A revised description and field guide for the Kimmeridge Clay Formation at Kimmeridge, Dorset, UK: Eudoxus and Autissiodorensis zones.

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Gallois, R. W. 2017. A revised description and field guide for the Kimmeridge Clay Formation at Kimmeridge, Dorset, UK: Eudoxus and Autissiodorensis zones. *Geoscience in South-West England*, **14**, 107–120.

A combination of cliff and foreshore exposures in the type section of the Kimmeridge Clay Formation at Kimmeridge, Dorset enables the succession to be accessed at beach 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 state in the intertidal zone from where all the better preserved fossils, mostly ammonites, bivalves, gastropods and vertebrates, have been collected in situ. The cliff and foreshore exposures are mostly separated by beach deposits that make bed-by-bed correlation between the two difficult at most stratigraphical levels because of the repetitively uniform lithology of the mudstones. Ortho-rectified air photographs and sidescan sonar surveys of the intertidal area have been combined with digitally rectified photographs of the cliff sections to produce a stratigraphical succession of numbered units based on the rhythmic nature of the Kimmeridge Clay. The revised classification has made it possible to collect material from any of the exposures in the exposed part of the Eudoxus and Autissiodorensis zones and place them in the stratigraphical succession with an accuracy of ± 0.1 m or better. This greater accuracy is important for describing fossil ranges and making correlations between outcrop and borehole sections.

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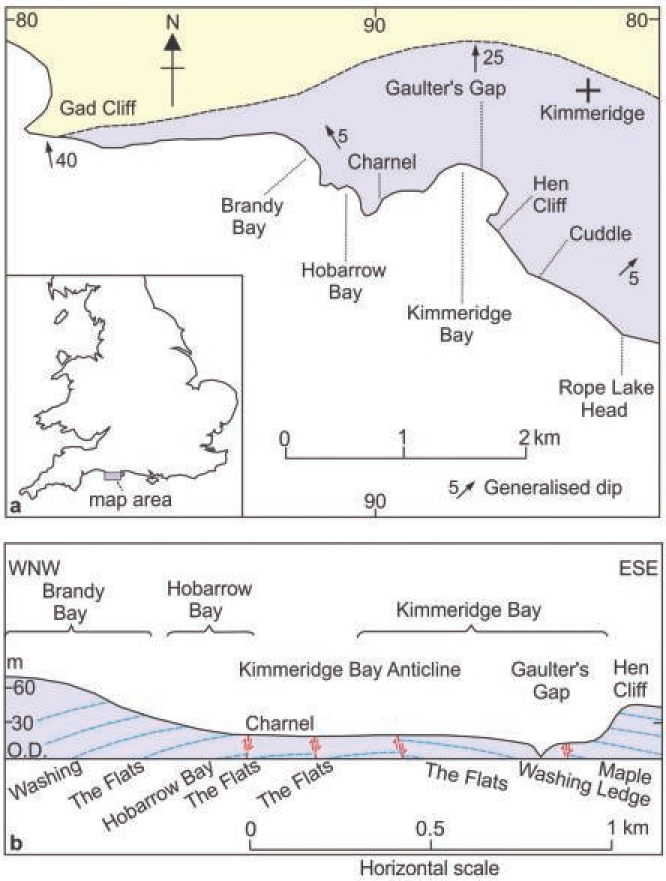
Keywords: Jurassic, Kimmeridgian, Kimmeridge Clay, Dorset, stratigraphy.

Introduction

The type section of the middle and upper parts of the Kimmeridge Clay Formation, cliff and foreshore sections close to the village of Kimmeridge, Dorset (Figure 1a), exposes a total of *c*. 400 metres of strata out of a total formational thickness of 550 metres which has been proved in continuously-cored boreholes in that area. The scientific and educational importance of the cliff and foreshore 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 and Dorset Coast World Heritage Site.

The stratigraphy of the formation is well documented. It has been divided into 13 biozones based on ammonite assemblages (Ziegler, 1962; Cope 1967, 1978) which cover the Kimmeridgian Stage and the correlatives of much of the Tithonian and Volgian Stages. All except the youngest zones have subsequently been re-defined as chronozones Page (*in* Simms *et al*., 2004). The succession has been futher divided into 63 chronostratigraphical units based on a combination of lithological, sedimentary, palaeontological and geophysical characters (Gallois, 2000 and references therein). The present account describes the succession exposed in the faulted Kimmeridge Bay Anticline in which all except the lowest part is repeated in Kimmeridge Bay and Brandy Bay (Figure 1b). The lithological succession ranges from the Hobarrow Bay Stone



Left Figure 1. *(**a**) Geological sketch map of the Kimmeridge Clay outcrop in the Kimmeridge area; (**b**) Sketch section showing the outcrops of the principal named 'stone' bands' in the cliffs between Brandy Bay and Gaulter's Gap.*

Band to the Maple Ledge Stone Band, *c*.55 m of strata that cover the upper part of the Eudoxus Chronozone, much of the Autissiodorensis Chronozone, and chronostratigraphical units KC 32 to KC 34. The base of the Eudoxus Zone is marked throughout England by a transgressive surface, sequence boundary Km6 of Taylor *et al*. (2003). It was recorded 102 m below the Hobarrow Bay Stone Band in the continuously cored Metherhills Borehole [SY 9112 7911], 200 m NE of Kimmeridge Bay (Gallois, 2000). Bed by bed collecting in the cliff sections at Kimmeridge Bay has shown that well-preserved *Aulacostephanus (Aulacostephanoceras) autissiodorensis* Cotteau, the incoming of which marks the base of the *A. autissiodorensis* Biozone, occurs at the Flats Stone Band. The stone band has been recorded from as far away as Yorkshire at what is presumed to be the same stratigraphical level (Herbin *et al*., 1995) and is taken as the base of the Autissiodorensis Chronozone.

The Kimmeridge Clay comprises a lithologically relatively uniform mudstone succession with little variation in colour other than shades of grey. However, the more resistant lithologies, organic-rich mudstones and widely spaced thin (up to 0.25 m thick) dolomitic limestones, the named stone bands of Arkell (1947), stand out as ribs in the cliffs. The limestones weather out as prominent pale grey beds in the cliffs and form ledges that can be traced across the intertidal area, and offshore in multibeam sonar images that cover the whole of Weymouth Bay (Figure 2). The most prominent sedimentary feature in the cliffs at Kimmeridge and adjacent bays is the rhythmic nature of the succession. The middle part of the formation (Eudoxus to Pectinatus Zones) is almost wholly made up of organic-rich rhythms, Type B of Cox and Gallois (1981), over 80% of which fall within the thickness range 1 to 2 m. The origin of the rhythms and their probable relationship to Milankovitch rhythms have been discussed by House (1995) and, Oschmann (1990). It has been suggested that this type of organic-rich rhythm represents a change in local water depth (Gallois, 2000) possibly in response to global climate changes associated with orbital cycles (Weedon *et al*., 2004). The rhythms are well displayed in the the cliffs between Brandy Bay and Kimmeridge Bay where the organic-rich beds weather out as laminated ribs

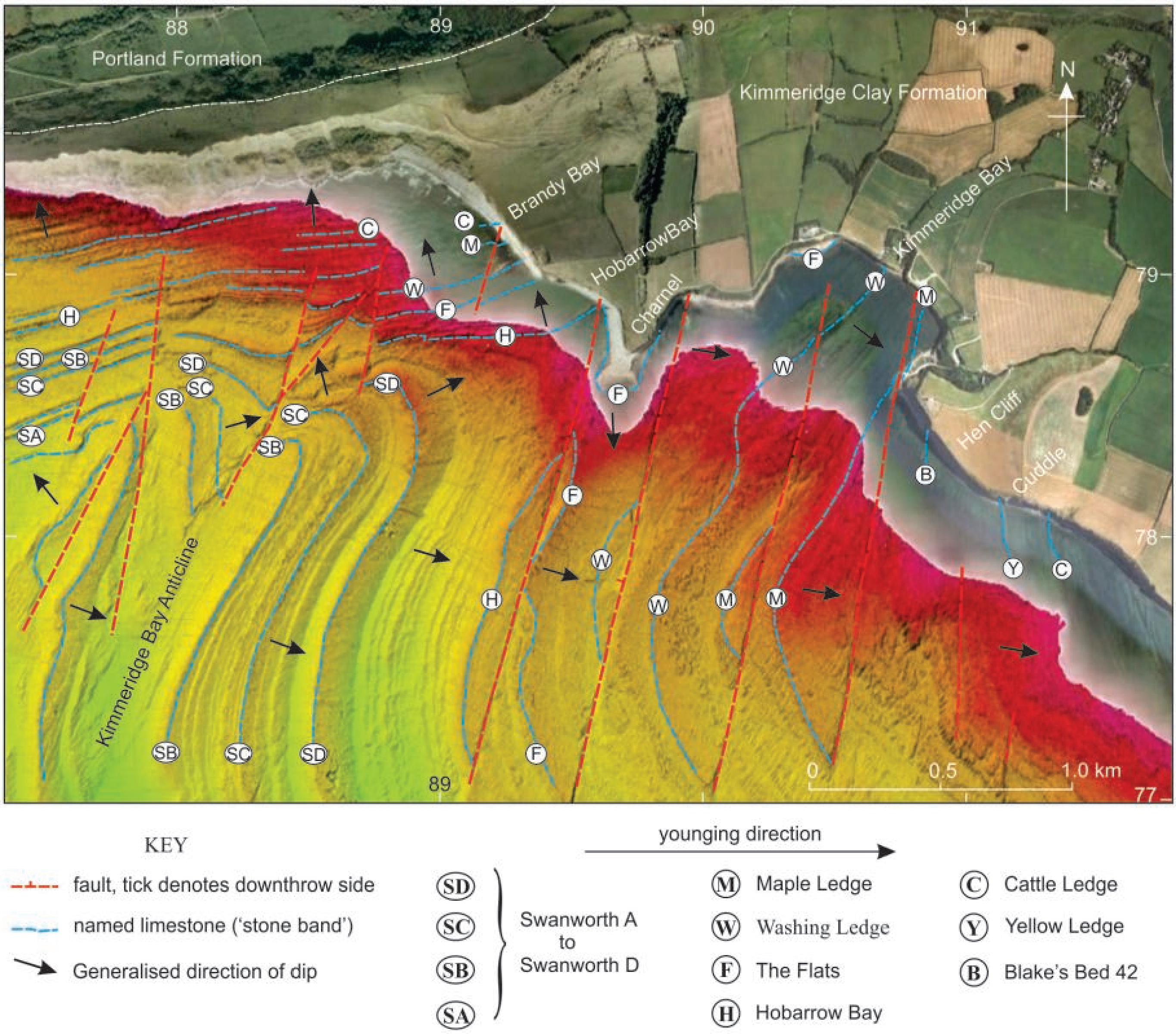


Figure 2. *Principal geological features superimposed on air photographs and a multibeam sonar image commissioned by the Channel Coast Observatory (CCO) 2008: reproduced by permission of the CCO (www.channelcoast.org). Named limestone beds ('stone bands') after Arkell (1947) and Gallois (2000).*

and the more calcareous mudstones as friable re-entrants. They are less obvious in the intertidal and shallow subtidal areas, but are well displayed in air photographs. When the sea is calm, they can be traced in the subtidal area in water depths of up to 10 m.

In the present account, the exposed Eudoxus and Autissiodorensis zone sediments have been divided into, in ascending order, the Hobarrow Bay Mudstone, Flats Mudstone and Washing Ledge Mudstone; the basal bed of each of these is marked by a named stone band. This retains the principal boundaries between the named 'shale' beds of Arkell (1947). The more obvious complete rhythms in the cliff and foreshore outcrops, those than can be matched with certainty across the intervening beach deposits, have been numbered HB 1 to HB12 (Hobarrow Bay Mudstone) and F1 to F14 (Flats Mudstone). Poorly developed rhythms that are well exposed in the cliffs but which cannot be identified with confidence in the intertidal area, are included in units comprised of two or more rhythms. Each rhythm is divided into a lower (organic-rich mudstone) part labelled **a** in the generalised vertical sections and an upper (undifferentiated mudstone) part labelled **b**. The succession exposed in Brandy Bay is on average up to 5% thinner than that exposed in Kimmeridge Bay due to contemporary differential subsidence rates adjacent to the nearby Purbeck-Wight Fault Zone (Gallois, 2000).

Cox and Gallois (1981) published a stratigraphical description of the cliff sections, and they were remeasured by Van de Vyver (1986) as part of a detailed study of the ammonite biostratigraphy. The present account is a revised description and field guide for the highest part of the Eudoxus Zone and much of the Autissiodorensis Zone. It is complementary to the published description of the highest part of the Autissiodorensis Zone exposed at Kimmeridge (Gallois, 2011). Access to all the sections described in this account is subject to tide and weather conditions. Most tides reach the foot of all the cliffs and there is, at the time of writing, only one access point. This is via the car park or SW Coastal path at Kimmeridge Bay. The cliff sections west of Charnel lie within the Ministry of Defence Lulworth Gunnery Range. They can be accessed during most weekends and public holidays: see https://www.gov.uk/government/publications/lulworth-firing-notice for details.

Hobarrow Bay Mudstone

The only complete section in the Hobarrow Bay Mudstone is that at Hobarrow Bay [SY 896 790] between the Hobarrow Bay Fault and the outcrop of the Flats Stone Band at the southern end of Brandy Bay (Figures 3 and 4). Up to 4 m of the highest part of the member are exposed below the Flats Stone Band in deeply weathered, fault-bounded exposures in the cliffs between Hobarrow Bay and Charnel (Figure 1). The lowest 1.5 m above the Hobarrow Bay Stone Band (HB2 and HB3) crops out in the intertidal zone where the outcrop is commonly largely covered by boulders and beach deposits. Up to 0.5m of calcareous mudstone is exposed below the Hobarrow Bay Stone Band at low spring tides. When traced across the wave-cut platform, the laminated coccolith-rich oil shale at the base of HB4 provides a prominent marker bed that allows correlation with the cliff section. The organic-rich parts of several of the overlying rhythms, notably HB4, HB5 and HB7, comprise thinly-bedded alternations of oil shale, bituminous mudstone and weakly organic-rich mudstone. For ease of recognition in the cliffs and foreshore outcrops, they are treated here as parts of single named units. They are probably condensed successions comprising up to ten incomplete rhythms in which the more calcareous parts have been removed by erosion at the bases of the organic-rich parts. A line of widely spaced fossiliferous cementstone nodules in HB4 was named the *Nannocardioceras* Cementstone by Cox and Gallois (1981) and was correlated with a similar bed at outcrop in Ringstead Bay [SY 763 813] *c.* 7 km farther west. A thin (up to

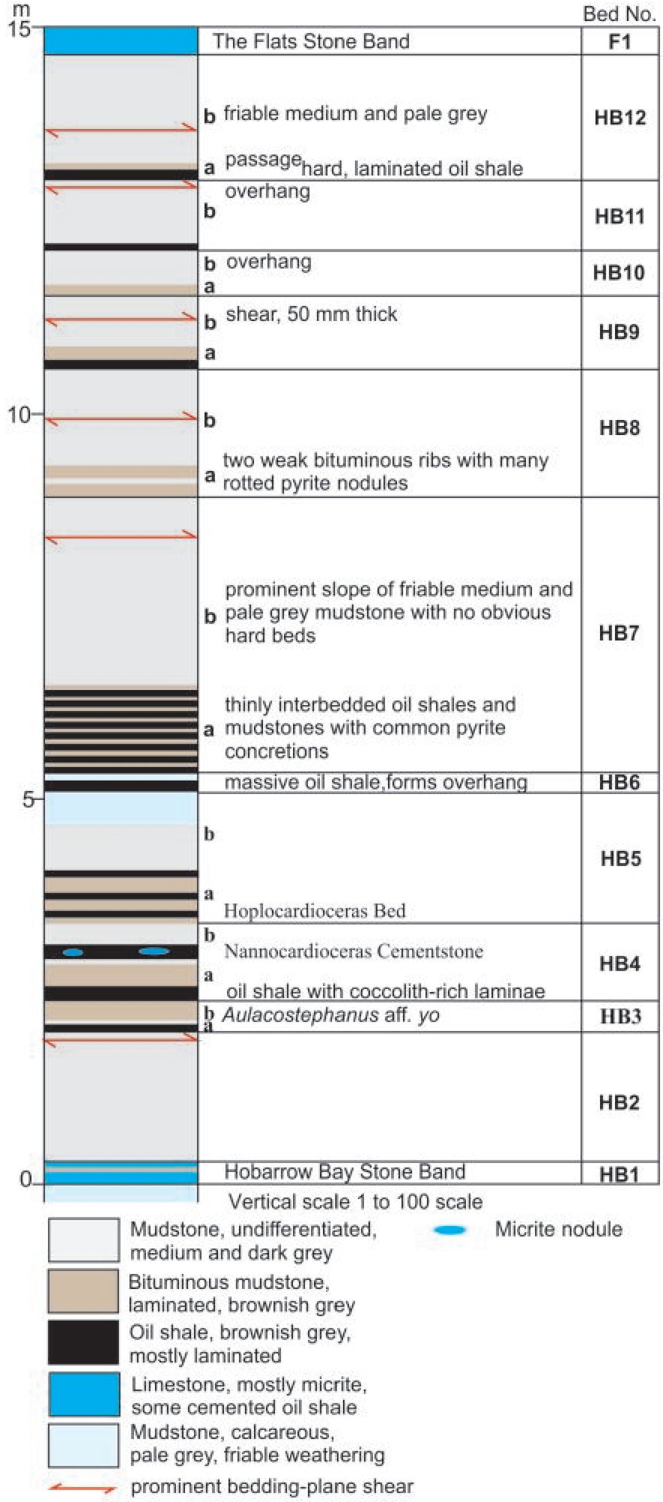


Figure 3. *The Hobarrow Bay Mudstone succession exposed in the cliff at Hobarrow Bay.*

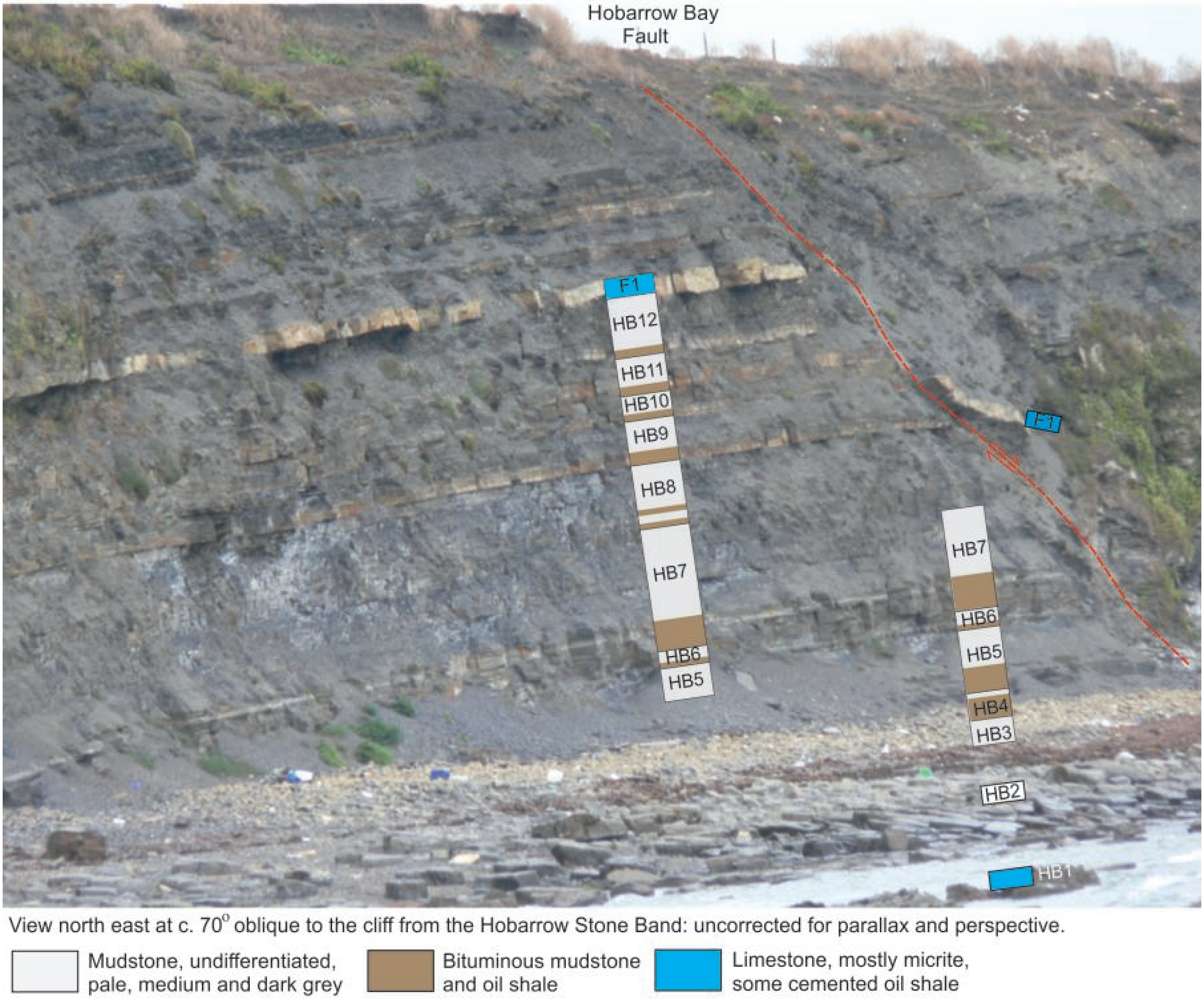


Figure 4. *The Hobarrow Bay Mudstone exposed in the cliff at Hobarrow Bay. See Figure 3 for bed thicknesses.*

30mm thick) bed of shelly mudstone with chaotic structures indicative of a seismic shock has been recorded in HB5. A similar bed was recorded at Ringstead Bay by Cox and Gallois (1981) as loose blocks of uncertain stratigraphical provenance. It is has also been recognised in the presumed correlative of HB5 in the Metherhills [SY 9112 7911] and Swanworth Quarry [SY 9675 7823] boreholes (the Hobarrow Bay Fluidised Bed of Gallois, 2000), and in an excavation at Icen Road [SY 6768 8380] dug for the Weymouth Olympic Relief Road.

The succession is fossiliferous throughout with ammonites and bivalves especially common on many bedding planes. In addition to the common occurrence of species of *Amoeboceras, Aspidoceras* and its microconch *Sutneria, Aulacostephanus* and *Subdichotomoceras*, the Hobarrow Bay Mudstone contains several faunal marker beds that have been traced throughout the onshore outcrop and subcrop of the Kimmeridge Clay. These include the late Kimmeridgian *Aulacostephanus yo* Horizon of Hantzpergue (1989) in HB3 (Gallois *et al.*, 2015); coccolith-rich marker bed EU3 of Gallois and Medd (1979) in HB4; and the Hoplocardioceras Bed of Van der Vyver (1986) in the oil shale in the lower part of HB5. Pyritised *Nannocardioceras* spp. are common in all the oil shales throughout the Hobarrow Bay Mudstone. Poorly preserved *Subdichotomoceras* are common in HB 12, but have not been recorded from the overlying Flats Mudstone. In addition, Van der Vyver (1986) recorded *Amoeboceras (Amoebites)* aff. *quadratolineatum* (Salfeld), *A. (Hoplocardioceras) decipiens* Spath, *Amoeboceras (Nannocardioceras) krausei* (Salfeld), *A. (N.)* cf. *anglicum* (Salfeld), *Aulacostephanus* cf. *eudoxus* (d'Orbigny), *Aul. jasonoides* (Pavlow), *Aul. kirghisensis* (d'Orbigny) and *Aul.* cf. *rigidus* Ziegler. *Laevaptychus*, common foraminifera and bivalves, including oysters, and the gastropod *Dicroloma* occur throughout these beds.

The Flats Mudstone

The Flats Mudstone is wholly exposed in the cliffs and foreshore ledges at the western end of Kimmeridge Bay [SY 905 792] and at the southern end of Brandy Bay [SY 894 791]. The lower 5 to 10 m are exposed in fault-bounded sections in the cliffs (Charnel) between the two bays. The Flats Stone Band, with its characteristic, roughly polygonal pattern of the teepee-structure ridges (Bellamy, 1977) forms an extensive seaward dipping wave-cut platform at each of these localities. The best developed of these is The Flats, from which the stone band takes its name, and Broad Bench up which "waves rush with spectacular fury in rough weather" (Arkell, 1947). The 14 units (F1 to F14) into which the Flats Mudstone is divided (Figures 5 and 6) show little lateral variation in thickness and lithology between Kimmeridge Bay and Brandy Bay. The organic-rich beds at the base of each of the units form prominent ribs in the foreshore outcrops (Figures 7 and 8) that enable correlations to be made with the cliff sections. Most of the 14 units are single rhythms: a few (notably F14) include more than one rhythm. Several bedding-plane shears are laterally persistent in the Kimmeridge Bay and Brandy Bay cliff outcrops, but none of these can be correlated with confidence between the two sections.

As with the Hobarrow Bay Mudstone, the succession is fossilferous throughout and contains a similar assemblage of ammonite genera. The widespread Rebholzi Marker Bed with abundant *Sutneria rebholzi* (Berckhemer) occurs in F9. *Nannocardioceras* spp. are common throughout and especially abundant in the oil shales in F10 to F14 where they comprise up to 50% of the rock on some bedding planes and are the correlative of the Nannocardioceras Beds of Callomon and Cope (1971). Species recorded by Cox (*in* Cox and Gallois, 1981) and Van der Vyver (1986) include *Amoeboceras (N.) krausei, A. (N.)* cf. *anglicum, Aspidoceras* cf. *longispinum* (J. de C. Sowerby), *A. sesquinodosum* (Fontannes), *Aulacostephanus* cf. *autissiodorensis* Cotteau, *Aul.* cf. *jasonoides, Aul.* aff. *kirghisensis* and *Aul.* cf. *volgensis* Vischniakoff. The crinoidal Saccocoma Marker Bed recorded in the lower part of the Autissiodorensis Zone in the Warlingham Borehole by Casey (*in* Worssam and Ivimey-Cook, 1971) has not been recorded at Kimmeridge Bay or Brandy Bay.

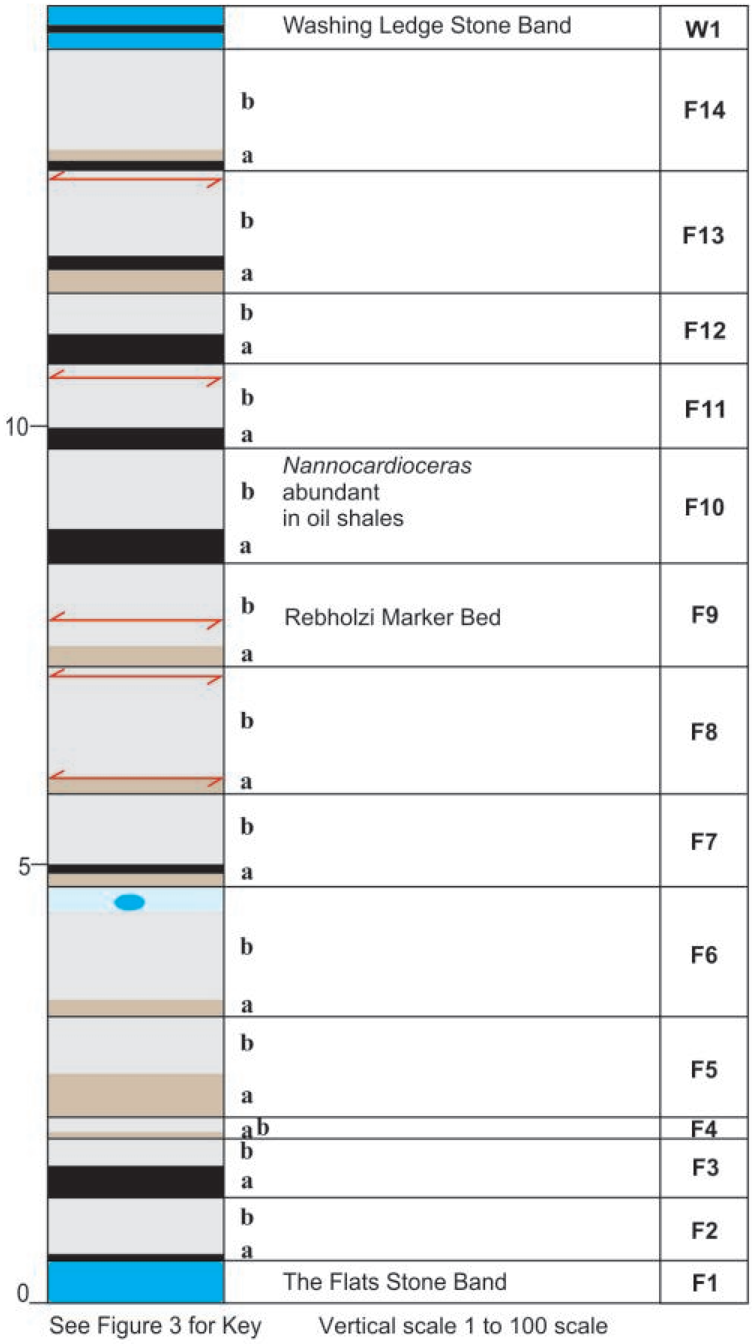


Figure 5. *The Flats Mudstone succession exposed in the cliffs in Kimmeridge Bay: a closely similar succession is exposed in Brandy Bay. See Figure3 for key and Figures 7 and 8 for outcrop maps.*

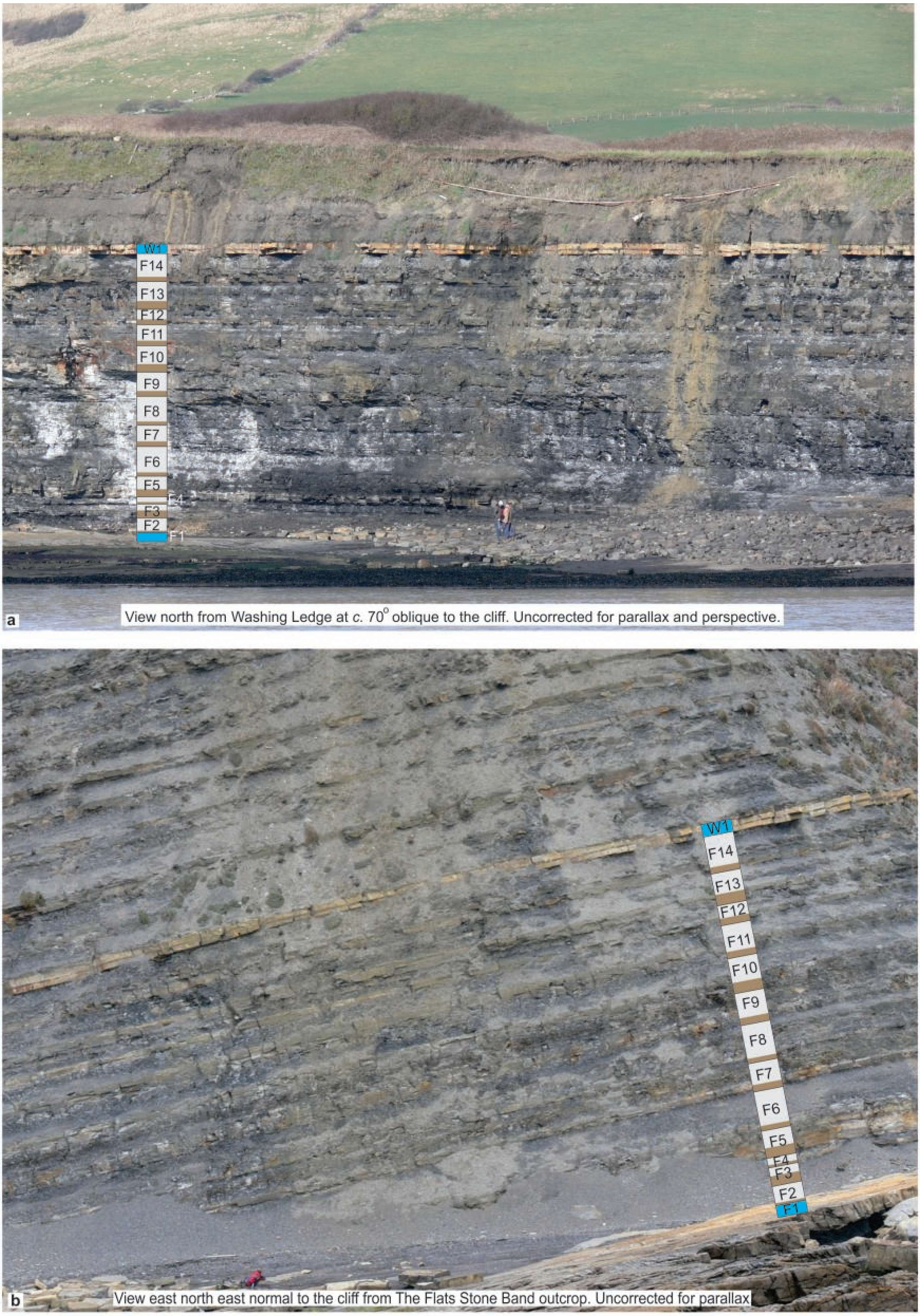


Figure 6. *The Flats Mudstone exposed in the cliffs. (**a**) West side of Kimmeridge Bay; (**b**) Brandy Bay. See Figure 3 for key and Figure 5 for bed thicknesses.*

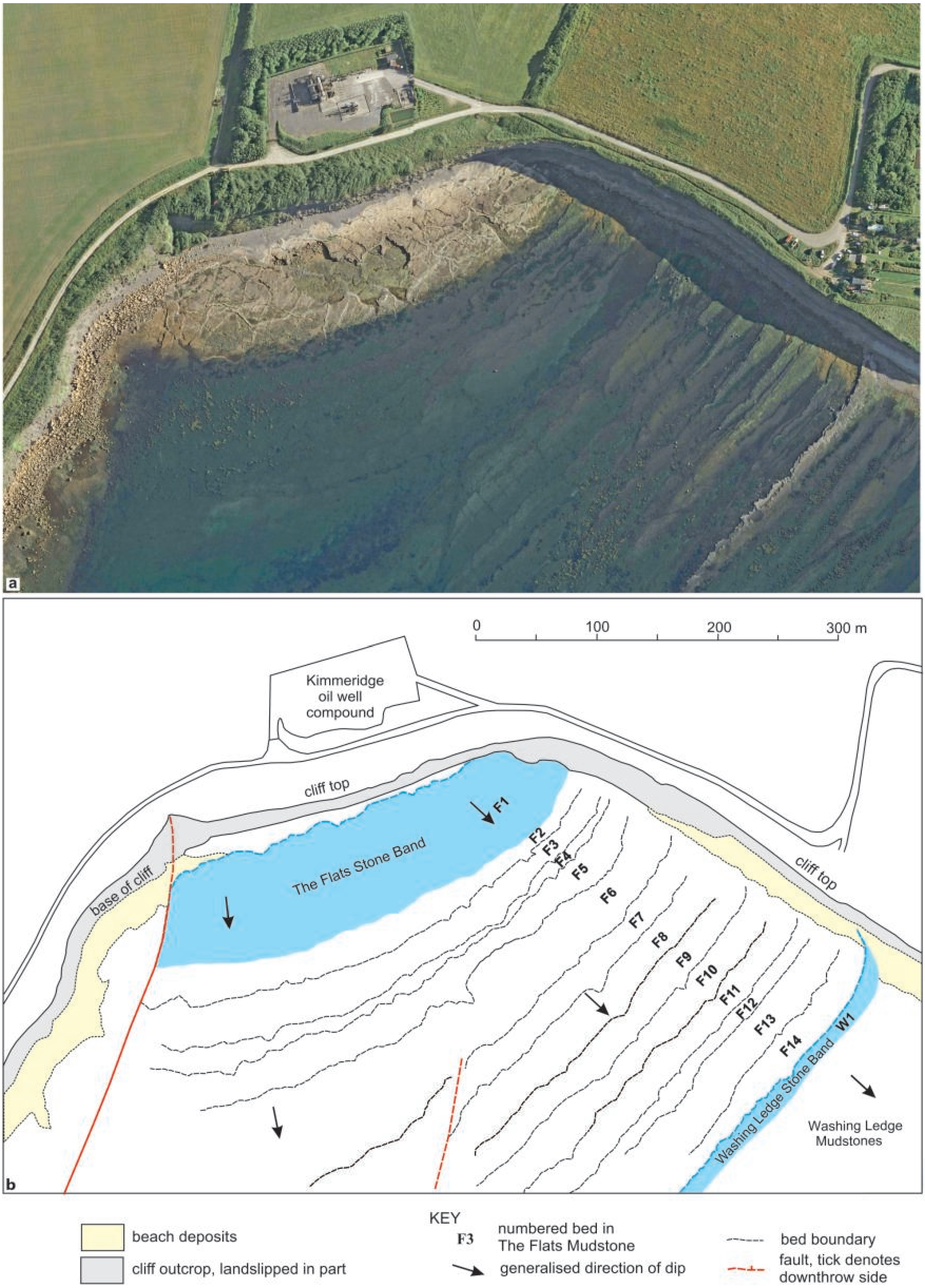


Figure 7. *(**a**) Composite aerial photograph based on parts of CCO ortho-rectified frames SY 98 70 NE and 99 70 SE, 5th May 2008. Image reproduced courtesy CCO; (**b**) Geological sketch map of the The Flats Mudstone outcrop in the intertidal and subtidal area on the west side of Kimmeridge Bay based on (**a**). See Figure 5 for bed thicknesses.*

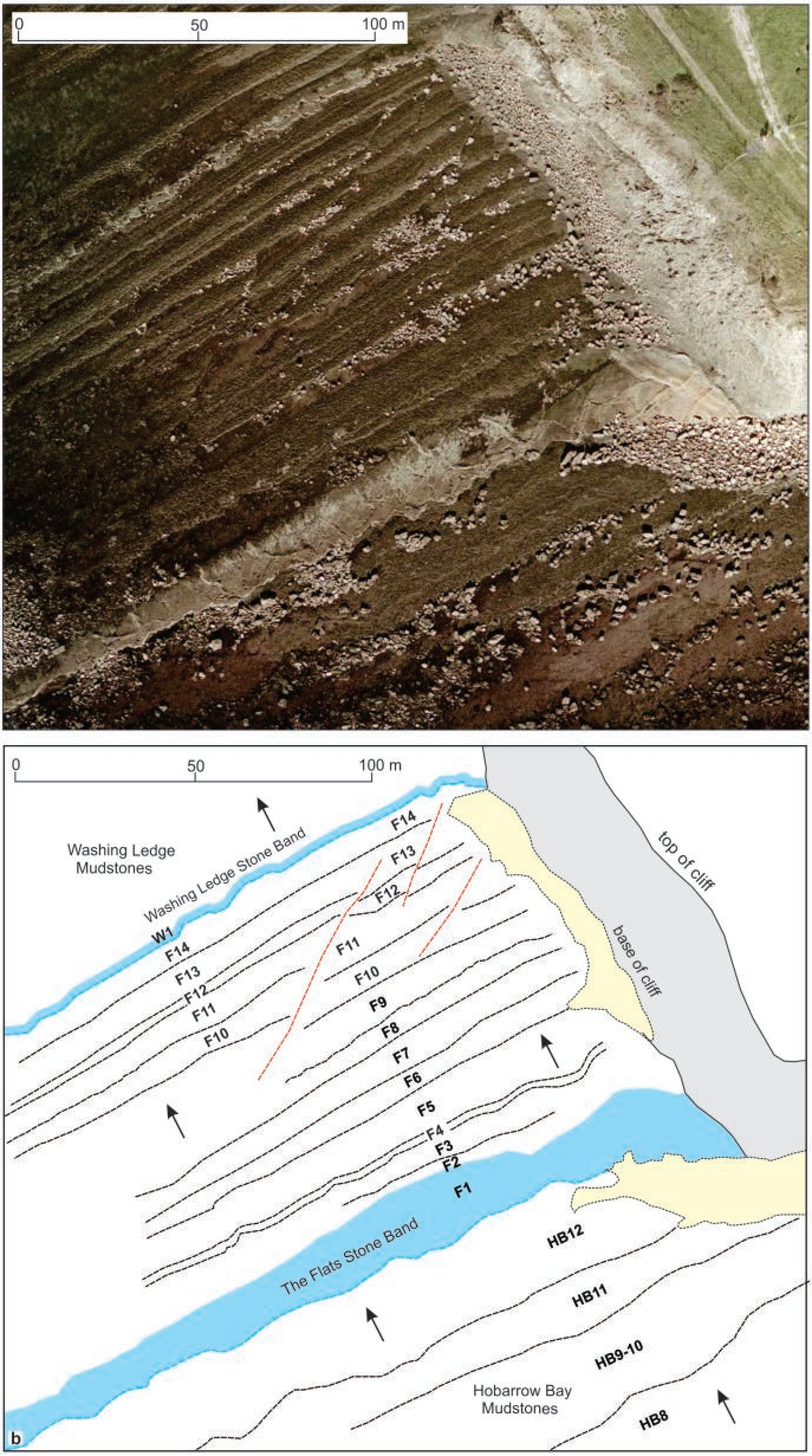


Figure 8. *(**a**) Composite aerial photograph based on parts of CCO ortho-rectified frames 5th May 2008. Reproduced courtesy CCO; (**b**) Geological sketch map of the The Flats Mudstone outcrop in the intertidal and subtidal area at Brandy Bay based on (**a**). See Figure 7 for key and Figure 5 for bed thicknesses.*

Washing Ledge Mudstone

The Washing Ledge Mudstone is wholly exposed in Brandy Bay and Kimmeridge Bay. At the base of the unit, the Washing Ledge Stone Band forms a prominent ledge in both bays. In Kimmeridge Bay, it is exposed seaward for up to 400 m at low spring tides. Uniquely among the Kimmeridge Clay stone bands, it contains a 0.1 m thick oil shale in its middle part that causes it to weather out as two limestone beds. The 21 units (W1 to W21) (Figure 9) into which succession is divided can be recognised in the cliff (Figures 10 and 12) and foreshore (Figures 11 and 13) sections in both bays. The highest bed is cut out in part by the Maple Ledge Fault in Kimmeridge Bay where Arkell (1947) estimated 6.1 m of strata to be missing. Comparison of the cliff section with that proved in the BGS Kimmeridge Bay Borehole [SY 9097 7899] (Gallois, 1979) which was drilled 20 m from the edge of the cliff shows that <0.5 m is missing from the cliff section. This was confirmed by correlation with the succession at Brandy Bay which is complete at this stratigraphical level (Figure 13). In the lower part of the succession, the oil shales in units W6 to W9 form prominent ribs in the cliffs. Widely spaced small (mostly up to

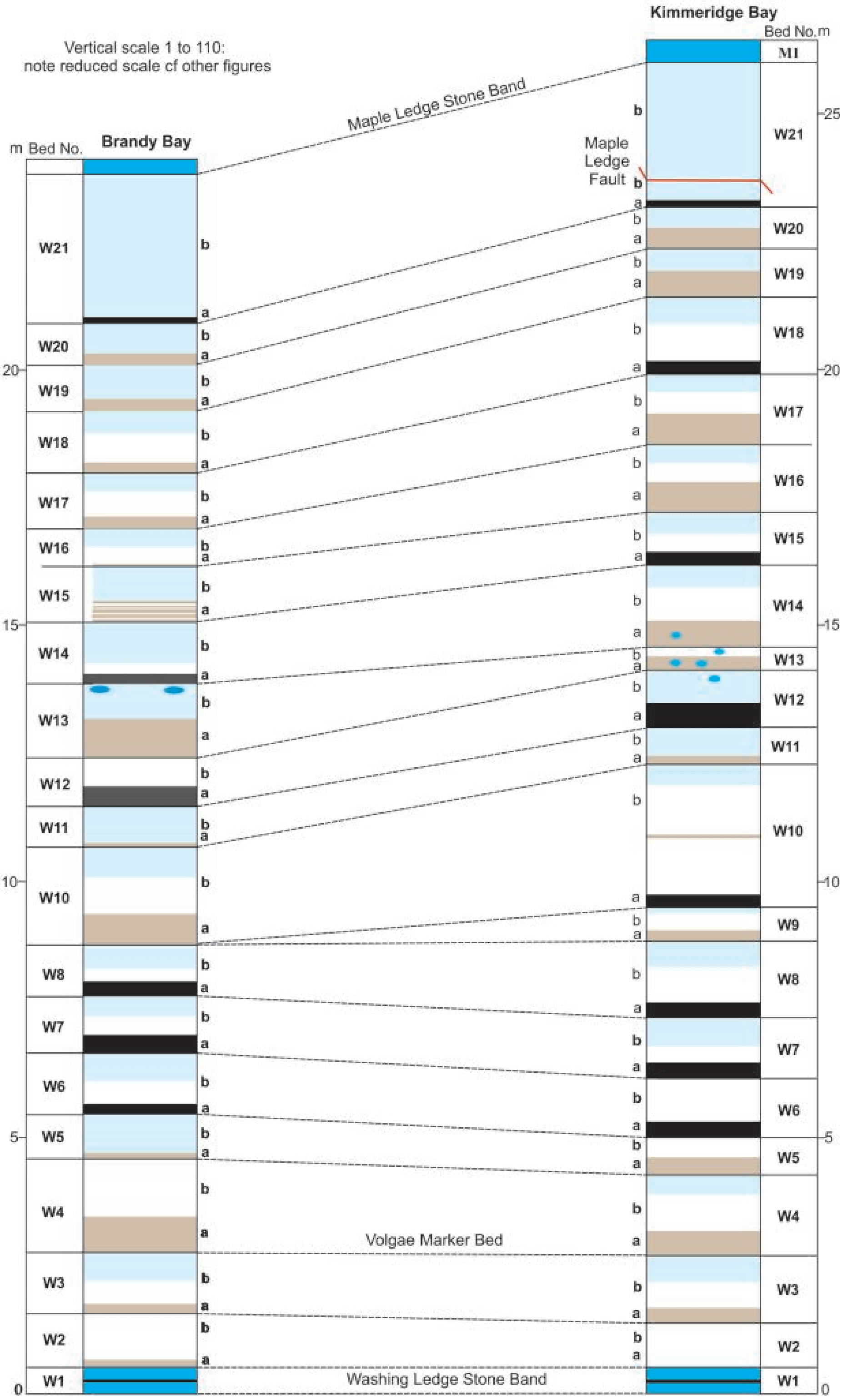


__Figure 9.__ The Washing Ledge Mudstone successions exposed in the cliffs in Brandy Bay and Kimmeridge Bay. See Figure 3 for key and Figures 11 and 13 for outcrop maps.

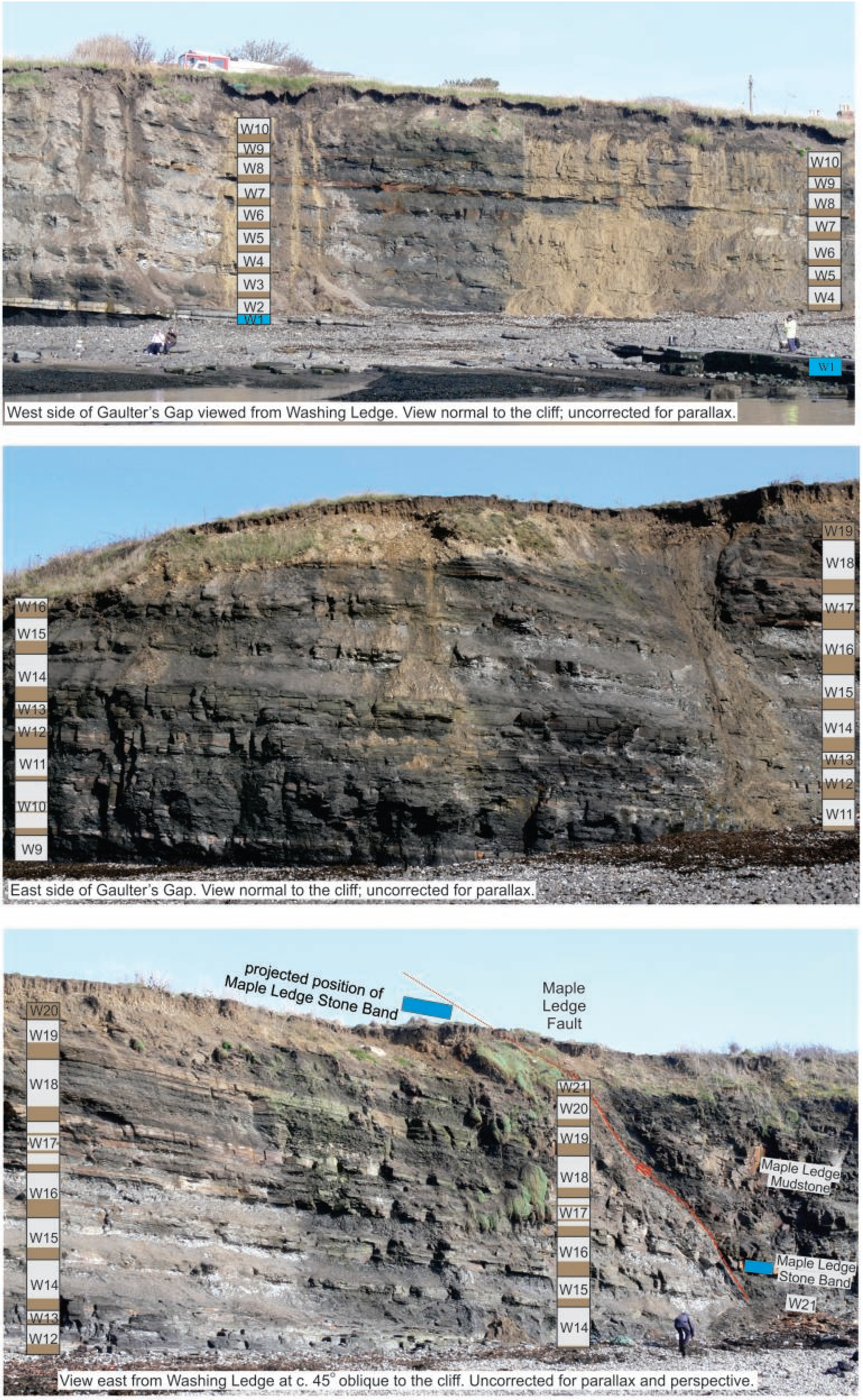


Figure 10. *The Washing Ledge Mudstone succession exposed in the cliffs in Kimmeridge Bay. See Figure 3 for key and Figure 9 for bed thicknesses.*

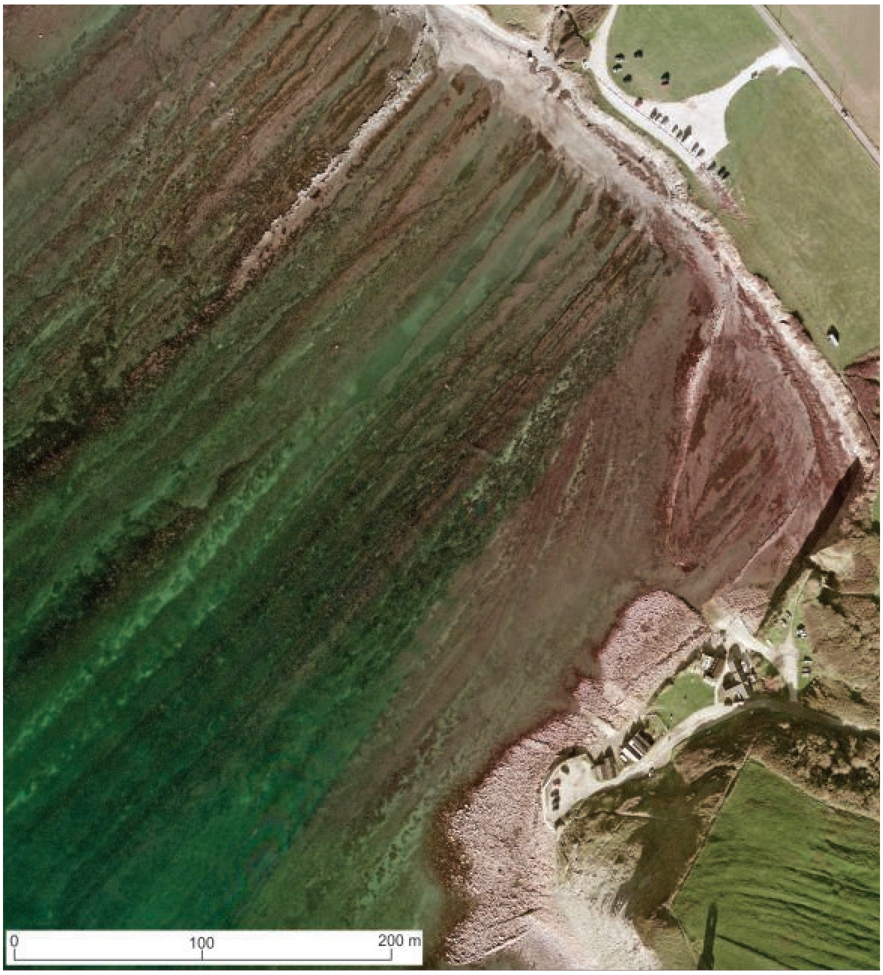


Figure 11a. *Composite aerial photograph based on parts of CCO ortho-rectified frames SY 98 70 NE and 99 70 SE, 2nd November 2001. Copyright CCO.*

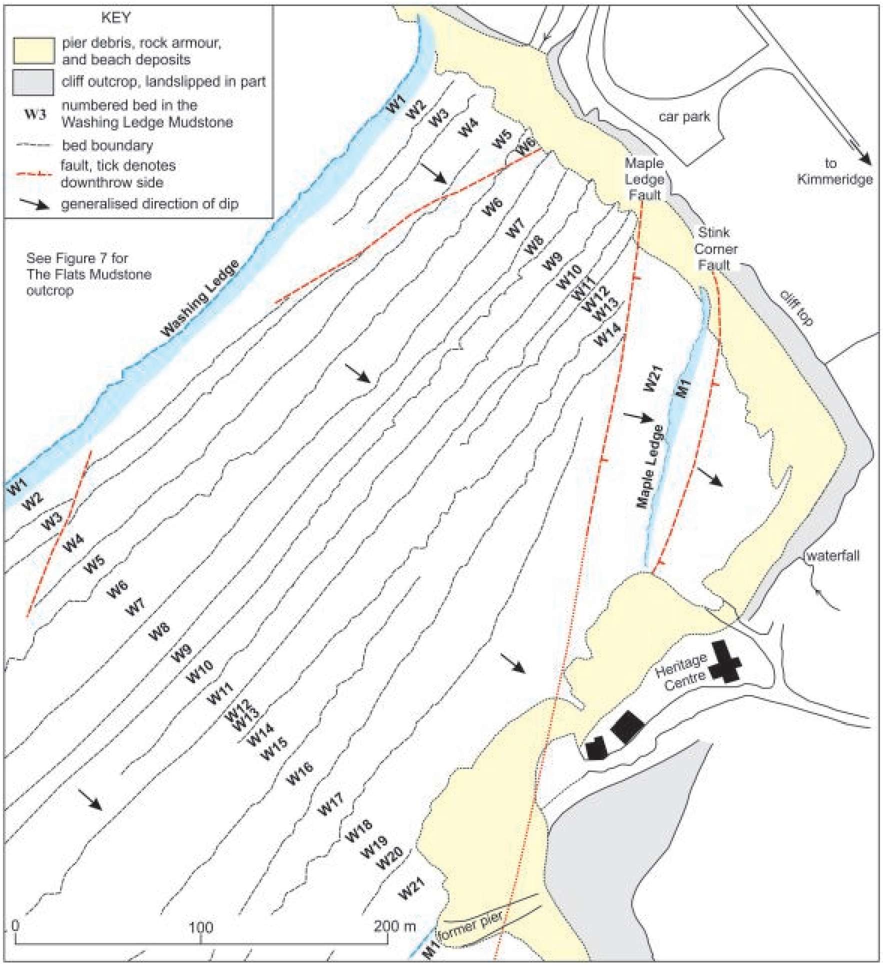


Figure 11b. *Geological sketch map of the Washing Ledge Mudstone outcrop in the intertidal and subtidal area on the west side of Kimmeridge Bay based on Figure 11a. See Figure 9 for stratigraphical succession.*

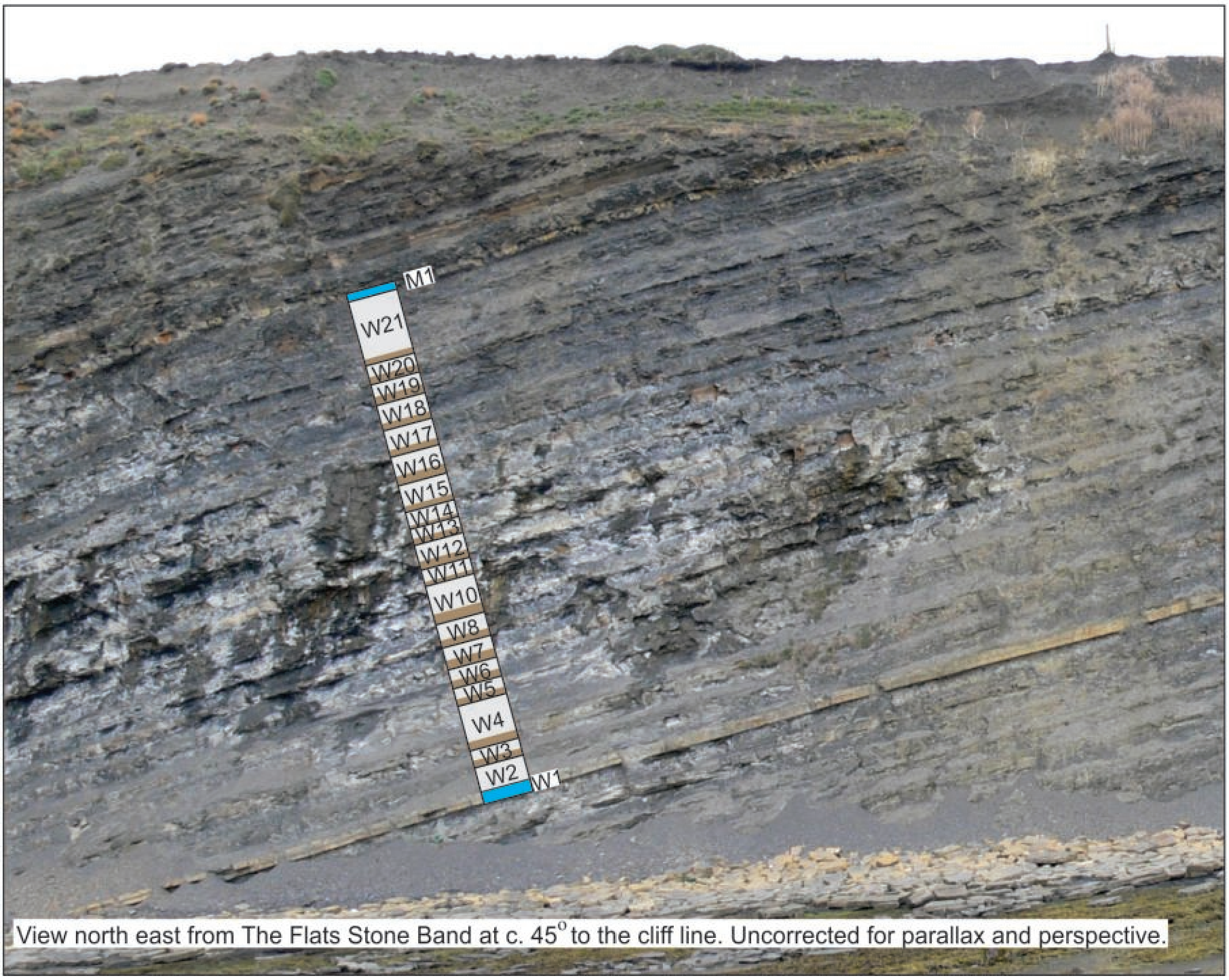


Figure 12. *The Washing Ledge Mudstone succession exposed in the cliffs in Brandy Bay. See Figure 3 for key and Figure 9 for bed thicknesses.*

0.1 m across) calcareous concretions occur at up to four laterally impersistent levels in W12 to W14. In contrast to the crushed preservation of almost all the ammonites in the mudstones, a few of the nodules have yielded well-preserved 3D ammonites, notably species of *Gravesia* and *Subdichotomoceras*, which have proved to be particularly important for comparison with the type specimens.

Crushed but otherwise well-preserved ammonites, mostly species of *Aulacostephanus* and *Subdichotomoceras*, are abundant on some bedding planes in both Kimmeridge Bay and Brandy Bay including specimens up to 350 mm in diameter. Cox (in Gallois and Cox, 1981) and Van der Vyver (1986) recorded *Aulacostephanus autissiodorensis, Aul.* aff. *rigidus, Aul. volgensis* and *Aul.* cf. *fallax,* and Enay *et al.* (2014) recorded *Subdichotomoceras lamplughi lamplughi* Spath, *S.* cf. *speetonense* Spath and *S. websteri* (Cope). The youngest *Aspidoceras* recorded to date is from W2 (Van der Vyver, 1986), and the internationally correlated Volgae Marker Bed with abundant *Amoeboceras (N.) volgae* (Pavlow) occurs in W2 and the lower part of W3. *A. (N.) krausei* (Salfeld) is present in W2. Rare examples of *Pseudogravesia* have been recorded from W13-14 (Enay et al., 2014) and slightly more common examples of *Gravesia lafauriana* Hantzpergue occur in W21 in Kimmeridge Bay and its correlatives in inland boreholes where it is the suggested correlative of the Lafauriana Horizon of western France (Gallois *et al.*, 2015).

Summary and conclusions

The cliff and foreshore exposures at and adjacent to Kimmeridge, Dorset are the type section for the middle and upper parts of the Kimmeridge Clay Formation. The present description of the successions exposed between Kimmeridge Bay and Brandy Bay builds on that of Cox and Gallois (1981) which provided graphic sections of the cliff sections in which the principal lithologies were shown as a succession of un-numbered beds. A revised description of the beds between the Hobarrow Bay Stone Band and the Maple Ledge Stone Band is presented here in which the rhythmic nature of the formation is used to divide the succession into 47 numbered units (HB 1 to W21). A similar description of the highest part of the Autissiodorensis Zone (Maple Ledge Mudstone Units M1 to M15) has already been published (Gallois, 2011).

Units HB 1 to 15 are only exposed in Hobarrow Bay. Units F1 to W21 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 together, the revised descriptions and 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.

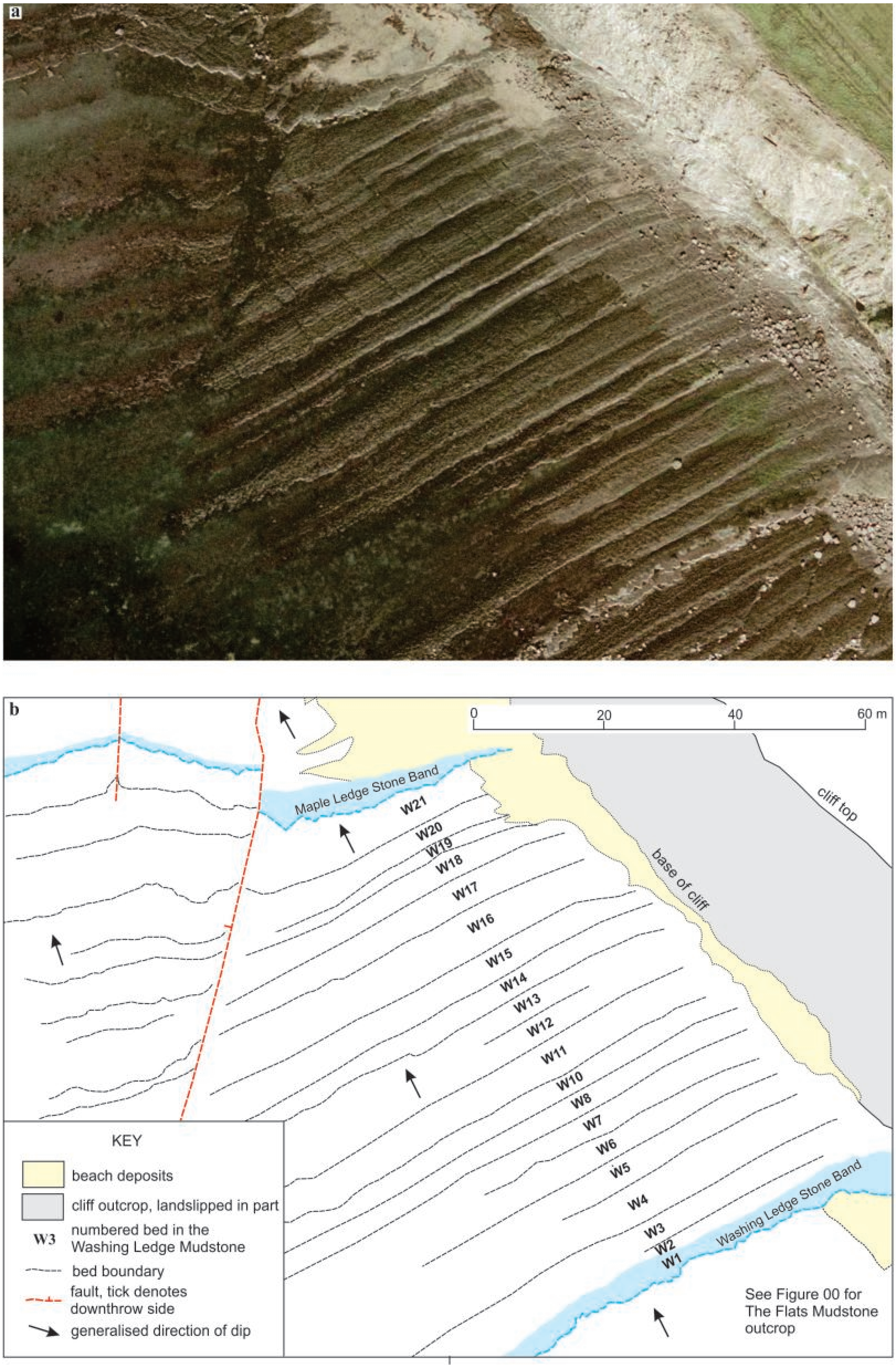


Figure 13. *(**a**) Composite aerial photograph of Brandy Bay based on parts of CCO ortho-rectified photographs 5th May 2008. Copyright CCO; (**b**) Geological sketch map of the Washing Ledge Mudstone outcrop in the intertidal and subtidal area in Brandy Bay based on (**a**). See Figure 9 for stratigraphical succession.*

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 PhD thesis and descriptions of the Kimmeridge Clay sections, and to the Channel Coast Observatory (*www.channelcoast.org*) for copies of their air photographs and multibeam sonar plots. Beris Cox, John Wright and an anonymous reviewer are thanked for their comments on an earlier draft that led to many improvements in the present account.

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