Engineering Geological Characterisation of Flints

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Abstract

The petrographic and mechanical properties of flints from the Burnham (North Landing, Yorkshire, UK), Seaford (East Sussex, UK, and Dieppe, France), and Lewes Nodular (Mesnil-Val-Plage, France) Chalk Formations have been investigated. Microtexture and mineral composition of flints are studied to understand how the geological and petrophysical properties of the flint affect drilling responses to the rock and investigate any spatial variation. The flints are categorised based on physical observation: white crust; light brown; brown grey, dark-brownish-grey and grey flints. Scanning electron microscopy shows textural variation in the classes. The white crust surrounding the light brownish grey, brownish grey and grey flints from Burnham Chalk Formation, from North Landing, in Yorkshire contain more calcite and have coarser more poorly cemented silica spherules by comparison to similar classes of flint from the Seaford and Lewes Chalk Formations from the Anglo-Paris Basin. In these latter flints, the structure is dominated by massive quartz cement with trace calcite independent of location. Strength tests show that the grey flints from North Landing are weaker than equivalents from the Anglo-Paris Basin. It is suggested that variation in engineering properties between grey and the dark brownish grey flints is caused by mineral composition, microtexture, structure and the local/site geology of flint materials.

Keywords: Engineering; Flint; Chalk; mechanical; properties; Mineralogy; Microstructure

Introduction

Flint is a siliceous, cryptocrystalline rock that forms in chalk. They are primarily composed of silica (87%-99%) with small amounts of calcite and clay minerals. It exists within chalk units and is found widely in Europe, parts of the USA and the Middle East. Flint has various morphologies (Fig.1): sheet; tabular; tubular; nodular; and Paramoudra (barrel shaped) (Bromley 1967; Clayton 1984; 1986).

The distribution of chalk in the Thames and Paris Basin means that it is often intercepted during drilling and engineering projects. Drilling is carried out for resource exploitation including e.g. water resources for instance in the UK, Denmark, Jordan and Israel and for hydrocarbons, for instance in the North Sea Basin (Mortimore, 2012) and also during ground investigations. Engineering projects include tunnelling for infrastructure such as for High Speed 1 (formally The Channel Tunnel Rail Link) Crossrail 1 and the Lee Tunnel Project both in south east England. Drilling and construction in the chalk can be affected by flints as they are generally extremely strong which contrasts with the very weak to weak chalk. These are also hard due to their silica content, resulting in significant wear and reduced rates of penetration (ROP) of drilling bits and the cutting heads of tunnel boring machines (TBM). As such they present a significant construction risk and should be incorporated into risk registers associated with the geotechnical baseline reports and the geological models. As a results this work provides a detailed investigation of what effects flints mechanical properties and behaviour within the context of their geological setting and the impact this may have on geotechnical projects in the chalk.

Background

The mineralogical and chemical compositions of flints have received considerable attention in both archaeology and the geosciences. In archaeology, various geochemical techniques have been employed for provenance studies to constrain the origins of flint artefacts (e.g. Olausson et al. 2012; Huges et al. 2012; Prudêcio et al. 2015). For the most part these studies, which are only examples of a wider field, draw on the colour and geochemistry of flints to identify their provenance.

In addition to the identification of sources, the use of flints as tools by early mankind has been investigated. Pradel & Tourenq (1967) investigated the strength and hardness of Grand-Pressigny Flint with a comparison to other potential tool materials (coarse sandstone and Jasper-Opal) and noted that the Grand-Pressigny Flint was the most durable rock among the

Palaeolithic geo-materials investigated. Domaṅski & Webb (2000) correlated the grain size, mineralogy and the microfracturing and compared these parameters to the measured fracture toughness to characterise their flaking properties and found that these parameters exerted a clear control on the ability of flints to maintain a good cutting edge.

In the geosciences, X-Ray diffraction (XRD) has been used to investigate the mineralogy of flint using qualitative and quantitative approaches (e.g. Graetsch & Grunberg 2012; Jakobsen et al. 2014). Energy Dispersive X-ray Spectroscopy (EDX) (Wasilewski 2002) and Energy Dispersive X-ray Fluorescence (EDXRF) analysis (Hughes et al. 2010) has also been applied to investigate the mineralogy of flints. It was established that α-quartz is the major mineral phase in flint with minor amounts of calcite and clay minerals.

Mineralogy and geological observations

Jeans (1978) recognised that the mineral composition of flint is non-uniform noting a differentiation between the flint core and the cortex (the original outer layers). The presence of different quartz phases in various flint samples was also noted. Clayton (1984) carried out detailed microstructural studies on flints and associated crusts and provides an explanation of textural compositions and growth sequence of flints and the surrounding crust. Madsen & Stemmerik (2010) differentiated between white and dark flints and showed that the dark flint possessed more massive silica cements than the white flint. Although variations in micro-structural/textural details combined with colour and structures of flints were investigated, the relationship between micro-structure/textures and the mechanical properties (especially the strength) of various flint morphologies (Fig. 1) from different regions remains unresolved.

The mechanical properties of flints

The variability of micro-structures/texture, chemical and mineral compositions of flint is reflected in the mechanical characteristics of flint. Iller (1963) examined the transverse rupture strength of flints and concluded that the fine grain nature of flints contributes to their strength. Since this work, a variety of different measures of the mechanical properties of flint have been investigated. These include Uniaxial Compressive Strength (UCS) (Varley 1990), tensile strength (Cumming 1999) and point load strength (Smith et al. 2003) with studies normally involving more than one test. While flints are generally considered to be extremely strong, considerable variability is observed. Cumming (1999) noted that weathered, fractured, carious (flint with network of crumbly, poorly silicified chalk) and pale flints from the White Chalk Subgroup of the Southern Province, UK, had lower strengths by comparison to other flints.

Such variability was attributed to the presence of internal microfractures associated with the flint samples. These observations were supported by the work of Smith et al. (2003) who suggested that the variation in material/strength properties of flints might also depend on its geographical location which is suggestive of mineralogical or macrostructural controls.

In this paper the mineralogy and mechanical properties of flints of different morphologies from three regions are described. The description is in terms of the mineralogy, strength, elasticity and abrasivity. The relationships between flint strength, deformation properties, morphology, microtexture and colour are described with the aim of providing useful guidance for engineers and geoscientists at the desk study stage of a ground investigation. A classification of flints based on colour is proposed.

Materials and Methods

Descriptions of flint

The nomenclature for samples is as follows: the first letter relates to the formation; the second/third relates to geographic location; and the final fourth or fifth letter relates to the country. For example, flints sampled from the Burnham Chalk Formation at North Landing in the UK are given the notation B-NL-UK (BNLUK).

The test materials were from the Burnham Chalk Formation, North Landing, Yorkshire, UK (BNLUK) [TA 243 706], the Seaford Chalk Formation, East Sussex, UK (SESUK) [TA 675 510] and at Dieppe, France (SDFr) [TW 196 769], and the Lewes Chalk Formation at Mesnil-Val-Plage, France (LMFr) [TW 539 265] (see Fig. 2). Samples were collected from sea-cliff exposures and occasionally, from fresh rock falls where the stratigraphy could be identified. In the latter case, samples were only collected where flints were still surrounded with thick chalk deposits that were assumed to protect the flint from impact damage. Some of the flint blocks from the different sites are shown in Figure 3 and description of flint samples are provided below.

Flints from the Burnham Chalk, North Landing, Yorkshire, United Kingdom.

The flint samples from the North Landing, UK are tabular, mostly grey (Figs. 3a, and b) and highly fractured (Fig. 3c, both macro/microfractures). Fracturing in these samples might be associated with tectonic activity as the collection site is near the Flamborough Head faults. The North Landing flint has a white crust (Fig. 3a) which is commonly exceeds 20 mm thickness, and is stronger than the surrounding chalk, but weaker than the enclosed flint core. These flint samples have higher calcite content than other flints. Most of these flint samples are up to 300 mm thick and comprise significant quantities of partially silicified carbonate inclusions (Fig. 3b) and in some cases most of the sample is dominated by the light grey flint. Brownish grey flints are also found in the North Landing Chalk with significant quantities of calcite inclusions (Fig. 3b).

Flints from the Anglo-Paris Basin, United Kingdom and France.

The flints in the Anglo-Paris Basin chalk are shown in Figure 3d-f. Figure 3d is a flint from the Seaford Chalk, East Sussex, UK, Figure 3e is a flint in the Seaford Chalk, Dieppe, France and Figure 3f is a flint in the Lewes Nodular Chalk, Mesnil-Val, France. These flint samples are mostly dark brownish grey, with a few silicified inclusions. These inclusions appear as light brownish grey irregular shaped zones in the samples. The dark brownish grey flints appeared more competent than the grey flints. Microfractures are rarely seen in these flints, and the white crust surrounding the dark brownish grey flints are thinner and harder when compared with those surrounding the grey flints from the Burnham Chalk Formation.

Geology of the Study Sites

The geology at North Landing is described in Mortimore et al. (2001). The Burnham Chalk Formation (Turonian-Santonian, see Fig. 4) includes the entire *Sternotaxis plana* zone to the lower part of the *Micraster cortestudinarium* zone. The Formation overlies the Welton Chalk Formation and is overlain by the Flamborough Chalk Formation. It is characterised by the tabular flints ($\geq$ 0.3m thick) (Wood & Smith 1978; Gale & Rutter 2006), Paramoudra and semi-tabular flints. It comprises thinly bedded chalk with flints and is 130-150 m thick in this area (Mortimore et al. 2001; Hopson 2005). The base of this formation has more flint bands than other parts of the formation (Wood & Smith 1978) and is characterised by conspicuous layers of light grey, highly fractured carious tabular flints.

The geology of the chalk at the sites sampled in the Anglo-Paris Basin is described by Mortimore et al. (2001) and Bristow et al. (1997). The Seaford Chalk Formation (middle Coniacian-middle Santonian, see Fig. 4) is described in Mortimore (1986); Mortimore & Pomerol (1997); Bristow et al. (1997) and Mortimore et al. (2001). The formation is composed of pure (>98%) calcium carbonate, very weak, white, fine-grained chalk, with extensive bands of dark nodular flints and sheet flints can also be commonly found in this formation. The formation is bound at the top by marl seams and by the basal marker the Shoreham Marl. The formation also includes the Seven Sisters Flint which is a conspicuous marker bed and is also traceable along the French coast (Upper-Normandy and Picardy) (Mortimore et al. 1986).

The French sampling site at Mesnil-Val in Picardy, is a coastal cliff section composed of the Lewes Nodular Chalk Formation (Upper Turonian-Lower Coniacian stage, see Fig. 4) as described in Mortimore et al. (2001). The Lewes Chalk Formation comprises marl seams, and well bedded, nodular chalk with nodular flint bands. These flint bands are parallel to the bedding, laterally extensive and traceable in the stratigraphy (Mortimore 1986; Mortimore & Pomerol 1987; Busby et al. 2004; Senfaute et al. 2009). Apart from nodular flint bands, tubular and semi-tabular flints are also present in places along the chalk cliff section.

Sample description

The flint samples are initially classified on the basis of the geological features, mainly body colour characteristics (Figs. 3a-f and 5). The flint colour classification is based on Munsell colour chart as given in Table 1. The frequently used notations representing flint types, geological units and geographical locations are provided in Table 2. Flint samples were tested at their natural moisture content and at laboratory temperature. The test method and typical sample sizes used for the geomechanical tests are provided in Tables 3 and 4 respectively.

Microstructure and mineralogical Characterisation

The external morphology, grain shape, orientation and degree of crystallisation/cementation of the flint are characterised using scanning electron microscopy (SEM) to aid in explaining the physical and mechanical properties of flints. The mineralogy, including the silica phases, is assessed using XRD.

Scanning Electron Microscope

SEM analysis, including secondary electron images (SEI) was conducted on samples with size of approximately 10 x 10 x 5 mm. The analysis was conducted on twelve flint samples selected to be representative of the various flint classes (Fig. 5). These were coated with gold in a BIO-RAD-SC500 Sputter coater for 4 – 5 minutes to inhibit the concentration of electrical charge on the samples. The coated samples were analysed using a JEOL-JSM-6610LV SEM machine equipped with an Oxford Instrument Energy Dispersive X-rays (EDX) detection analyser, which is used to identify and quantify mineral phases of the samples. Images were captured using an accelerating voltage of 15 keV.

X-Ray Diffraction

XRD analysis was carried out using a Bruker D8 XRD instrument, it was performed on flint specimens similar to those characterised using the SEM. These samples were ground into powder and pressed into a mount in order to produce a randomly oriented powder. The mounts were analysed in turn. A Cu kα radiation source was used. The specimens were scanned over an angular range of 2-90° 2θ, with a step size of 0.01°. The data were processed using Bruker EVA search match software for phase identification while Bruker TOPAS profile and structure analysis software were used to quantify the mineral phases present.

Geomechanical Properties Tests

The methods used for testing samples are outlined in Table 3 and the geometry of tested samples reported in Table 4. The majority of these methods use standard test procedures. Deviations from the standard method will be discussed. Two testing machines were used. These were the MAND Universal Compression Testing Machine (250 kN capacity with a precision 0.1 kN) for the tensile testing and the Denison compression machine (capacity of 2000 kN with precision of 0.05 kN) for compression testing.

Bulk density ($\boldsymbol{\rho}$)

The bulk density ($\boldsymbol{\rho}$) of flint was determined using the caliper method. The bulk mass of each specimen was measured using a digital scale. The bulk volume was obtained from the mean of five readings for each dimension taken at various points of the specimens. Bulk density was calculated from the relationship between the bulk mass and the bulk volume of each flint specimen (Equation 1).

$$\rho = \frac{bulk\ mass\ (M_b)}{bulk\ volume\ (v_b)} \qquad (1)$$

Where: ρ is the bulk density (Mg m^{-3})

Tensile strength (T_o)

For the tensile strength (T_o), the Three-point beam method described by Brook (1993) was used to determine the tensile strength of flint by bending. The test was developed to estimate tensile strength by subjecting samples to stress by applying steady central load between two ball bearings until the samples fail by bending. The positioning of the bearings is dictated by sample length. The concentrated load applied to the sample causes tensile deformation along the point of the applied load, which leads to a tensile failure.

The Three-point beam method was used instead of the direct tensile test and the Brazil test because:

1) Less sample preparation and no surface finish was required;

2) Smooth or flat ends were not required.

These requirements mean that a beam of flint can be more easily prepared and tested using this method than the standard disc required for the Brazil test or the direct tensile test. The tensile strength derived from beam method was found to compare well with that of direct pull test (Brook 1993) and with tensile strength obtained from the Brazilian test for flint (Cumming 1999). The Three-point-beam test was carried out using the MAND universal compression testing machine. Tensile strength was calculated using Equations 2 and 3.

$$T_0 = \frac{P}{G} \qquad (2)$$

$$G = \frac{4bd^2}{3l} \qquad (3)$$

Where: T_o is the tensile strength (MPa), P is the failure load (kN), G is the geometry factor, b is the breadth of the sample (mm), d is the thickness of the sample (mm), l is the span between the ball bearings.

Point Load Strength Test

Point load strength index ($I_{s(50)}$) of flint was measured on an ELE International point load machine with a loading capacity of 56 kN and a precision of 0.05 N. Both blocks and irregular specimens were tested in accordance with ISRM (2007) suggested methods. The dimensions of the specimens range from length=25-90 mm, width=19-45 mm, and diameter=15- 44 mm. Sample geometry was constrained by challenges of preparing flint samples. The samples sizes used were within the 50±35 mm tolerances contained in the suggested method. Samples were tested at a loading rate resulting in failure between 10-60 seconds after the start of the test. The failure loads were then recorded, the $I_{s(50)}$ for each specimen was calculated using Equations 4 to 9 (ISRM 2007).

$$A = W \times D \qquad (4)$$

$$De^2 = \frac{4D}{\pi} \qquad (5)$$

$$De = \sqrt{De^2} \qquad (6)$$

$$I_s = \frac{(P \times 1000)}{De^2} \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (7)$$

$$F = \left(\frac{De}{50}\right)^{0.45} \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (8)$$

$$I_{s50} = F \times Is \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (9)$$

Where: A is the minimum cross sectional area of the point of contact for the loading platens on the sample (mm^2), De is the equivalent sample diameter (mm), F is the Size correction factor, Is the Uncorrected Point load strength index (MPa), and $I_{s(50)}$ is the corrected Point load strength index (MPa).

Uniaxial Compressive Strength (UCS) Test

Uniaxial compressive strength (UCS) of flint was measured using Denison machine with the capacity of 2000 kN at loading rate of 0.5 $MPas^{-1}$. The machine has an accuracy of 0.05 kN. The test was conducted on both cores and cuboid flint specimens in accordance with ASTM D2845 2000; ISRM 2007; ASTM D7012-07 2010 suggested methods. A typical sample size of 25 mm diameter was used. The choice of this size was informed by the repeated failure of attempts to produce cylindrical core samples of NX size (54 mm). The cuboid flint specimens were only prepared for the flint samples from the Burnham Chalk Formation due to difficulty in preparing cylindrical samples because of fractures/joints and carbonate inclusions in the samples.

Young's modulus and Poisson's ratio

The deformability (Young's modulus and Poisson's ratio) of flint specimens was determined in accordance to ISRM 2007 suggested methods from the strain measurements. Strain was measured using 5 mm electrical resistance strain gauges. The axial stresses, axial, and lateral strains, were recorded using a windmill logger. These data were used to plot stress-strain curves from which elastic properties comprising static Young's modulus (E_s), and static Poisson's ratio (ν_s) were determined. The average method was used to determine the E_s of flint using Equation 10. This involves deriving E_s from the approximate linear part of the axial stress-strain curve (ISRM 2007). The ν_s was then calculated from the relationship between E_s and the slope of diametric curve using Equation 11.

The deformability of all the investigated flint specimens was measured except the flint specimens from the Burnham Chalk Formation. The deformability of these specimens was not measured because the strain gauges detached from the specimens at early stage of loading due to spalling of the flints under load. The spalling of these flints was likely associated with closely spaced (c. 10 – 15 mm) orthogonal incipient fractures in the specimens.

$$E_s = \frac{\Delta\ Axial\ stress}{\Delta\ Axial\ strain} \qquad (10)$$

$$v_s = \frac{E_s}{Slope\ of\ diametral\ curve} \qquad (11)$$

The physical and mechanical properties were subjected to statistical analysis using One-way ANOVA and Post-Hoc tests using Tukey's test. The One-way ANOVA was used because normality test using the Shapiro-Wilk shows most of the data was drawn from normally distributed population (Table 5) except in four cases where normality was rejected (bold in Table 5). In the four cases, two have about 50 specimens in which case normality can be assumed due to large sample size in the population. The two remaining cases E_s for SDFr and T_o for LMFr (both in Table 5) were treated as non-normally distributed data. Thus, to check the influence of distributions of data, both parametric and non-parametric statistics were used to analyse the overall results (summarised in Tables 6 and 7).

Results

Petrographic Observations

The principal minerals identified in all the flint samples investigated were α-quartz and calcite, the percentages of which vary with flint structure and geographic locations (Table 5). A summary of the mineralogy of different flint structures and class by location is given in Table 8.

In the white crusts of the Burnham Chalk Formation, granular, flaky calcite crystals with clusters of quartz microspheres and traces of cryptocrystalline quartz are evident (BNLUK, Fig. 6a).

The white crust of the Seaford Chalk from both sites have a homogeneous phase dominated by cryptocrystalline quartz (Figs. 6a-c). The recrystallisation of quartz grains into massive quartz cements is apparent in the white crust (WCr) of the Seaford Chalk Formation Dieppe, France (Fig. 6c). The WCr from both Seaford Chalk Formations are relatively more cemented than those from BNLUK and have amorphous silica particles (enclosed in white in Figs 6b & c) with some clusters of quartz microspherules (indicated by the arrows in Fig. 6c).

Spherical quartz grains that have transformed into clusters of quartz microspheres are seen in the light brown grey, brown grey and grey flints of the Burnham Chalk (Figs. 6d, h, and l). Quartz cements also occur intermittently in these samples and are also observed in the light brownish grey flints (Fig 6. e-g). The clusters of quartz microspheres are more pronounced in the GF (Fig. 6l) from the Burnham Chalk Formation, North Landing, UK (BNLUK) than light brownish grey flints from the same chalk formation. Spherical quartz grains with interparticle pores and microfractures are seen in the LBG of the BNLUK samples (white arrows in Fig. 6d). These interparticle microfractures are also evident in the BG flint of the BNLUK category.

The LBG and DBG flints in the Seaford Chalk at East Sussex, (SESUK), Seaford Chalk at Dieppe, France (SDFr) and Lewes Chalk Mesnil-Val, France, (LMFr) appeared distinct (Figs. 6i-k). These flint samples exhibit networks of massive quartz cements forming agglomeration of quartz grains/flakes and cements (Fig. 6k). These flint types show greater cementation compared to those of GF (BNLUK).

Mechanical Properties by Location

The results of the mechanical properties of flints are expressed as box and whisker plots Figure 7. The main statistical analysis of the results is given in Tables 6 and 7 presented according to locations and geological units which vary with flint class. Box and Whiskers are used to show the overall distribution of the results. Cross plots are used to show the influence of sample sizes on strength of flints and the distribution of some engineering geological parameters.

Figures 7a-d show data for the flints obtained from North Landing and the Anglo-Paris Basin. It can be seen that by comparison to flints from the south of England and France, are denser than those from North Landing (mean density 2.42 Mgm^{-3} as opposed to 2.66-2.69 Mgm^{-3}). This tends to suggest a lower degree of silicification (see Fig. 6a) than in the flints found within the Southern Province chalk. Concurrently, it is therefore unsurprising that T_o, UCS and $I_{s(50)}$ for the North Landing flints are significantly lower than those from elsewhere. In 7b, c and d, it is clear that the flints from the Anglo-Paris Basin (extracted from the Seaford and Lewes Chalk formations) show a range of mechanical properties which are broadly similar. Equally, as can be seen in 7e and 7f, Young's Modulus and Poisson's Ratio for flint samples extracted from the English and French sites are broadly similar. While it can be seen that there is some overlap in the natural material variation, the overlap is small (Tables 6 and 7).

Tensile Strength (T_o)

Figure 7b shows results of variations in tensile strength (T_o) as summarised in Tables 6 and 7. Flints in the Burnham Chalk Formation, North (BNLUK) generally show the lowest mean and ranges of tensile strength compared with those of Seaford and Lewes Chalk Formations. In some specimens of the BNLUK flints a weak correlation between tensile strength and carbonate content was observed. This correlation is indicated by the absence of the two major data point cluster (observed in Figs. 7c and d) exhibiting differences in strength between samples with higher calcite inclusions and samples with lower calcite inclusions. The T_o values for samples from the Seaford and Lewes Chalk formations were all greater than those for the Burnham Chalk Formation and were similar (in both the mean and median values, Table 6).

Point Load Strength Index ($I_{s(50)}$)

A similar pattern to that seen during the tensile testing program was observed during the point load strength index testing. The plot of $I_{s(50)}$ for the four flint types is provided in Figure 7c. Again, the $I_{s(50)}$ values for flints from the Burnham Chalk are distinctly lower than those from other locations. The recorded values of $I_{s(50)}$ were in the range of 3.07-12.31 MPa flint in the Burnham Chalk Formation, North (BNLUK). A comparison of the $I_{s(50)}$ values between dark brownish grey flints in the Seaford Chalk Formation at East Sussex, UK, Dieppe, France and flints in the Lewes Chalk Formation does not show any significant differences (Tables 6 and 7) even between the results of parametric and non-parametric statistics.

Uniaxial Compressive Strength

The UCS of the flints studied is shown in Figure 7d and the statistical observations are presented in Tables 6 and 7. It should be noted that in both statistical approaches employed, grey flints in the Burnham Chalk, North Landing (BNLUK) consistently remain the weakest material as against the stronger, dark brownish grey flints from other formations. This is consistent with the trends in T_o and $I_{s(50)}$ results. The UCS of flints in the Seaford Chalk Formation at East Sussex, Dieppe, France and for flints in the Lewes Chalk Formation corresponds to the extremely strong category. However, a significant difference exists in the UCS of the flints from Burnham Chalk Formation forming two major clusters with mean UCS and standard deviation as low as 112.2±71.0 MPa within a range of 25.2 to 232.4 MPa were recorded. The wide range observed in these samples is associated with calcite inclusions and microfracturing in the samples.

In order to define the deformation characteristics of flints, elastic properties comprising Young's modulus (E_s), and static Poisson's ratio (ν_s) were determined (Figs. 7e and f) and Tables 7 and 8 provides the summary of the overall results. The E_s ranges, mean and standard deviation values for flints in the Seaford Chalk Formation from East Sussex and from Dieppe and flints in the Lewes Chalk Formation indicate these flints are extremely stiff, with very slight variation in stiffness among the samples (Tables 6 and 7). As observed in all the mechanical tests, the ν_s for the dark brownish grey flints from the Seaford and Lewes Chalk Formations representing the three respective sites were similar (Fig. 7f and summarised in Tables 6 and 7). These ν_s values range from 0.050-0.181 and the overall data points mimicked the heterogeneity within the individual flint specimens characterised by the presence of partially silicified inclusions and minor variations in mineral composition.

Discussion

General observations

The characterisation of flints reported in this paper focused on both physical and mechanical properties of flints and relate these with the petrographic observations to understand how the behaviour of flints is shaped by the mineralogy and microfractures. Due to the different tectonic setting of each site an investigation into the effects this has on the geo-mechanical properties of the flint was possible.

The results of physical and mechanical investigations (summarised in Tables 6 and 7) indicate that the engineering properties of flints vary with flint class. The relationship between ρ and UCS is presented in Figure 8. The effects of sample sizes on the overall strength results assessed from the cross plots of strength and sample sizes (Figs 9a and b; Fig. 10) suggest that variations in sample sizes do not affect the present findings as there was no observed clear relationship in the cross plots.

The results of density measurements, tensile and compressive strength tests and point load strength index tests (I_{S50}) are shown in Figures 7. The results from the mechanical tests show considerable variation in flint strengths which is consistent with other studies (e.g. Cumming 1999; Mortimore et al. 2011; Smith et al. 2003) as shown in Table 9 which highlights previous studies and shows the variation in the results.

If flints are classified into dark brown-grey flints (DBG) and grey flints (GF), it is generally observed that the densest, strongest and stiffest materials fall into the DBG category. This is consistent with the mineralogical observations which show that in that DBG flints have the highest silica content over 99% regardless of location (Table 8). So in general at any given location the higher silica content (and correspondingly lower calcite content) leads to the densest, strongest and stiffest flints.

The Burnham Conundrum

Even at the stage of sample preparation and field observation it was apparent that the flints sampled from the Burnham Chalk at Flamborough Head were significantly different from those observed in the chalk of the Anglo-Paris Basin. This difference is characterised by the presence of centimetre scale fractures in the flint (Fig. 1a). These tend to form in a bedding-parallel orientation and at 90^o to bedding. This has led to two possibilities: (i) the flints in the Burnham Chalk are fractured or (ii) the flints at Flamborough Head are fractured. The higher calcite content observed could explain the weaker strength properties of these flints, but not the presence of the fracturing. These flints showed less cement and possessed larger, more spherical quartz grains compared with other flints (see SEM images Figs. 6a-l).

In order to investigate these hypotheses grey flints from the Burnham Chalk Formation were collected in Lincolnshire (mean UCS=310 MPa, mean ρ=2.49 gcm^{-3}). These flints do not contain similar centimetre scale fractures and so it is most likely that the Burnham Chalk flints at North Landing have been intensely fractured because of the complex tectonic structures related to faulting such as those seen in Selwick Bay (TA 205 687) less than 2 km to the south east where major a fault complex of normal and reverse faults related to east-west faulting and folding movements initiated as frontal movements from the offshore Dowsing Fault (Mortimore et al., 2001). In the chalk itself, this movement is readily accommodated via layer parallel slip, whereas for the more brittle flints shearing and fracturing due to the large stiffness differences is the only available mechanical option. This tends to confirm the postulated effects of tectonics on the strength of flints from the Southern Province of the UK suggested by Cumming (1999). It seems likely that this is an effect associated with extensional tectonism rather than compressional since the extremely high compressive strengths of flint are unlikely to allow brittle compression fracture to develop.

Mineralogical controls on mechanical properties.

The main mineralogical control on the mechanical properties of flint is the percentage of silica within the sample. The colours of flints generally reflect the silica-calcite ratios within the rock. Although some halite was observed on XRD traces, this is believed to be contamination from sea spray. Generally there is an increase in the quartz content from the white crust through the light brown grey; brownish grey; grey flint and into the dark brown grey flints (Table 8). There is conversely an increase in the carbonate content.

The evidence of high sphericity of quartz grains and interparticle voids in the weaker, less dense grey flints compared to the stronger, denser, intensely silicified micro fabrics of the dark brownish grey flint supports the hypothesis that the microtexture and the microstructure of flint exert significant control on the engineering behaviour of flint (Tables 6-8). Figure 8 shows that the highly cemented/silicified dark brownish grey flints showed significantly higher strength and density than the predominantly grey flints. There is some natural scatter which is a function of natural variability of the flint materials. Density can be used at a proxy to strength for example the more siliceous dark brownish grey flints were observed to be denser and stronger compared to the less siliceous grey flints as shown in Figure 8.

Reported values of Young's Modulus show small variations from previously reported observations (Pabst & Gregorová 2013). However, it is likely that such variations fall within the range of uncertainty of natural materials and can be attributed to observational bias due to different techniques being used in the measurement. Similarly, measured Poisson's ratio (ν_s) of flint samples from the Seaford Chalk and Lewes Chalk Formations are broadly consistent with the results of Gercek (2007).

Summary and Conclusions

An investigation of three groups of flints from the United Kingdom and France is reported. Significant differences in the mechanical properties of flints exist.

The principle control on the mechanical properties of flint is the relative proportions of quartz to calcite in the rock. Such proportions also control the colour of the materials and therefore it is possible to classify flints on the basis of colour. The observed colour ranges from the white crust (often found around flints), which is in effect a highly silicified chalk, through to the dark brown grey flints with the lowest percentage of calcium carbonate. Given the empirical relationship between abrasivity and quartz content, colour may be a useful predictor of potential abrasivity at the desk study stage approach of a site investigation. Further investigation is required to confirm the validity of this relationship outside the Anglo-Paris Basin.

It is observed that the flints found in the Burnham Chalk Formation from North Landing in Yorkshire show lower densities and lower strength properties than other materials. The dark brownish grey flints in the Seaford and Lewes Formations have similar strength values supporting the view that colour is a useful predictor regardless of geographic location and stratigraphic control. The fracturing in the flints found at North Landing is likely to be a tectonic effect and the potential for such fracturing should be considered during site investigations in the proximity of large extensional faults. Further research is required to clarify whether such effects exist for compressional tectonic environments given the significantly higher strength of flints in compression.

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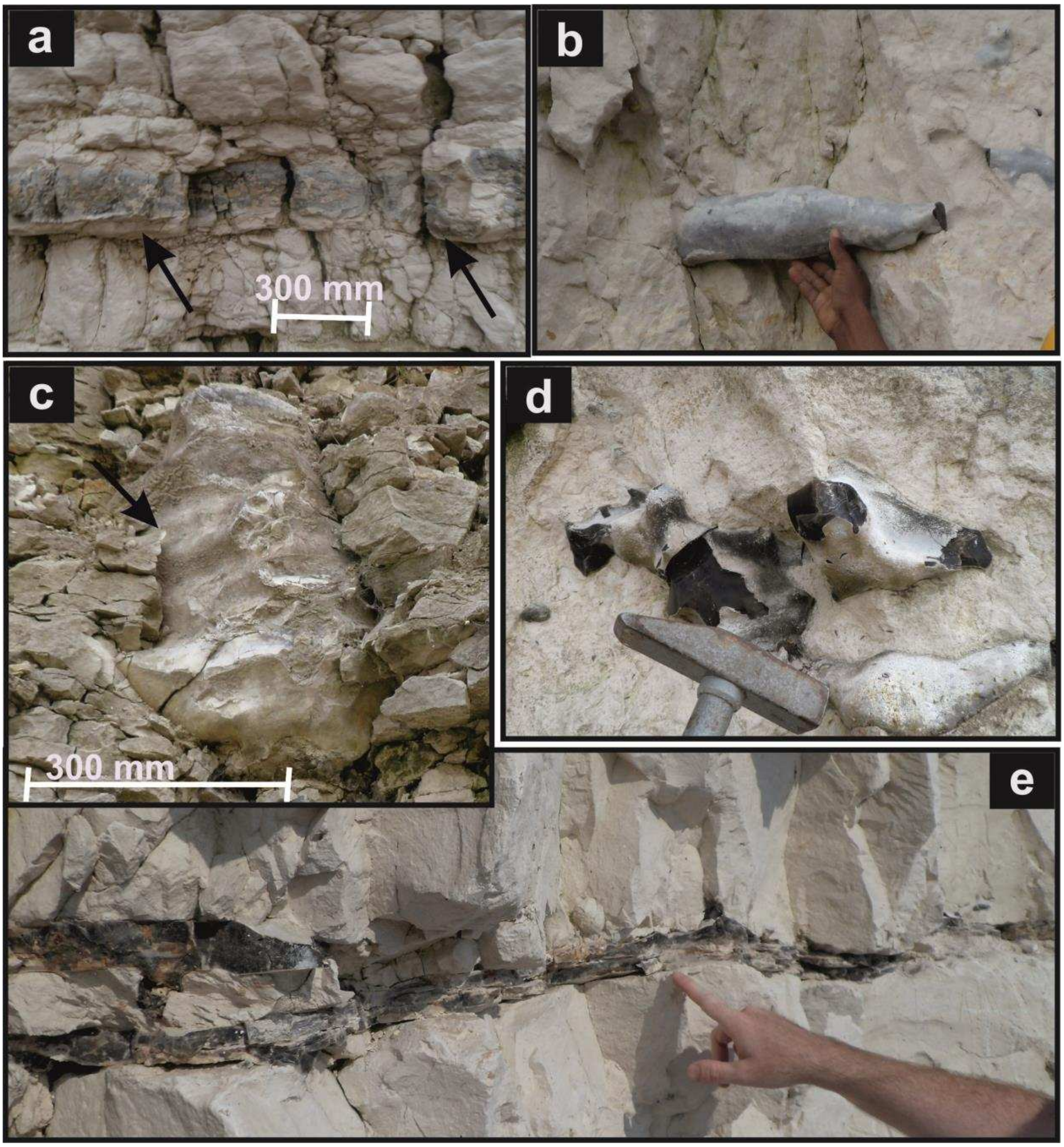


Fig. 1. (a) Tabular Flint in Burnham Chalk Formation, North Landing, UK ; (b) Tubular Flint, Lewes Chalk Formation, France; (c) Paramoudra Flint, Burnham Chalk Formation, Ucerby Vale Quarry, Lincolnshire, UK; (d) Nodular Flint, Seaford Chalk Formation, East UK; Sussex, (e) Sheet Flint, Seaford Chalk Formation, East Sussex, UK.

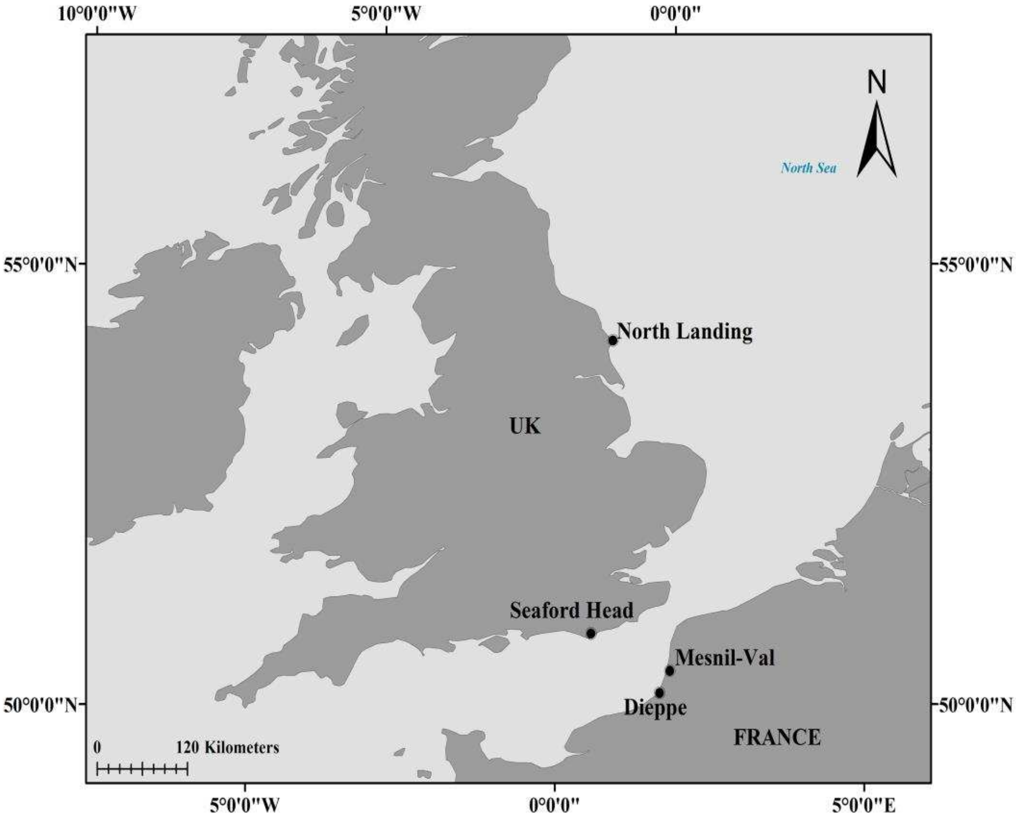


Fig. 2. Map of UK and north western France with the study locations highlighted.

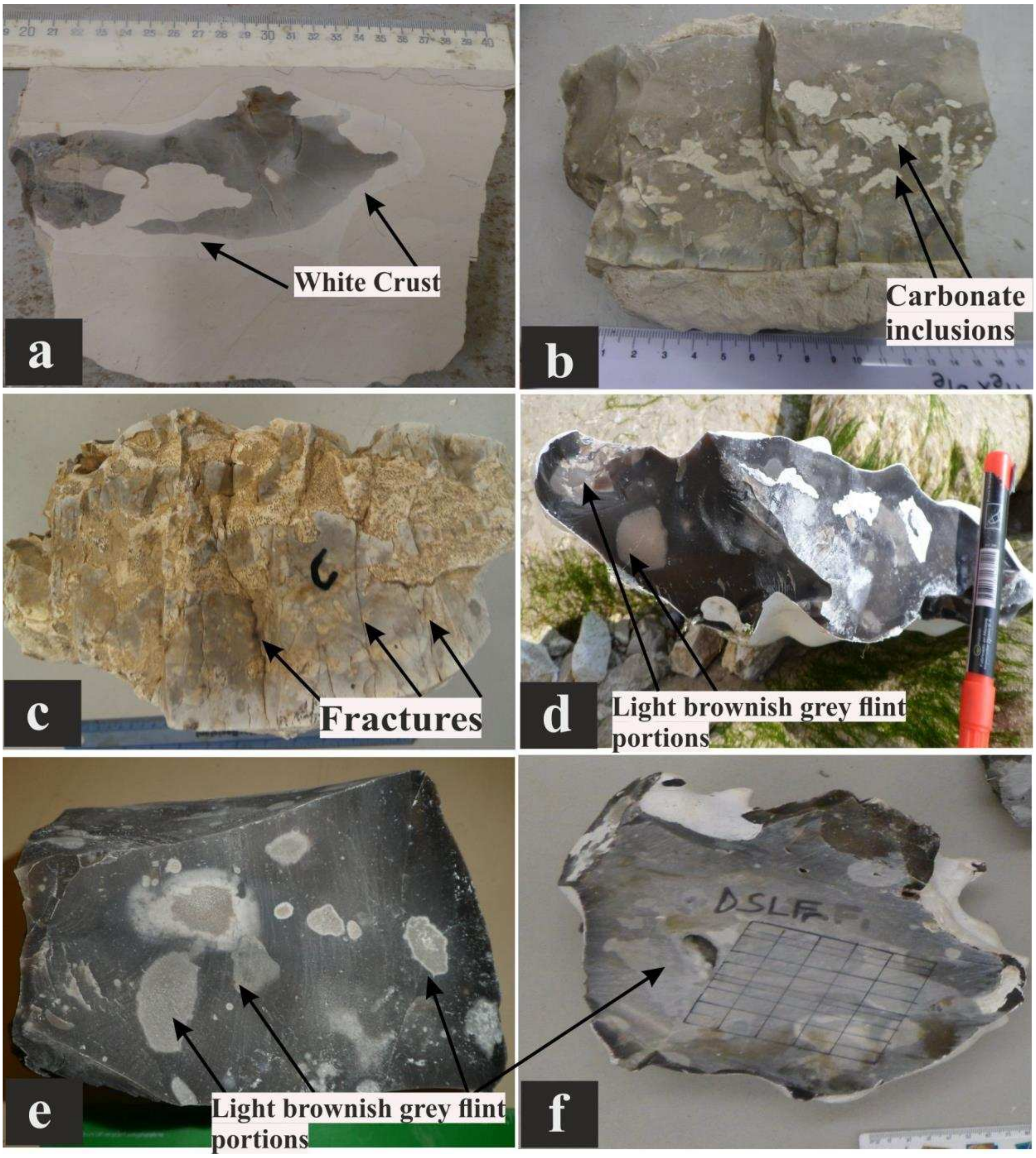


Fig. 3. (a-f) Flint Blocks from the four (4) study sites showing different structures and colours of flint. (a-c) Represent flint blocks from the North Landing, UK. Note the white crust in (a), brownish grey flint with white inclusions in (b), and highly fractured grey flint in (c). (d, e and f) Dark brown flint from Seaford Chalk, UK, France and Lewes Chalk, France respectively. Note the presence of light brownish spots on all the dark brown flints.

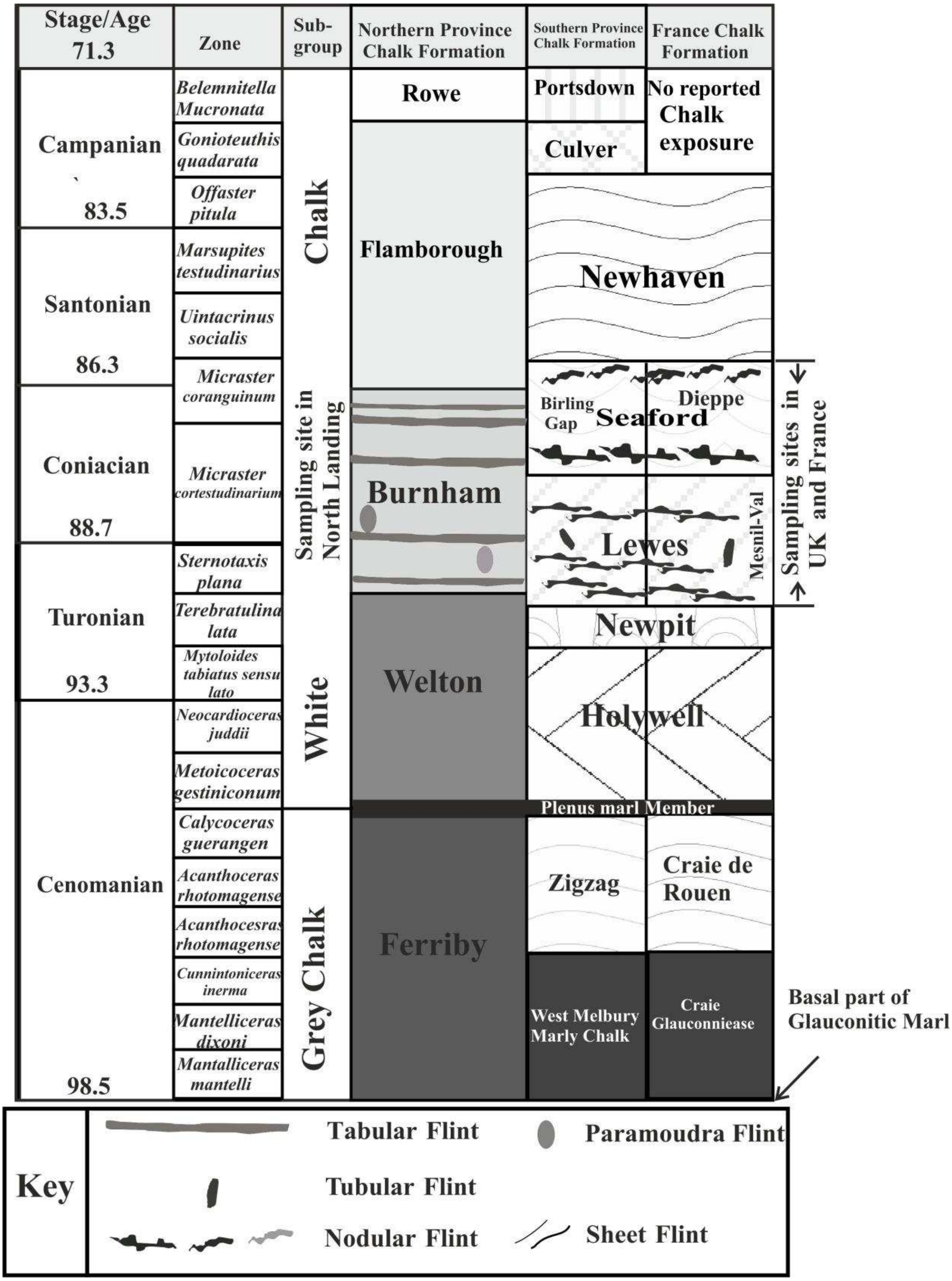


Fig. 4. Simplified Stratigraphy of the Upper Cretaceous Chalk in the study sites, contrasting the Northern Province chalks of northern east England with the Southern Province chalks of southern England and North France. The figure identifies and compares the main flint horizons in the chalk which were sampled, the key shows the main types of flint and where they occur in the stratigraphy (Adapted from Bristow et al., 1997; Mortimore et al. 2001; Mortimore 2011; Duperet et al. 2012).

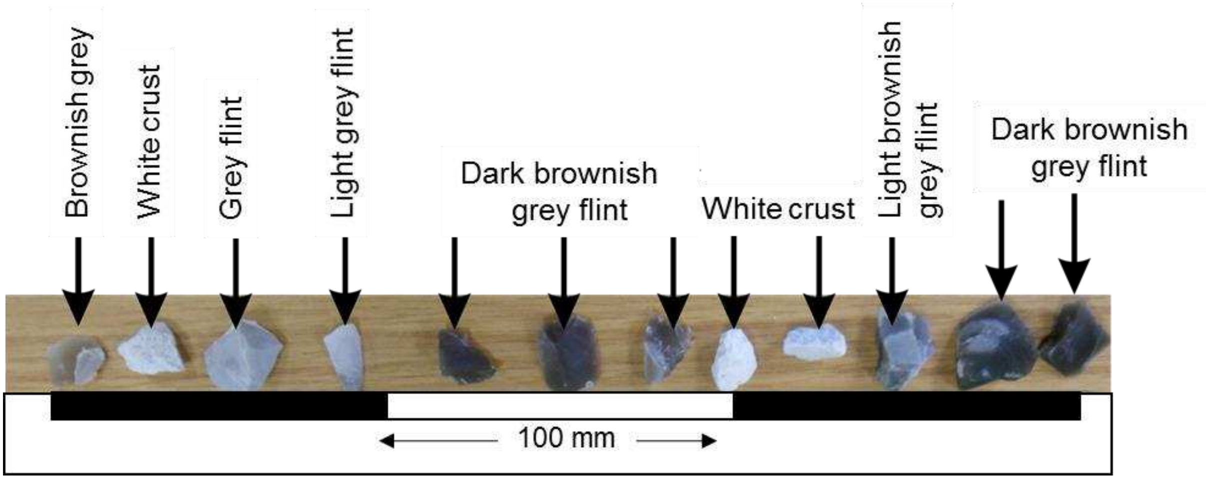
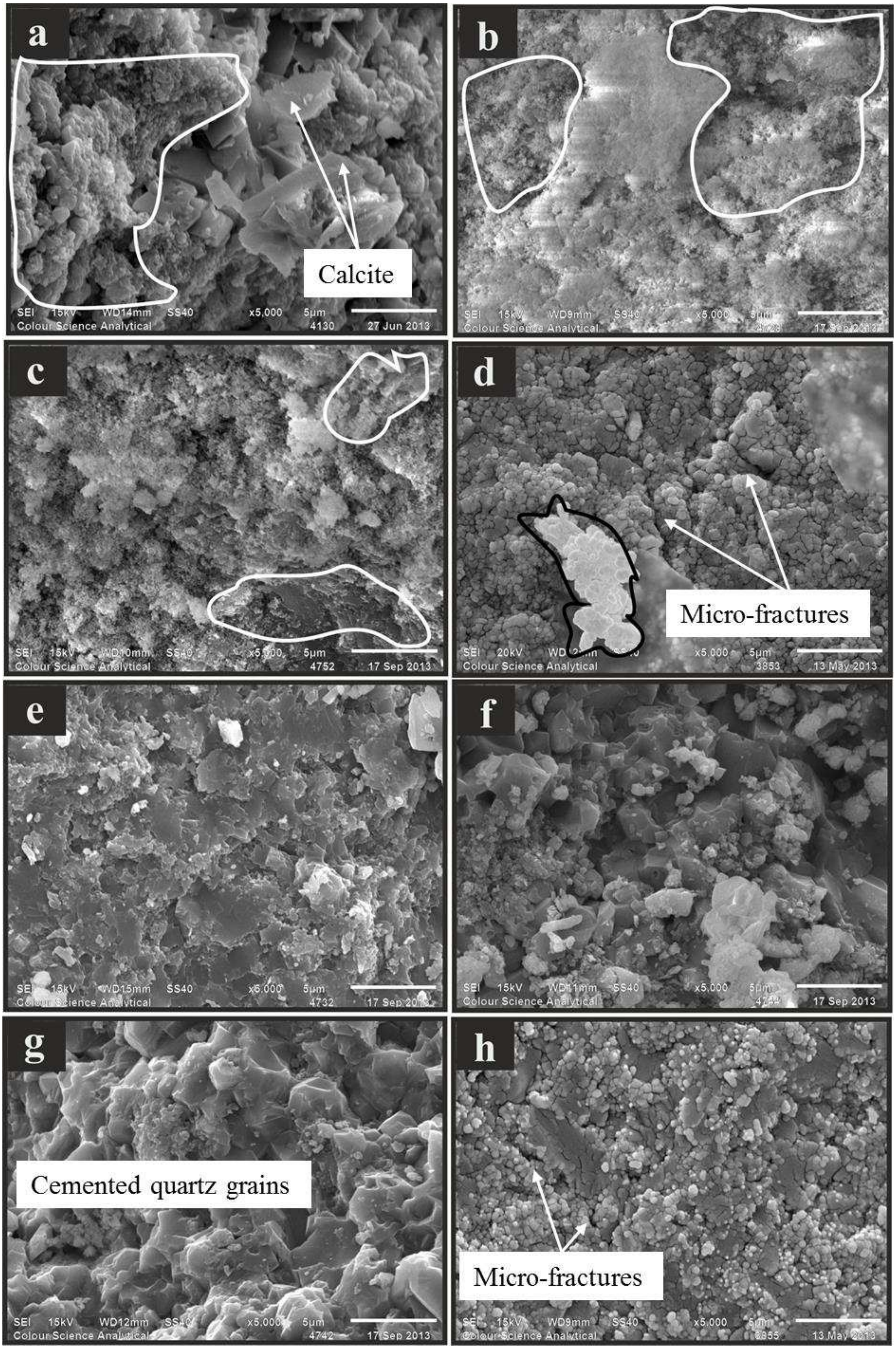


Fig. 5. Different flint structures and colours used for petrographic analysis.


a
Calcite
b
c
d
Micro-fractures
e
f
g
Cemented quartz grains
h
Micro-fractures

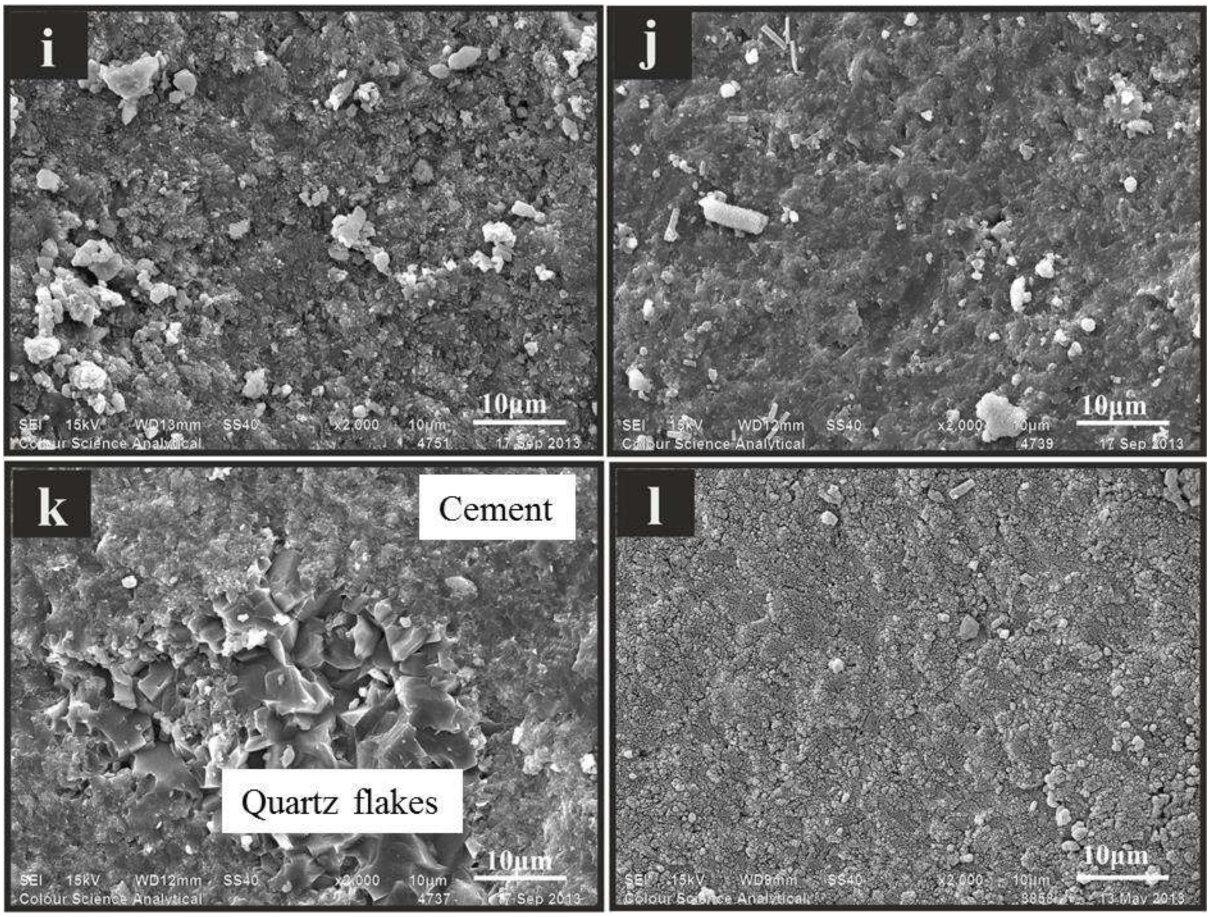


Fig. 6. SEM images flint samples showing different morphologies. (a) WCr from BNLUK with white arrows showing calcite crystals. White outline enclosed clusters of quartz crystals. (b) and (c) WCr SESUK, and WCr SDFr respectively with white outline enclosing amorphous silica particles with some silica cements (d) LBG from BNLUK matrix dominated spherical quartz grains with interparticle pores. Arrows show interparticle microfractures. Dark outline enclosed clusters of quartz crystals. (e) LBG from SESUK shows a matrix dominated by massive quartz cement. (f) LBG from SDFr shows a matrix rich in cemented quartz grains (g) LBG from LMFr showing a matrix dominated by cemented quartz grains. (h) BG from BNLUK showing microfractures, and equigranular microspheres forming clusters. The white arrows show interparticle microfractures. The matrix of this sample is dominated by quartz microspherules with some interparticle quartz cement. (i) DBG from SESUK shows a matrix dominated by massive quartz cement. (j) DBG from SDFr shows a matrix dominated by massive quartz cement. (k) DBG from LMFr shows a matrix dominated by massive quartz cement surrounding quartz flakes. (l) Grey Flint (GF) from BNLUK is a sample dominated by cemented spherical quartz grains.

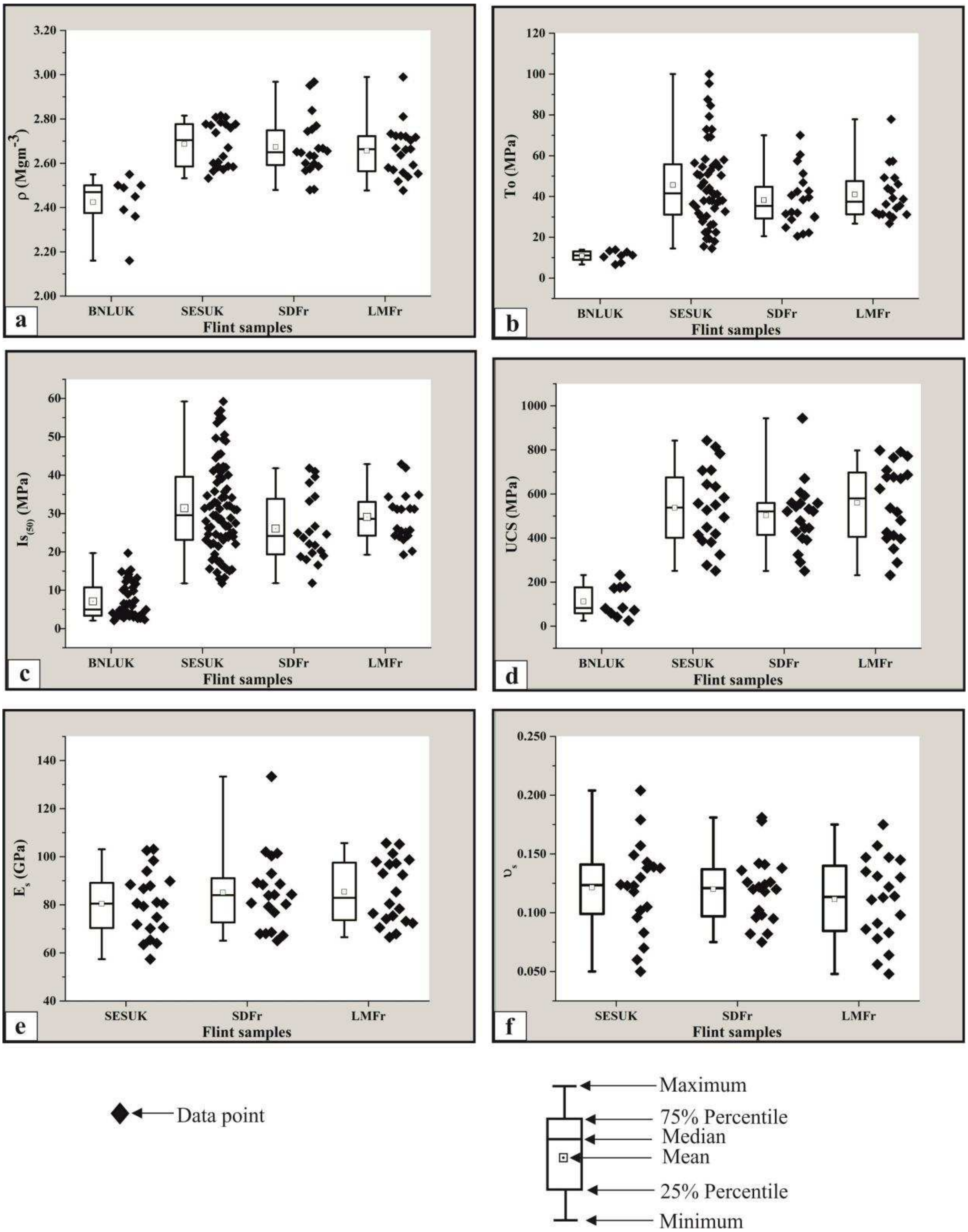


Fig. 7. (a) Density of flints (Mgm^{-3}); (b) Tensile strength (MPa); (c) Point load strength index (MPa); (d) UCS (MPa); (e) Static Young's Modulus (GPa); (f) Static Poisson's ratio of flints from all the study sites.

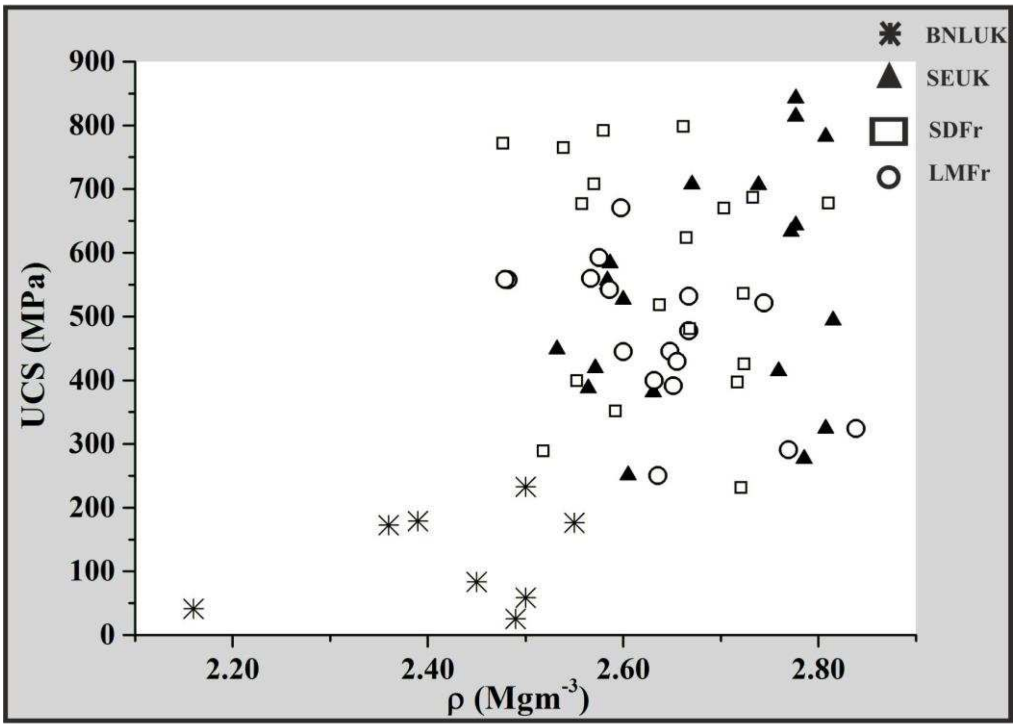


Fig. 8. UCS against density of flints

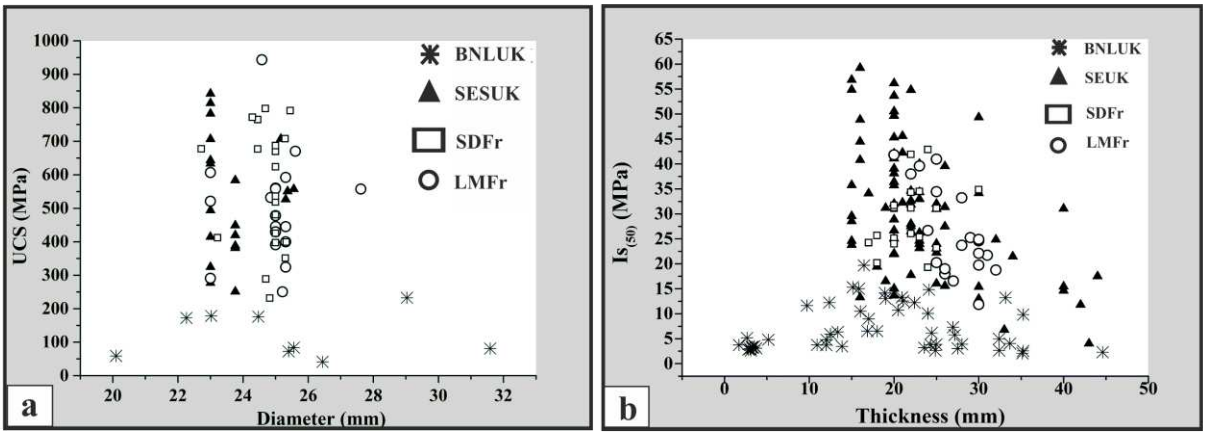


Fig 9. Sizes of samples against (a) UCS, (b) $Is_{(50)}$ of flints.

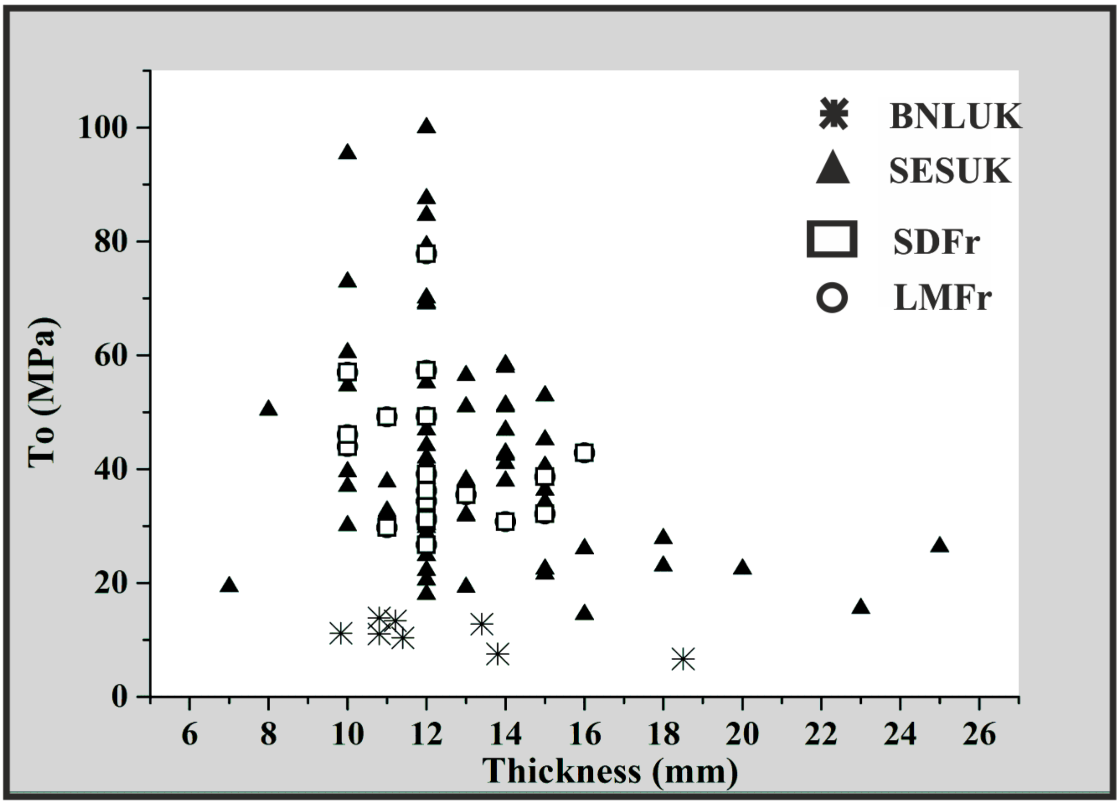


Fig. 10. Tensile strength of flint against sizes of flint samples.

Table 1. Flint colour classification and Munsell colour chart code.

Colour Description	Classification Code	Munsell Colour Code
White crust	WCr	-
Grey flint	GF	N5
Light brown flint	LBG	5YR 6/1
Brownish grey flint	BG	5G 2/1
Dark brown grey flint	DBG	5YR 2/1

Table 2. Sampling sites, location and flint categories present.

Location	Formation	Notation	Flint Type Present
North Landing, Yorkshire, UK	Burnham Chalk	Flint from Burnham Chalk North Landing, UK (BNLUK)	White crust (WCr) Light brown flint (LBG) Grey flint (GF)
East Sussex, UK	Seaford Chalk	Flint from Seaford Chalk, East Sussex, UK (SESUK)	White crust (WCr) Light brown flint (LBG) Brownish grey (BG) Dark brown grey (DBG)
Dieppe, France	Seaford Chalk	Flint from Seaford Chalk, Dieppe, France (SDFr)	White crust (WCr) Light brown flint (LBG) Brownish grey (BG) Dark brown grey (DBG)
Mesnil-Val Plage, France	Lewes Chalk	Flint from Lewes Chalk, Mesnil-Val, France (LMFr)	Light brown flint (LBG) Brownish grey (BG) Dark brown grey (DBG)

Note: The abbreviations used in this paper will follow the following format: FORMATION- LOCATION-COUNTRY. Therefore, a notation of BNLUK represents flint sample from the Burnham Chalk from North Landing in the UK. The exception to this notation is the white crusts (WCr).

Table 3. Testing methods and specifications

Property tested	Method	References
Density (ρ)	Caliper	ISRM (2007)
Tensile strength (T_o)	Three-Point Disc	Brook (1993)
Point Load Index ($Is_{(50)}$)	Block and irregular lump tests	Broch and Franklin (1972) ISRM 2007
Uniaxial Compressive strength (UCS) Test	Cylindrical and Cuboid shapes	ASTM D2845 2000 ASTM D7012-07 2010 ISRM 2007
Young's Modulus	5mm electrical resistance strain gauges due to fine grain nature of the rock.	
Poisson's Ratio		

Table 4. Sample sizes and geometries used in the testing program

	Sample Sizes					
Tests	**Length (mm)**	**Breadth (mm)**	**Depth (mm)**	**Diameter (mm)**	**L/D**	**Number of tests**
Three-Point Disc method	40-72	14-50	7-28	-	-	106
Point Load Strength	25-90	19-45	15-44	-	-	102
UCS (Cylinder)	48-77	-	-	23-37	2.1-2.5	60
UCS (Cuboidal)	50-68	23-32	18-29	-	2.0-3.5	12

Note: The UCS test was conducted in accordance with ASTM D2845 (2000); ASTM D7012-07 (2010) and ISRM (2007). Specimen specifications followed these standards. The specimen ends were prepared and flattened using surface grinder. Paralellism and flatness of the specimen ends were maintained within a tolerance of 0.02 mm, and within 0.30 mm for the straightness of specimen sides over the complete length of the specimen.

Table 5. Summary of normality test using Shapiro-Wilk

Flint Types		BNLUK	SEUK	SDFr	LMFr
Parameters	UCS (MPa)	N (11)	N (20)	N (20)	N (20)
	$I_{s(50)}$ (MPa)	**NN (49)**	N (82)	N (20)	N (20)
	To (MPa)	N (8)	**NN (55)**	N (20)	**NN (20)**
	E_s (GPa)	-	N (20)	**NN (20)**	N (20)
	υ_s	-	N (20)	N (20)	N (20)

Note: N refers to normally distributed, NN in bold refers to not normally distributed and numbers in bracket refers to the number of tests.

Table 6. Summary of mean, standard deviation and median (in bracket) of physical and mechanical properties of flints

Flints Class	**UCS (MPa)**	**ρ (Mgm^3)**	**To (MPa)**	**$I_{s(50)}$ (MPa)**	**E_s (GPa)**	**ν_s**
BNLUK	112.19±71.04 (81.01)	2.43±0.12 (2.47)	10.85±2.63 (11.11)	6.79±3.85 (4.97)	-	-
SESUK	537.23±176.41 (538.60)	2.69±0.10 (2.70)	43.01±20.61 (41.56)	29.01±6.89 (29.57)	80.49±13.34 (80.50)	0.122±0.035 (0.124)
SDFr	502.88±150.35 (520.99)	2.67±0.13 (2.65)	38.58± 13.65 (35.33)	26.06±8.93 (24.15)	85.13±16.12 (84.02)	0.120±0.121 (0.121)
LMFr	560.31±178.41 (579.76)	2.66±0.12 (2.66)	41.01±12.49 (37.43)	29.12±6.50 (28.59)	85.44±13.28 (82.91)	0.112±0.035 (0.114)

Table 7. 25th and 75th percentile of physical and mechanical properties of flints

	Parameters	**UCS (MPa)**		**ρ (Mgm^3)**		**To (MPa)**		**$I_{s(50)}$ (MPa)**		**E_s (GPa)**		**ν_s**	
	Percentile (%)	**25**	**75**	**25**	**75**	**25**	**75**	**25**	**75**	**25**	**75**	**25**	**75**
Flint Class	BNLUK	60.45	174.32	2.38	2.50	9.65	12.93	3.38	10.72	-	-	-	-
	SESUK	407.78	674.90	2.59	2.78	31.43	55.47	23.48	39.34	70.47	88.76	0.101	0.141
	SDFr	422.25	559.03	2.59	2.75	29.49	43.68	19.54	33.52	74.75	91.05	0.098	0.137
	LMFr	408.52	692.06	2.57	2.72	31.26	46.83	24.25	32.37	73.90	97.40	0.085	0.138

Table 8. Mineral compositions of flints and white crust

Classification	Location	Quartz (%)	Calcite (%)	Halite (%)
WCr	North Landing	35.64	64.36	-
	East Sussex	92.48	5.17	2.36
	Dieppe	98.51	1.12	0.38
LBG	North Landing	86.09	13.21	0.70
	East Sussex	98.02	1.98	-
	Dieppe	99.11	0.89	-
	Mesnil-Val	93.74	6.26	-
BG	North Landing	97.84	1.96	0.20
GF	North Landing	98.09	1.91	-
DBG	East Sussex	99.16	0.84	-
	Dieppe	99.50	0.50	-
	Mesnil-Val	98.79	1.21	-

Note: (-) Are samples whose strength properties cannot be determined due to size requirements of the testing methods.

Table 9. Mechanical and mineralogical data for flint comparing present paper with previous studies

Author/Source	Location/Flint types	ρ (Mgm³)	UCS (MPa)	To (MPa)	I_{s50} (MPa)	E_s (GPa) / ν_s	Quartz (%) / Calcite (%)
This paper	WCr	-	-	-	-	-	35.64 - 98.51 / 1.12 - 64.36
	DBG	2.66 - 2.69	502.88 - 560.31	38.58 - 43.01	26.06 - 29.12	85.13 - 85.44 / 0.112 - 0.122	98.79 - 99.50 / 0.50 - 1.21
	GF	2.43	112.19	10.85	6.79	80.49	98.09 / 1.91
	LBG	-	-	-	-	-	86.09 - 99.11 / 0.89 - 13.21
Jakobsen et al. 2014	Flint from Tyra Field, North Sea	-	-	-	-	-	97.00 - 99.00 / 0.70 - 2.70
Garcek 2007	α - Quartz	-	-	-	-	0.079	-
Smith et al. 2003	Brighton & Cray, UK	-	419	-	14.94	-	-
Pabst & Gregorová 2013	Low Quartz	-	-	-	-	95.40 / 0.082	-
Cumming 1999	Southern Province, UK	-	777	49.54	24.32	-	-
Fowell & Martin 1997 (Report)	Portsmouth	-	832	34.30	-	-	-
Cumming & Kageson-Loe 1995 (Report)	Bermondsey, London	-	-	-	7.60	-	-
Varley 1990	Killinghome	-	332	-	-	-	-
Waite 1985	Cromer	-	414	-	-	-	-
Pradel et al. 1967 & 1972	Grey Illustrous	-	409	57.00	-	-	-
	Grand Pressigny	-	391	68.00	-	-	-
	Fontmaure Jasper	-	57 - 178	8.00 -38.00	-	-	-
	Grey Non lustrous	-	244	-	-	-	-
Iller 1963	English Flint	-	-	59.00 - 93.00	-	-	-
	Chalcedony	-	-	81.00 - 82.00	-	-	-
	Fused Silica	-	-	35.00 - 63.00	-	-	-
Weymouth & Williamson 1951	Flint	2.62	-	-	-	-	-
Washburn & Navias 1922	Flint	2.65	-	-	-	-	-