A revised description of the lithostratigraphy of the Kimmeridgian-Tithonian and Kimmeridgian-Volgian boundary beds at Kimmeridge, Dorset, UK

R.W. Gallois

Gallois, R.W. 2011. A revised description of the lithostratigraphy of the Kimmeridgian-Tithonian and Kimmeridgian-Volgian boundary beds at Kimmeridge, Dorset, UK. *Geoscience in South-West England*, **12**, 288-294.

The type sections of the Kimmeridge Clay Formation and the upper part of the Kimmeridgian Stage are cliff and foreshore exposures close to the village of Kimmeridge, Dorset. The succession is made up of rhythmic alternations of mudstone, organic-rich mudstone and calcareous mudstone that contains only minor sedimentary breaks. The exposures provide the only complete section in the UK of the succession adjacent to the Kimmeridgian-Tithonian and Kimmeridgian-Volgian boundaries, and are one of the most complete in Europe at this stratigraphical level. Accurate thickness measurements can be made in the cliffs, but palaeontological collecting is difficult due to their weathered state. In contrast, there are extensive outcrops in a relatively unweathered condition in the intertidal zone. This is where almost all the better preserved fossils recorded to date have been collected from. The cliff and foreshore outcrops are mostly separated by beach deposits that make precise correlation between them difficult. The stratigraphical accuracy with which specimens from the intertidal outcrops have been recorded with respect to the succession exposed in the cliffs has mostly been not better than ± 2 m. The use of ortho-rectified air photographs of the intertidal-shallow subtidal areas combined with digitally rectified photographs of the cliff sections has made it possible to produce more accurate correlations between the cliff and foreshore exposures. These have been combined with a revised description of the cliff sections based on rhythms to divide the succession into numbered units that can be recognised in all the outcrops. The revised classification makes it possible to place samples and/or specimens collected from the cliff and intertidal exposures in the stratigraphical succession with an accuracy of ± 0.1 m or better.

92 Stoke Valley Road, Exeter, EX4 5ER, U.K.
(E-mail: gallois@geologist.co.uk).

Keywords: Jurassic, Kimmeridgian, Tithonian, Volgian, Kimmeridge, Dorset, stratigraphy.

Introduction

The Kimmeridge Clay Formation takes its name from the continuous cliff and foreshore sections between Brandy Bay [SY 889 795] and Chapman's Pool [SY 955 771] close to the village of Kimmeridge, Dorset (Figure 1a). These expose a total of *c.* 400 metres of strata in the middle and upper parts of the formation out of a total of 550 metres that has been proved in boreholes in that area. Almost complete successions are exposed farther west at Black Head, Osmington Mills and at Ringstead Bay, but the sections there are deeply weathered and tectonically disturbed.

The cliff and foreshore exposures in the Kimmeridge area provide the only complete succession in the UK of the beds adjacent to the Kimmeridgian-Tithonian and Kimmeridgian-Volgian boundaries. Elsewhere in Europe and on the Russian Platform all the sections described to date contain one or more major sedimentary breaks at this stratigraphical level. The scientific and educational importance of the Kimmeridge exposures is recognised by their status as a Geological Conservation Review (GCR) site (Wright and Cox, 2001), a Site of Special Scientific Interest (SSSI) and their inclusion as one of the key localities in the East Devon-Dorset Coast World Heritage Site. The sections at Kimmeridge Bay are readily accessible. As a result, they are one of the most visited geological sites in the U.K. by educational and research groups, and by commercial organisations interested in oil-source rocks.

The sections exposed in the actively eroding cliffs and foreshores crop out in a faulted anticline that repeats the succession on either side of Kimmeridge Bay (Figure 1b). The outcrops between the east side of Kimmeridge Bay and Houns-tout (the Upper Kimmeridge Clay of later authors) was first described by Blake (1875) who allocated bed numbers (1 to 42 in stratigraphically descending order) to the more lithologically distinctive beds and groups of beds. Arkell (1947) retained Blake's numbering system, but revised the thickness measurements and introduced names (Washing Ledge Shales, Maple Ledge Shales, etc) for the mudstones between named 'stone bands', beds of strong dolomite that form prominent marker beds in the cliffs and broad ledges in the intertidal areas. These names continued to be used by most subsequent authors until Cox and Gallois (1981) published a description of the cliff sections accompanied by graphic logs at a 1 to 100 scale. This, and subsequent accounts by Van de Vyver (1986) and Coe *et al.* (2009), described the cliff sections in Kimmeridge Bay as a repetitive succession of thin (mostly 0.1 to 1.0 m thick) beds of organic-rich mudstone (bituminous mudstone and oil shale), calcareous mudstone and undifferentiated mudstone. With the exception of the dolomite marker beds, few of the individual beds at outcrop in the cliffs can be correlated with confidence with the outcrops in the intertidal area, partly because of the repetitive nature of the lithologies and partly because of an intervening shingle beach. There is also sufficient lateral variation in the succession, due largely to the presence of minor erosion surfaces, to make detailed correlations between the successions exposed in the cliffs in Kimmeridge Bay and Brandy Bay uncertain.

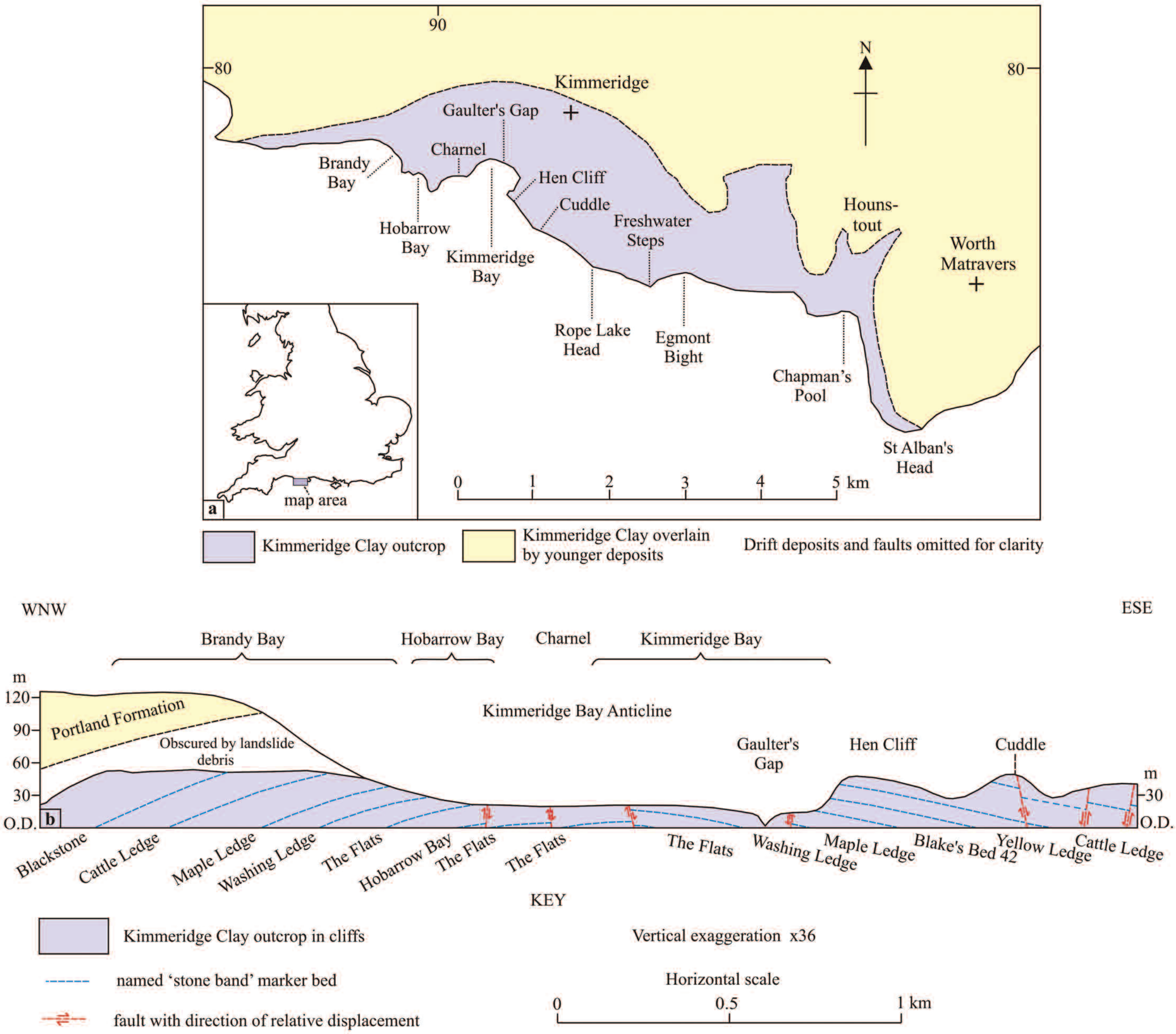

Figure 1. *(**a**) Geological sketch map of the Kimmeridge Clay outcrop in the Kimmeridge area showing localities referred to in the text. (**b**) Geological sketch section showing the principal named marker beds in the Kimmeridge Clay in the cliffs between Brandy Bay and Cuddle.*

The present account describes the strata exposed between the Maple Ledge Stone Band and Bed 42 of Blake (1875) in Kimmeridge Bay and Brandy Bay. The stratigraphical range covers parts of units KC 35 and KC 36 of the standard chronostratigraphical classification that includes parts of the *Aulacostephanus autissiodorensis* and *Pectinatites elegans* biozones (Gallois, 2000). The succession is divided into numbered units based on laterally persistent rhythms that can be used to make correlations between the cliff and foreshore sections in both bays. This part of the succession thins westwards from 24.0 m at Kimmeridge Bay to 20.6 m at Brandy Bay as part of an almost linear trend in which the full thickness of the Kimmeridge Clay Formation decreases as the steep limb of the Purbeck Monocline is approached (Gallois, 2000, figure 8).

Revised descriptions of sections

The Kimmeridge Clay Formation comprises a relatively uniform succession of mudstones with little lithological variation and few colours other than shades of grey. There are, however, marked variations in the cliff profiles and ledges in the intertidal area in which the more resistant horizons stand out as ribs/ledges separated by more friable lithologies. These correspond principally to rhythmic variations in the clay mineral, calcium carbonate and organic contents of the mudstones at scales ranging from millimetres to tens of metres in thickness. The organic contents are mostly kerogens, high-molecular-weight polymers formed by chemical and bacterial degradation of biogenic organic matter. The kerogens impart a brown colour to the mudstones, and when present in sufficiently high concentrations give rise to oil shales. Increases in calcium carbonate content cause the mudstones to become paler grey and more friable when weathered.

The most prominent marker beds in the cliffs and foreshores are thin (mostly < 0.3 m thick) tabular beds of densely cemented dolomite and ferroan dolomite (Irwin, 1980). These weather out as prominent pale grey to pale greyish yellow ribs in the cliffs and give rise to ledges that extend seaward for up to 200 m in the intertidal area. The more laterally persistent beds can be recognised as ledges on the sea floor throughout Portland Bay in multibeam sonar images (e.g. Gallois, 2010, figure 7). Some of the ledges had local names and these were used by Arkell (1933) to describe geological marker beds (e.g. Washing Ledge Stone Band) and to divide the mudstones into named groups of beds (e.g. Washing Ledge Shales).

The rhythmic nature of the Kimmeridge Clay Formation at all stratigraphical levels has long been recognised, and its origin and relationship to Milankovitch rhythms has been much discussed (House, 1985; Oschmann, 1990). The middle part of the formation is almost wholly made up of organic-rich rhythms (Type B of Cox and Gallois, 1981) that are thought to represent changes in water depth (Gallois, 2000) in response to global climate changes associated with orbital cycles (Weedon *et al.*, 2004). This type of rhythm is especially well displayed in the cliff sections in Kimmeridge Bay where the organic-rich parts of the rhythms weather out as laminated ribs and the more calcareous mudstones as friable re-entrants and steep slopes with accumulations of friable debris. The sharp lithological contrast at the bases of the rhythms, particularly where the basal bed is an oil shale, commonly gives rise to small overhangs in the cliffs. In the middle and upper parts of the rhythms the upward change from clay-mineral-rich to calcareous mudstone is mostly gradational with the result that many of the lithological boundaries chosen when measuring the sections were arbitrary and in some cases inconsistent. In contrast, the bases of the rhythms are everywhere lithologically clearly defined. The rhythms are less obvious on the wave-cut platform where beach deposits tend to collect in the hollows formed on the outcrops of the calcareous mudstones, and marine colonisers are more concentrated on the ledges formed by the organic-rich beds. However, the rhythms are well displayed in air photographs and when the sea is calm and clear they can be traced in the subtidal area in water depths of up to 10 m.

Bedding-plane shears, commonly up to 50 mm thick with anastomosing thin (< 1 mm thick) sheets of calcite occur throughout the succession. Some of these can be traced laterally for hundreds of metres at the same stratigraphical level in a single section and can be used as marker beds. They can rarely be used for correlation between sections because of the difficulty of distinguishing a shear in one section from a shear at a similar stratigraphical level in another section.

The rhythmic nature of the succession is used in the present account to divide the beds between the two named stone bands. This retains the principal boundaries between the named beds of Arkell (1947) and allows the positions of individual horizons in the cliff and foreshore outcrops to be determined with greater accuracy than previously possible. The term shale in Arkell's descriptions (e.g. Maple Ledge Shale), which was used to describe the fissility of some of the mudstones when weathered, is replaced here by mudstone (Maple Ledge Mudstone Member). A pragmatic approach has been adopted in which the more obvious complete rhythms at outcrop in the cliff and foreshore sections have been allocated numbers. Incomplete and poorly developed rhythms that can be identified in the cliffs, but which cannot be traced with confidence into the intertidal area, are included in numbered units that are comprised of two or more rhythms or partial rhythms. Over 80% of the numbered units fall within the thickness range 1 to 2 m. All have sharp bases: by taking these as datums the position of any fossil or sample within a bed can be identified in the overall succession with an accuracy of ±0.1 m or better. For ease of reference, each bed is divided into a lower (oil shale/bituminous mudstone) part labelled **a** in the generalised vertical sections and an upper (undifferentiated mudstone) part labelled **b**.

Maple Ledge Mudstone Member

The Maple Ledge Mudstone Member at outcrop in the Kimmeridge area comprises 20.6 to 24.0 m of thinly interbedded organic-rich, clay-mineral-rich and calcareous mudstones. These are grouped into 15 units (M1 to M15) in the present account (Figure 2). The member is wholly exposed in the cliffs in the NE part of Kimmeridge Bay (Figure 3), in the intertidal zones in the same area and below Hen Cliff. The complete succession is exposed in the cliffs (Figure 4) where weathered sections in most of the member (M1 to M11) can be accessed from the beach. Higher beds (M12 to M15 can be accessed in weathered sections on the east side of Kimmeridge

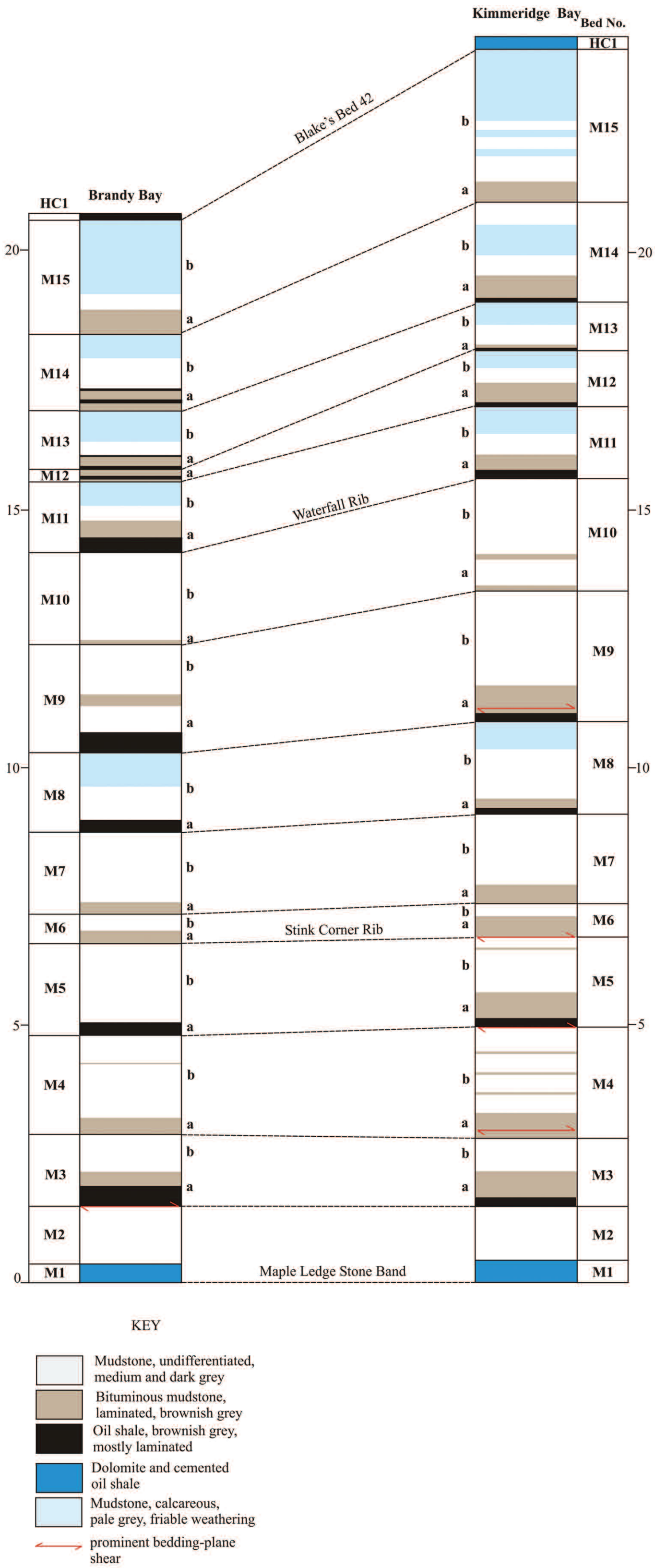

Figure 2. *Correlation of the Maple Ledge Mudstone successions exposed in Kimmeridge Bay and Brandy Bay.*

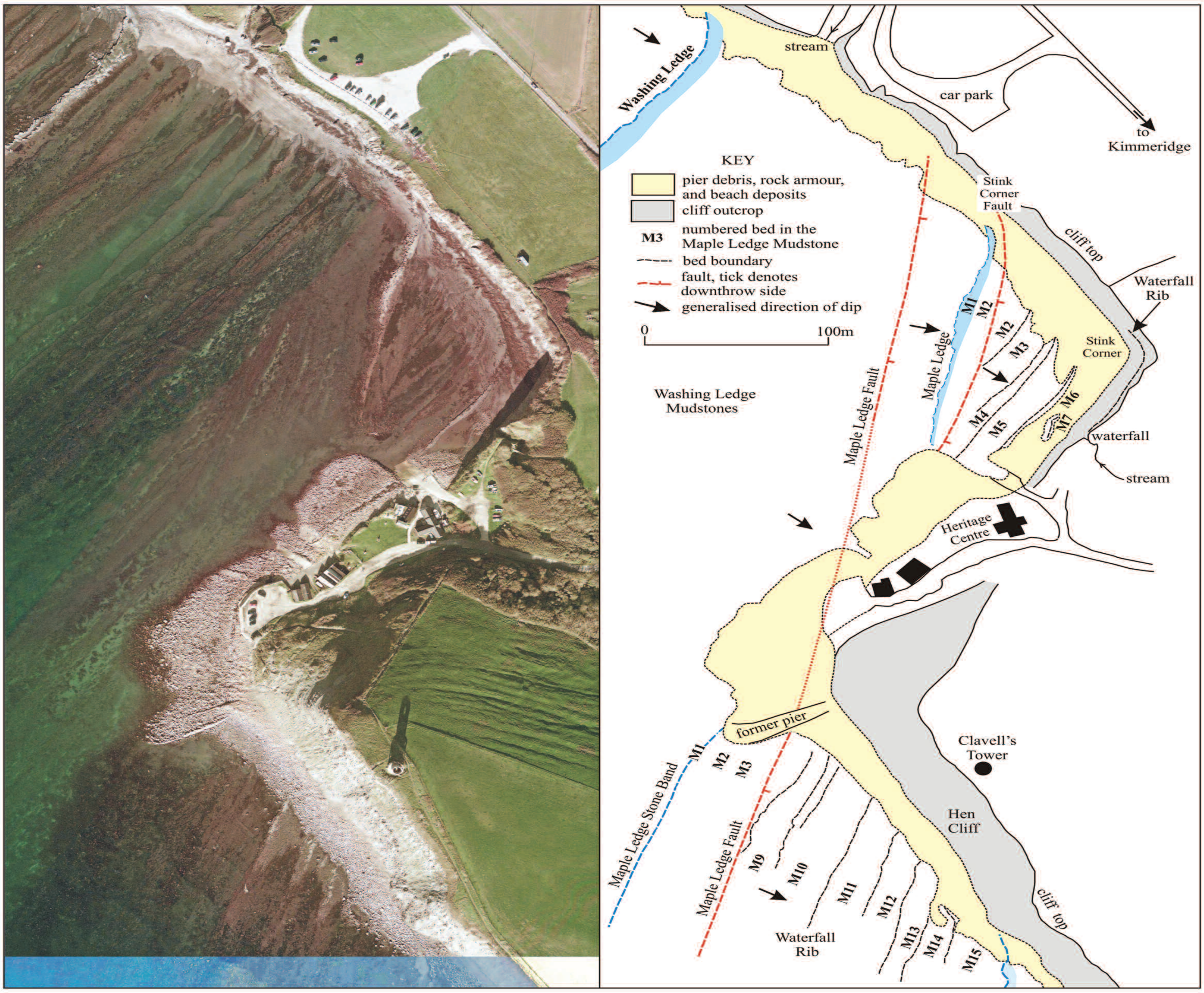

Figure 3. *(**a**) Composite aerial photograph of the eastern part of Kimmeridge Bay based on parts of Channel Coast Observatory (CCO) ortho-rectified frames SY 90 78 NE and SE, 2nd November 2001. Image courtesy of CCO (www.channelcoast.org). (**b**) Geological sketch map of the Maple Ledge Mudstone outcrop in the intertidal and subtidal area on the east side of Kimmeridge Bay and below Hen Cliff based on (**a**). See Figure 2 for stratigraphical succession.*

Bay and in Hen Cliff. Units M1 to M7 are well exposed in the intertidal area in Kimmeridge Bay: the upper part of the member (M9 to M15) is exposed in the intertidal area below Hen Cliff where it is largely covered by algae throughout much of the year. The member is also fully exposed in the intertidal area (Figure 5) and in the cliffs (Figure 6) in Brandy Bay where the outcrop is complicated by faulting.

The Maple Ledge Stone Band forms a prominent ledge at the base of the succession in both bays, and its seaward extension is exposed at low tide adjacent to the old pier below Hen Cliff (Figure 3). Some of the oil shales are sufficiently lithologically distinctive to be used as marker beds in all the exposures. The oil shale at the base of M5 is prominently laminated with alternations of brown kerogen-rich and pale coccolith-rich laminae. Some of the organic-rich beds are calcareously cemented and form prominent foreshore ledges and ribs in the cliffs in both bays. The most strongly cemented of these is referred to here as Stink Corner Rib (basal bed of M6) which forms a prominent ledge in Kimmeridge Bay, the upper surface of which contains large numbers of ammonites and pyritic concretions. The same bed forms a lithologically distinctive ledge in a contorted zone between two faults in Brandy Bay. Waterfall Rib (basal bed of M11) forms the lip of a waterfall on the east side of Kimmeridge Bay and a prominent ledge in the intertidal area below Hen Cliff.

The upper recorded limit (Last Appearance Datum) of the ammonite *Aulacostephanus*, which is taken throughout NW Europe as a proxy for the Kimmeridgian-Tithonian (Hantzpergue, 1989) and Kimmeridgian-Volgian (Scherzinger and Mitta, 2006), stage boundaries pending decisions on the Global Boundary Stratotype Section and Point sections for these boundaries, is 0.3 m below the base of M11.

SUMMARY AND CONCLUSIONS

The cliff and foreshore exposures at and adjacent to Kimmeridge, Dorset are the type sections for the Kimmeridge Clay Formation and the middle and upper parts of the Kimmeridgian Stage. A revised description of the beds between the Maple Ledge Stone Band and Blake's (1875) Bed 42 is presented here in which the rhythmic nature of the formation is used to divide the succession into fifteen numbered units (M1 to M15). The present work forms part of a larger study that will apply the same type of classification to the whole of the Kimmeridge Clay Formation outcrop between Brandy Bay and Chapman's Pool. Units M1 to M15 can be recognised in all the cliff and foreshore outcrops in Brandy Bay and Kimmeridge Bay where they have been used to make detailed correlations between the cliff and foreshore exposures. The outcrops in the cliffs and intertidal areas are photographically illustrated. Taken

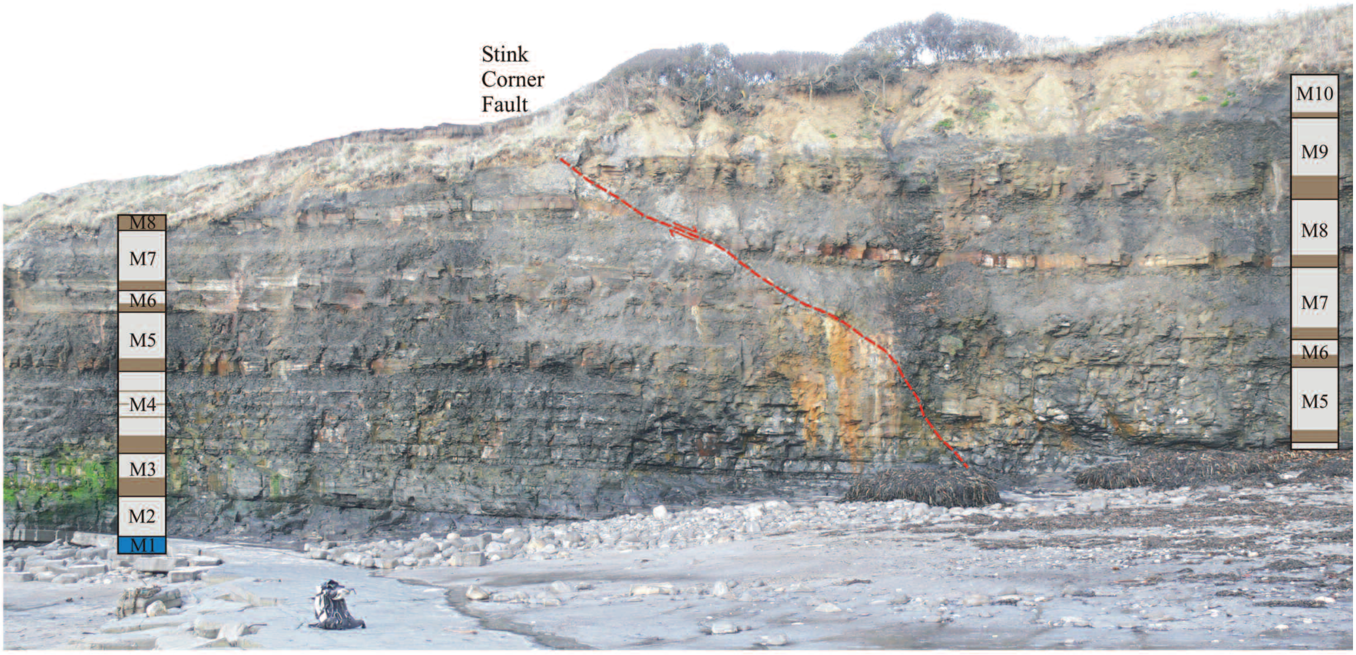

Figure 4. *The Maple Ledge Mudstone (beds M1 to M15) succession exposed in the cliffs in the north east part of Kimmeridge Bay. See Figure 2 for bed thicknesses. All views north east normal to the cliff from Maple Ledge; uncorrected for parallax.*

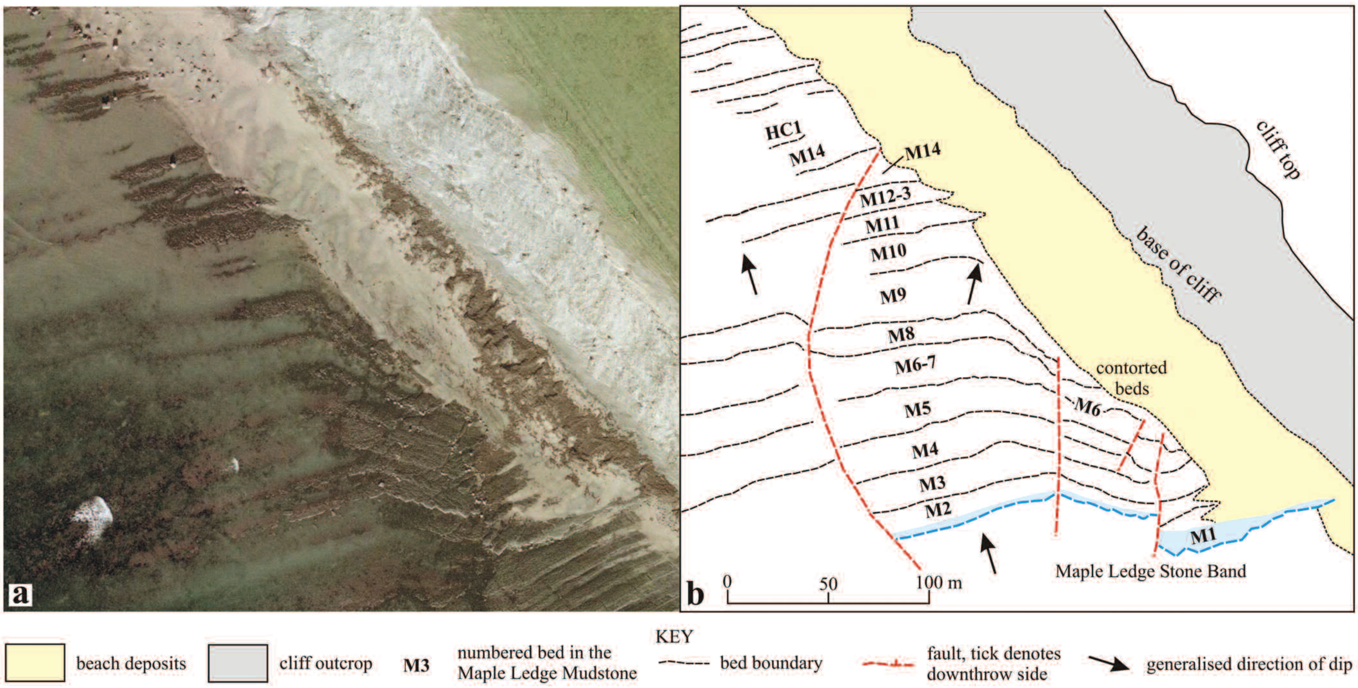

Figure 5. *(**a**) Composite aerial photograph of the central part of Brandy Bay based on parts of Channel Coast Observatory (CCO) ortho-rectified frames SY 89 79 SW, 2nd November 2001. Image courtesy of CCO. (**b**) Geological sketch map of the Maple Ledge Mudstone outcrop in the intertidal and subtidal area in Brandy Bay based on (**a**). See Figure 2 for stratigraphical succession.*

Figure 6. *The Maple Ledge Mudstone (beds M1 to M15) succession exposed in the cliff in Brandy Bay. See Figure 2 for bed thicknesses. View north east normal to the cliff from the Maple Ledge Stone Band outcrop; uncorrected for parallax.*

together, the revised descriptions and the photographs enable samples and fossils collected from the extensive wave-cut platforms to be placed in the succession with an accuracy of ±0.1 m. This is an order of magnitude better than that given in published accounts to date for most fossil and other samples.

Acknowledgements

The author is grateful to Steve Etches for stratigraphical advice and assistance in the field, to Chris Van der Vyver for access to his unpublished descriptions of the Kimmeridge Clay sections, to Ian West for improvements to the first draft of this account, and to the Channel Coast Observatory (*www.channelcoast.org*) for copies of their air photographs.

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