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GREENSANDS - THE STORY THEY TELL ABOUT THE GEOLOGICAL PAST

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ABSTRACT

Greensands are regarded as loose, shallow marine sediments that contain a common, yet useful palaeoenvironmental (i.e. past environment) and chemical indicator, a green mineral called glauconite. So far, glauconite has been used as a low sedimentation rate and sea level rise indicator in geoscience. Its occurrence in the United Kingdom indicates, together with other geological evidence, that during the Lower Cretaceous (140Ma-100Ma), the mainland was partially submerged due to higher global temperatures and sea-levels. In this paper, physical and chemical differences between two samples of greensands from New Zealand have been assessed in order to reconstruct a past environment and therefore gain further insight into the formation of this type of sediment. The occurrence of greensands in UK has been theoretically investigated in this study by using data gathered from New Zealand samples. While a new use for glauconite as a past marine acidity indicator has been proposed, further investigations must be undertaken before this can be validated. The overall aim of this paper is to explain a process of thinking and of analysis which starts from sample characteristics and small details that builds up to form a bigger geological picture. This includes novel research and a review of the literature that cumulatively aid in determining the environmental conditions that existed in the past for specific geologic units.

INTRODUCTION

As in the case of other geological units, the main reason for looking in depth at a single sample of marine sediments is to discover more about the environmental conditions that prevailed at the time of its formation and deposition. This will aid our understanding of the geological past and relationships between the atmosphere, hydrosphere, and biosphere. By combining physical observations, such as colour, grain size, hardness, lustre, and shape with chemical data obtained from laboratory techniques, we can find out what chemical elements in that particular marine setting and at that particular time were needed to create the described sediment. We can start thinking of the sources of those chemical elements (i.e. land, sea or atmosphere) and of the pathways involved in delivering them to that particular setting in order to understand how different environments were linked. The study of fossil assemblages present within sediments aids in estimating the age of the formation and assessing the depth of deposition. This is possible because we know that some calcite-secreting organisms are restricted to specific depths, depending on the light levels required for particular metabolic processes. Of course, the accuracy of the technique can be low in first observations, as some sediments or fossils could have been transported from various depths, and as sampling levels and procedures between outcrops of the same formations may not be consistent. However, by studying the same formation type in different regions and geological periods, various reoccurring patterns arise and lead to a better understanding of the way in which the sediment type had formed. Once norms are confirmed by individual studies, the simple occurrence of such units in the geological record can tell a story of the past. Greensands are a type of these units.

Numerous studies have been conducted in glauconitic deposits in the United States (Ashley, 1917; Seed, 1964, Chafetz and Reid, 2000), New Zealand (Hutton and Seeley, 1941), Russia (Sanchez-Navas et al., 2008) and the United Kingdom (Carson and Crowley, 1993; Loveland, 1981), allowing premature constraints and viable comparisons with the results presented in this study.

This paper investigates two greensand units, **Kokoamu Greensand** (**KG**) and **Orari River Greensand** (**ORG**) from New Zealand, in order to make educated assumptions about greensand units found in the UK. It is also the first paper to present any geochemical or palaeoenvironmental data and interpretations about ORG; thus, although a comparison between the first two samples, as well as their palaeoenvironments and modes of formation are provided, much of the focus of this paper will be on the ORG.

Furthermore, some unusual features that resemble rounded depressions have been observed under high magnification in molluscs from the ORG sample that are here referred to as 'pit-like structures'. These structures have been studied in detail for three main reasons: i) from the beginning of this study, their occurrence has been linked to the higher maturation degree of the sample and thus, to certain palaeoenvironmental factors specific only to ORG; ii) they could indicate a new or poorly studied post-mortem process that occurs during glauconitisation; and iii) they might be an indicator of palaeoacidity. The latter implication could help correlate the degree of maturation and time spent in the glauconitisation zone (Figure 2) to the decrease in pH. Here, pH changes are related to oxidizing organic matter that fuelled the glauconitisation process in the first place. The ultimate aim is to relate the apparent colour of the sediments (Figure 2; Amorosi, 1997), to the palaeoacidity of the environment.

In the **United Kingdom**, the occurrence of greensands bears the same palaeoenvironmental significance as the discussed samples from New Zealand. Here, glauconite-bearing units are divided into Lower and Upper Greensand and, apart from their

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agricultural use (Carson and Crowley, 1993), they have been exploited for their aquifer and building-stone value.

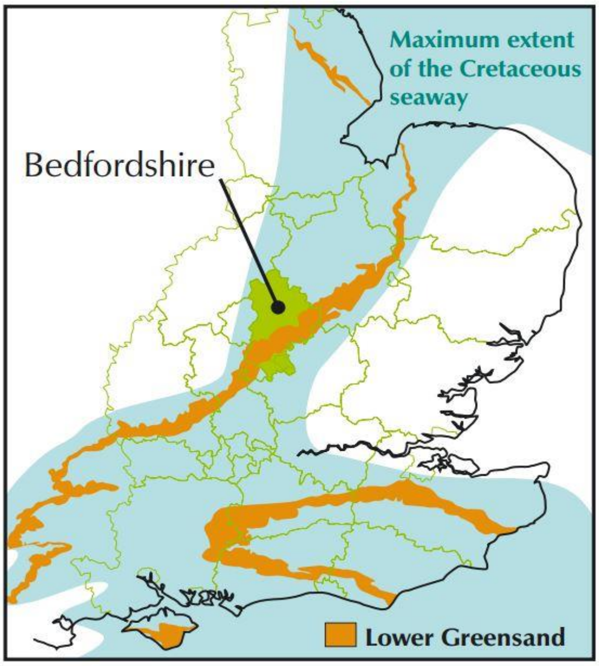

Figure 1: Geographical distribution of Lower Greensand in the United Kingdom and palaeosea level during Cretaceous (website 1), a period of high temperatures and lack of continental glaciers (Li et al., 2016).

In the south of the UK, the **Lower Greensand** can be found stretching both in the East and West (Figure 1) and is best exposed in locations such as Weald, where it reaches its maximum thickness of 220m (Shand et al., 2003), Shanklin on Isle of Wight, West and East Sussex, Cambridge-Bedford area, Kent and Surrey. The tourist route, *The Greensand Ways*, runs between the latter two localities, following the unit's geological occurrence. The unit has been the subject of hydrology research and reports (Allen et al., 1997) as it is considered an important aquifer in southeast England for public and private water source supply (Shand et al., 2003) and, furthermore, its rocks successions have been used as building stones in London in the past (Lott and Cameron, 2005).

Upper Greensand is best known in the United Kingdom by its occurrence in Weald and Seaton where it reaches its maximum thickness of 60m, South Dorset (Allen et al., 1997) and along the coast of Devon from Sidmouth to Lyme Regis (Carson and Crowley, 1993). Here, however, due to its long aerial exposure, the iron within the glauconite was oxidized and gave the formation a brown-yellow colour which might make the unit hard to recognize (Hamblin, 2013). Its basal unit, Cambridge Greensand, contains marine reptile and dinosaur fossils such as lepidosaur and pterosaur bones (Unwin, 2001; Barrett and Evans, 2002).

GREENSANDS-GENERAL CHARACTERISTICS

Greensands are regarded as loose, unconsolidated sands that contain a green mineral, glauconite (Ashley, 1916). Studies have been concerned with the formation, occurrence, and uses of glauconite since the 1760's and was first reported by Cook (1868) as it was considered an important source of potash (reported here as K_2O) for agriculture and horticulture (McRae, 1972). Geological interest came from the fact that glauconite, a common authigenic constituent (i.e. that did not undergo transport processes and is found at the same place where it had formed) in marine settings, can be used as a relative indicator of sea level (Carson and Crowley, 1993) and low sedimentation rate (Ross, 1926) and, given more recent studies, as a useful palaeoenvironmental and chemical constrainer (Smaill, 2015; Banerjee et al., 2016).

The most common occurrence of glauconite has been observed at depths below wave-action (50m to 500m). Furthermore, sea level rise is known to facilitate deposition of glauconite through the decrease of sediment input that allows grains to spend more time in the glauconitisation zone (Thompson, 2013; Odin and Fullagar, 1988; Odin and Matter, 1981; Amorosi, 1997), by increasing the organic matter availability (i.e. from adjacent landmasses) and the area of faecal pellets accumulation (McRae, 1972; Odin and Matter, 1981; Amorosi, 1997). As the general formula of glauconite is $\mathbf{K_{(x+y)}(Si_{4-x}, Al_x)_{\sim 4}(Fe^{3+}, Al, Mg, Fe^{2+})_{\sim 2}\, O_{10}(OH)_2}$, certain chemical elements such as Fe, Mg, Al and Si need to exist in a free state from parent grains (i.e. grains that deliver those ions to the environment) or need to be pre-existing in the host material in which glauconite will precipitate (Huggetts, 2005). In the above described environments, decaying organic matter creates neutral to reducing conditions in which Fe and K ions move freely in solution and can later precipitate to form glauconite (Odin and Matter, 1981).

The degree of maturation is one of the most important characteristics of glauconite-bearing grains, as it contains information about the time sediments have spent in the glauconitisation zone (i.e. while the glauconitisation process was active). Maturity is inversely proportional with sedimentation rate and directly proportional with the relative percentage of K_2O (Figure 2). Here, the terms low, intermediate, medium and high maturation degree are used to describe the K_2O percentages and, hence, maturity of samples (Amorosi, 1997).

SAMPLES

Knowledge of the region from where the samples came is just as important as the samples themselves. By looking at a geological map of the area, a geologist can make assumptions about how the environment changed on a million-year time scale and the rate at which the sea level oscillated. Certain neighbouring geological units, such as fossil-bearing sandstones, limestone, and mudstones indicate the presence of the ocean in the past, even if the region is now at the surface, covered by forests or a well-known city. Indeed, in the case of samples discussed throughout this paper, they occur in regions of marine sediments.

The first sample from KG, is late Oligocene in age (~26Ma, Forsyth, 2001). It was collected from Earthquakes, New Zealand, and has a wide range of green colour shades (Figure 2.a). This unit has been well studied and documented throughout scientific literature (Gage, 1957; MacKinnon et al., 1993; Smaill, 2015) and its rich fossil content has been the subject of many scientific papers (Ayress, 1993; MacKinnon et al., 1993; Clementz et al., 2014) which is why it has been used as a reference in this study.

The second greensand sample comes from the proximity of Orari River (ORG), dates back to mid Miocene (~14Ma), and has a dark-green colour (Figure 2.b). It has a lower diversity and abundance of fossils than KG and has never been the subject of any glauconite-related studies.

These two samples from New Zealand, Otago, have been studied and their maturation degrees have been assessed based on both superficial color (Figure 2) and chemical difference (Table 1). The exact sampling place (i.e. geographical and height in unit) is unknown, thus the palaeoenvironments of deposition were assessed with caution.

METHODS

Both samples had been previously sieved and placed in size-labelled transparent containers. They were analysed starting from the coarsest component towards the finest under high-magnification (stereomicroscope) and fossil assemblages were hand-picked, described, and identified.

Maturity was first assessed based on the superficial colour characteristics of each sample, as described by Amorosi (1997) and detailed below (Figure 2), where the lighter green-shade represents low maturity and the darkest shade, high maturity. Once initial assessments were made, maturity of both samples was studied under the Scanning Electronic Microscope (SEM). Spot analysis was conducted on glauconite-bearing pellets of both samples and their chemical composition (Table 1) was recorded with the aid of a software (EDAX Genesis).

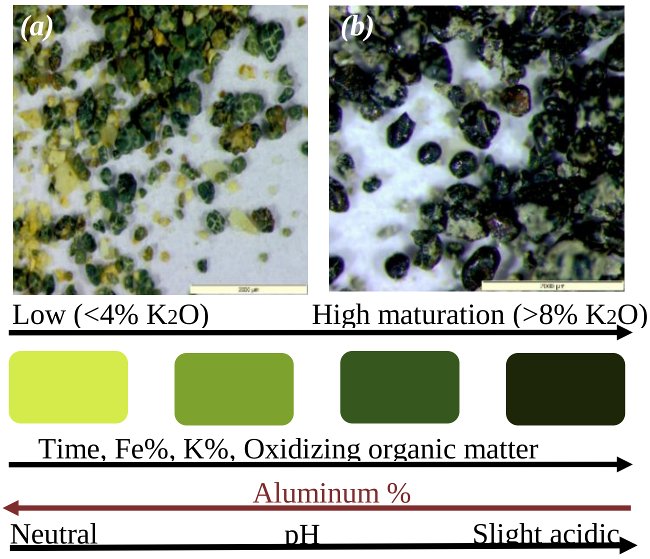

Figure 2: Visual assessment of the maturation degree of the two samples based on their superficial colours (light microscopy) and a green-scale for reference. Notice the difference in colour between (a) KG which plots on the green-scale diagram towards the left suggesting that is has a low- intermediate maturation degree and (b) ORG, that plots in the right end of the diagram, indicating that it has high maturation degree and a relatively higher content of Fe and K. Scale bar 2000µm.

Following spot analysis, one resin block containing loose and aggregate greensands from the two samples (Figure 3.a) and one block containing ORG molluscs (Figure 3.b) were made. Molluscs were selected under high magnification and embedded in 2cm thick resin. Both resins blocks were polished until components were exposed on the surface. This allowed the study of glauconite-bearing grains and of pit-like structures in cross section under various analysers (SEM and backscattered electron detector-BSE, Figure 7).

Seven carbon-coated molluscs from ORG were placed on a stub and examined under the microscope, using two different analysers (BSE and Secondary Electron-SE). This allowed a 3D visualization of the pit-like structures (Figure 6c and 6d) and more precise measurements of their sizes to be taken. Examples of pit-like structures have been studied under the stereomicroscope (Figure 5) and under the BSE component of the SEM (Figure 6, 7).

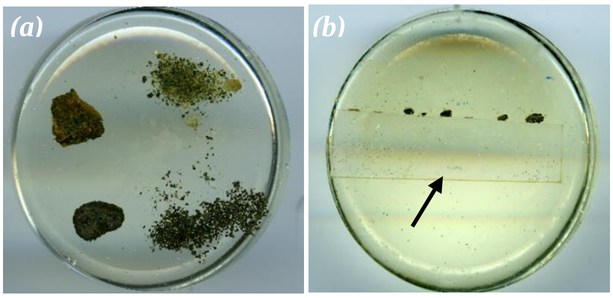

Figure 3: Two resin blocks after final polishing step. (a) represents both samples taken as poorly cemented and loose constituents while (b) shows ORG's molluscs that contained pit-like structures. Notice that they were first glued onto a thin strip of resin (arrow) that was later embedded in resin. Both blocks are 4cm across.

Furthermore, crystallographic orientation of an 10,000µm^2 area below the pit-like structure was analysed using the Electron Backscattered Diffraction (EBSD) technique. The analyser's phase was set as aragonite, allowing: i) to confirm that the shells are indeed aragonitic in nature; and ii) to focus only on those crystals. This was done in order for the relative angle of orientation of crystals to be depicted (Figure 7d).

RESULTS

Under high magnification, KG was described as a fossil-rich unit, with glauconite-grains of various colours, but plotting overall in the low-intermediate area of maturation (Figure 2a). More than 95% of glauconite-bearing grains proved to be clay faecal pellets, of various morphologies (Smaill, 2015). The remaining 5% is composed of glauconitised bioclasts (i.e. noticed as green shaded areas in calcite bioclasts). The samples contained numerous fossils and fossil fragments of brachiopods, echinoderm plates, primary and secondary spines, pennatulaceans, ostracods and species of foraminifera that lived both on the sea floor and in the water column. Fossil bioclasts showed different degrees of erosion (Figure 4a) and iron oxide deposition in cements or on parts of the shells. Shark teeth have also been found (Figure 4b).

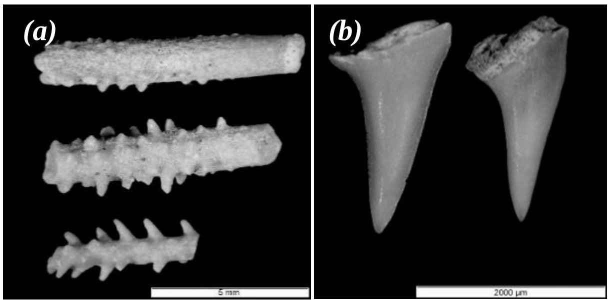

Figure 4: Bioclast components of KG. (a) shows echinoderm spines that indicate various degrees of erosion that point towards a reworked and possibly allochthonous material. (b) shows two teeth found in the same sample. Scale bars 5mm and, 2000µm.

ORG has a lower biodiversity and fossil abundance than KG. The apparent colour of glauconite-bearing pellets plots in a very narrow range, all having a dark-green colour. Again, more than 95% of glauconite-bearing components are faecal pellets, with the remaining 5% being composed of glauconite-bearing fossil components. In terms of fossil assemblages, the sample contains two species of brachiopods, only two examples of echinoderm plates, less than five examples of mm-scale snail shells, numerous ostracods, two types of sea-floor living and abundant water column foraminifera. One species of a mm-scale mollusc has also been sampled and will be discussed later.

Chemical composition of samples was examined via spot-analysis using the Energy Dispersive Spectroscopy (EDS) component contained in the SEM and with the aid of EDAX Genesis software. The composition of glauconite-bearing pellets was further investigated and averages of N=10 grains per sample are presented in the table below.

Table 1: Averaged chemical composition (wt% = weight percentage) of 20 glauconite-bearing pellets from KG and ORG. The empirical formula of glauconite for the averaged values verifies conditions proposed by Huggett (2005).

	O wt%	**Mg wt%**	**Al wt%**	**Si wt%**	**K wt%**	**Fe wt%**
KG	34.03	3.35	3.17	29.59	8.35	19.46
ORG	34.19	3.01	4.94	29.80	6.48	21.49

At a close investigation of ORG's aragonite molluscs, rounded, pit-like structures or depressions could be observed on either the interior or the exterior of the valves (Figure 5 and 6). The mollusc shells were very fragile and few intact examples were seen. When structures occurred on the interior, growth lines can be seen beneath (Figure 5a) and when they occur on the exterior of the valves, growth lines were erased (Figure 5b), thus the whole structure of the shell was affected.

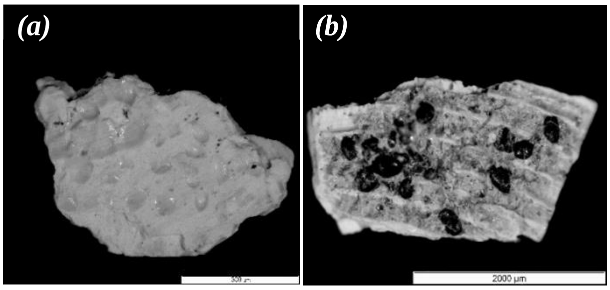

Figure 5: Pit-like structures present in molluscs bioclasts in ORG. (a) displays over 20 such structures that were created on the interior of a valve. (b) shows glauconite-bearing pellets attached to the exterior valve of a mollusc bioclast. Scale bar 300µm and 2000µm respectively.

When investigated in cross-section, the area below pit-like structures was composed of a thick, nacre-table layer capped by a prismatic layer of aragonite crystals (Figure 7b and 7c). The nacre layer is made of aragonite lamellar tablets (Olson et al., 2013) and shows interesting features just below the pit-like structure (see arrows in Figure 7a and 7b). First, there is a high degree of disorder as spacing between tablets appears to vary across the shell: just below the pit-like structure they have a greater thickness and appear to be in part sutured together across vertical distance (i.e. varying apparent thicknesses between 5-20µm). Micrometric-scale fissures are seen propagating downwards from the surface in the affected areas. This causes the nacreous tablets to collapse in a domino-style towards the fissures' centres (Figure 7c). Furthermore, the larger crystals that are part of the prismatic layer appear to overprint parts of the nacreous layer. A higher degree of order could be seen in other areas of the shell, away from such structures.

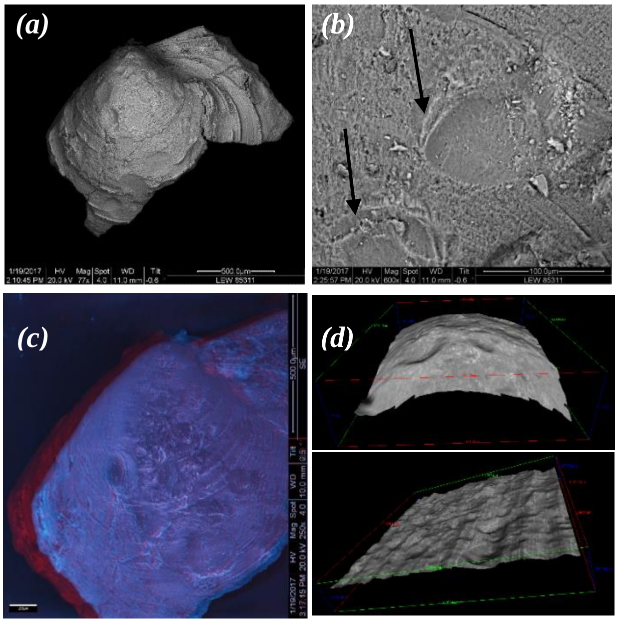

Figure 6: Mollusc valve with pit-like structures. (a) entire valve (scale bar 500µm) and (b) zoom-in on two of the structures. The two arrows point towards areas where recrystallization of aragonite took place in a 'wave-like' fashion. Also notice how the growth line is erased by the occurrence of a pit-like structure. Scale bar 100µm. (c) and (d) 3D views of the shell and extent of depressions on the surface.

Crystallographic orientation was analysed in a mollusc sample that presented such a pit-like structure (Figure 7d). Different colours in Figure 7d indicate different orientations of aragonite tablets and prisms. Indeed, the nacreous tablets show varying crystallographic orientations, yet most of the changes appear to be rather abrupt below the pit-like structure as indicated by the abrupt changes in colour in Figure 7d, with no overall gradients in orientation (Olson et al., 2013). Some gradients were observed towards the right-hand side of the analysed structure (Figure 7d arrow). Larger prismatic crystals displayed in the top layer just below the pit like structure have various orientations, but no gradients in orientation can be seen within individual crystals across the whole analysed area.

DISCUSSION

Kokoamu Greensands

The detailed study of the KG sample helped to better understand the unit and one of the formation environments of greensands. The time of deposition (~26Ma) coincides with the Mi-1 Cooling when the Antarctic continental ice-sheets rapidly expanded, yet marine organisms thrived in the slightly cooler ocean (Zachos et at., 2001). The high diversity and abundance of fossils and bioclasts indicated that the unit was deposited in a well-oxygenated, medium to high energy, shallow marine environment, around 70-100m deep, during a transgressional event (i.e. at a time when sea levels were rising). This kind of environment would have maintained the temperature of ocean water at an optimal point in tropical latitudes, providing increased nutrient availability due to differences in oceanic temperature and salinity across the globe. The high diversity and abundance of biomineralizing organisms in KG, and in the underlying unit (Smaill, 2015), encouraged pH neutral water conditions as ocean available CO_2 was incorporated into shells and skeletons. Neutral conditions were vital in the formation of greensands as the K and Fe ions moved freely in solution and could precipitate to form glauconite (Amorosi et al., 2007). Furthermore, KG appears to be, in part, a reworked unit. This is supported by the various degrees of erosion seen in the fossils (Figure 4a), the differences in apparent colour of grains (Figure 2a) and by the fact that it is situated between two limestone units (Smaill, 2015). The latter argument implies that currents or waves could have mixed the bottom of KG with the top of the underlying limestone and that later, after its deposition, organisms from the overlying limestone could have burrowed into KG and mixed it vertically. Currents or wave action probably oxygenated bottom waters periodically, interrupting the glauconitisation process and causing Fe to be deposited as iron oxide on shell surfaces and as a cement, hence the slightly varying apparent green colour of the sample.

Orari River Greensands

Much of the focus of this research was placed on this unit as, unlike KG, it was never previously studied with respect to glauconite formation. This unit was deposited during the mid-Miocene Climatic Optimum (i.e. mid Miocene, ~14Ma), a period of relative higher temperatures. It has a lower diversity and abundance of fossils than KG, although Ca input and availability were expected to be higher as a consequence of higher temperatures, weathering, and erosion rates onto adjacent landmasses (Zachos et al., 1994). A small-sized brachiopod (~2cm) was the main macrofossil found in this sample. The lack of abundant fossils in these apparent favourable conditions (i.e. high availability of Ca, relative higher temperatures) points towards an inhospitable environment. The unit was deposited in a lower energy, deeper marine setting (~250m) during a stronger and longer-lived period of transgression than KG. Water column organisms thrived in the surface waters as there are numerous examples of ostracods and globigerina microfossils. As the sea advanced onto the adjacent landmass, terrestrial organic mass was covered by waters and started to decompose. Decomposing organic matter, the low biodiversity and abundance of biomineralisers (i.e. organisms that could intake CO_2 into their shells), and the deeper marine setting that lacked vertical mixing meant that the environment accumulated CO_2. This happened, in part, via the oxidation of organic matter and also through a higher CO_2 input from the atmosphere due to warm climatic conditions (Odin and Matter, 1981). In this setting, the slowly decreasing pH explains the darker colour of the glauconite-bearing pellets and the higher degree of glauconitisation of bioclasts. The K- and Fe-ion content in the marine environment was also higher than for KG as suggested by the chemical composition of the glauconite-bearing pellets (Table 1) and, as expected during periods of higher continental weathering rates. The ions precipitated into the pellets' microspaces and led to the formation of glauconite. The pellets resided probably for a long period of time in the glauconitisation zone as no visible direct iron oxide precipitation could be seen as cement or on fossils as in KG, yet the exact location of the unit and sample provenance is unknown, and thus, no assumptions can be made when it comes to further changes in the environment at the site.

Furthermore, mm-scale mollusc valves have been seen in this unit displaying pit-like structures on either their inner or outer surfaces (Figures 5 and 6). When analysed with the EBSD technique, the molluscs were entirely comprised of aragonite, the metastable version of calcite (Constantz, 1986). Some glauconite-bearing pellets were attached to the shell and once removed they left behind a pit-like structure. The nature and formation mechanism of such structures were examined as they can further add to the palaeoenvironment of deposition for ORG.

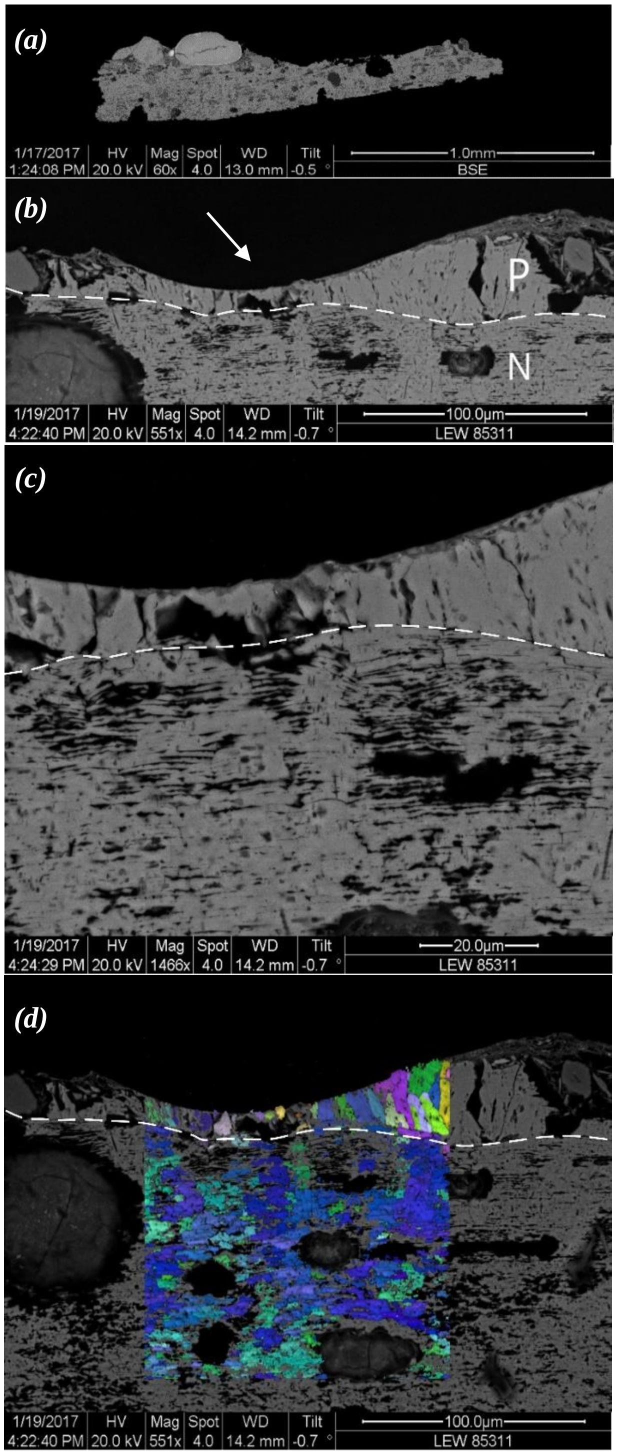

Figure 7: Cross section through a mollusc valve (a) with a zoom-in on one independent pit-like structure (arrow) as seen in figure 5b under the stereomicroscope. Note the boundary between the prismatic and nacre layers (N-P boundary). Note the high degree of disorder in the first top part of the nacreous layer in figure (c), towards the N-P boundary. Crystallographic orientation (d) depicts again the same layering as in (c). Notice that the prismatic crystals have different orientation than nacre tablets.

The initial assumption about the pit-like structures was that they were formed through compression (Figure 8b) as the areas around these structures showed aragonite precipitating in “waves” (Figure 6b), however the molluscs are highly fragile and they would have fractured under a force that would have led to the formation of such structures. After a close investigation of the crystallographic orientation of an area below one of these structures, a small compressive component was seen (i.e. slight gradients in crystal orientation in the nacre layer, arrow, Figure 7d), however these are found away from the pit-like structure, indicating weak recrystallization. The fact that there are no deformation gradients across the prismatic layer, and as the crystals are visibly shorter in the area below pit-like structures (Figure 7b, 7c and 7d), is a strong indicator that they have not been compressed, but dissolved (Figure 8c). The different crystallographic orientations are explained through the competitive growth of prismatic crystals (Checa et al., 2009). Dissolution was hence correlated with the lower pH level of the environment (i.e. chemical dissolution), and thus, with the higher degree of maturation of glauconite. The chemical dissolution was probably initiated by the weak pressure exerted by grains and was sustained by the slightly acidic conditions that prevailed in the environment during glauconitisation.

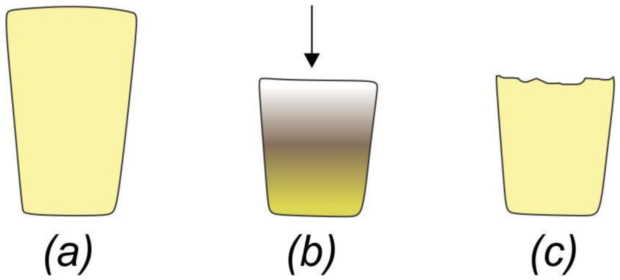

Figure 8: Two hypotheses of the pit-like structures’ formation mechanism in the prismatic layer. The undeformed or unaltered prismatic crystal in (a) shows the full length and uniform crystallographic orientation; (b) presents the scenario in which the prismatic crystals would have been compressed in order to form the pit-like structures (also notice the gradient in crystallographic orientation) and, (c) represents what we actually see under the EBSD: crystals with a single crystallographic orientation, with a dissolved top boundary.

Chemical composition

Further evidence of relative palaeoacidity comes from the wt% of chemical elements of glauconite-bearing pellets (Table 1). By studying the literature on the subject, several correlations or contradictions appeared. One of the most interesting aspects presented here is the Fe wt% component that is higher in ORG than in KG (see Table 1) and seems to be the only one that explains the overall darker colour and hence, maturation degree, of ORG. The higher degree of maturation of ORG could thus be correlated with a longer residence time of sediments in the glauconitisation zone in a reducing palaeoenvironment in which the Fe ions could enter and move freely in solution before and during glauconitisation. Furthermore, as showed by Smaill (2015), the lower wt% of K in ORG correlates with relatively more acidic pH values that existed in the palaeoenvironment during deposition. Similarly, the lower wt% of Fe in KG, correlates with more basic pH values.

GEOLOGICAL SIGNIFICANCE OF GREENSANDS IN THE UNITED KINGDOM

As discussed earlier, greensands are being deposited in shallow marine environments, at the interface between the oxic and anoxic levels in low sedimentation rate environments. It can be thus used as a relative indicator of past sea levels in the United Kingdom (Carson and Crowley, 1993). By analysing the formations in the regional geological context, (i.e. together with fossils occurring within other neighbouring units), the timing and the extent of sea level fluctuations in the past could be calculated (Wilkinson and Hopson, 2011). Lower Greensand was deposited between 140Ma and 100Ma (Casey, 1961), while Upper Greensand was deposited between 113Ma and 100Ma (Gallois, 2004), thus during Lower Cretaceous, a period of high temperatures, the south of United Kingdom was mostly submerged underwater (Figure 1). The greensands are rich in ammonite, corals, echinoids, sponge and mollusc fossils, and in microfossils such as foraminifera. The occurrence of both marine and terrestrial fossils in the Upper Greensand unit indicates that it was deposited in shallow water along the coastline. The green-shade intensity points towards the degree of maturation and to the time spent at a constant depth in the water column, thus it could be used as a relative indicator of the rate of sea level rise. The main sediment type in which glauconite mineral occurs (i.e. fine, medium or coarse sands, fossil assemblages) holds information about the energy of the environment and about the depth of deposition, and a more in-depth study could reveal data that might complete the geological history and story told by the occurrence of this unit in the UK.

CONCLUSION

Glauconite and greensand formations are closely tied to environmental conditions. It was already known that KG was deposited during a transgressional period (i.e. during sea level rise, Smaill, 2015) and this study confirms a similar geological context for the deposition of ORG. The transgressional event was yet greater and it lasted for a longer period of time for the latter unit. As the adjacent landmass was covered by water, terrestrial and pellet-derived organic matter started to decay, leading to reducing conditions, to an inhospitable environment, to a drop in pH and, finally, to a greater degree of maturation for glauconite. It was already known that glauconitisation occurs in the suboxic zone in marine settings, at the transition between the anoxic and oxic environments (Carson and Crowley, 1993). As oceanic acidity is positively correlated with the CO_2 levels and as biomineralizing organisms intake CO_2 in the form of $CaCO_3$ (calcite aragonite) or $MgCO_3$ (dolomite), the lack of fossil abundance in ORG could explain the greater pCO_2 and thus, the higher relative acidity.

This study proposes a new use for the degree of maturation: that of a palaeoacidity indicator, as assessed primarily through the apparent colour as described by Amorosi (1997). Data shows that slightly lower oceanic pH values were correlated with the occurrence of medium and high maturation degrees of glauconite-bearing pellets given the necessary environmental conditions that are required for their formation. Although this proposal is made only after studying two greensands units and the presented pH differences are relative, similar palaeoenvironmental conditions should apply to similar degrees of maturation. This new approach could aid us in forming a better understanding of how and why greensands form and of the environments in which they occur. Moreover, it can lead to the development of a new pH-related proxy. If calibrated with the colour, and more precisely, with the Mg, K and Fe content

(Table 1), this proxy would allow maturation degree to be used in glauconite-occurring areas in direct assessments of palaeoacidity. This would be especially useful in settings where fossils or bioclasts are either absent or are suspected of biological control (i.e. buffering) over pH changes during biomineralization.

This proposed palaeoacidity tool, although restricted to greensands-occurring areas, could lead to a wider comprehension of oscillations that occurred in the sea-level and, ultimately, in the environment and climate in the past. On the background of present climate change scenarios and future sea-level increase threats, knowledge of the geological past could aid in appreciating the extent of future environmental threats, allowing us to anticipate the areas of high risk and to prevent or mitigate climate-induced pressures.

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