Marine bioluminescence: mechanisms, ecological functions and biotechnological applications

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Abstract

Bioluminescence is a biological phenomenon characterized by the production of light by living organisms, mainly in deep marine environments. This study is based on data from the Monterey Bay Aquarium Research Institute (MBARI), obtained through the exploration of the deep sea using remotely operated underwater vehicles. These observations show that a large proportion of organisms, including siphonophores, jellyfish and many fish, possess the ability to produce light, especially in the mesopelagic zone.

The production of light is based on a chemical reaction involving specific molecules, allowing the emission of photons without significant heat release. This mechanism varies according to the species and can be produced directly by the body or by bacteria living in symbiosis.

The analysis highlights that bioluminescence plays a central role in biological interactions, particularly for predation, defense and certain forms of communication. It is therefore an essential adaptation in environments characterized by permanent darkness.

In addition, this phenomenon is of significant scientific interest, particularly in the fields of biology and medicine, where it is used as a tool for observation and analysis. The study of bioluminescence also contributes to a better understanding of deep marine ecosystems and highlights the importance of their preservation.

Introduction

Bioluminescence is not a recent phenomenon in the history of science. It has been observed since ancient times, in particular by sailors who described "luminous" seas at night, a phenomenon sometimes called the "sea of milk". At that time, these observations were often interpreted as mysterious or supernatural manifestations, due to a lack of scientific knowledge. It was not until the Renaissance and the seventeenth century that scientists began to study this phenomenon more rigorously, seeking to understand its natural origin.

In the seventeenth and eighteenth centuries, the first scientific experiments demonstrated that this light was produced by living organisms, and not by an external chemical or physical phenomenon. Researchers have observed that some sea creatures, such as jellyfish or microorganisms, can emit light when disturbed. These discoveries marked an important step in the understanding of bioluminescence, establishing its biological origin.

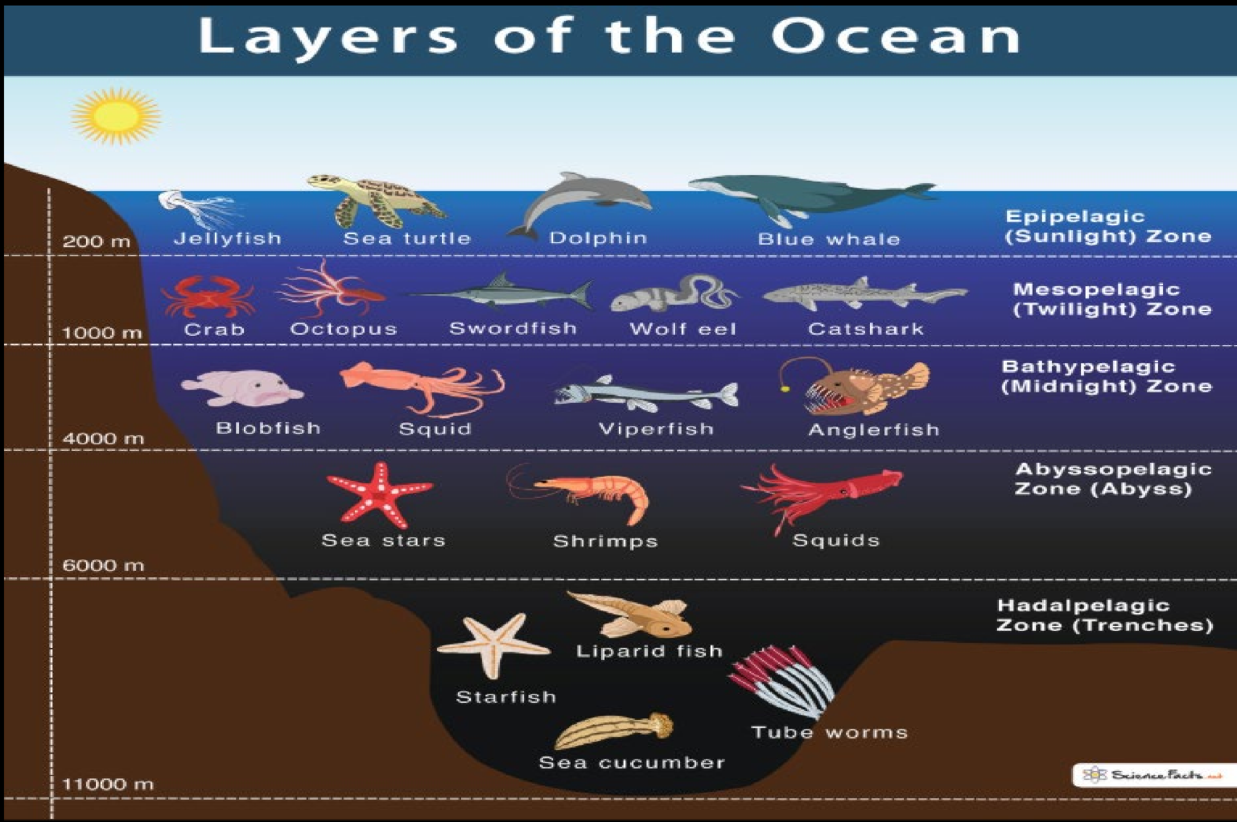
In the nineteenth century, advances in chemistry made it possible to deepen this research. Scientists have begun to identify the substances responsible for light production, paving the way for a more precise understanding of the phenomenon. However, the exact mechanisms were still poorly understood, due to the technological limitations of the time.

In the twentieth century, advances in biochemistry have made it possible to understand the precise mechanisms of bioluminescence. The work of scientist Osamu Shimomura has made it possible to isolate the GFP (Green Fluorescent Protein) protein, which has marked a major step in the understanding and use of this phenomenon. This discovery then led to important applications in molecular biology, particularly to observe living cells. Today, bioluminescence is studied in many scientific fields, ranging from marine ecology to medicine and biotechnology.

Researchers generally distinguish between several types of bioluminescence based on their origin. In some organisms, light is produced directly by their own cells through internal biochemical reactions. In other cases, it is generated by symbiotic bacteria living inside the host organism, such as in some fish and squid. This diversity of mechanisms shows that bioluminescence did not appear once in evolution, but that it developed independently in several groups of living beings.

Studies conducted by the MBARI show that about 76% of species in environments with permanent darkness are bioluminescent, and that this proportion is even higher in the mesopelagic zone (see Figure 3). Bioluminescence is an important element in the functioning of deep-sea ecosystems and a central topic for the understanding of marine biodiversity. In order to better understand this complex phenomenon, it is necessary to question its mechanisms, its ecological functions and its scientific applications.

Osamu Shimomura holds a test tube containing a solution of green fluorescent protein (GFP), along with a lamp that emits ultraviolet light, causing the GFP to glow bright green. Shimomura purified this small amount of GFP from 20,000 specimens of Aequorea. (Source : Tom Kleindinst).



Layers of the Ocean (Source : ScienceFacts.net)

Problem

Although bioluminescence is a particularly spectacular phenomenon, it remains insufficiently understood from a scientific point of view. Only a small proportion of bioluminescent species have been studied in detail due to the difficulties of exploring the ocean and the technical constraints associated with these extreme environments. This lack of knowledge limits our understanding of the real role of bioluminescence in deep marine ecosystems as well as its scientific and technological potential. To answer this problem, several essential questions must be examined.

What are the chemical mechanisms behind bioluminescence?

Bioluminescence is produced through a chemical reaction in the body of certain living organisms. This reaction involves a molecule called luciferin and an enzyme called luciferase (Wilson & Hastings, 1998). Luciferin reacts with oxygen, which creates an excited molecule. When the light returns to its normal state, it releases energy in the form of light (see Figure 9). This process is very efficient, as it produces almost only light and very little heat. The color of the light varies according to the species. In the oceans, blue and green colors are the most common, as they diffuse better in the water. In some organisms, the reaction also requires energy provided by a molecule called ATP (see Figure 10). However, in many marine organisms, light can be produced without this extra energy, which is an advantage in resource-limited settings.

What are its ecological functions?

As discussed earlier, bioluminescence has several important functions in nature. First of all, camouflage, to blend in with their environment and avoid predators. Then the defense, for example by producing flashes of light to surprise or frighten a predator. Finally, reproduction and communication, by sending signals to attract a partner.

How do humans exploit these phenomena?

Humans use bioluminescence especially in scientific and medical research. For example, luminous proteins from jellyfish are used to observe cells and better understand the human body. In medicine, it helps to study certain diseases and test treatments. It also inspires robotics and exploration, helping to develop technologies adapted to dark environments.

Bioluminescent imaging techniques in a medical diagnostic laboratory (Source : Pichapob Bovornsakulchok | Dreamstime.com)

Methodology

In order to provide reliable answers to these questions, a rigorous methodology has been put in place. In this project, several methods were used to study bioluminescence in depth. A systematic review of the scientific literature was conducted. This involves analysing scientific papers, oceanography reports and databases to gather reliable information on the mechanisms, functions and diversity of bioluminescent living beings.

Then, a data visualization was used to facilitate the understanding of the information. This includes diagrams of the bioluminescence process as well as maps showing the distribution of bioluminescent species in the oceans. The main sources used for this project come from recognized scientific journals, such as Nature, Science, PNAS and Marine Biology. Data from specialized organizations such as NOAA, IFREMER and the Ocean Biogeographic Information System (OBIS) were also used to guarantee the reliability of the information.

In order to concretely illustrate the mechanisms and functions of bioluminescence, it is relevant to examine some emblematic organisms. These case studies provide a better understanding of how this phenomenon is used in different biological and ecological contexts. To illustrate these concepts in concrete terms, the analysis of several representative bioluminescent organisms is presented below.

Aequorea victoria

Aequorea victoria (Source : Photo from the Monterey Bay Aquarium, author : Mnolf, Wikimedia Commons)

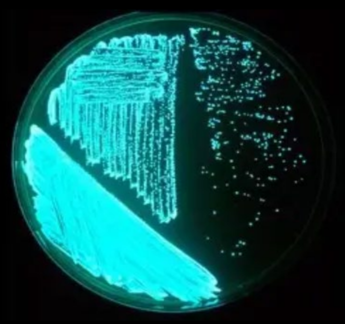
This jellyfish is one of the most studied bioluminescent organisms, due to its major importance in molecular biology. It produces light through an interaction between a protein called aequorin and the Green Fluorescent Protein (GFP), which emits green light when activated. This discovery, made in the twentieth century, profoundly transformed scientific research.

GFP is now used as a genetic marker in many fields. By inserting the gene encoding this protein into cells or organisms, scientists can visualize biological processes invisible to the naked eye. For example, it makes it possible to observe cell division, the expression of certain genes or the spread of cancer cells.

In addition, this technique is essential for the development of new medical treatments, as it facilitates the study of the inner workings of living cells. The use of GFP is a perfect example of how a natural phenomenon, such as bioluminescence, can be transformed into a powerful scientific tool, contributing to major advances in biology and medicine.

Vibrio fischeri

This bacterium represents an emblematic example of symbiotic bioluminescence. It lives in close association with certain marine organisms, including squid, in a beneficial relationship for both partners. Bacteria produce light through a biochemical reaction, while the host organism provides them with a protected, nutrient-rich environment.



Vibrio fischeri (Source : MBARI, Vibrio fischeri culture)

In some squids, such as those of the genus *Euprymna*, this bioluminescence plays a crucial role in camouflage. Thanks to the phenomenon of counter-illumination, the light produced by the bacteria mimics that coming from the surface, making the animal almost invisible to predators below. This mechanism is based on precise control of the light intensity, adjusted according to the ambient light.

Euprymna Berry (Source : MBARI, Deep-sea Euprymna and bioluminescence)

In addition, this interaction is based on a process called quorum sensing, in which bacteria emit light only when there are enough of them. This shows that bioluminescence can be regulated collectively, depending on population density.

This case study illustrates the importance of species interactions in the functioning of marine ecosystems and shows that bioluminescence can result from complex biological cooperation.

The Anglerfish

The Anglerfish (Source : MBARI, Deep-sea anglerfish and bioluminescence)

The anglerfish is an outstanding example of adaptation to life in the deep sea. This fish uses bioluminescence as a particularly effective hunting tool. It has an appendage above its head, called an illicium, at the end of which is a luminous organ containing bioluminescent bacteria.

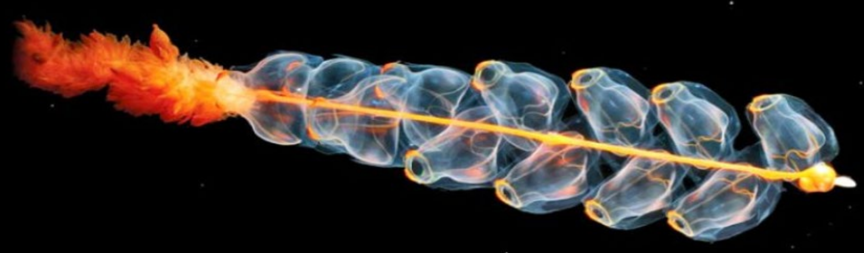
In the total darkness of the deep sea, this luminous lure attracts prey, which mistakes it for a food source. Once the prey is close enough, the anglerfish quickly captures it thanks to its large mouth and sharp teeth. This strategy optimizes the chances of capture in an environment where food resources are scarce.

In addition, some anglerfish species exhibit extreme adaptations, such as sexual dimorphism, where the male is much smaller and can fuse with the female. Although this is not directly related to bioluminescence, it shows the set of evolutionary strategies developed in these environments.

Thus, anglerfish bioluminescence illustrates an active and specialized use of light, directly related to survival in an extreme environment.

Siphonophores

Siphonophores are fascinating colonial organisms, made up of several specialized individuals called zooids, which function together as a single organism. Many of them possess the ability to produce bioluminescence, often in the form of complex, coordinated light signals.



Siphonophores (Source : Monterey Bay Aquarium Research Institute, Frillagalma vityazi bioluminescent siphonophore https://www.mbari.org/news/new-study-shows-that-three-quarters-of-deep-sea-animals-make-their-own-light/)

These signals can have several functions. They can be used to deter predators by producing sudden flashes of light, or to create visual illusions that disrupt their perception. Some species also use bioluminescence to attract prey or to communicate between different parts of the colony. In addition, the light patterns observed in siphonophores can be very elaborate, with repetitive sequences or variations in intensity. This suggests a certain level of coordination and specialization between zooids.

This collective organization, combined with the use of light, shows that bioluminescence can play a role in complex strategies involving several individuals. It also illustrates the diversity of marine life forms and how cooperation can enhance the effectiveness of biological adaptations.

Findings

The analysis of the data highlights several key characteristics of bioluminescence. Many organisms have specialized structures, such as candle holders, that allow them to produce light and modulate its intensity or direction. In some species, this emission is regulated by physiological mechanisms, offering the possibility of turning it on or off as needed.

Bioluminescence plays a central role in the food webs of deep marine environments. In environments without sunlight, it makes it easier to locate prey and avoid predators. Some predators emit light signals to attract or locate their prey, while other species use lightning or diversion signals as a defense strategy. These interactions influence the distribution and abundance of species, contributing to population balance and ecosystem dynamics. They also participate in the flow of matter and energy, in particular the vertical movements of organisms and the transfer of carbon to the deep ocean, thus playing a role in the regulation of the global climate.

Beyond trophic interactions, bioluminescence facilitates social communication. It allows the transmission of signals for reproduction or grouping and promotes recognition between members of the same species, improving the efficiency of reproductive behavior. It is also involved in camouflage strategies influencing the vertical distribution of species, particularly in the mesopelagic zone. Bioluminescence is also an indicator of biodiversity. Observing its presence or intensity makes it possible to assess the state of ecosystems and detect environmental disturbances.

Finally, research on bioluminescence has led to major scientific applications, particularly in molecular biology. The properties of bioluminescent organisms also inspire the development of innovative technologies, especially in the fields of the environment and sustainable lighting.

However, bioluminescence remains vulnerable to environmental pressures. Warming oceans can alter species distribution and disrupt established balances, while acidification of waters affects the biochemical reactions needed to produce light. Chemical, plastic and light pollution in the marine environment can interfere with natural signals, compromising essential functions such as communication and reproduction. These factors show that, despite its adaptive efficiency, bioluminescence is closely dependent on ecological conditions and requires careful protection of deep marine ecosystems.

Discussion

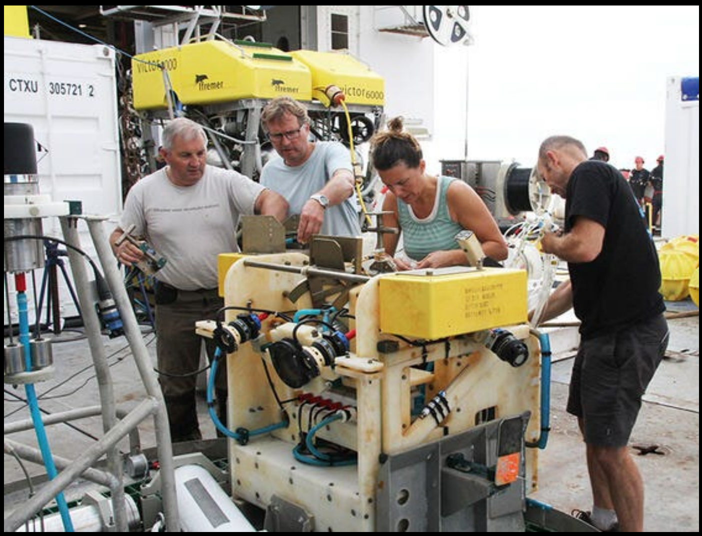
The results obtained clearly show that bioluminescence plays a major role in deep marine ecosystems. In the absence of sunlight, this ability allows organisms to compensate for a crucial lack of visibility, performing several vital functions related to survival and interactions between species. The ability to produce light in an environment where encounters with other organisms are rare illustrates the effectiveness of evolutionary adaptations in extreme conditions.

The analysis also highlights the remarkable diversity of bioluminescent systems (see Figures 6 and 7), which testifies to multiple appearances during evolution (Rees et al., 1998). Some species have developed specialized photophores capable of modulating the intensity and direction of light, controlled by nervous or hormonal mechanisms. These adaptations show significant energy optimization: producing light without generating heat allows organisms to minimize their calorie expenditure while increasing their efficiency for hunting or defense.

Bioluminescence is not limited to the deep seabed. It also occurs in terrestrial and freshwater environments, although its frequency and functions are much more restricted. In fireflies or certain fungi, light is mainly used for communication and reproduction, while in freshwater environments, its scarcity reflects different ecological constraints, such as more ambient light or particular biodiversity. This inter-media comparison underlines that bioluminescence is an adaptation profoundly modulated by environmental conditions, reaching its maximum level of complexity and diversity in the deep oceans, where it becomes a structuring element of ecological functioning.

In the energy field, the natural properties of light production, which are extremely efficient, motivate the development of sustainable lighting solutions, using bacteria or bioluminescent proteins to reduce electricity consumption and environmental impact. Prospects even include combining bioluminescence with artificial intelligence to create autonomous ecological monitoring or ecosystem management systems.

However, several limitations remain in the study of bioluminescence. The deep sea remains largely unexplored, and many species still escape observation. The complexity of the biochemical mechanisms, with varied luciferin-luciferase systems, makes it difficult to interpret and generalize the results. In addition, some species do not survive outside their natural habitat, which complicates experimental studies in the laboratory. These challenges underscore the need to develop new exploration and analytical technologies.



Aboard the vessel "Pourquoi pas?", the scientific team from the Emso-Azores observatory prepares the Tempo observation module. It is a monitoring system designed for real-time tracking of underwater ecosystems, integrating an HD camera and physicochemical sensors.
(Source: Blandin Jerome / Ifremer – MoMARSAT Campaign 2017)

Recent advances, such as aquatic drones, autonomous underwater vehicles, miniaturized sensors, and sophisticated computer models, offer unprecedented opportunities to study bioluminescent behaviors and their impact on ecosystems. Genomics and molecular biology now make it possible to quickly identify the genes involved and to understand the underlying biochemical pathways. The integration of these methods will contribute to a more precise knowledge of the interactions between organisms and the environment and to the preservation of deep environments.

Thus, bioluminescence is much more than a fascinating natural phenomenon. It is a driver of scientific and technological innovation, an indicator of biodiversity and a key element in maintaining ecological balances. His in-depth understanding offers far-reaching perspectives for basic research as well as for sustainable and medical development, demonstrating that the light produced by nature can inspire solutions to some of the most complex challenges of our time.

Conclusion

At the end of this study, several essential elements can be retained. In conclusion, bioluminescence is a remarkable adaptation, essential for the survival of many marine organisms (see Figure 5). It makes it possible to carry out vital functions already described, which are essential for survival in these environments. This phenomenon illustrates the complexity and diversity of life in the deep sea, showing that even in difficult conditions, organisms develop effective strategies to adapt. It also highlights the ability of living organisms to exploit sophisticated physico-chemical mechanisms to respond to the constraints of their environment.

In addition, research on bioluminescence reveals promising applications in several fields, including biology, medicine and technology. These applications confirm that this natural phenomenon can be exploited in research and innovation. These advances show that the study of sometimes little-known organisms can have a major impact on modern science and contribute to significant advances in biomedical and environmental research.

However, these findings also underscore the importance of preserving deep marine ecosystems, which still remain largely unknown and fragile, not only to maintain biodiversity, but also to enable future scientific advances. The disappearance of some species could lead to the loss of knowledge and untapped resources.

Finally, bioluminescence remains a rapidly expanding field of research, whose future discoveries could transform our understanding of life and open up new avenues in science and technology. It thus represents a concrete example of the link between basic research and practical applications, while reminding us of the importance of exploring and protecting natural environments that are still unknown.

Beyond current knowledge, bioluminescence still raises many scientific questions. For example, researchers are seeking to better understand the precise evolutionary origin of certain bioluminescent systems, as well as the chemical variations between the different luciferins observed in marine species. New techniques, such as advanced genetic sequencing and robotic exploration of the abyss, could identify as yet unknown organisms and discover new mechanisms for light production.

In addition, bioluminescence could play an important role in emerging fields, such as the search for extraterrestrial life. Some scientists envision that life forms on other planets, especially in dark environments like the subglacial oceans of Europa (a moon of Jupiter), could use similar mechanisms to produce light. Thus, the study of bioluminescence is not limited to Earth's oceans, but also helps to expand our understanding of the conditions necessary for life in the universe.

Recommendations

Based on the results obtained and the limitations identified, several recommendations can be proposed in the fields of conservation, science and education. It is necessary to continue research by developing exploration tools adapted to great depths, in order to directly observe these organisms in their natural environment. For example, the use of more efficient underwater robots, equipped with cameras sensitive to low light, would make it possible to better study bioluminescent behaviors without disturbing species. It is also important to encourage collaboration between different disciplines, such as biology, engineering and computer science, in order to develop new methods of analysis and data collection.

First, when it comes to conservation, it is important to protect deep marine habitats from human activities that can disturb them, such as underwater mining or certain forms of pollution. These activities can destroy little-known ecosystems and lead to the disappearance of species before they are even discovered. Light pollution, even at sea, can also affect bioluminescent organisms by disrupting their natural behaviors, including communication, reproduction, and hunting. It is therefore essential to put in place international regulations and marine protected areas to preserve these fragile ecosystems in the long term.

Secondly, in the scientific field, it would be useful to strengthen data sharing among researchers on a global scale. The creation of accessible databases would improve the overall understanding of bioluminescence and facilitate comparisons between different ocean regions. It would also promote advances in biotechnological applications, particularly in medicine and the environment.

Finally, at the level of education, it would be useful to integrate bioluminescence more into school science curricula. This topic can help raise students' awareness of marine biodiversity, the importance of the oceans, and current environmental issues. The use of visual aids, documentaries or simple experiences in the classroom could make this learning more concrete and engaging. This would help to train a new generation that is more aware of the need to protect these environments.

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Appendices

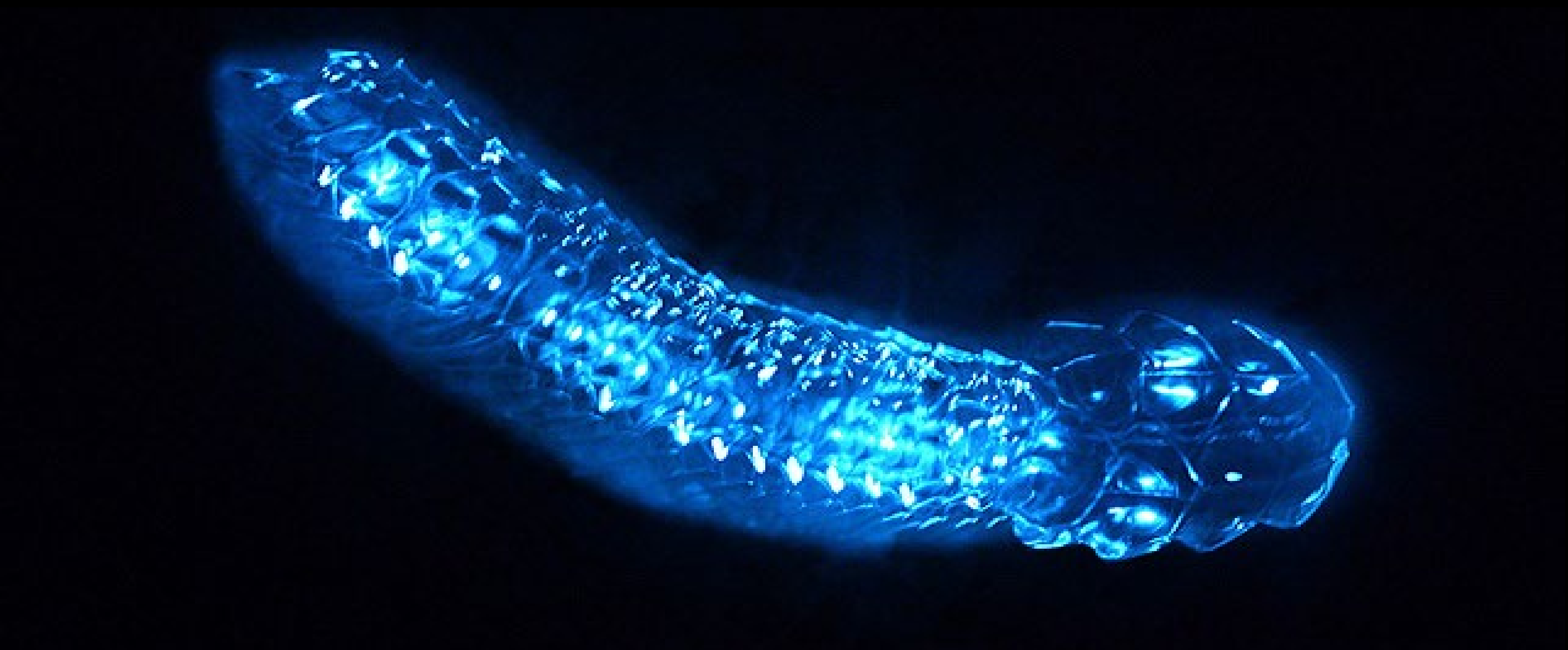

Figure 1. This image shows the siphonophore Frillagalma vityazi emitting bioluminescence in the laboratory (source: MBARI)

Taxon	Observations (%)
Hydromedusae	17.9
Appendicularia	15.1
Siphonophora	14.1
Chaetognatha	11.5
Crustacea	10.3
Polychaeta	9.8
Ctenophora	7.5
Fishes	4.6
Thaliacea	4.2
Rhizaria	2.8
Cephalopoda	1.3
Scyphozoa	0.7
Pteropoda	0.2

Figure 2. The monophyletic taxa are Cnidarians (Hydromedusae, Siphonophora and Scyphozoa) with 32.7% of the data, Molluscs (Pteropoda and Cephalopoda) with 1.5% of the data and Urochordata (Thaliacea and Appendicularia) with 23.9% of the data (Source: NCBI)

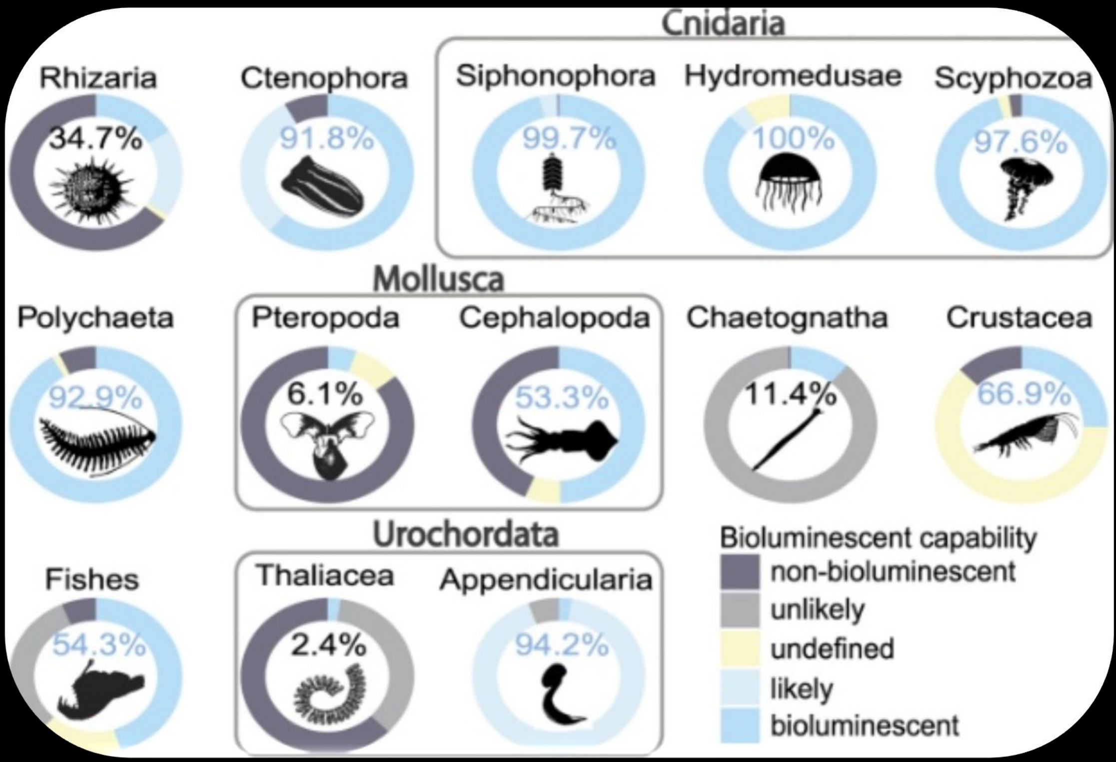

*Figure 3. (**a**) Number of observations (counts per hour) in the water column for organisms that are probably non-bioluminescent (non-bioluminescent and unlikely) and probably bioluminescent (bioluminescent and probable). (**b**) Proportion of the bioluminescence capacity distributed according to depth. In the lower box, the overall percentage of bioluminescent organisms is represented by 76%. The variability of this percentage, depending on the classification of unidentified animals, is indicated on the yellow bar (from 69 to 78%).*

Source: NCBI

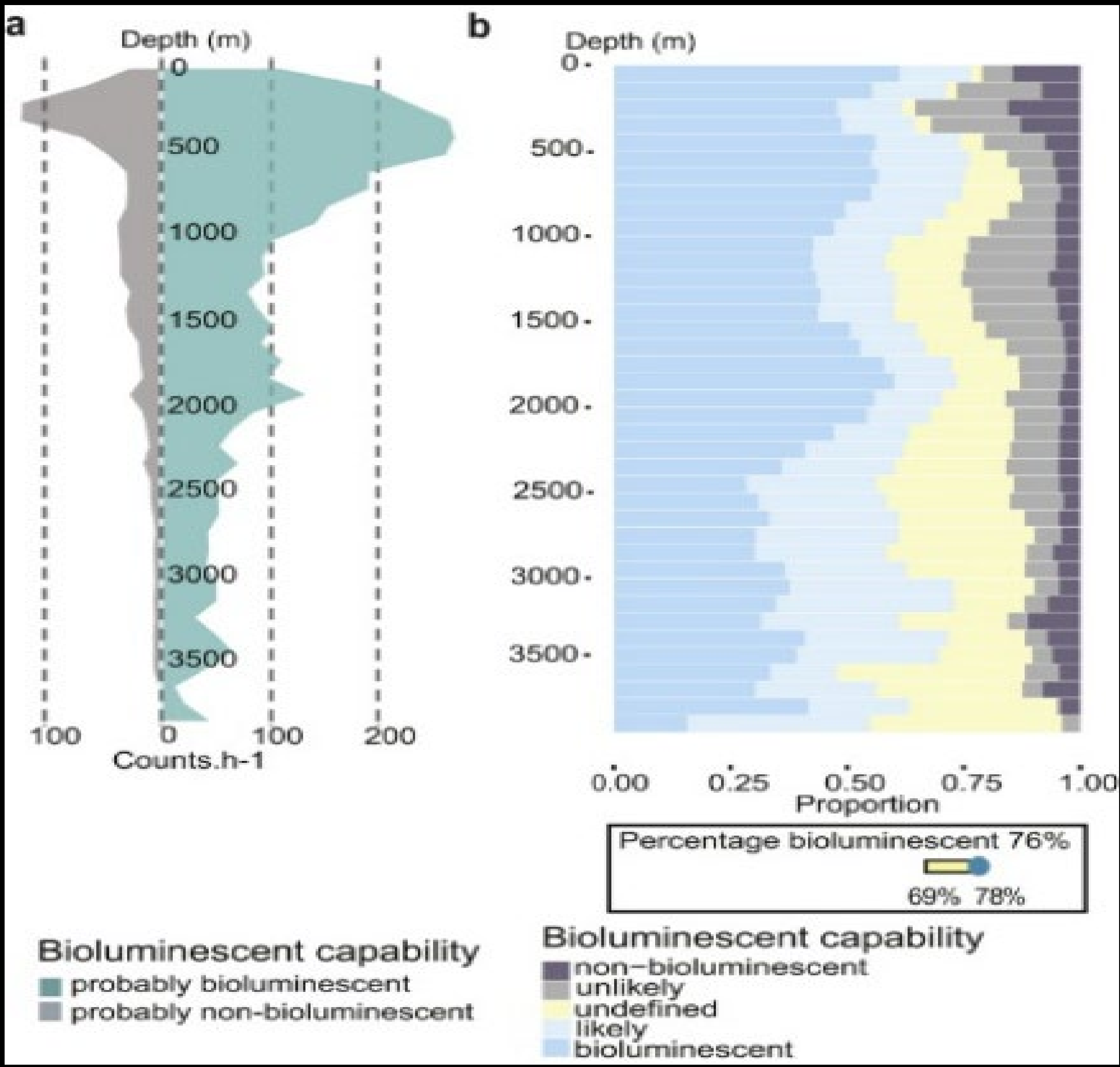

Figure 4. The percentages represent only the probably bioluminescent organisms in relation to the sum of the probably bioluminescent and probably non-bioluminescent organisms. Unidentified organisms were not included in these percentages. The color of the text indicates the predominance of ability. The grey frames delimit the major taxonomic groups: Cnidarians (Hydromedusae, Siphonophores and Scyphozoans), Molluscs (Pteropods and Cephalopods) and Urochordates (Thaliaceae and Appendiculars).

Source: NCBI

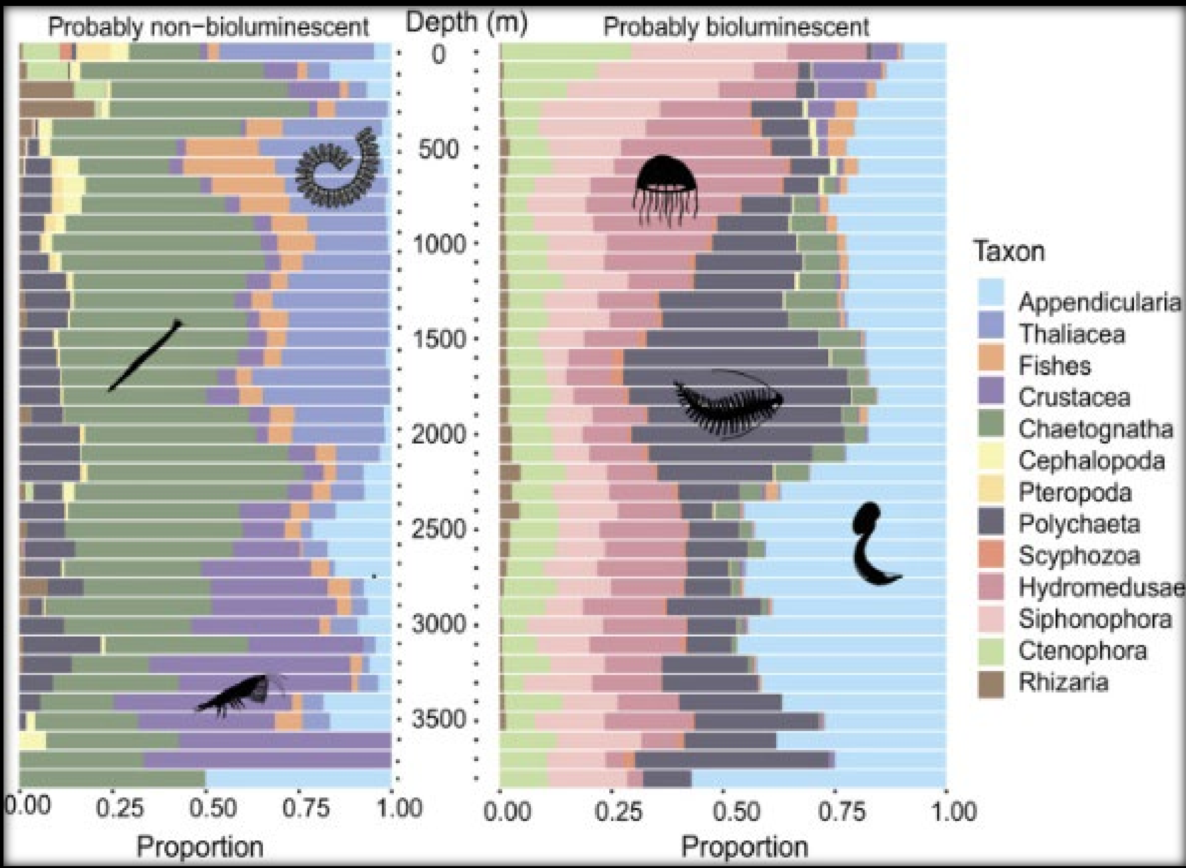

Figure 5. On the left, taxonomic composition of probably non-bioluminescent observations (including unlikely observations). On the right, taxonomic components of probably bioluminescent observations (including probable observations). The total number of observations differs between the two panels and by depth, but the proportion of each group (0 to 1) is represented as a function of depth (0 to 3,900 m) in 100 m intervals.

Source: NCBI

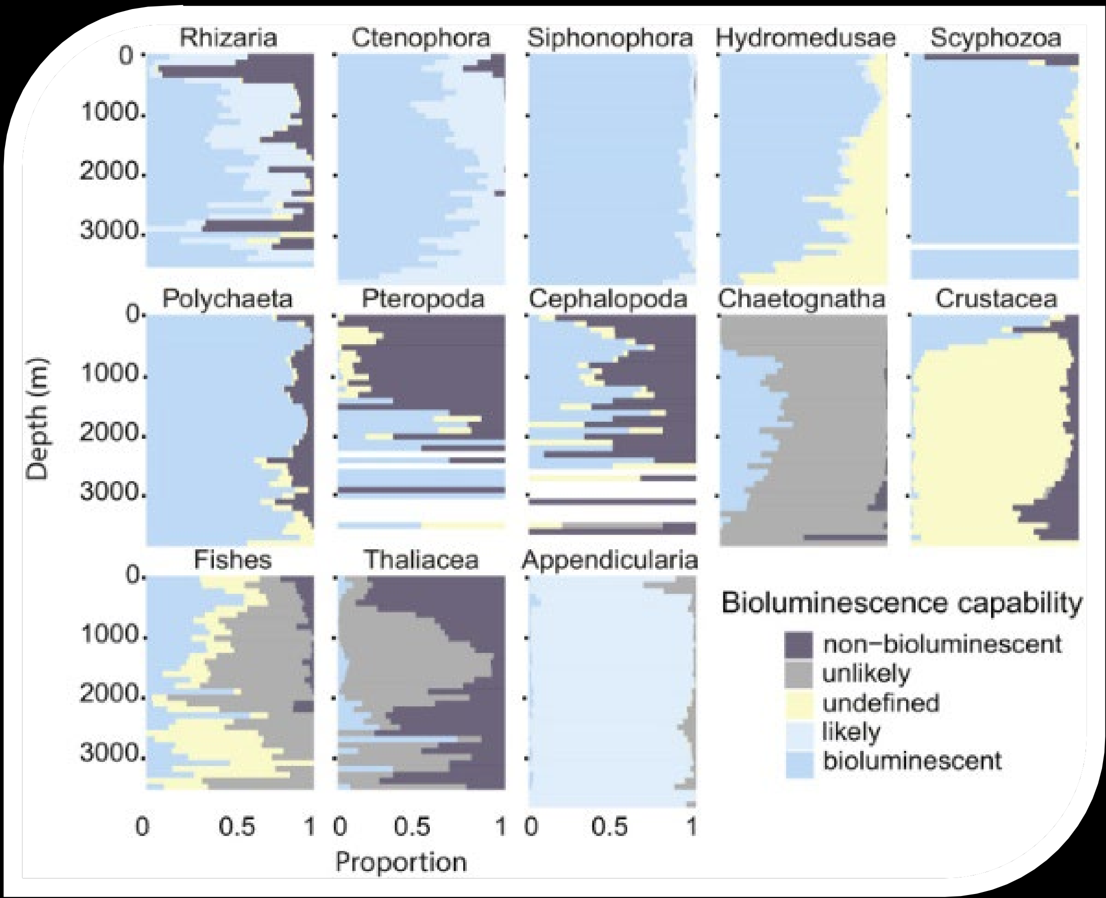

Figure 6. The proportion between 0 and 1 of each group is represented using 100 m classes from 0 to 3,900 m.

Source: NCBI

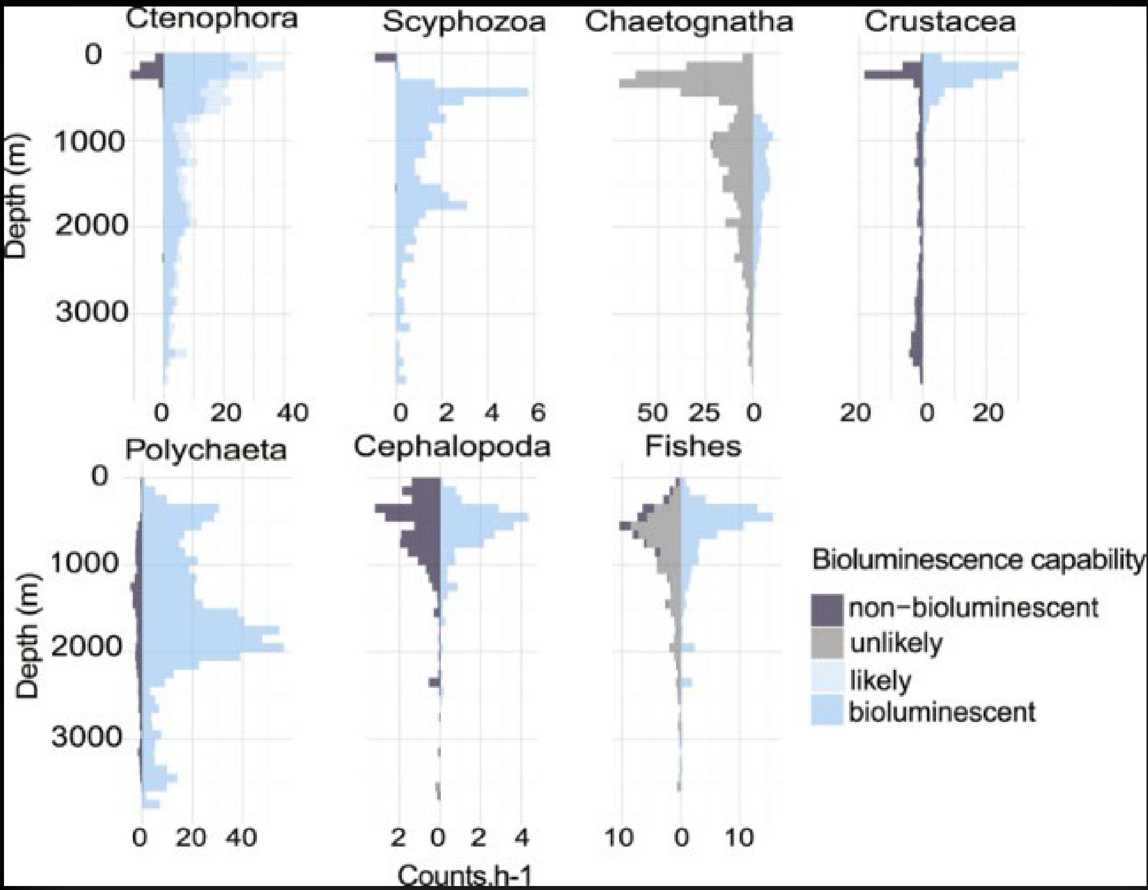

Figure 7. The number of animal counts is normalized per hour for each group and is represented as a function of depth (0 to 3,900 m) using 100 m intervals.

Source: NCBI

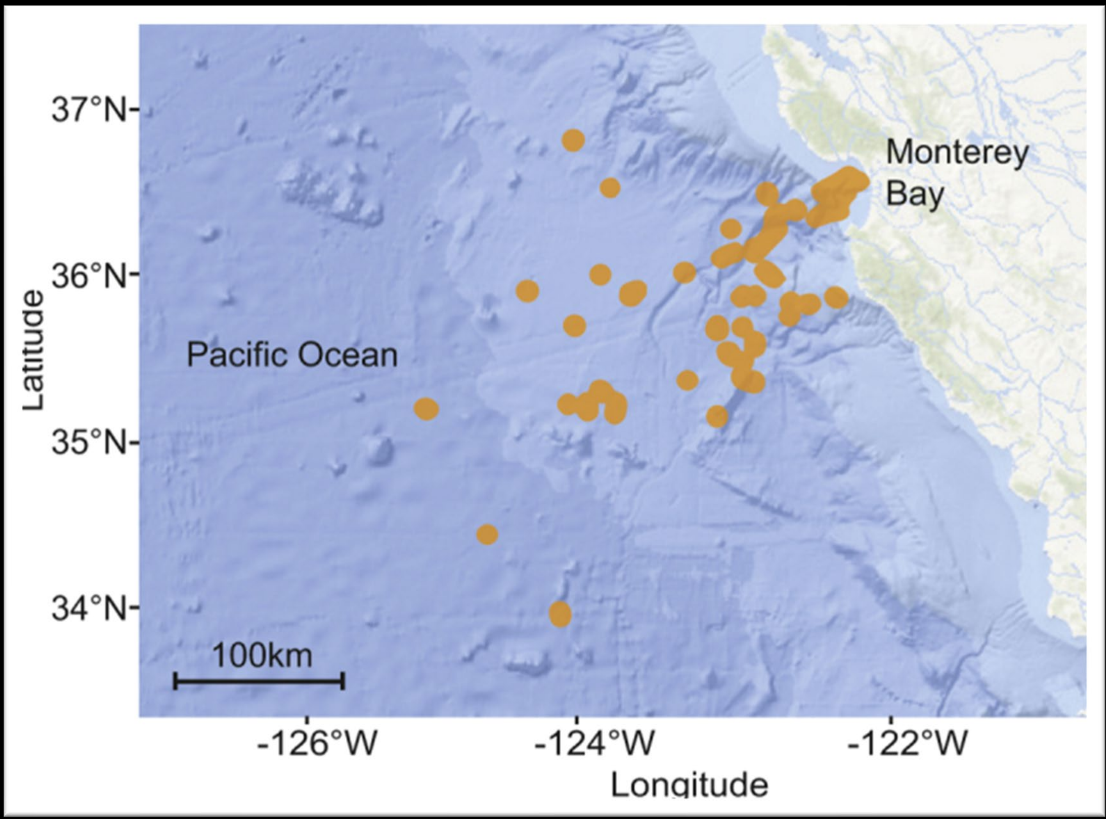

Figure 8. Map of the eastern Pacific Ocean and California coast showing sampling stations (orange dots) from March 1999 to June 2016 in the Monterey Bay area.

Source: NCBI

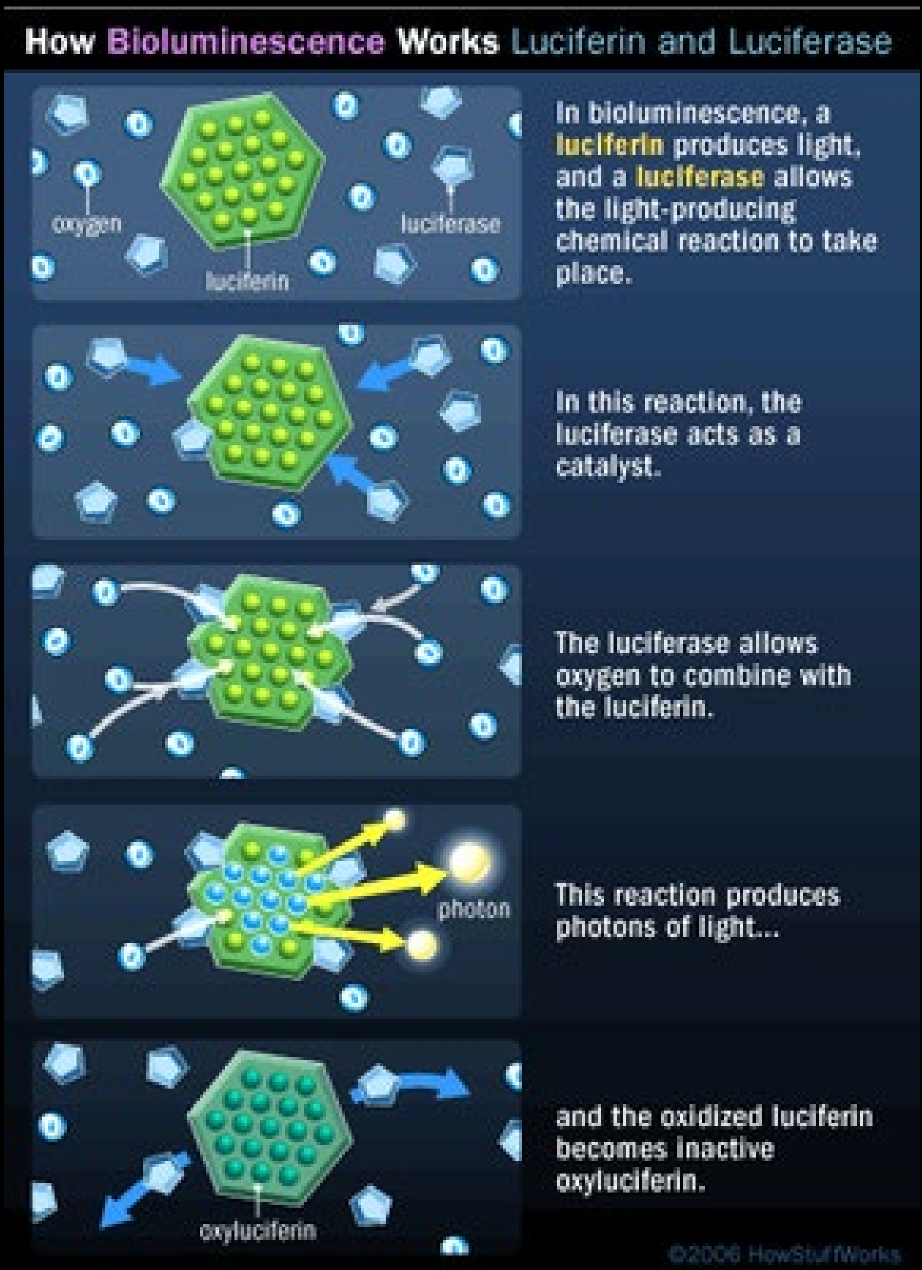

Figure 9. How Bioluminescence Works: Luciferin and Luciferase

Source: Howstuffworks.com

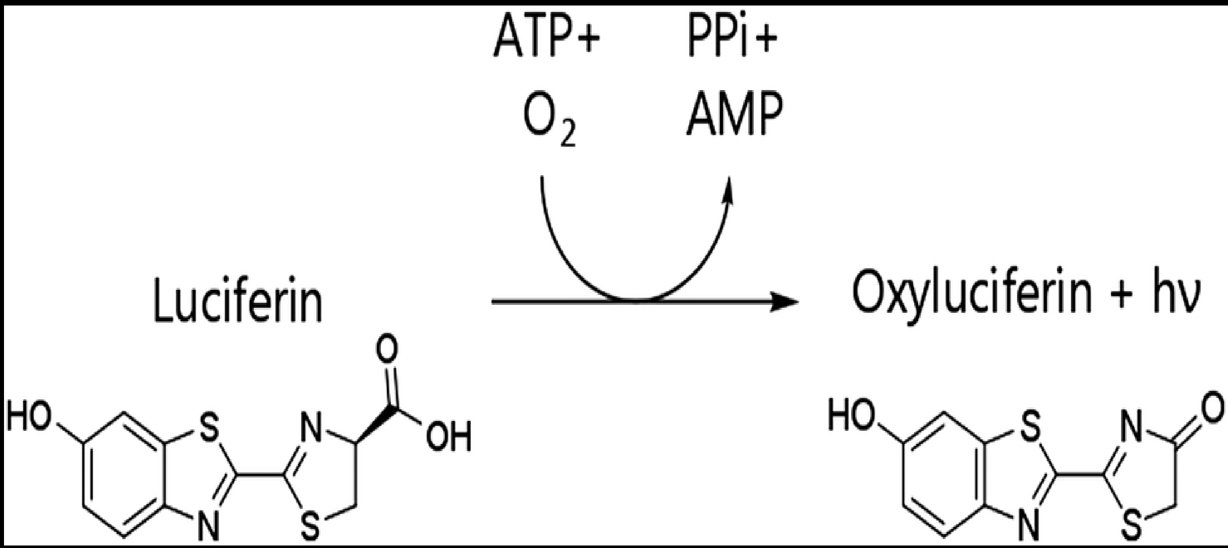

Figure 10. Diagram of the bioluminescence reaction that occurs in the luciferin–luciferase system

Source: https://pubs.rsc.org/