Chalk: all we need is a fracture log!

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Abstract: Chalk fracture logging is reviewed in the context of the broader geology needed to build conceptual ground models. Examples of drilled damaged core illustrate the many issues faced by core loggers including identification of marker beds (marl seams, hardgrounds, flint bands, fossil shell beds) and the ‘interpretations’ necessary to complete a fracture log. Stratabound fractures impart a special style of fracturing to each Chalk formation. Lithology is a key factor in development of fracture style where marl seams control inclined conjugate fracture sets, development of listric growth faults and interbed slides. Lateral changes in lithology and thickness and consequent controls on fracture evolution are related to intra-Chalk tectonic episodes and tectonic setting with onshore interpretations supported by offshore seismic profiles. Strike-slip faults are illustrated in the Chalk cliffs of the Sussex coast. Fracture log reports should highlight special features such as shear zones and use annotated core photographs to illustrate issues requiring discussion.

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When asked to identify marl seams, flint bands and fossil shell beds as part of Chalk core logging a response from some contractors has been: ‘Should we be expected to recognize and log these features?’ Surely all we need is a fracture log?’ Fracture logging is an important part of a site investigation; however, the other aspects of the geology are just as important to developing a ground model and are identified as part of best practice in Chalk site investigation (CIRIA 574, Lord et al. 2002). At its simplest, how can boreholes be correlated on fracture logs alone and how can the location, scale and sense of faulting be identified or presence of dissolution features be recognized from fracture logs? How can geophysical logs and seismic reflectors be interpreted from fracture logs? It is also quite usual in site investigations to find features that are not common or may not have been recorded before and these need highlighting. Whilst sympathizing with the commercial issues of time and money, such considerations should not override the science and engineering. Core logging should be about gaining the maximum geological information possible, as the success of a construction project may depend on recognizing all aspects of the geology across a site, not just fractures.

Fracture logging chalk can be the bane of a site investigation geologist’s life, time consuming, controversial, frequently requiring ‘interpretation’ where core is fragmented or fractures have been induced during drilling. Clients usually demand a numerical figure even in core intervals where drilling fragmentation has occurred and such demands can seem unreasonable. How should such intervals be recorded in terms of fracturing?

In the last three decades since the forerunners of the CIRIA grades were first mooted during and after the Brighton 1989 Chalk Symposium and then developed to become an industry standard (Lord et al. 1994, 2002) there has been a continuous debate on how to recognize the grades in drill cores and how they integrate with ‘standard’ fracture logging. In the hard-nosed business of site investigations the time (and money) taken to complete fracture logs and apply CIRIA grades has sometimes detracted from the value of recording other aspects of the geology including details of the stratigraphy (marl seams, flint bands, nodular chalk beds and fossil bands). Part of the problem is the time allocated to core logging in contracts and the absence in the specifications of the requirements to log stratigraphical details. A further issue is what is expected from the core log results by the client and consultant and frequent differences of opinion between parties on the results especially with fracture logs and CIRIA grades. Sometimes this has led to costly relogging or rewriting the core logs. Sometimes these requests and revisions have come from ‘office-based’ staff who have not seen the core and who have little experience of the real problems associated with logging and are simply interpreting contract requirements without reference to ‘field’ staff. Good attempts have been made to overcome these difficulties on many contracts by running logging courses and having experts help with the logging so that all parties can agree with the results. Chalk is especially difficult as drill-core is frequently disturbed during borehole drilling. Core disturbance is most pronounced (1) in chalk with flints, (2) in nodular chalk beds or hardgrounds and (3) in intervals with fracture zones. Drillers’ records such as rate of progress, loss of flushing medium and interruptions caused by lithology are invaluable in helping to recognize intervals where such disturbances have occurred and the depth of potential fracture zones but are not always available. A requirement to keep these records should be a mandatory part of any contract (for some recent contracts there have been no drillers’ logs or comments in situations where these would have been invaluable).

A concentration on the contractual side of core logging (and core sampling and testing), although very necessary, can lead to a loss of focus on the wider geological context and the requirement to log other aspects of the geology. These aspects include the style of fractures, which, in the Chalk, are characteristic of particular lithologies and formations, and the tectonic and geomorphological settings of the site being investigated. In addition, lithological features such as marl seams play a critical role in the mechanical behaviour of chalk including generation of fractures and fracture styles, slope instability and short- and long-term deformation. Not recognizing and logging even thin wispy marl seams reduces the engineering value of the site investigation.

Other questions relating to fractures raised during major construction projects include: ‘Is there evidence for strike-slip faulting in the Chalk and how common is it?’ This paper attempts to answer some of these questions and provide a geological context for fractures, fracture logging and CIRIA grades to aid the extrapolation...
of the borehole information to the level of the ground model. The place of fracturing and fracture logging in the engineering geology of the Chalk is reviewed and ways of enhancing fracture logging are suggested as well as emphasizing the need to record other features. Some of the causes and the timing of fractures in the Upper Cretaceous Chalk and how this influences fracture distribution are discussed in the broader geological context of stresses developed in the European Platform. Fractures related to Quaternary weathering processes have been comprehensively dealt with elsewhere (Lord et al. 2002; Mortimore 2014) and are not considered here.

The key issues addressed are: (1) how to recognize and distinguish natural fractures from drilling-induced fractures in chalk-core; (2) what evidence can be used to determine CIRIA grade, such as fracture fill and staining, and whether these are always a reliable guide; (3) how to identify marker beds such as thin marl seams, flint bands and fossil shells even in drilling damaged core.

Unless otherwise stated, references to ‘vertical’ or ‘inclined’ fractures in this paper are relative to the borehole cores, which, in the majority of cases, have been drilled vertically and are perpendicular or nearly so to bedding.

### Examples of drilling damaged core and fracture log problems

#### Shallow depth, inclined conjugate fractures, Zig Zag Chalk Formation

Drilling fragmentation of chalk core can occur at any depth and in any style of fracturing (Figs 1–4). In the shallow depth Zig Zag Chalk Formation (Fig. 1) and immediately overlying Plenus Marls the primary inclined conjugate fractures are labelled on each core-run, indicating a frequency of about five per metre. Core fragmentation has occurred where the drill-bit has sheared the thinner parts of the core along each inclined fracture and where fractures meet. There are two intervals labelled N/A (not applicable) where identification of fractures is not possible. The primary natural fractures are black stained whereas the drilling-induced fractures are not stained. Despite the shallow depth below ground surface there is no obvious fill along the fractures and given the drilling disturbance it is difficult to determine aperture of each fracture and, therefore, apply a CIRIA grade.

Taking the core-run downwards below the Plenus Marls as being all one stratum (Fig. 1) a fracture index could be given for the entire core down to 9.62 m or an index could be given for each core run. The core logger has a quandary. Should fractures in fragmented intervals be included in the index or should we just count the...
primary, stained fractures? In practice, the core should be described first and the description should include an honest account of fragmented intervals and then a description of the primary inclined fractures (and subhorizontal fractures if present) including the degree of staining and fill if any on the fractures. The predominant style of fracture in this case is steeply inclined conjugate sets. Recognition of style of fracture is a key part of the mechanical stratigraphy of the Chalk (Mortimore 2001, fig. 19). The heavy black staining and absence of fracture fill suggests that this is well-structured chalk with slightly open fractures (i.e. grade B). Given there are about five inclined fractures per metre the grade would be B3 to locally B4. The completely disintegrated intervals are excluded from the classification but would be highlighted in the description and on the core log.

Fig. 3. Core fragmentation through moderately to heavily orange, iron-stained and partly filled multiple vertical open fractures (CIRIA grade C) in the Seaford Chalk Formation. (b) is a close-up of (a) and (d) is a close-up of (c).

Fig. 4. Core fragmentation in the Holywell Nodular Chalk Formation. Despite the depth of 90.50–93.50 m core has fragmented where rough closed fractures meet.

Fig. 5. Steeply inclined conjugate fractures in the Holywell Nodular Chalk Formation, CTRL North Downs Tunnel North Portal Drive at depths >80 m below ground surface.
**Haven Brow Beds vertical fracture sets**

In contrast to the Zig Zag Chalk Formation with inclined conjugate fractures (Fig. 1), the Haven Brow Beds in the Seaford Chalk Formation have typically vertical joint sets (Fig. 2). The example shown here from a depth between 17.00 and 24.00 m (Fig. 2) has clean, very lightly orange stained subparallel, stepped vertical joints that were probably closed (grade A) and have opened readily during drilling and placing core in the core boxes. The very weak, low-density chalk fragments very easily during drilling and, in this example, has been additionally disturbed during core logging. Nevertheless, the vertical and subhorizontal joints can be seen with at least two subparallel vertical joints passing through several core boxes in the 96 mm diameter core, giving a fracture spacing of 48 mm (CIRIA grade A4 for vertical fractures). Clean, closed subhorizontal fractures are more widely spaced with about five per metre (i.e. >200 mm spacing; CIRIA grade A2). Describing both the subhorizontal and vertical fractures and classifying them separately provides a full account of the fracturing in this core. An issue...
that regularly arises between contractor and consultant or client is what overall fracture index and CIRIA grade to apply. Consultants or clients generally want only one grade. In this case the closest fracture spacing (48 mm) and lowest grade (A4) would be applied. As long as the grade used is accompanied by the full description of all the fractures and the reasoning is explained then a single grade can suffice. There is a need, however, for the consultant or client and the contractor teams to discuss the method to use prior to and during the contract and to have regular workshops on site with the core to agree the classifications being used. Too often the contractor’s core loggers, despite having relatively little experience, are left to make decisions that are then subsequently questioned or have to be revisited, involving considerable time and cost.

An overall grade may not be what the client or designer actually wants or needs. Identifying fractures present at a specific depth may be essential for interpreting field test results or, for example, for deciding grouting strategies. This is where the full description on the core log is vital, not just the overall classification.

**Deeply weathered core fragmented by drilling**

Determining a fracture index and CIRIA grade in deeply weathered core that has also been fragmented by drilling can be difficult (Fig. 3). Degree of weathering can be partly determined by the intensity of staining on joints and internal discoloration in the chalk core and the presence of chalk-fines or fragments as fracture fill. The example here is from the Haven Brow Beds in the Seaford Chalk Formation and, like the example in Figure 2 at a similar stratigraphic level, the predominant fractures are vertical joints with subsidiary subhorizontal fractures. Heavy to moderate orange, iron-staining is present on both types of joint accompanied by fracture fill brown sediment. In such loose chalk, drilling fragmentation has been severe, especially where flints are also present (Fig. 3c).

A key criterion for recognizing CIRIA grade C in core (discontinuity aperture >3 mm) is fracture fill. This is often the only criterion that consultants or clients will accept, as drilling damage makes using direct measurement of aperture unreliable.
Downhole photographic logging, however, illustrates that open fractures can be present at almost any depth (Mortimore 2014) and open fractures are usually moderately to heavily stained and rarely filled. How reliable, therefore, is fracture fill as the only way of recognizing CIRIA grade C? Greater use of downhole camera logs would help answer this question. Degree of staining should also be a guide to the possibility of open fractures and grade C chalk, and such intervals need highlighting on core logs.

Holywell Nodular Chalk inclined conjugate fractures

The final example of fracturing in the Chalk and issues related to core logging a fracture index and CIRIA grade is from the Holywell Nodular Chalk Formation (Fig. 4) at considerable depth below the ground surface (90.50–93.50 m depth). Steeply inclined conjugate fractures are a characteristic feature of this Chalk Formation. The nodularity of the chalk creates rough, undulating fracture surfaces that are moderately to heavily stained, becoming orange iron-stained in oxidizing conditions. These fractures in core are usually closed and have to be pulled apart and are, therefore, closed CIRIA grade A despite the heavy staining. In tunnels such fractures at depths >80 m have been found to be open and sometimes filled (Fig. 5a and b).

The Holywell Nodular Chalk Formation example (Fig. 4) also illustrates core breaking up along thin marl seams and increased drilling fragmentation where fractures meet.
Nodular beds and hardgrounds

A further complication when core logging the Chalk is created by nodular chalks and hardgrounds (Fig. 6). The change in strength or density from low- or medium-density to high- and very high-density chalks cannot always be identified immediately by the driller and, as with coring through flints, core fragmentation is common. When encountering the thicker hardgrounds, such as those associated with the Chalk Rock (Figs 6 and 7), drillers have regularly recorded the drill string ‘bouncing’ and making a ‘chattering’ noise. Hardgrounds represent mineralized seafloors including calcite-cemented layers up to 700 mm thick (more commonly 300–400 mm thick) described as chalkstone (Fig. 7). Additional minerals include orange iron staining, coatings of green glauconite and brown phosphate. Hardgrounds also contain burrow networks filled with soft low-density chalky sediment that washes out easily during drilling leaving behind the high-density, nodular, chalkstone pieces (Fig. 6).

In many cases producing a fracture log in fragmented nodular chalk is not possible (e.g. Fig. 6c–g) and this needs to be understood by all parties. A way forward would be to use annotated core photographs like those in Figure 6. More use could be made of core photographs generally by adding notes to aid explanations supporting the descriptions and classifications. This would help office-based checking engineers as well as designers and contractors understand the reasons for classifications used or absence of classifications.

Fig. 10. Long, vertical fracture in the Seaford Chalk Formation (Haven Brow Beds) between 94.50 and 107.00 m below ground surface, apparently filled and, therefore, CIRIA grade C. The fill and apparent grey staining is, however, artificial derived from drilling fluid.

Fig. 11. Marl seams are easy to identify in good quality core, in this case in the topmost New Pit Chalk and basal Lewes Chalk formations.
In addition to standard fracture logs and CIRIA grades there are places where the Chalk is characterized by zones of intense fracturing (Figs 8 and 9). Such a case is in the Chalk on Portsdown, Hampshire, first illustrated by White (1913) and shown in more detail in Paulsgrove Quarry by Mortimore et al. (2001). Cores through such fracture zones show that the primary

Fracture zones

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inclined and subhorizontal fractures are all mineralized with calcite, striated, polished and speckled with black manganese (Fig. 8a). Drilling stress has opened some fractures whereas others (dotted lines) remain closed. Fragmentation of the core has occurred where fractures meet and where the core is thinnest along the inclined fractures. All the fractures are clean (no fill or heavy staining) probably closed to slightly open CIRIA grades A to B.

Fracture logs frequently contain great detail and it can be difficult to identify key features and extract critical information. Highlighting fracture zones on the logs and core photographs (e.g. Figs 8 and 9) provides an instant illustration of frequency and location of such zones and assists with deciding a strategy for downhole testing.

Fracture fill, staining and mineralization and application of CIRIA grades

Fracture fill and/or degree of fracture staining are critical to determining CIRIA grade C. Fracture fill is not always a reliable guide, as illustrated in Figure 10, where the fill has been artificially introduced during drilling. The fluid used as a flushing medium in this case has been recirculated, picking up sediment from the Thanet Formation on its way and then flowing along the fractures in the Chalk. The uncertainty about this fracture ‘fill’ was solved with confidence only when the drillers’ logs were inspected. Given the depth below ground surface (94.00–107.00 m) this quantity of fracture fill and the material seemed unlikely but this supposition needed to be proved, especially as open fractures within this

Fig. 15. Fossils in core from Holywell Nodular Chalk and New Pit Chalk formations, southern North Sea. The composition of the gritty Holywell Chalk is shown to comprise entire and fragmented shells of inoceramid group of bivalve fossils, various species of the genus *Mytiloides* (a–h). The shell beds in the New Pit Chalk contain abundant *Inoceramus cf. cuvieri* with a key marker bed containing *Conulus subrotundus* (j, k) towards the base of the New Pit Chalk Formation.
engineering setting where a shaft was to be constructed were critical
to groundwater flow, pump sizes and extent and grade of grouting
required. Drillers’ logs proved to be essential.

The seven examples above illustrate that fracture logging in the
Chalk is not always straightforward and requires interpretation and
training. Ways of improving the presentation include annotating
core photographs (an under-used resource) and emphasizing special
features on the log. Specific training for core loggers and seeking
expert opinion should form part of a ground investigation strategy.

**Identifying marker marl seams and shell beds in destructured chalk-core**

Identification of marker beds is essential to correlation of
boreholes, determination of tectonic structure and extrapolation
of physical properties across a site. Despite the invaluable nature
of marker beds there is frequently resistance to identifying them.
This is partly related to the general ignorance about the Chalk (it
rarely forms part of any undergraduate study at university) unlike
many other parts of UK geology, and assumptions are frequently
made about the uniformity of the Chalk. Most marker beds in the
English Chalk are illustrated in the book *Logging the Chalk* (Mortimore 2014). Some of the more important marker beds
include marl seams and flint bands. One group of marker beds,
the marl seams, have a special influence on the mechanical
properties, including the distribution and style of fracturing in the
Chalk. Flint bands also have an impact on mechanical properties
of chalk with respect to wear on machine cutters, tunnel spoil
removal belts, and rubber tyres on scrapers and trucks in
earthworks operations.

**Fig. 16.** Fossil inoceramid bivalve shells
typical of the Seaford Chalk Formation and
commonly found in core. (a) A fine
example of *Cladoceramus undulatoplicatus*, the base Santonian
international index fossil in the marine
Cretaceous in the crown of a tunnel in
Langdon Cliffs, Dover, in the basal layers
of the Haven Brow Beds. (b, c) Fragments
of *Cladoceramus undulatoplicatus* in the
top core of a Wiltshire borehole. (d–f)
Fragments of the very large plate-like
bivalve *Platyceramus* sp. from core through
the basal Cuckmere Beds. (g) 1, 2, 3 and 4,
further fragments of *Platyceramus* sp.
shells in the Belle Tout Beds. 5, a fragment
of *Volviceramus* sp. shell. (h, i) A very fine
example of *Volviceramus involutus* from
the Belle Tout Beds in a Wiltshire
borehole.
Marl seams

Marl seams are the most visible and continuous layers representing true bedding planes in the Chalk, having formed on the seafloor. Hardgrounds can be discontinuous surfaces also formed on the seafloor, whereas flint bands formed in the sediment parallel to but below the seabed (i.e. diagenetic bands not primary bedding). Marl seams in the Chalk fall into two groups; the first and more limited in number are of proven volcanic ash-fall origin (bentonitic) and the second are of clastic origin. Some formations contain abundant marl seams (Holywell, New Pit, part of the Lewes Nodular Chalk, the basal Belle Tout Beds of the Seaford Chalk, and the Newhaven and Portsdown Chalk formations) and in the Northern Province, the Welton and Flamborough Chalk formations. Other formations have no or few marl seams (Cuckmere and Haven Brow Beds of the Seaford Chalk, the Margate Chalk Member and the Culver Chalk Formation). Before beginning a drilling programme it is useful to identify the probable range of Chalk stratigraphy of the site so that any expected marker beds can be looked for in the core (e.g. Figs 11–13). This is especially important where core has been degraded by drilling (Figs 12 and 13).

Identifying shell beds

Gritty, shell beds can be readily identified when using a paint scraper to clean the core. Concentrated shell beds are characteristic of the Grit Beds in the Holywell Nodular Chalk Formation (Fig. 13) and in the Belle Tout Beds of the Seaford Chalk Formation (Mortimore 2014). Scraping shell-gritty core sounds and feels very different from smooth chalks such as present in the New Pit and higher beds of the Seaford Chalk formations. With a little palaeontological knowledge it is possible for all core loggers to identify the shelly beds and many find it rewarding to identify the shells as well (see key Chalk fossils illustrated by Mortimore et al. 2001; Smith and Batten 2002; Mortimore 2014, 2021). Some typical index shells from the most commonly cored part of the Chalk, the Seaford Chalk Formation, are the various forms of inoceramid bivalves (Figs 14–16). These fossils provide supporting evidence for the identification of key marker beds, especially the Belle Tout Marls and flint bands including the Seven Sisters Flint and Bedwell’s Columnar Flint.

Finding a key fossil in core can make the difference between uncertainty and the exact stratigraphical position of a marl seam or flint band. In the southern North Sea the small echinoid fossil Conus subrotundus, associated with small forms of the inoceramid bivalve Inoceramus cuvieri (Fig. 15) and k, was found in beds with conspicuous marl seams in the basal beds of the New Pit Chalk Formation. These fossils helped identify the lithological and physical property changes related to seismic reflectors, making it possible to map the Chalk across the entire wind farm area.

Similarly, the inoceramid bivalve fossil Cladoceramus undulatoplicatus in the topmost, degraded core run of a Wiltshire borehole (Fig. 16b) proved the base of the Haven Brow Beds in the Seaford Chalk Formation. The next horizon below identified in core was the horizon with abundant fragments of the inoceramid bivalve Platymerus and then below that the wonderful example of another key inoceramid Volviceras involutus (Fig. 16h and i). Identifying these key marker fossils allowed the bed subdivisions of the Seaford Chalk Formation to be identified with confidence and provided the basis for correlations with similar shell beds in the many boreholes in the area, which, in turn, formed the basis for a ground model. Without these shells there would have been great uncertainty about the stratigraphy and borehole correlations at this site.

Identifying flint bands

Flints have many shapes and sizes, which are consistent in a band over very long distances (e.g. across the Paris Basin (Mortimore and Pomerol 1987)) and from Sussex to Yorkshire (Mortimore and Wood 1986; Mortimore 2019c, 2021). Recognizing flint shape and size in core is frequently made difficult because of drilling damage caused while coring through flint (e.g. core with flints from the southern North Sea Fig. 17). A typical range of flint sizes, types and bands has been illustrated by Mortimore (2014). One group of flints...
that require further illustration are the tabular flints typical of the Northern Province of Lincolnshire and Yorkshire and in the southern North Sea. These flints are unlike the nodular flint bands typical of southern England or sheet flints that form on subhorizontal and inclined fractures. Tabular flints are stratigraphically continuous solid flint bands with generally flat top and bottom surfaces (bedding parallel) frequently with a thin cortex along bottom and top contact surfaces. The examples of large to very large continuous tabular flints (Fig. 17, using the size scale given by Mortimore (2014) (>100 mm thick)) have implications for cable trenching, pipe laying and small tunnel boring machine (TBM) tunnelling onshore and offshore. Identifying these flint types during core logging and establishing their stratigraphy allows the risks to engineering to be assessed.

**Fig. 18.** Borehole log from the southern North Sea through the upper part of the Grey Chalk Subgroup and basal White Chalk Subgroup (modified from Mortimore and James 2015) showing the contrasting lithologies that create two of the seismic reflectors used to map an area of the southern North Sea for wind turbine foundations.
modifying the 1.9 m diameter Iseki Unclemole TBM and a supplementary ground investigation to correlate the flint bands along the tunnel line (Mortimore 2012, pp. 291–297): (2) the Brighton and Hove Stormwater Tunnel, which illustrated a detailed link between marker beds, identification of tectonic structure, fracturing and weathering of the Chalk and relation to TBM tunnelling (Mortimore 2012, pp. 297–314). In open face tunnelling the design zones in the CTRL North Downs Tunnel depended on the depth of cover and the Chalk lithostratigraphy (Warren and Mortimore 2003). Similarly, for the CTRL Thames Crossing, London Tunnels, Crossrail and Tideway Tunnels flint band correlations, flint band frequency and concentration of flints required detailed logging of flint bands in cores. To aid this process the stratigraphy of the flints was correlated with local Chalk quarries where the same flint bands were present and could be measured in detail. Other key marker beds for these tunnels included the Shoreham and Belle Tout Marls (Mortimore et al. 2011; Mortimore 2014).

A further key reason for identifying and logging marker beds, especially marl seams, is their role in controlling the mechanical and hydrogeological properties of the Chalk mass. A single thin marl seam across a tunnel face can change the stress distribution and the design of short- and long-term support. Marls act as local décollement zones yielding to interbed sliding, as can be seen in many palaeo-slides (Mortimore 2019a). Downhole camera logs show groundwater flowing along marl seams in both the saturated and unsaturated zones (Mortimore 2014, figs. 6.61–6.64).

Fracture distribution in the Chalk

Treating the Chalk as a homogeneous medium masks the many types of fracture present and their possible origins. A typical model used for illustrating fractures in the folded Chalk of southern England is the general model for fractured, folded strata of Price (1966) (Figs 23 and 24). Such a model does not take account of polyphase deformation or Chalk formations with different layering leading to stratabound fracture evolution.

Stratabound fractures: vertical joint sets and steeply inclined conjugate fractures

A feature of the Upper Cretaceous Chalk is the style of fracturing characteristic of each formation (stratabound fractures; e.g. Figs 22, 25 and 26a–c). A determining property of the Chalk that appears to control fracture development is the presence or absence of marl seams. Those formations with many marl seams, such as the Holywell, New Pit and Newhaven Chalk formations in southern England (Fig. 26a and b) and the Welton and Flamborough Chalk formations in northern England (Fig. 26c), are characterized by inclined conjugate fractures (Figs 1, 5, 8, 22, 25 and 26). Subdivisions of other formations, such as the Belle Tout Beds in the lower part of the Seaford Chalk Formation containing the Belle Tout Marls, are also characterized by steeply inclined conjugate fractures (frequently sheet flint filled) (Fig. 26b). The parts of the Seaford Chalk Formation without marl seams (Cuckmere and Haven Brow Beds) and other similarly marl-free formations (Culver Chalk) contain predominantly nearly orthogonal vertical joint sets (Figs 2, 10, 22 and 26b; Mortimore 1993, 2001) with fewer inclined conjugate fractures. These fracture patterns shown in Figure 26a–c illustrate that Chalk fracture evolution is related to lithology and intra-Chalk events rather than later folding, indicating that the Price (1966) model is inappropriate for the Chalk. A special feature of the Belle Tout Beds, the Newhaven Chalk Formation and the Flamborough Chalk Formation is the radial pattern of steeply inclined conjugate fractures (Fig. 26b and c). As Hibsch et al. (1993, 1995) found, this radial pattern makes it difficult to identify regional

Fig. 19. Two borehole logs illustrating marker marl seams and shell beds in the top Holywell and lower New Pit Chalk formations in the southern North Sea (modified from Mortimore and James 2015).

Applying Chalk marker beds to ground models in engineering

Each type of marker bed (marl seam, shell bed and flint band) can be represented graphically on borehole logs (e.g. Figs 18–20). Plotting physical properties alongside such logs (Fig. 18) helps identify how physical properties relate to lithology. This in turn can be used to interpret field test data such as seismic velocity profiles and cone penetration tests (CPTs). A windfarm area in the southern North Sea provides one example of the application of this marker bed stratigraphy linked to physical properties for the identification of wind turbine foundation conditions in the Chalk. Identification of seismic reflectors in relation to the Chalk stratigraphy allows ground conditions to be extrapolated over a much wider area than just the borehole location. An initial interpretation of the seismic profiles shown (Figs 21 and 22) placed the key marker bed, the Plenus Marls, at a different reflector much higher in the profile. Only when the information from the cored boreholes (e.g. Fig. 18) was available was the correct interpretation possible, and these results completely changed the ground model in terms of types of chalk at the various wind turbine foundations (Mortimore and James 2015).

Two other examples of applying the marker beds to developing ground models for tunnels are: (1) the Shoreham Harbour Siphon Tunnel, where the presence of bands of large flints required the
trends in fracture orientation (see further discussion by Mortimore 1999a).

A pattern of fractures

Fracture orientations have been measured along the coastal cliffs and inland quarries in the Chalk of southern England and part of this dataset for the eastern South Downs of Sussex is shown as stereogram and cyclographic plots (Fig. 26a, from Mortimore 1979). The stereograms show the steeply dipping inclined conjugate patterns in the Holywell Chalk (Fig. 26a, D), Lewes Chalk (Fig. 26a, C and K) and the Newhaven Chalk (Fig. 26a, A, B, E, F, G, H and I). These patterns for inclined conjugate fractures contrast with the near-vertical orthogonal pattern of joints in the Cuckmere Beds of the Seaford Chalk (Fig. 26a, J). In all the stereograms, regardless of fracture style, there are two predominant fracture orientations, NW–SE and NE–SW, especially with the major shears and faults, and this is a consistent pattern in the Chalk of southern England. Rose diagrams for fracture orientations in each...
Chalk formation across southern England are shown (Fig. 26b). Similar fracture patterns are present in the Chiltern Hills (e.g. inclined conjugate fractures in the New Pit Chalk Formation, Kensworth Pit, Mortimore et al. 2001; Mortimore 2011, 2014). Cored boreholes beneath London for projects such as the Lee Tunnel, Thames Tideway and Crossrail all illustrated the consistent presence of similar strata-bound fracture styles (summarized by Mortimore et al. 2011; Mortimore 2014, fig. 3.29).

Fracture style and orientation are consistent within formations from the south coast of England (Fig. 26b) to the Yorkshire Wolds (Fig. 26c) and across the Paris Basin. The exceptions are areas where faulted blocks such as the Pays de Caux Block in Upper Normandy, France, have a different sedimentary history and consequently different fracture style (Mortimore 2011, 2019a). Southwest of the Fécamp Fault on the ‘block’ the extraordinary Chalk sediments with numerous synsedimentary seafloor channels have few fractures. In contrast, NE of the Fécamp Fault ‘normal’ chalks return, which contain the stratabound fractures seen everywhere else in the Paris Basin and in England (see discussion by Mortimore 2011). Lateral variations in tectonic setting have to be considered in any fracture model for the Chalk.

Interbed sliding and growth faults

The Late Santonian and Early Campanian Newhaven Chalk Formation illustrates the interplay between bed sliding along marl seams and the generation of listric growth faults, which bottom out along thin interwoven marl seams (Figs 27–29). The listric growth faults show increased displacement downwards and displacement reducing upwards, eventually passing out and stopping in the overlying Culver Chalk Formation (Fig. 29a and b). This suggests that there was a period of ‘growth’ tectonics generating shallow downslope faulting constrained, in this case, to the Early Campanian Offaster pilula Zone. Many of the early synsedimentary and penecontemporaneous fractures are filled or replaced by early formed sheet flints, in turn offset by interbed sliding along marl seams and subhorizontal shear planes (Fig. 27c–f; see also Mortimore 2011). The generation of slopes that created the environment for this interbed sliding and listric faulting is discussed further below.

Strike-slip faults, slickensides, striae and palaeostress studies

‘Are strike-slip faults likely in the Chalk?’ is a regular question asked in relation to tunnelling, especially beneath London. Strike-slip faults are common at some localities, with some of the best examples occurring in the coastal cliffs of East Sussex at Beachy Head (Fig. 28) and Newhaven (Fig. 29c and d). The deeply grooved slickensides with pinnate shears (Fig. 29c and d) provide the evidence for sense of movement and, alongside the less deeply grooved striae on many fractures (e.g. Fig. 8), have been used to identify the orientation of palaeostresses that caused them (Fig. 29) following the method developed by Angelier and Bergerat (1983), Bergerat (1987), Angelier (1990) and Vandycke (2002). This method has subsequently been applied to the Mons Basin (Belgium) and the Chalk of the Boulonnais and North Kent (Vandycke and Bergerat 1989; Vandycke et al. 1991; Vandycke 1992; Bergerat and Vandycke 1994) and to the Isle of
Fig. 22. A fracture stratigraphy related to the standard lithostratigraphy for the Southern Province Chalk (modified from Mortimore 1993, 2001; Soley et al. 2012), showing some of the key horizons associated with enhanced groundwater fissure flow and spring lines from the Chalk of Hampshire and Dorset.

Fig. 23. The Price (1966) model (fig. 43, p. 114) of fracture patterns in relation to an anticline. This model has been used to explain fracture patterns in the Chalk (e.g. Bloomfield et al. 1995; Bloomfield 1996). (i) master joints; (ii) stereogram of master joints; (iii) typical relationship of joints in the limbs of an asymmetrical anticline; (iv) stereogram of master joints in the gently dipping limb; (v) stereogram of joints in the steeply dipping limb.
Wight (Vandycke and Bergerat 2001). Using the fracture analyses of Mortimore (1979) and further records made for the ROCC programme along the English and French Chalk coasts of the eastern English Channel (Mortimore and Duperret 2004, and papers therein) this same method of palaeostress analysis has been applied to show phases of extension and compression affecting the Chalk of the eastern English Channel coast (Duperret et al. 2012; Figs 30 and 31).

**Tectonics, fracturing and sedimentary history**

Identifying the timing of palaeostress changes that led to fracturing episodes (Figs 29–31) is one method of investigating tectonics that affected the Chalk. Another way is to investigate lateral variations in thickness and lithofacies with respect to tectonic structures. Broad-scale patterns of Chalk sedimentation in relation to shelves and basins are relatively well established (Drummond 1970; Mortimore 1983). More controversial has been the impact on Chalk sedimentation of local-scale tectonic structures such as the en echelon fold belts that cross the Chalk of southern England and similar folds offshore in parts of the North Sea. Seismic profile...
evidence shows that these folds are controlled by underlying faults (e.g. Mortimore and Pomerol 1991, 1997; Butler 1998; Chadwick and Evans 2005) and the folds are generally asymmetric anticlines (periclines) with steeper north-facing limbs (e.g. Fig. 32, an offshore structure). Resolution in the Chalk on the onshore vibroseis sections is inadequate for identifying seismic reflectors related to marker beds, formations and lithofacies and these seismic sections are, therefore, of little help for investigating lateral variations. Ideas about lateral variation onshore have been constructed from field sections and boreholes (e.g. Mortimore 1983, 2011, 2012; Mortimore and Pomerol 1991, 2012b). Offshore, the relatively shallow depth seismic profiling for wind farms has provided, for the first time, the detailed evidence supporting the tentative and controversial onshore interpretations (Mortimore and James 2015; Fig. 32).

As uplift and folding progressed in pulses through the Late Cretaceous and into the Paleogene the early formed fractures, including the steeply inclined conjugate fractures and bedding-slip planes, were rotated in the folds and partly reactivated (e.g. Purbeck Fold, Durdle Door, Fig. 33). House (1989) agreed with Bevan (1985) that, using the original near-horizontal bedding surfaces as datum, many of the slickensided fractures, classified and interpreted as late-stage fractures caused by the latest phases of ‘Alpine’ Tertiary folding (Arkell 1938, 1947; Phillips 1964), can be reinterpreted as early, pre-folding, conjugate fractures that have been rotated into their present position by the monoclinal fold (Ameen and Cosgrove 1990; Mortimore 2019). This latter interpretation is also made for similar slickensided conjugate fractures in the Chalk of Sussex and on the Isle of Wight Sandown Pericline (e.g. Mortimore 2011, figs 67–70).

Ameen and Cosgrove (1990) produced schematic block models illustrating the geometric–kinematic classification of meso-fractures symmetrically oriented in relation to bedding in the Purbeck fold.
Ameen and Cosgrove (1990) also investigated the classic Ballard Fault at the eastern end of the Jurassic Coast (Ballard Point), interpreting it as a ramp developed with a north-moving thrust subsequently rotated in the Purbeck monocline. These observations suggest that significant pre-monocline (i.e. pre-Miocene) and probably intra-Late Cretaceous tectonics affected the Chalk. Such observations support the idea of intra-Chalk fracturing episodes related to tectonic episodes (Figs 30 and 31).

The uplifts causing the folds are driven by major underlying faults, which appear to show a reversal of movement between the

**Fig. 26 Continued.** (b) Rose diagrams for fracture orientations in all the White Chalk Subgroup formations in southern England. Measurements were obtained from coastal cliffs, road cuttings and inland quarries. (From Mortimore 2012, fig. 74.) A noteworthy feature is the radial steeply inclined fracture patterns in the chalks with numerous marl seams (e.g. Belle Tout Beds in the Seaford Chalk Formation) in contrast to near-vertical fractures in the Cuckmere and Haven Brow Beds in the Seaford Chalk Formation.
Ameen (1990) agreed with Stoneley (1982), and all subsequent interpretations based on seismic section evidence (e.g. Underhill and Patterson 1998), that the Purbeck and Isle of Wight monoclines result from the sedimentary cover (Late Cretaceous to Miocene) draping over reversed movements on the underlying ‘basement’ Purbeck Fault. In relation to these monoclinal folds a consistent pattern of sedimentation emerges. The ‘draping’ was not a passive process in the Chalk, as tectonic pulses uplifted the seafloor, creating axes of sedimentation with crestal areas of condensed

Lower and Upper Cretaceous (i.e. inversion faults; e.g. Fig. 32). Ameen (1990) agreed with Stoneley (1982), and all subsequent interpretations based on seismic section evidence (e.g. Underhill and Patterson 1998), that the Purbeck and Isle of Wight monoclines result from the sedimentary cover (Late Cretaceous to Miocene) draping over reversed movements on the underlying ‘basement’ Purbeck Fault. In relation to these monoclinal folds a consistent pattern of sedimentation emerges. The ‘draping’ was not a passive process in the Chalk, as tectonic pulses uplifted the seafloor, creating axes of sedimentation with crestal areas of condensed

Fig. 26 Continued. (c) Rose diagrams for fracture orientations and frequencies in the White Chalk Formations of the Yorkshire Wolds (modified from Foster and Milton 1976 and Mortimore, 2019a). The results suggest that relatively simple fracture orientations in the older Chalk formations are replaced by more complex ‘radial’ fractures in the younger Flamborough Chalk Formation. This same complex radial pattern is present in the Newhaven Chalk (the same age and similar lithology with marl seams (Fig. 26b).
successions and basinal areas with thicker successions. Downslope space was also created for bed sliding and slumping (Fig. 32).

In the Grey Chalk Subgroup (West Melbury Marly Chalk and Zig Zag Chalk formations), with clay mineral content between 12 and 70%, the sedimentary cyclicity between carbonate and clay-rich bands is more obvious than in the purer (>95% carbonate) White Chalk Subgroup. In the Grey Chalk Subgroup formations the beds are referred to as marl–limestone cycles (e.g. Mortimore 2014, pp. 1–15, figs 1.13–1.16). In the purer carbonate White Chalk Subgroup the harder beds are referred to as nodular beds, hardgrounds and/or chalkstone. Marl seams (and marly beds) tend to become occluded towards the crests of anticlines and increase in number into the thicker, synclinal successions. Conversely, limestone bands and hardgrounds or nodular chalks tend to coalesce towards the axes of uplift. These lateral lithological changes also affect the style and frequency of fractures. For example, the coalescence of more brittle limestone bands in the Cenomanian Grey Chalk Subgroup (Chalk Marl) over a local anticline along the line of the Channel Tunnel led to increased fracturing and the ‘wet zone’ at kilometre 21 on the UK side (Warren et al. 1996; Mortimore and Pomerol 1996; Mortimore et al., 1996). Similarly, lateral changes involving occlusion of marl seams and condensed sections over the Hollingbury Dome in the Late Santonian–Early Campanian Newhaven Chalk Formation along the route of the A27 Brighton Bypass led to marked changes in lithology and fracturing, affecting cutting slope stability (Mortimore et al., 1996; Mortimore 2012).

**Discussion**

Chalk engineering geology has to consider all aspects of the rock including the various geological processes that have produced the range of sediments as well as fractures. One continuing problem with the Chalk is perception of uniformity. Chalk is frequently still treated as a blanket of coccolith limestone containing some marker beds and not much in the way of structure. This misconception extends to physical properties and engineering behaviour. Formations such as the Seaford and Culver Chalks can appear to
be very homogeneous, and the Seaford Chalk in particular is the part of the stratigraphy most frequently encountered in engineering and hydrogeology, compounding this view. A further issue has been an inability to correlate boreholes in settings where marker beds have been difficult to identify, also giving the impression of uniformity. In reality, the Chalk of southern England in particular is underlain by a complex tectonic picture of reverse inversion faults, in turn driving the evolution of monoclinal folds or domes over which sediments and fractures have evolved (Figs 34 and 35). The inversion faults are considered by many to be driven by a strike-slip fault regime (Fig. 34; Lake & Karner 1987; Ziegler 1990, 1993; Hibsch et al. 1995; Mortimore 2011).

Studies of orientations of fractures in the Chalk (Cawsey 1977; Bevan and Hancock 1986) have recognized general NW–SE and NE–SW trends. These trends have been broadly confirmed by later studies (Mortimore and Duperret 2004; Duperret et al. 2012); however, the fracture patterns are much more complex than these trends suggest, especially as each formation has its own stratabound sets of fractures. Evolution of the inclined conjugate fractures is closely related to lithology, especially the marl seams and interbed slides. Marl seams control the pore fluid pressure distribution in the rock mass, as seen in many contexts (e.g. fracturing and glacitectonics; Mortimore 2019).

Distribution of Chalk lithologies and thicknesses are strongly controlled by tectonic setting (Fig. 32); in turn this potentially influences properties such as density, porosity and hardness of the Chalk, as well as fracturing. It has been suggested that lateral variation in physical properties is partly controlled by position within a fold in relation to the hanging wall or footwall of the underlying regional fault(s) (Jones et al. 1984; Ameen and Cosgrove 1990; Mortimore 2019a, b). There is also evidence for intact dry density values being marginally greater in units with marl seams; for example, the Belle Tout Beds with marl seams compared with the overlying Cuckmere and Haven Brow Beds without marl seams in the Seaford Chalk Formation in East London (Mortimore et al. 2011).

Having a geological context for core logs and results from laboratory, field and borehole tests including geophysics enhances the possibility of extrapolating these results widely. A similar geological context needs to be developed for training core logging
teams so that everyone involved in a project can see how their site investigation information can be used. This will encourage core loggers to use their wider geological knowledge. Workshops run during the site investigation with the logging teams and engineers have proved especially useful.

Conclusions
Fracture logging is a vital part of any site investigation. Questions that have arisen during core logging with respect to fractures have included the following. (1) Is a fracture index an adequate representation of all the fractures? (2) Over what intervals should fracture frequency or index be calculated in core with no obvious strata changes? In these latter cases it is suggested that the fracture index should be measured by core-run. If summaries for longer intervals of core are required these core-run records can be combined by those who need the information. A fracture index should not be used on its own without reference to the log descriptions, where fracture style should also have been recorded.

Producing a fracture log in the Chalk can, however, be fraught with issues requiring ‘interpretation’ and ‘experience’ for which adequate training and guidance is vital. A standard fracture log

Fig. 29. (a, b) Listric growth faults in the Newhaven Chalk Formation, Newhaven with increased displacement downwards as lateral slip develops along marl seams (bedding planes). (c, d) One of the many strike-slip faults along the coast of Sussex especially in the Newhaven Chalk Formation. The fault is also the locus of collapsed and weathered Paleogene sediments. Modified from Mortimore, (2011, 2014, 2021). The orientation of striae (slickensides) provides the basis for the palaeostress analyses (Figs 29c, d and 30).
could be improved by annotating the core photographs to show the actual fractures being logged, with notes identifying style of fractures and illustrating uncertainties. A second improvement to fracture logs would be the identification of fracture zones (Fig. 9). All parties in a contract need to recognize the difficulties of fracture logging and appreciate where it is not possible to provide definitive numbers (annotated core photographs greatly assist this process of evaluation). There will be intervals of core destruction, which require an honest account without over-interpretation.

In the context of fracture evolution in the Chalk part of this review has focused on formation of early, stratabound ‘primary’ conjugate inclined fractures associated with subhorizontal slides and listric growth faults. This ‘package’ of early fractures is closely integrated with ‘growth’ tectonic movements caused by inversion faults beneath the folds that form en echelon ‘belts’ across southern England. Episodes of synsedimentary tectonic uplift along these fold belts led to lateral facies and thickness changes in the Chalk. Such changes included thickening of deposits into local ‘synclinal’ basins with increased marl seams and increased development of inclined conjugate fractures with interbed sliding. Conversely, thinning of Chalk successions over anticlinal domes led to occlusion of marl seams, development of hardgrounds and predominantly vertical joint sets (Fig. 35). Any model for Chalk fracture evolution and distribution has to recognize lateral variations in lithology in relation to tectonics. Early formed fractures have been rotated into their present positions by later folding in the Cenozoic that over-steepened the fractures.

Fig. 30. Palaeostress analyses of the coastal Chalk cliffs of East Sussex from the Cenomanian to Campanian deduced from sense of movement provided by striae or slickensides on normal and strike-slip faults. Vertical exaggeration of the cliffs is ×50. III–V represent the chronological order of palaeostress events (see also Fig. 31). Modified from Duperret et al. (2012).

Fig. 31. Summary of palaeostress conditions recorded in the Late Cretaceous Chalk coastal cliffs of the English Channel in Sussex, England and Normandy, France. Events: (i) NE–SW extension in Normandy; (ii) NW–SE extension in Normandy (iii) NNE–SSW extension in Normandy and Sussex with additional ESE–WNW compression in Sussex; (iv) north–south compression and east–west extension in Sussex; (v) east–west extension in Sussex. (Modified from Duperret et al. 2012.)
north-dipping limbs of early folds to produce the north-facing monoclines seen today.

Following best practice in Chalk engineering recommended in CIRIA 574 (Lord et al. 2002), a further part of this review has re-emphasized the need to record marker beds as well as fractures and how this can be achieved in drilling degraded core. A marker bed stratigraphy is needed if the correct ground interpretations are to be made. Core logging cannot simply focus on producing a fracture log, however important that might be. For example, recent offshore seismic profiles could be correctly interpreted only by recognizing marker beds in cored boreholes. These offshore seismic profiles have also supported the onshore model of Chalk sedimentation in relation to tectonic growth movements on inversion faults (Figs 32 and 35). The consultant or designer is the only party who understands the potential project impact of this broader geology. Ideally, specifications should identify Chalk sub-units that the

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**Fig. 32.** A rare seismic line with sufficient resolution in the Chalk to identify lateral variation in thickness and lithology in relation to tectonic structure. A fault-controlled asymmetric anticline with a more steeply dipping northern limb is typical of folding in the Chalk onshore in southern England. In this offshore case (to the NE of the Norfolk coast), the Early Turonian Holywell Grit Beds expand northwards into the complementary syncline, suggesting that the tectonic structure was active and growing during the Turonian. There is also the hint of reversal of displacement along the regional fault between the Lower and Upper Cretaceous. This could not have been interpreted without carefully logged fully cored boreholes (e.g. Figs 18–20). This seismic section is similar to others in this part of southern North Sea and provides a model for onshore asymmetric anticlines with similar lateral changes in thickness of Chalk sediments. (Modified from Mortimore and James 2015.)

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**Fig. 33.** Looking west from Durdle Door across Durdle Bay to Bat’s Head, Dorset coast onto vertical and partly overturned strata. The steeply dipping bedding is in the northern steep limb of the Purbeck Fold. Structures in the Chalk at Bat’s Head include post-depositional and penecontemporaneous inclined conjugate fractures formed pre-monoclinal folding (i.e. when beds were near horizontal) now rotated in the later monocline and partly re-mobilized during folding as thrust planes (modified from Mortimore 2019b).
A ground investigation contractor is expected to encounter and should provide the detailed guidance on how logging this ‘extra’ detail should be done. This should also reduce the consultant’s checking time.

It is hoped that by providing a geological context for Chalk sediments and fractures curiosity will flourish and enhance the core and field logging process, which will improve the quality of information gained from a Chalk site investigation. For Chalk engineering we need much more than just a fracture log! Stratigraphy, especially the lithostratigraphy, forms the skeleton onto which all geotechnical, geophysical and groundwater data can be attached. Regular workshops and training during a ground investigation will ensure the successful development of the stratigraphic skeleton.

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to the Chalk in a large area of the southern North Sea and made it possible to map lithofacies and structure in the Chalk in a way previously not possible (e.g. Figs 20 and 21). Her's is a very sad loss, and far too early.

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