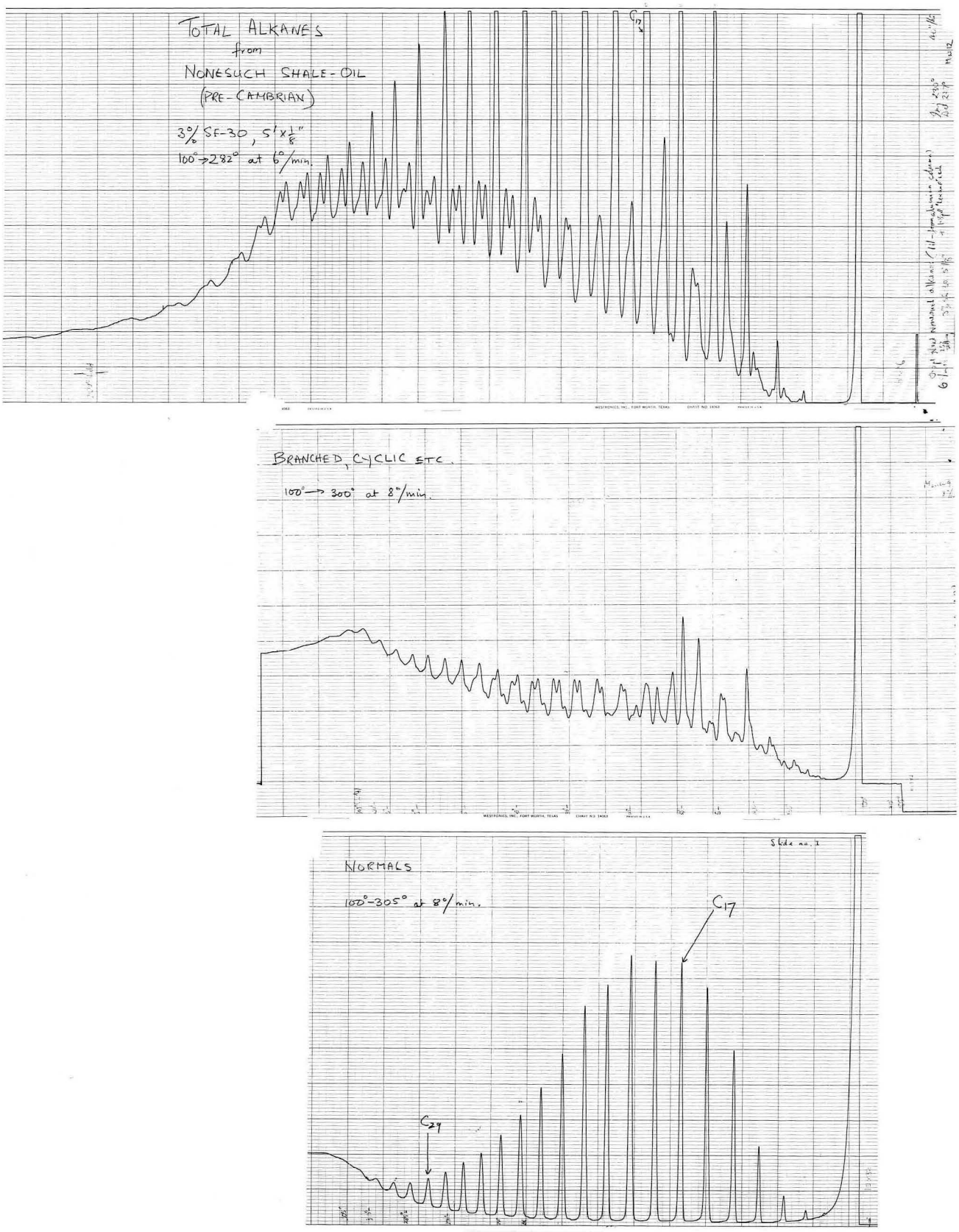

TOTAL ALKANES
from
NONESUCH SHALE-OIL
(PRE-CAMBRIAN)
3% SF-30, 5' x 1/8"
100° → 282° at 6°/min.
C17
BRANCHED, CYCLIC ETC.
100° → 300° at 8°/min.
NORMALS
100°-305° at 8°/min.
C17
C29

Fig. 5.

INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA

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LRL GRAPHIC ARTS
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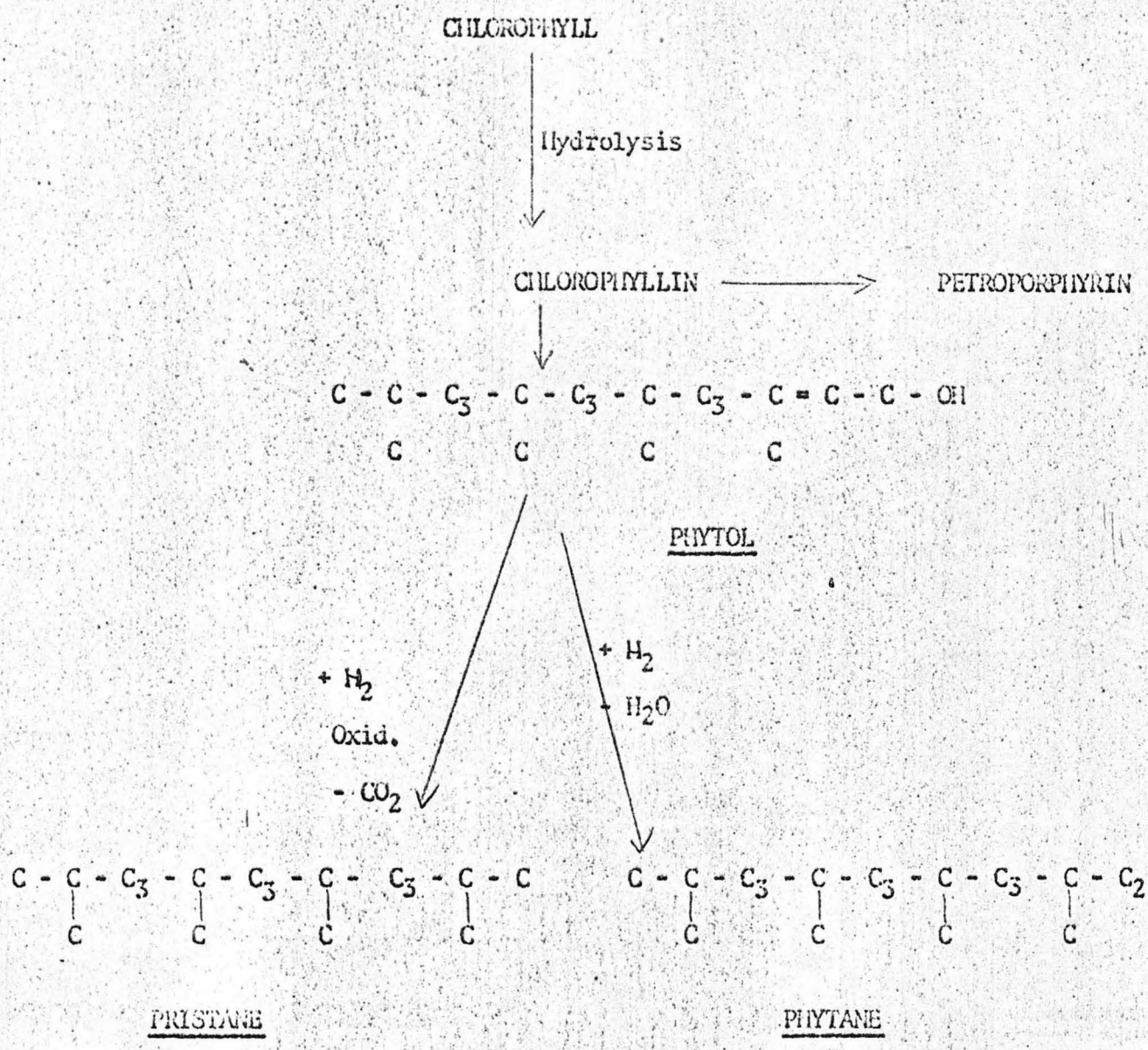


Fig. 6. A possible source of pristane and phytane.

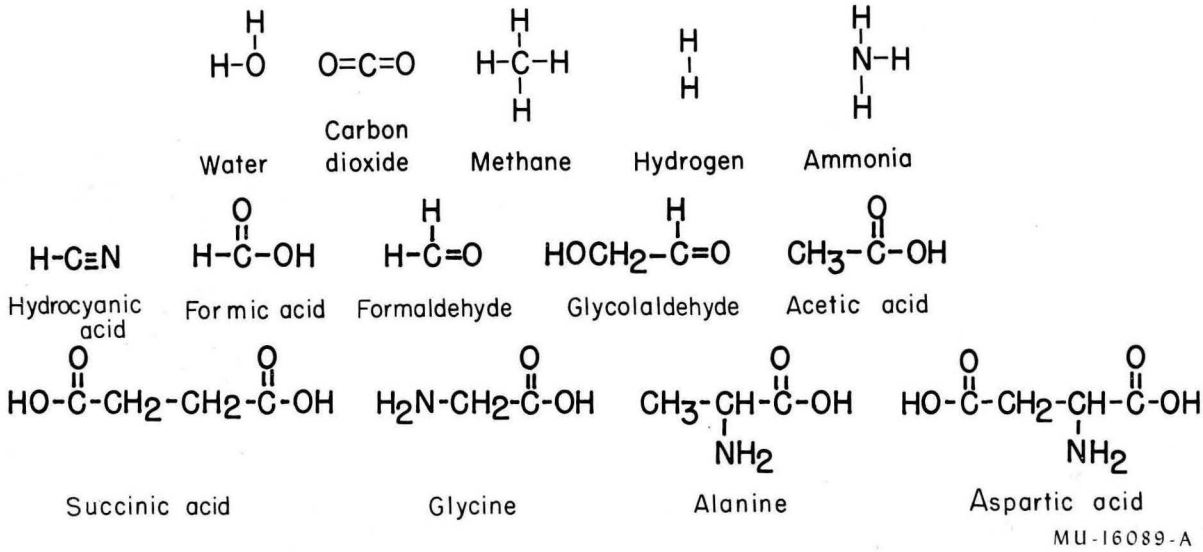

Water
Carbon dioxide
Methane
Hydrogen
Ammonia
Hydrocyanic acid
Formic acid
Formaldehyde
Glycolaldehyde
Acetic acid
Succinic acid
Glycine
Alanine
Aspartic acid
MU-16089-A

Fig. 7

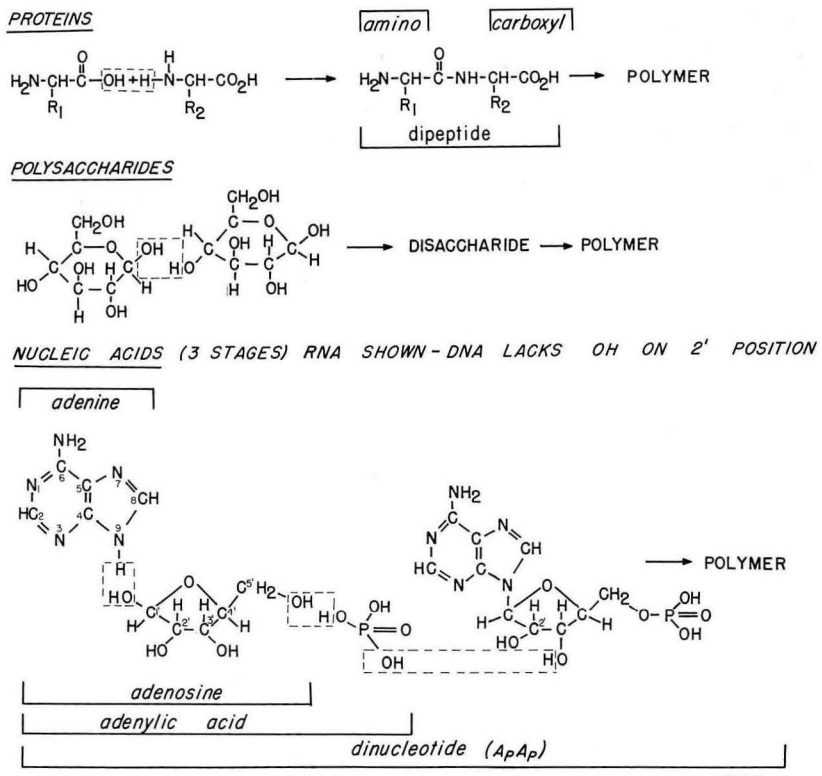

PROTEINS
amino
carboxyl
POLYMER
dipeptide
POLYSACCHARIDES
DISACCHARIDE
POLYMER
NUCLEIC ACIDS (3 STAGES) RNA SHOWN - DNA LACKS OH ON 2' POSITION
adenine
POLYMER
adenosine
adenylic acid
dinucleotide (ApAp)
MU-27657

Fig. 8

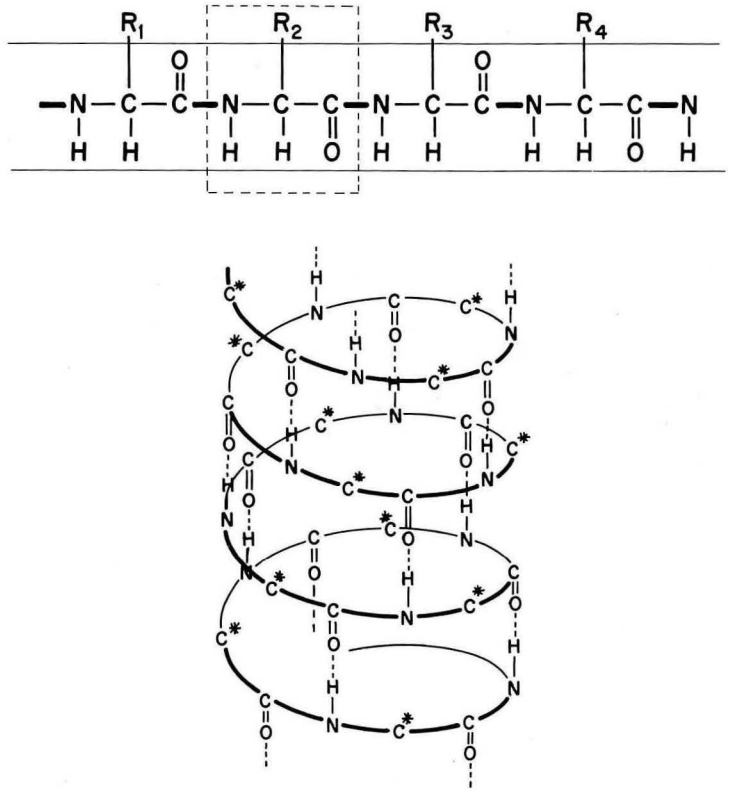


Fig. 9

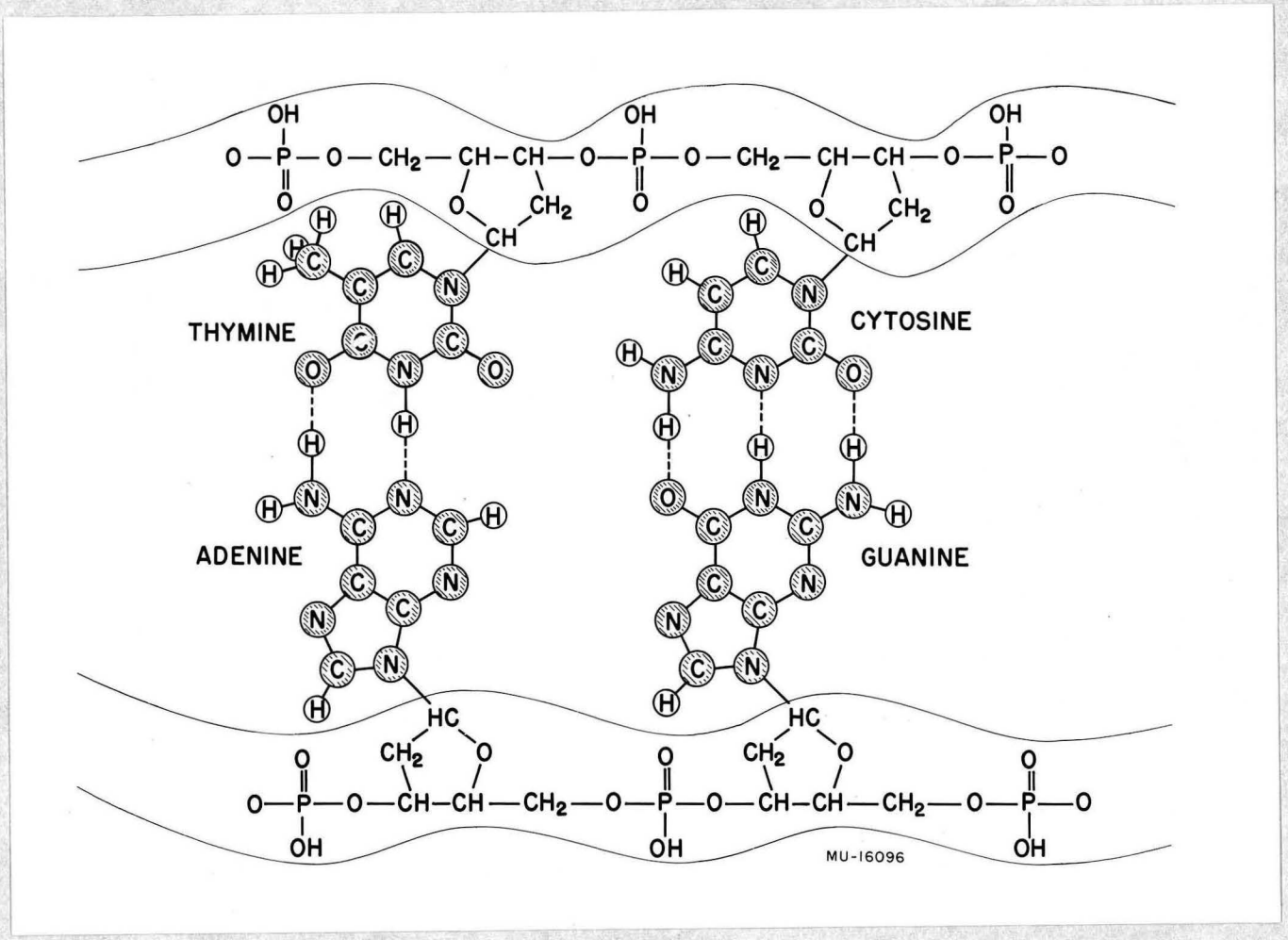
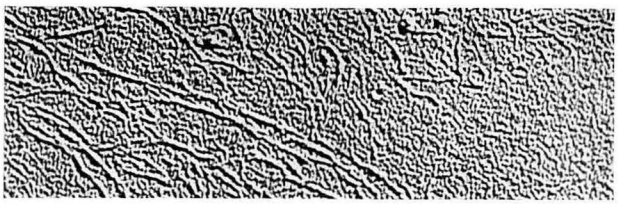
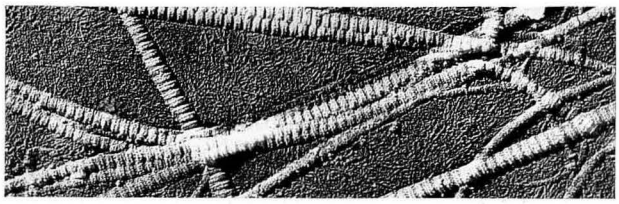


Fig. 10

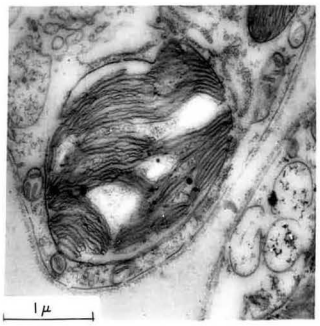


FILAMENTS OF COLLAGEN, a protein which is usually found in long fibrils, were dispersed by placing them in dilute acetic acid. This electron micrograph, which enlarges the filaments 75,000 times, was made by Jerome Gross of the Harvard Medical School.

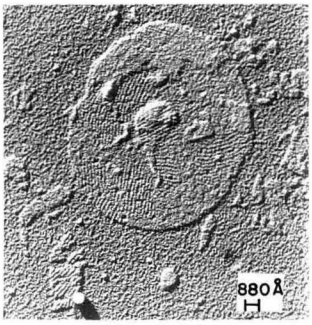


FIBRILS OF COLLAGEN formed spontaneously out of filaments such as those shown above when 1 per cent of sodium chloride was added to the dilute acetic acid. These long fibrils are identical in appearance with those of collagen before dispersion.

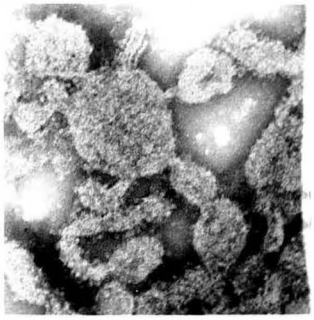
Fig. 11



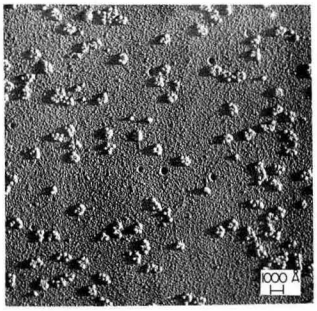
CHLOROPLAST WITH MITOCHONDRIA
CHLAMYDOMONAS (SAGER)



QUANTASOMES FROM SPINACH
(PARK and HEALEY)



NEG.-STAINED MITOCHONDRIA
(PARK and PACKER)



POLYSOMES MAKING HEMOGLOBIN
(WARNER, RICH and HALL)

Fig. 12