Pearson Edexcel Level 3 GCE

Biology A (Salters-Nuffield)

Advanced

Unit 3: General and Practical Applications in Biology

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The Energy of Life

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1. The images displayed on the wall of screens in front of me (Marlow) show a shadowy, alien world, with bizarre life forms moving in and out of frame like apparitions. Slow-moving crabs dance precariously on submerged cliff sides, bug-eyed pink rockfish hug the crevasses, and serpentine fish slither across the sediment in search of food. It's September 2011, and my fellow scientists and I are bobbing comfortably aboard the research vessel *Atlantis* on the surface of the eastern Pacific Ocean. Seven hundred meters below, the robotic craft *Jason* dangles beneath the ship, exploring a marine methane seep known as Hydrate Ridge while skirting calcium carbonate mounds that rise hundreds of meters above the seafloor.

2. At Hydrate Ridge and many similar sites around the world, methane derived from deeply buried hydrocarbons or subseafloor microbial communities is squeezed upward through cracks in the Earth's crust. This narrow zone of methane-rich waters near the seafloor is home to one of the most extreme and confounding biological processes known to science: the anaerobic oxidation of methane, likely a key climate regulator and a phenomenon that could hold important clues to finding life elsewhere in the universe.

3. We look on with nervous excitement as *Jason* collects an intact plug of seafloor sediment, stows it in its sample basket, and begins the long trip back to the surface.

4. The ocean is well stocked with mysterious creatures, and while the tentacled and the sharp-toothed may be the Gorey-esque stuff of nightmares, humble microbes also deserve a nod as some of the most biologically exotic denizens of the deep sea. These single-celled organisms have found ways to "breathe" metals, survive without oxygen, and fix carbon into biomass in several distinct ways, allowing them to handle nearly the full range of physical and chemical extremes that our planet has to offer.

5. The marine archaeon *Geogemma barossii*, for example, can survive at a blistering 121 °C, while other microbes have retained metabolic activity at temperatures as low as –20 °C in Siberian permafrost. The bacterium *Deinococcus radiodurans* remains viable after exposure to 1,000 times the fatal human radiation dose, and the aquatic archaeon *Ferroplasma acidarmanus* can withstand extremely acidic water, with pH values as low as 0. Such flashy feats have earned these and other microbes the title "extremophiles"—lovers of extreme conditions. But as remarkable as their metabolic capabilities are, calling them "extreme" is a bit human-centric. Because of our own requirement for oxygen and narrow acceptable ranges of temperature, salinity, pressure, pH, and radiation, the survival of other organisms in a wide range of environments seems extreme to us. But for a microbe that has come to depend on the abundant hydrogen ions of acidic hot springs, an air-conditioned suite at the Ritz is a threatening proposition. The wide variety of biochemical modes of existence reflect billions of years of evolution, adaptation, and niche differentiation rather than a standardized characterization of biological fortitude.

6. For the title of "extremophile" to be broadly meaningful, it must refer to a more objective measure of extremeness—an advantageous capability enacted in response to a common challenge. One such challenge, something that all living organisms must face, is the acquisition of chemical energy to drive cellular reactions. Perhaps the ways in which organisms handle this task could separate the truly industrious from the merely viable.

The energy of life

7. Energy is the currency of biology. By harvesting electrons from a stunning range of starting materials, Earth's organisms produce adenosine triphosphate (ATP), which powers biological reactions. In the case of mammals and most eukaryotes, sugars and other organic molecules are common electron sources, the oxidation of which drives ATP production. Bacteria and archaea can use a range of other chemicals, from sulfide to iron to ammonium.

Courtesy of Jeffrey Marlow

Oceanic extremes

This experimental setup on Hydrate Ridge off the coast of Oregon samples microbial metabolism in deep-sea methyl seeps, which host a variety of seemingly strange creatures, including some truly extreme archaea and bacteria that cannot survive without each other.

8. Cells take up these electron-rich molecules and capture their electrons, which jump down an electron transport chain in the mitochondrial or cell membrane. As electrons move along the membrane toward a final electron acceptor, protons are pumped from the cell's interior to the exterior, setting up a chemical gradient. Finally, protons stream back into the cell, releasing the chemical pressure and generating ATP. With each energy-requiring reaction, from flagella construction to cell division and growth, cells draw upon their ATP bank.

9. This elegant, multistep process is a pervasive feature of life as we know it, but energetic challenges are ever-present. If the electrical potentials of electron donor and acceptor are too closely aligned, for example, it won't be possible to squeeze much energy from their coupling. The concentrations of the reactants and the speed at which enzymes can mobilize them are also key factors. These two components—the magnitude of energy available from a particular pairing and the rate of such reactions—determine how much energy a cell can produce.

10. The other half of the equation—the cost of living, as it were—is often harder to evaluate. Cataloging the biochemical parts list of a particular cell is one challenge. Individual biosynthetic pathways—the production of lipids from glycerol derivatives, for example—are relatively well characterized under "standard" conditions, but a cell's ever-changing chemical environment can render baseline calculations inaccurate. Scaled over millions of such reactions, the margin of error may be a substantial proportion of the available energy. And this is just considering the biosynthesis of new cellular material. In most environments, microbes must always be vigilant against biochemical breakdown resulting from environmental stresses, calling on energy reserves to restore old enzymes or patch holes in cell walls. Competition among residents may also demand additional energy expenditure, such as powering flagella to swim around in search of food or producing antibiotic molecules to keep predatory neighbors at bay.

11. If, however, we are able to estimate how much energy is required for survival, and compare that to how much energy is available to be extracted from the environment, we can begin to consider "extreme" organisms in a more objective fashion. Some of the most "exotic" environments actually offer luxurious energetic balances; it's the microbes with low net energy availability that are the real extremophiles, whether they live an expensive existence in a high-energy environment, or an ascetic life in an energetic desert.

Easy living

High energy availability, low energy requirements

12. The hot springs of Yellowstone National Park are uniquely beautiful palettes: concentric rings transition from blue in the pools' centers to green, then yellow, orange, and red at the water's periphery. The mesmerizing visuals contrast sharply with the damp, sulfurous odors wafting across your nostrils and the stern warnings from signs and rangers to keep your distance. Against this otherworldly backdrop, the 1966 discovery of viable cells living in the ultrahot waters came as a surprise that forced a reconsideration of microbial limits. After all, water temperatures frequently topped out well above the tolerance range of most known organisms. Nearly all of *E. coli*'s enzymes, for example, unfold and become ineffective at 60 °C.

13. Hot-springs microbes have traditionally been labeled "extremophiles," yet their energetic bank account is typically well in the black. Like their moderate-temperature relatives that ply the planet's oceans, thermophilic cyanobacteria gain energy from light-driven reactions that mobilize electrons from water. Along the outer edges of thermal springs, energy-generating light is abundant, and cyanobacteria flourish. Indeed, the vibrant colors we see are the plentiful microbial pigments that coat the limestone surfaces.

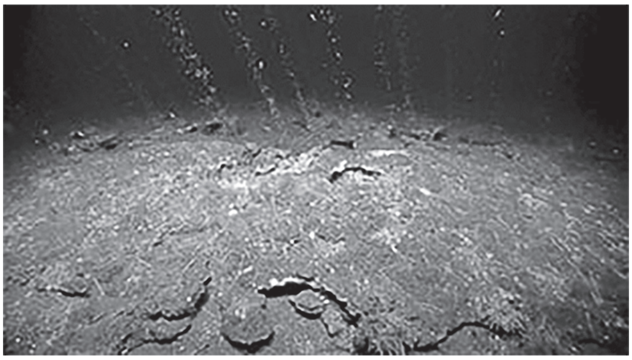
14. This is not to say that life at high temperatures is easy. On the contrary, only through a range of sophisticated molecular adaptations, encoded by subtle edits in thermophiles' genomes, has this forbidding niche become habitable. Protein stability is perhaps the main challenge for life at high temperature. Higher thermal energy causes hyperactive atoms to vibrate with more kinetic energy, threatening the structural integrity of the molecules that perform biochemical reactions. If sulfur-containing cysteine amino acids are positioned strategically within protein structures, disulfide bridges can form interatomic support beams that resist unfolding. Some thermophilic enzymes also have larger hydrophobic cores, away from the proteins' exposed active sites, which act as additional glue to fight thermal destabilization. Other adaptations, such as simpler protein folds or fewer bound metal ions, further guard against molecular destabilization in the face of thermal stress.

15. Evolving the capability to handle high temperatures may not have been straightforward, and biosynthetic construction costs might have presented some hurdles, but the payoff does seem to have been worth it. By constructing heat-stable enzymes, the cyanobacteria inhabiting hot springs are able to photosynthesize in relative peace, away from the feeding frenzy of predatory microbes or larger creatures in habitats such as the ocean's surfaces. Thus, while Yellowstone's hot springs may seem like an extreme environment, not all of the microbes that inhabit them are struggling to survive.

An expensive lifestyle

High energy availability, high energy requirements

16. One needn't travel to the bottom of the ocean or into a scalding hot spring to find microbes living at the edge of energetic feasibility. Sometimes, the most remarkable habitats are in your own backyard, beneath well-manicured Kentucky bluegrass or a haphazard array of lawn furniture. "Generic" temperate soils are among the richest microbial milieus on the planet, with each pinch of dirt hosting up to a billion cells, and down there, it's all-out biochemical warfare.



NOAA Okeanos Explorer Program, 2013 ROV Shakedown and Field Trials

Methane munchers
Off the coast of Virginia, methane bubbles flowing out of the seafloor sediment support a variety of life, including some truly extreme microbes.

17. Among the more prominent denizens of this dense microbial metropolis are representatives of the bacterial genus *Streptomyces*: stringy, rod-shaped organisms that develop centimeter-scale networks branching through the soil. *Streptomyces* gain energy through heterotrophy, the consumption of organic molecules such as sugars, amino acids, or aromatic compounds. These are energetically juicy molecules, and they're abundant given the high density of plants in the vicinity, but it's far from a free lunch.

18. *Streptomyces* capture organic molecules largely by secreting enzymes into the soil to access and degrade energy-rich polymers before other competitors can get to them. It's a bold strategy susceptible to freeloader hijacking, with no guarantee that the processed material will find its way back to the same organism that went to the trouble of producing the enzyme. But at scale, the odds become more palatable, and the benefit from degraded organics that find their way to one Streptomyces or another outweighs the inefficiency of the strategy. Building a large network of interconnected cells is the only option that makes this spendthrift approach worthwhile.

19. Oxygen is the highest-potential electron acceptor on the market, and transferring electrons to O_2 provides the biggest payoff per electron-donating molecule. This makes the upper, oxygen-perfused layers of soil highly sought-after real estate, but it comes at a price. In a 2005 study, geomicrobiologists Tom McCollom of the University of Colorado, Boulder, and one of us (Amend, then at Washington University in St. Louis) calculated the energetic costs of synthesizing an extensive list of biomolecules, including amino acids, nucleotides, fatty acids, saccharides, and amines, from inorganic precursor molecules. We found that biosynthetic costs were actually higher—by more than an order of magnitude—in oxygen-infused conditions than in anaerobic settings. Part of this discrepancy is due to the fact that many precursors must be reduced from their oxidized state prior to biomolecular construction, but it suggests that the energetic windfall from using oxygen as an electron acceptor may be a necessary copay, not a bankable nest egg.

20. Perhaps *Streptomyces*'s most impressive adaptation is the genus's remarkable array of antibiotics, which can attack competitors' cell walls or protein-synthesis machinery. But these large, sophisticated weapons require a high flux of electron-rich intermediates and the repurposing of cellular supply chains. An analysis led by J. Stefan Rokem of the Hebrew University of Jerusalem showed that antibiotic production represents an enormous drain on biosynthetic pathways, frequently costing more than half of the stocked supply of precursor building blocks (such as pyruvate or acetyl-CoA) that would otherwise be used to construct biomass and generate new cells. But, while expensive, antibiotic synthesis is critical for survival in this crowded environment, minimizing competition for much-needed resources. From an energetic perspective, *Streptomyces* is an extreme organism, and it's hiding in plain sight.

Just getting by

Low energy availability, low energy requirements

21. As *Jason* is hauled back on deck, packed to the brim with samples from deep-sea methane seeps, *Atlantis* becomes a hive of activity. We rush the cores of seafloor sediment along with chunks of carbonate rocks to the onboard laboratory, where they're partitioned and allocated for experiments. Liquid is extracted for geochemical measurements, and a few grams of sediment are frozen for DNA and microscopic analyses. A separate aliquot is scooped into a shiny silver mylar bag, mixed with filtered seawater and isotopically labeled chemicals, and flushed with nitrogen and methane gas. The bag is heat-sealed and set aside, a time capsule to be opened several months later to determine how much of the isotope-labeled substrate has been taken up by the mysterious process of anaerobic methane oxidation.

22. What we ultimately find is confirmation of a bizarre biological partnership operating at the edge of what is energetically possible. As has been found at other methane seep sites around the world, certain types of archaea and bacteria aggregate together in multicellular clumps, with tens, hundreds, or occasionally thousands of microbes linked by mutual energetic necessity. The details of the association are still up for debate, but it appears that archaeal partners oxidize methane and transfer electrons to the bacteria to enable the reduction of sulfate to sulfide, generating energy to power cellular functions. Remarkably, when the energetics numbers are crunched, the archaea come out in the red—their half of the arrangement does not appear to produce enough energy for their own survival. This means that the sulfate-reducing reaction performed by their bacterial partners must supply power to both species. How this mutualism works, especially in an evolutionary framework, is far from certain.

23. The energetic demands for biosynthesis are relatively low given these organisms' very slow rates of growth, doubling only every few months. Nevertheless, given the difficulty of extracting and sharing energy in methane seep environments, anaerobic methane-oxidizing partnerships deserve the title of extremophiles, as characterized by the energetic framework. Hopefully, future studies will illuminate the nature of this symbiosis and provide insight into how the energetically improbable becomes possible, untangling the intricacies of these and other slow-growing extremophiles.

An impossible situation

Low energy availability, high energy requirements

24. The final permutation of energetic cost-benefit ratios seems like a non-starter: having higher energy demands than the rates of supply does not make for a sustainable situation. And while growth under such conditions seems impossible (with the notable exception of tightly-coupled metabolisms like those described above), an energy debt need not mean cell death.

25. When the going gets tough, some microbial species, such as the bacterium *Bacillus subtilis*, initiate a hibernation protocol, shutting down the furnace and turning off the lights before forming a life raft that will hopefully ferry them to greener pastures. The process is called sporulation, and it's a life-or-death decision not to be made lightly. *B. subtilis* is commonly found in soil environments susceptible to feast or famine swings in energy availability. When one of these cells senses nutrient stress, it draws on energy stores, activating flagella to search for food, flooding its surroundings with antibiotics to kill off competitors, or desperately importing foreign pieces of DNA in hopes that a novel capability will be the ticket out of a bad situation. If all else fails, it replicates its genetic material and partitions it into a protective capsule that can withstand extreme heat, radiation, chemical stress, desiccation, and energetically untenable conditions. Sensors located on the spore's outer surface probe the environment for friendlier surroundings and assess the possibility of returning to a more active way of life. Powering up is an extremely energetically demanding undertaking, permitting full resurrection only under ideal circumstances. Thus, while this behavior may be considered extreme in itself, spore formers dodge the true test of their extremophilic nature by waiting out the impossible in a state of metabolic hibernation.

Rethinking extremes

26. For millennia, microbes have searched for loopholes and experimented with novel molecular machines in an attempt to gain a foothold where others can't. From backyard soils to seafloor methane seeps, these extremophiles eke out a living, revealing adaptations to the energy equation that may point us toward other organisms awaiting discovery in the headlights of a future robotic spacecraft.

27. Many of the most promising astrobiological targets in our solar system may well possess the baseline requirements for life such as liquid water and key elements, but net energy availability is an unknown. The lakes of Titan, Saturn's largest moon, have plenty of organic fuel for the taking, but maintaining a viable microenvironment would likely be very difficult given the lack of an appropriate solvent at such frigid temperatures. The Martian subsurface, on the other hand, may lack easily obtainable energy sources, but with relatively few apparent hazards, a low-energy way of life could be feasible.

28. Researchers have yet to fully sample the diversity of bioenergetic regimes on Earth. With continued exploration of the seafloor or the planet's deep interior, we find novel geochemical cocktails that demand microbial innovation. And so, back on the Atlantis, we load *Jason* with cleaned collection tubes and send our robotic emissary on yet another journey into the unknown, in search of new microbial responses to the extreme conditions of the deep.

The Energy of Life by Jeffrey Marlow and Jan Amend, February 1, 2015. The Scientist Magazine.
http://www.the-scientist.com/?articles.view/articleNo/41990/title/The-Energy-of-Life/