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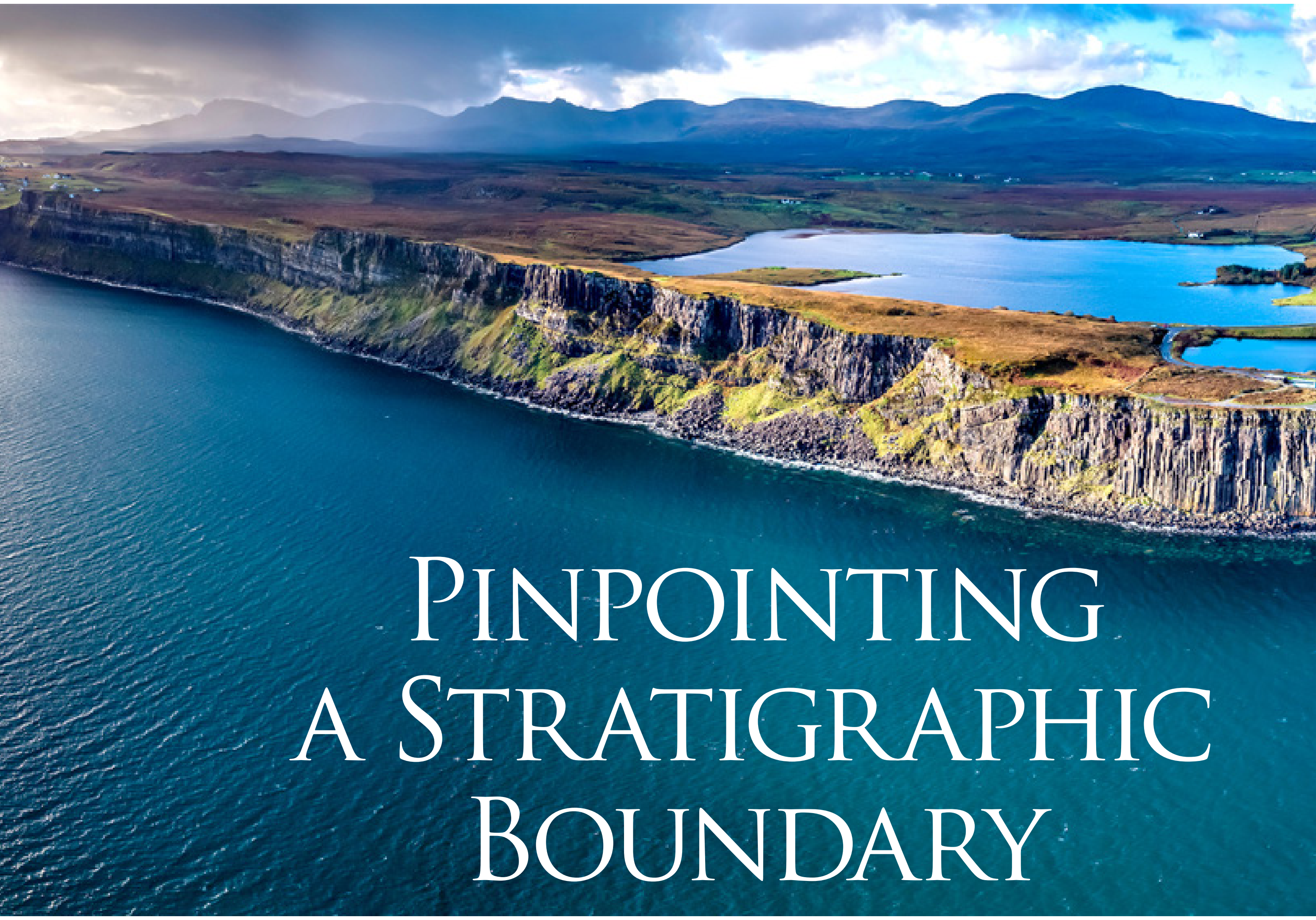

Pinpointing a Stratigraphic Boundary

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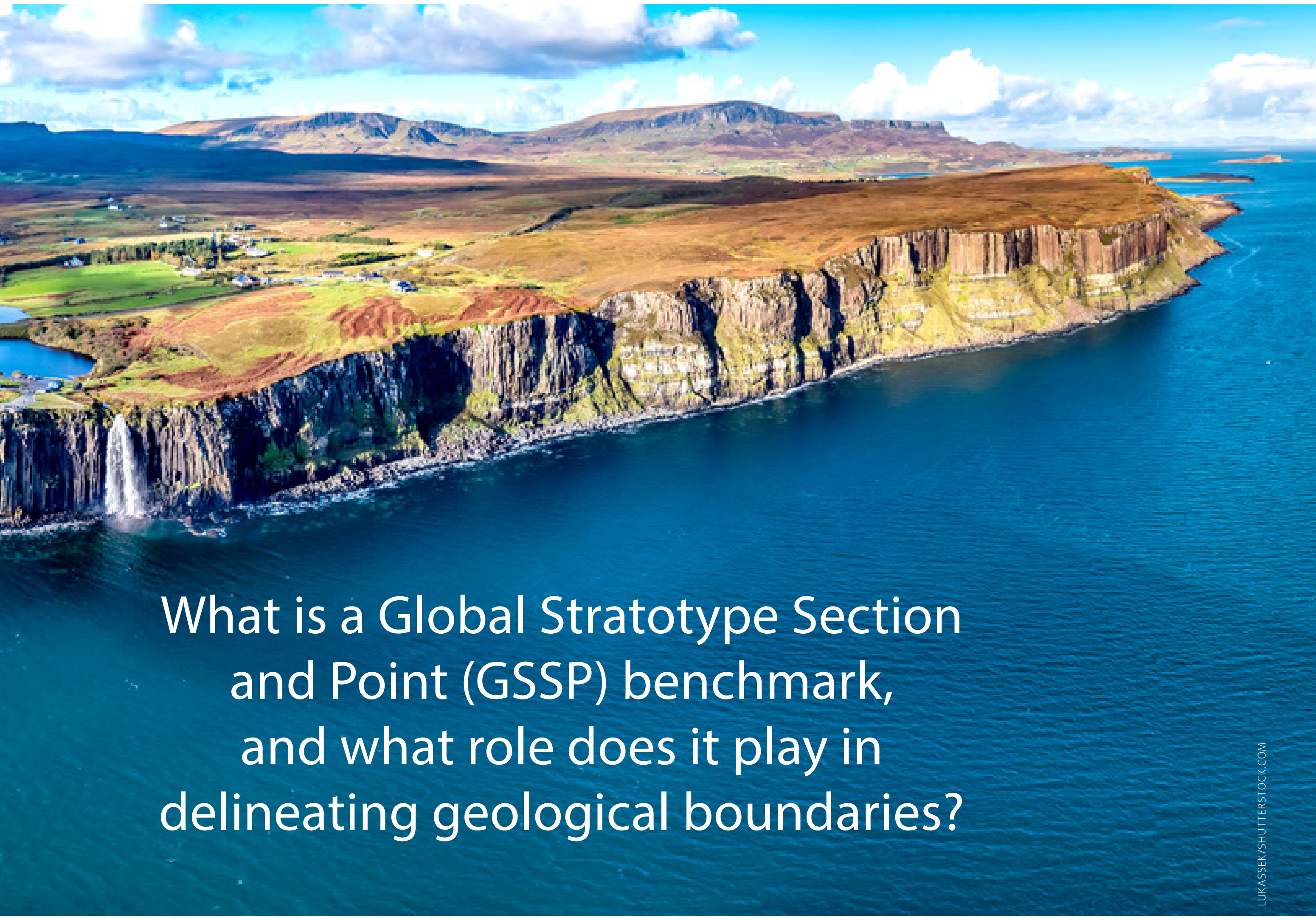
On 15 February 2021, the International Union of Geological Sciences (IUGS) ratified a proposal to place the GSSP (Global Stratotype Section and Point) for the base of the Kimmeridgian Stage (Upper Jurassic) near the hamlet of Flodigarry on the Isle of Skye, Scotland, thus finally concluding the procedure of its adoption. The proposal had been prepared by a team of dozens of geologists from many countries around the world, under the auspices of the International Subcommission on Jurassic Stratigraphy (ISJS), and was previously ratified by the International Stratigraphic Commission.

The news brief on the adoption states: "The boundary will be placed 1.25 ± 0.01 m below the base of Bed 36 in the foreshore at Flodigarry, Staffin Bay, Isle of Skye, Scotland, UK where it is marked by the appearance over a short stratigraphic interval of several new ammonite taxa. A significant advantage of this section and point is that abundant and well-preserved ammonites from two faunal provinces are found together and this considerably facilitates global recognition and correlation of the boundary in the field. The ammonite faunas delineate the base of the Subboreal ammonite Baylei Zone, the corresponding base of the Densicostata Subzone marked by the base of the *flodigarriensis* horizon, and, independently, the base of the Boreal ammonite Bauhini Zone. Additional markers of the boundary are provided by dinoflagellate cysts, magnetostratigraphy and strontium- and carbon-isotope data."

The preparation of the proposal, from the start of the team's work all the way to its final approval, took about 20 years. In what follows, we will provide more information regarding the accompanying circumstances, the terminology used, the expediency



What is a Global Stratotype Section and Point (GSSP) benchmark, and what role does it play in delineating geological boundaries?

Ile of Skye, Scotland

and complexity of the delimitation procedure, and also the long duration of the study.

History

From the very beginnings of the science of geology, determining when a rock was formed in comparison to others (whether it is younger or older) has posed a considerable challenge to successive generations of researchers. Initially, age comparisons of rocks from distant locations focused on their similarity or lack thereof, but it was later realized that similarity alone was not a good criterion for judging age. Similar rocks may appear many times in the geological record, and modern observations show that completely different types of rocks may be formed at the very same time, albeit under different conditions. That is why back in the nineteenth century, rocks started to be grouped into time units of a global nature: into geological *systems* and their corresponding time equivalents, or *periods*, and higher-order formations known as *erathemes* and their corresponding time equivalents, or *eras* (grouping several systems and periods). One of the first criteria to be used was to relate the time of rock formation to changes in the evolution of the organic world. Over the course of evolution, successive groups of organisms appeared and disappeared on the Earth, and the fossils they have left behind make it possible to compare the age of rocks from sometimes quite distant locations.

These geological systems were not defined by any single geological committee. Rather, they grew out of the efforts of many geologists working independently of one other, and only some of the proposals were accepted, while others were eventually forgotten. The same has been true for the identification of lower-order units, or geological *stages*. They have also been defined mainly by using paleontological methods, with most of them having been proposed back in the 19th century and are still defined in this way today. Geological stages form the structural basis of any geological system, as the lower boundary of the lowest stage in the system also represents the lower boundary of the system as a whole. This study of the order and relative position of strata and their relationship to the geological time scale is known as stratigraphy.

Alignment

Later research led to the development of more methods for comparing the age of rocks (known as "stratigraphic correlation"), based on such criteria as geochemical features (e.g. isotopic composition), recorded traces of shifts in the Earth's magnetic field, and others recorded in mineral matter. However, the actual succession of rock layers found in different places on Earth vary in terms of completeness. Certain time intervals may simply be materially absent at a particular location, either as a result of the original lack of a rock record or the removal of rocks by later erosion. Other circumstances may also have altered the original record at a later date (e.g. due to inflows of chemical solutions changing the original composition of the rock) or eliminated useful indicators (heating, for example, may erase recorded palaeomagnetic indicators). The result is that such rocks may fail to provide information about its age position (or worse, it may provide "false" indicators).

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Consequently, a need arose to define reference models to be used in identifying the boundaries between geological units, primarily the geological stages (as all higher-order units are defined by the lower boundary of the lowest stage), by identifying an ideally preserved, complete and unaltered succession of rocks at a specific location, with a specific point indicated as the pattern marking the boundary. This gave rise to the term GSSP (Global Stratotype Section and Point), denoting the global standard profile of rocks (i.e. rock layers presented in the order of their origin in a place considered to be a reference model) and a point in it marking the boundary, as denoted by a "golden spike" (symbolically speaking, as no one actually drives a golden spike into the rock there). The GSSP boundary patterns have been commonly assigned since 1977 under the auspices of the International Union of Geological Sciences (IUGS) and, once accepted, become the binding reference for the whole world.

Why such a procedure?

One might ask: Why is it so important to precisely identify a particular rock or rock layer as belonging to a particular geological stage or system? Well, it turns out to be crucial for thoroughly understanding the geological structure of a site (creating a geological map), for instance when identifying the correct localization of a borehole when prospecting for mineral resources, recognizing conductive layers to be mined (e.g. hydrocarbons), or planning major construction projects. Of course, it is also important for scientific research, which requires precise determination of the age of rocks. Sometimes, research into identifying a GSSP reference model also provides completely new, unexpected results and corrects old errors in the previously used stratigraphic correlations. It is under such circumstances that the aforementioned reference model for the base of the Kimmeridgian Stage in the Jurassic system should be considered.

Establishing a new benchmark

The present author chaired the international team which, acting under the auspices of the Jurassic Stratigraphy Subcommittee (under the framework of the IUGS), has worked on with determining the reference site for the base of the Kimmeridgian – one of the three stages of the Upper Jurassic, and upper part of the Jurassic system. The stage was named after the village of Kimmeridge on the Dorset coast of southern England and was introduced over 200 years ago, defined on the basis of recorded changes in ammonite shells in rocks exposed at the site in 1913. These changes reflect the appearance in the evolutionary process of a new genus of ammonites, *Pictonia*, and its successive species. Their presence is used to determine the lowest stratigraphic units of the Kimmeridgian mentioned at the beginning of the article – the zone (Baylei), sub-zone (Densicostata) and horizon (Flodigarrienis). Ammonites from this area belong to the group of northern (subboreal) ammonites and are typical for the whole of north-western Europe and much of the Arctic. However, because the profiles in southern England were characterized by an incomplete geological record, with temporal (stratigraphic) gaps, they did not meet the requirements to serve as the GSSP standard, so another profile with a similar ammonite fauna had to be found. Profiles in Arctic areas such as Greenland and Siberia, although evidencing similar ammonite fauna, failed on the other hand to meet the requirement for easy access to the reference standard. The only Kimmeridgian profile that meets all the guidelines for a GSSP standard turns out to be the one exposed on the Isle of Skye in northern Scotland. This profile is located at the base of a cliff, in the intertidal zone, which, although hampering access to some extent, ensures that the rocks present are well exposed at all times, as the fine rock debris does not lie on the exposure but is removed by strong currents at low tide.

The Flodigarry profile on the Isle of Skye also meets the other requirements to become a GSSP standard. It contains numerous well-preserved fossils of extinct cephalopods: ammonites and belemnites, as well as microfossils (cysts of dinoflagellates, composed of calcareous or organic matter), allowing for the precise determination of stratigraphic succession and studies of the composition of stable isotopes (oxygen, carbon, strontium) in the calcium carbonate belemnite skeletons. Moreover, the rocks occurring there, mainly dark siltstone and shale, have preserved the original record of past changes in the directions of the Earth's magnetic poles, used in palaeomagnetic dating. It is also important that comprehensive comparisons can be made between changes in ammonite faunal assemblages of this profile and assemblages from other parts of Europe and the world, partly on the basis of so called auxiliary profiles, and therefore to use this reference standard to determine the exact age equivalent of the accepted pattern of the Oxfordian-Kimmeridgian boundary in other areas.

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Staffin Bay near the village of Flodigarry on the Isle of Skye, where a new benchmark (GSSP) for the lower boundary of the base of the Kimmeridgian Stage has been established. The site of the GSSP profile is situated near the large boulder indicated by the arrow; geologists can be seen working nearby

Correcting for error

Work on studying the Flodigarry profile led to the unexpected discovery of an error made in stratigraphic correlation (ca. 1950), whereby ammonites from northern and southern Europe, which in fact represent different assemblages developing at different times, were recognized as being equal in age. This error resulted in the Lower Kimmeridgian boundary being identified much higher in the southern part of Europe, more or less two ammonite levels higher (corresponding to about 1–1.5 million years later) than in the north. As a result, there were two unofficial boundaries regarded as the lower limit of the Kimmeridgian (and indeed there still are today – although this will have to be rectified), very different in position, in northern and southern Europe, though geologists did not realize this. With regard to the Jurassic stages, this was probably the biggest mistake ever identified in the established stratigraphic divisions, which further demonstrates the usefulness of identifying universal GSSP references.

The work of the Kimmeridgian group, in addition to documenting the GSSP reference site on the Isle of Skye, therefore had to be supplemented with work in other areas of Europe in order to correctly perform the correlation between northern and southern areas on the continent. As part of this work, complementary surveys of additional profiles were carried out, primarily to investigate the assemblages of ammonite faunas, key to the correlation exercise. Such studies were carried out at three sites in Europe: in northern Russia near the village of Mikhalenino near the town of Makariev (Kostroma region), in central Poland at the village of Bobrowniki in the Wieluń Upland and in central Spain near the village of Fuentelspino de Moya near the town of Landete (Castilla region). In addition to paleontological work at the mentioned profiles, other time-consuming research was carried out by geologists of various specializations, all of which had to be compared, reconciled, and at least partly published. Moreover, the procedure of having the new GSSP reference approved required discussions at each of the successive levels, and sometimes also certain modifications.

The adoption of a global reference model for the boundary of Oxfordian and Kimmeridgian stages eliminates significant discrepancies between the existing regional divisions, which are particularly significant between northern and southern Europe (i.e. the areas of the former Boreal and Mediterranean biogeographic provinces, inhabited by different assemblages of organisms), and thus significantly clarifies the stratigraphic subdivision of the Upper Jurassic. It also makes it necessary to update geological maps and divisions of the Jurassic in various places, including in Poland, where the presently accepted boundaries of the Oxfordian and Kimmeridgian will shift considerably towards older strata, requiring the adjustment of numerous maps, cross-sections, and geological schemes. It also provides persuasive proof of the effectiveness of international scientific collaboration, while likewise bearing testimony to Poland's strength in the field of geology, as several Polish geologists took active part in the work on identifying the new GSSP reference model. ■