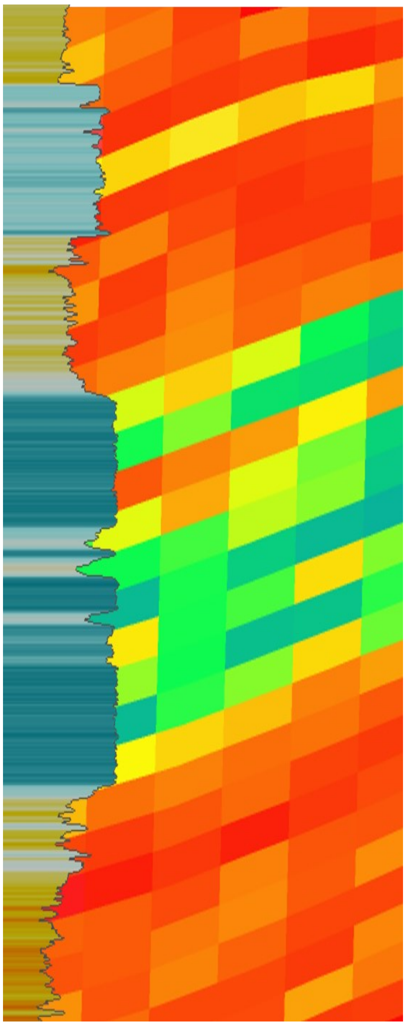
Chapter 17: Examples of correlating, integrating and applying stratigraphy and stratigraphical methods

Matthew I. Wakefield, Mark W. Hounslow, Matthew Edgeworth, John E.A. Marshall, Rory N. Mortimore, Andrew J. Newell, Alastair Ruffell and Mark. A. Woods

Running header: Correlation, integration and application of stratigraphy



17.1 Introduction

In addition to stratigraphy providing a framework that underpins the interpretation of the geological record, it is a key tool for many societally relevant applications. For example, the first steps in civil engineering projects (Section 17.5) and the identification, location and extraction of mineral, water and energy resources.

Although geological maps, particularly those showing the location of resources, have existed since at least 1150 (BCE; the Turin Papyrus), William Smith's maps, and those he produced of smaller areas from 1799, were arguably the first to use stratigraphical principles including faunal succession, and also highlighted resources of contemporary societal importance (coals). His work was not the first to interpolate between isolated outcrops, but there are clear differences between his publication (Smith, 1815) and, for example, that of Cuvier and Brogniart (1808; see Rudwick, 1996). Smith was essentially a geognost (one who is interested in the structure of rocks and their minerals), his map being based on empirical field surveys of the strata enhanced by his use of faunal succession. Brogniart, also a geognost, was influenced by Smith's idea of faunal succession, while Cuvier brought a geohistorical aspect to their work. Today stratigraphical mapping, without which society would not function, is undertaken in universities, by national geological surveys and by commercial or nation-state resource companies in the search for raw materials for building (stone, clay, sand and aggregates), manufacturing (minerals, metal ores) and energy resources.

Stratigraphy also impacts on other aspects of society, such as identifying the best areas for wine, whisky or beer production (Huggett, 2006, Maltman, 2019). Both archaeology (Section 17.6) and forensic science (Section 17.7) use stratigraphical principles. There is overlap between these two disciplines and scope for shared technique usage and development, both in what is studied but also the techniques employed e.g. consider the stratigraphy of grave cuts and fills, be they recent (murder victims) or thousand year old burials. In the future a detailed knowledge of stratigraphy, particularly the use of stratigraphical models of the subsurface (see Section 17.4) is highly likely to become more publicly visible as governments strive to address issues of pollution (radioactive waste disposal, CO_2 capture and 'burial') and other strategic resource requirements including water (aquifer modelling and management), minerals for advanced technology (batteries and electronic devices) and alternative energy sources e.g. ground sourced heating and geothermal energy.

This chapter cannot detail all specific procedures relating to quantitative correlation, the integration of stratigraphical techniques or their applied application. It therefore aims to cover some of the most common techniques and applications but, more specifically, to act as an introduction to subjects which stratigraphers may find useful. The first part of this chapter concentrates on quantitative stratigraphical correlation methods (Section 17.2), as correlation is critical in applications such as finding and extracting resources, understanding the extent of rock units for engineering projects and deciphering the spatio-temporal extent of changes in Earth systems processes. The second part of the chapter covers the challenge of correlating within non-marine strata as well as correlating non-marine to marine strata (Section 17.3), a topic that requires careful integration of several stratigraphical techniques covered earlier in this book. The final parts of the chapter illustrate specific examples of where stratigraphy and integrated stratigraphical disciplines/techniques are frequently used these are: rock property modelling (Section 17.4) which is used for purposes such as aquifer monitoring, resource extraction or storage, and is directly relevant to engineering geology (Section 17.5); archaeology (Section 17.6) and forensic geosciences (Section 17.7).

17.2 Correlation techniques (Wakefield and Hounslow)

Quantitative correlation techniques can enable small or large data sets from few or multiple stratigraphical sections to be integrated, compared and for stratigraphical correlations to be optimised (Fig. 17.1). These methods are critical at all scales be they global, regional, basinal or for specific locations and form a vital part of geological timescale construction (Chapter 15). Data from one or more of biostratigraphy (Chapter 4), magnetostratigraphy (Chapter 5), chemostratigraphy (Chapter 6) and radio-isotope stratigraphy (Chapter 14) may be used. The development of Graphic Correlation, Constrained Optimisation (CONOP), Unitary Associations (UA) and Ranking and Scaling

(RASC) centred upon biostratigraphical data. The first three are deterministic (range maximisation) techniques, which try to find the total range of a taxon, an approach badly affected by unrecognised false range extension e.g. reworking. RASC is a probabilistic approach that seeks the average range (Fig. 17.2).

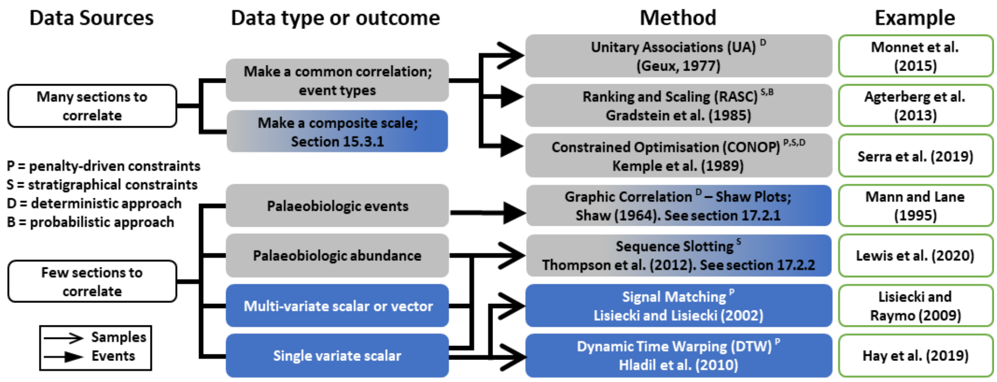


Fig. 17.1. Work-flow of quantitative correlation methods. For multiple sections decide on the outcome required (zonation or composite scale). Grey boxes inherently use biostratigraphical datasets, although some may utilise other data particularly isochronous events e.g. tuff bands, seismic horizons. [Text width, 5 cm high = 1/4 page + 37 word caption]

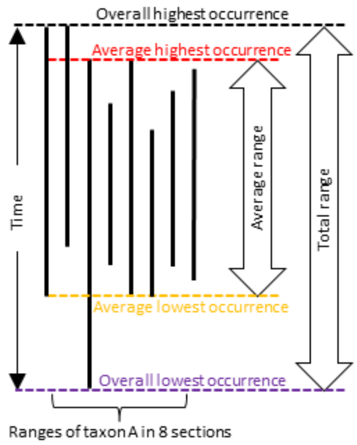


Fig. 17.2. The difference between probabilistic (average) and deterministic (total) ranges (modified after Cooper et al., 2001 with permission of the AAPG whose permission is required for further use). [marginal, 5.7cm high + 27 word caption]

The following are brief descriptions of the methods from Fig. 17.1; see GIP/DEH/17-1 for additional information and links to freeware computer programs.

Graphic correlation: a manual, range maximisation technique that produces an event order and a correlation. Event data (e.g. biostratigraphical plus assumed isochronous data such as tuffs, seismic horizons etc.) plotted on an x-y graph, with a Line of Correlation (LOC) drawn as a subjective best fit of those data points. Reworking and caving of palaeontological data can be an issue, while the method can be slow with multiple sections. See Section 17.2.1 and chapters 4, 8, 9, 12 and 15.

Ranking and Scaling (RASC): a fully automated probabilistic approach to generating a zonation scheme with biostratigraphical data. Creates an optimum order and spacing of events observed in multiple sections subject to stratigraphical inconsistencies with respect to time. Correlation of sections using RASC output is undertaken using CASC (the Correlation and Standard error Calculation programme), an automatic graphic correlation method that employs a mathematically constrained spline curve for its LOC. CASC estimates confidence intervals for calibrated positions of events in sections, enabling evaluation of the quality of events for correlation; it is also fast to undertake compared with Graphic Correlation.

Constrained Optimisation (CONOP): a mostly deterministic fully automated graphic correlation method simulating probabilistic solutions. It searches for a global (composite) succession of events with minimal total amount of range extension (set as a penalty) in individual sections. It operates simultaneously on all events and all sections. The user must decide on the allowed degree of 'misfit' between possible composite and measured sections, and the constraints used to identify impossible solutions. Information on reworked and caved events can be used. Fast to undertake when compared with Graphic Correlation. See Worked example 12.2.

Unitary Associations: a deterministic approach that creates optimal assemblage/concurrent range zones of taxa observed to co-occur (real association) or deduced from biostratigraphical data (virtual association). Robustness is favoured over resolution, aiming to give maximal stratigraphical resolution with a minimum of superpositional contradictions. Based on samples rather than events and is therefore applicable to sparse datasets.

Sequence Slotting: seeks to minimise dissimilarity between pairs of data points, when two successions are stratigraphically interleaved with each other. Enables high-resolution correlation at the sample scale of data such as chemical, geophysical, magnetic and biostratigraphical. See Section 17.2.2.

Dynamic Time Warping (DTW): calculates an alignment between two, time dependant single variate sets of samples. Similarity between successions is constrained by penalizing the variations in accumulation rate-distortions or degree of incompleteness of the patterns. Sample sets are warped in a non-linear manner (the "warping path") to match each other.

Signal matching using penalties: constrains the sequential ordering of single variate data. Matched segment interval are scored by the square of the difference. Subject to two penalty functions that minimise accumulation rate changes: 1) a penalty proportional to each deviation from the site's average sedimentation rate; 2) a rate change penalty each time the sedimentation rate changes.

The following sections illustrate different approaches that could be applied to the same data set. The first, Graphic correlation (applied examples in Chapters 4, 8, 9, 12, 15 and 16) uses events that may be widely spaced i.e. it uses only part of the dataset, producing a zonal resolution scheme. RASC or CONOP could replace Graphic Correlation in this context. The second, Sequence Slotting, uses sample data, having the potential to provide a higher resolution of correlation than that of events alone i.e. within zone correlations.

17.2.2 Graphic correlation

Graphic correlation uses cross plots to enable the likely total ranges of taxa to be determined based on data from a number of sections, and sections to be correlated to a reference section (Shaw, 1964). This simple but effective technique can be undertaken using a range of stratigraphical data. It demands user interactivity, encouraging thorough stratigraphical understanding of the data and its geological context. The beauty of the technique is the variety of ways in which it can be used;

- Plotting one section against another to understand correlation and relative sedimentation rates (Fig. 17.3; e.g. Shaw plots in chapters 8, 9 and 12)

- Plotting sections against an existing scheme/timescale e.g. those generated by RASC or CONOP to understand correlation and sedimentation rates (Chapters 4, 12 and 16)
- Generating a standard reference section for correlation (discussed below).

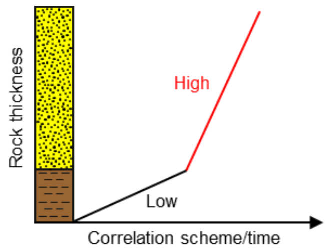


Fig. 17.3. Relative sedimentation rates from a graphic correlation plot (does not account for differential compaction). [marginal, 3.4 cm high + 14 word caption]

Graphic correlation has many technical terms; Standard Reference Section (SRS), Line of Correlation (LOC), Composite Standard Reference Section (CSRS; the resulting correlation scheme). Only two sections can be correlated at a time, unlike RASC and CONOP. In many instances biostratigraphical datums (bioevents; see Table 4.3) are used. Other data, considered isochronous e.g. seismic horizons, airfall tuffs, magnetic polarity boundaries, astronomical cycles, bed boundaries over short distances or isotopic changes can also be used either in an integrated manner with biostratigraphical data or on their own. To derive a CSRS, the user must select the two most stratigraphically complete sections to be correlated (lack of faults, most complete succession and/or correlative data set), the best being the SRS. These are plotted on a scatter plot; the *x* and *y* coordinates being the depths in the SRS and second section respectively. A LOC is drawn as a best fit between those data points. Event positions in the SRS are modified as each successive section is plotted against the SRS until a CSRS is completed (Fig. 17.4). The CSRS is scaled in Composite Standard Units (CSU's) that do not directly convert to a linear time scale; see discussion in Carney and Pierce (1995; pp. 29-31). However, correlation from one depth section to another via the CSRS avoids this technicality.

Updating the SRS: When using bioevent data ensure that a) bioevent tops have not been affected by reworking, b) with well-cuttings be aware of caving of bioevent bases (see Fig. 4.9), and c) inaccurate LOC positioning. All can result in falsely extended taxon ranges. **[44 words]**

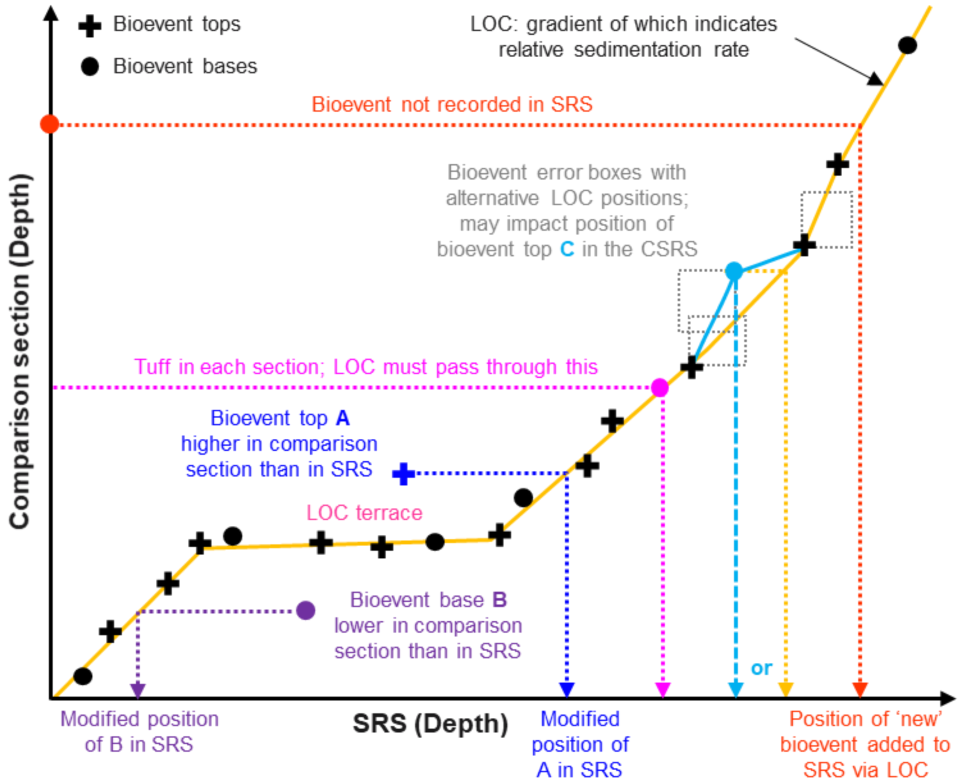


Fig. 17.4. Graphic correlation fundamentals illustrated using bioevents. Relative positions of events in the comparison and SRS sections define the position of the LOC. New events are included in the SRS via the LOC. Bioevent positions in the SRS may be modified e.g. top A that occurs *above* the LOC and base B that occurs below the LOC can be repositioned via the LOC as indicated. Alternative LOC positions will impact on where bioevent C appears in the CSRS i.e. if the existing LOC (orange) is used C will appear 'higher' in the SRS than if the LOC (blue) is placed through event C. [Text width, 10.7cm high = 1/2 page + 102 word caption]

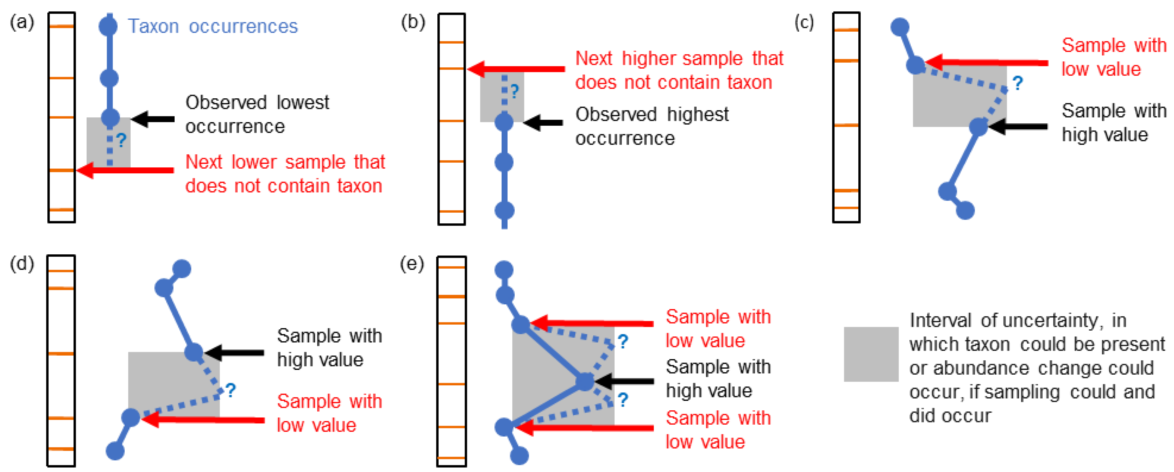


Fig. 17.5. Many data sets are discontinuous e.g. fossils might occur between biostratigraphical samples, particularly in industrial data where often samples are metres to tens of metres apart. Seismic horizons have uncertainty due to depth conversion factors. The LOC can be guided by an understanding of uncertainty for specific event types. Bioevent uncertainties are: (a) FAD/LDO; (b) LAD/FDO; (c) FDCO (d) LDCO and (e) single sample occurrence peaks (see Table 4.3 for bioevent type). Barren samples do not count! Depth uncertainty will extend beyond such samples to the next taxon bearing sample. Uncertainty bounds can be shown (Fig. 17.4). Modified after Edwards

(1995) with author permission. [Page width for readability, 7cm high =1/3 page + 102 word caption]

Line of Correlation: The line of correlation is monotonic, cannot have a negative slope but can have multiple segments that account for variations in sedimentation rate and/or missing sections. Using the technique with thrust faulted successions is problematic. **[38 words]**

Event ordering: Event ordering within the CSRS is determined via correlation, they are inter-related. Each section should be replotted against the SRS in a different order from which they were originally included. This will allow bioevent and LOC positioning to be checked and improved. This is critical but time consuming. **[50 words]**

The Line of Correlation

The most critical part of the building process is defining the LOC, which can be highly subjective so is often criticised e.g. Kemple *et al*. (1995). In the early steps only a small fraction of the data may be available, so LOC definition may be poor, although these steps have a large impact on the outcome (Edwards, 1984). There are a number of key considerations when defining the LOC with bioevent data, but also other data types that have uncertainty on event position:

- Differential weighting of bio and other events such as seismic horizons. Key index fossils and those with consistent records are favoured over those with patchy records. Positions of the latter can be updated and stabilised via the LOC;
- Uncertainty associated with particular bioevent types (Fig. 17.5; see also Figs. 9.14, 9.15 and 9.16) can be used such that the LOC should pass as close to weighted bioevents and preferably within their uncertainty bounds, unless the bioevent position needs updating in the SRS/CSRS (Fig. 17.4);
- Isochronous data can be used e.g. bentonites through which the LOC must pass;
- The identification of LOC terraces (see below);
- The user must decide which LOC position is most geologically plausible.

Line of Correlation terraces

These are near horizontal sections of the LOC, for which other geological data are needed to understand them. They are caused either geologically due to:

- Missing section (unconformity, slumping, dissolution or a fault);
- Slow sedimentation; condensation or sediment bypass;

Or due to the sampling and data strategy; too wide sample spacing results in the nesting of bioevents, reduction in stratigraphical resolution and produces artificial LOC terraces (see Fig. 4.3).

Graphic correlation and sequence stratigraphy can be integrated through an understanding of hiatal intervals/LOC terraces (Chapter 8; Neal *et al*., 1994, 1995). LOC terraces can represent either a MFS (basinal position), sediment starvation or bypass (shelf-slope break position) or sequence boundary (shelfal position); Neal *et al*. (1995; Fig. 4). Overlapping LOC terraces have been applied outside sequence stratigraphical studies e.g. in conjunction with other data they enabled the identification of laterally continuous condensed mudstone horizons within a stacked turbidite sandstone reservoir (Wakefield *et al*., 2001).

17.2.1 Sequence slotting

Sequence slotting, an objective numerical correlation method, can be applied to many types of stratigraphical data; biostratigraphical (Gary et al., 2005; Lang et al., 2010; worked example 17.1), chemical (Lewis et al., 2020), geophysical (Thompson et al., 2012; worked example 5.3) and magnetostratigraphical (Worked example 5.1). With biostratigraphical data it uses biotal abundances in samples for correlation, although isochronous events can be used to constrain (or tie) the correlation. The procedure combines two successions to form a single joint succession such that similar features in each input set are placed with respect to each other (slotted), preserving the original stratigraphical ordering (Gordon, 1973). The slotting is parameterised by a distance metric that measures the samples similarity when datasets are slid past each other. Depth or height is not directly used in the slotting, but for display only, so sedimentation rates take no part in the slotting process. Various software versions of the algorithm have been implemented including 1) SLOTSEQ (Gordon, 1980); 2) SLOTDEEP (Maher, 1993, 1998); 3) BioSlot (Gary et al., 2005) and 4) most recently CPLSLot (Hounslow and Clark, 2016; based on Clark, 1985; see GIP/DEH/17-1).

Both BioSlot and CPLSlot can utilise correlated events to 'force and pin' the correlation between particular points in the two sets, such as MFS, ash layers or other isochronous events. Uniquely BioSlot can generate confidence limits on species relative abundance when using taxon torpedo plots (i.e. abundance fluctuations) to pick events to tie the correlation; see Gary et al. (2005, pp.212-214) and Fig. 17.6.

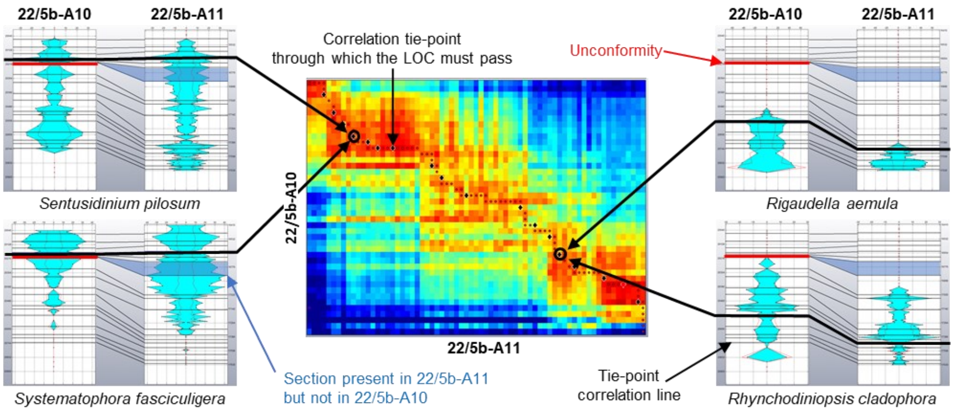


Fig. 17.6. Correlation steerage in BioSlot using tax torpedo plots to pick tie-points; percentage plots with 95% confidence limits (red lines on the torpedo plots; see Gary et al., 2005 p.212). Data is from Gary et al. (2009) where the similarity matrix (mid panel) of range normalised dinoflagellate cyst data uses a chord metric scaled to 0-1; high similarity in red, low in blue. Access to well data courtesy of Harbour Energy (license holder, Seymour Field area, UKCS). BioSlot software provided by Tramontane. [Text width, 5.6 cm high = 1/4 page + 81 word caption]

Worked example 17.1. Sequence slotting using pollen abundance data

This worked example illustrates correlation of palaeobiological abundance data where no biostratigraphical markers (tops or bases) are present using two pollen records from Lago di Monticchio (MONT82 and LGM90D), Italy, spanning about 76ky (Watts, 1985; Watts et al., 1996a and b; Kelly and Huntley, 1991). Inter-core comparison of 16 selected taxa from a much larger dataset is undertaken using CPLSlot (Hounslow and Clark, 2016; data files in GIP/DEH/17-2).

In CPLSlot the two core records are referred to as sequence-A (the longer 'master' dataset), which is slotted to sequence-B (the shorter dataset). Distance metrics are used to determine the discrepancy between points from the two sequences (dictated by the nature of the input data). No use is made of the absolute distance (m or cm) between samples ('distance' used here is in a statistical sense). For biotic-abundance type data, available distance measures are shown in Table 17.1. The sum of the distance measures for all data pairs for the two slotted successions is the combined path length (or CPL). The main measure of the success of the slotting is the Δ -value (Table 17.2), but also shown are association-type statistics, which consider the overall fit of the data in the slotted models (Table 17.2).

Table 17.1. Types of distance measures for abundance-type palaeobiological data. In the above formulas P_{ik}, P_{jk} are the value of sequence A and B at level I and j respectively of variable k. d_{ij} is the distance between I and j in sequence A and B. [worked example, page width = 70 words but take as 100 because of equations = 1/8 page]

Squared-chord distance	$d_{ij} = \sum_k (\sqrt{p_{ik}} - \sqrt{p_{jk}})^2$ Trials by Gavin et al. (2003) suggest squared chord was superior to other distance measures for pollen data.
City block (or Manhattan) distance	$d_{ij} = \sum_k \lvert p_{ik} - p_{jk} \rvert$ Compared to Euclidean, this metric may be more appropriate for 'spiky' data.
Euclidean distance	$d_{ij} = \sqrt{\sum_k (p_{ik} - p_{jk})^2}$
χ^2 distance	Uses a contingency table evaluation as the metric, accounting for differences in the absolute fossil counts. No additional scaling is appropriate. Data should be counts, not proportions.

Table 17.2. Some key indicators of the goodness of the slotting solution. [worked example, page width 139 words = ¼ page]

Indicator	Notes
Δ- value	Measure of success. Smaller values indicate better success, but a small value does not necessarily mean that the slotting is meaningful. Association statistics provide additional indicators.
N-CSTAT	The normalised sensitivity statistic. A measure of the robustness of the fit, largely independent of changes in the CPL between different slotting solutions. Values below 1 indicate the average sensitivity statistic is less than the average distance between adjacent points. Smaller N-CSTAT values generally associated with better, more robust slotting solutions.
Rc, RV2, sRV.	The congruence (Rc) and RV-coefficients of Abdi (2010) are measures of similarity (or association) of the two multivariate datasets. They have useful ranges of 0 to +1 for positive association. The modified RV-coefficient (RV2) of Smilde *et al*. (2009) is used, since it behaves more-like familiar regression coefficients. sRV is the standardized RV coefficient.

With abundance data we normalise the counts for each sample ('normalise levels' in CPLSlot), otherwise the differing total counts of pollen in the samples would influence the correlation. As we have no direct evidence of which distance metric may be most appropriate for these data, slotting for all four possible distance metrics are shown (Table 17.4). The resulting correlation paths are shown in Fig. 17.7, three of the metrics produce similar correlation paths, which align with the position of the Younger Dryas inferred from the pollen data by Watts et al. (1996a and b). The χ^2 metric is the poorest (Fig. 17.7). Datasets that have less-well constrained correlations could have used distinctive intervals in the pollen records to allow constraints that pin the match at around these positions (e.g. the Younger Dryas etc). The squared chord model produces the lowest joint Δ and N-CSTAT values from the slotting statistics (Table 17.3). In contrast the association statistics (Rc, RV2, sRV) when ranked in order and using the summed rank score indicate that the squared-chord and city-block metric produce similar overall best associations (Table 17.3). The slotting statistic Δ is slightly worse (larger) for the city-block model (Table 17.3), suggesting that the squared-chord model is marginally better. The match of the raw pollen data between cores is clearly satisfactory (Fig. 17.8).

CPLSlot can also express the raw similarity data in the so-called H-matrix (Fig. 17.9). Possible correlation paths are shown by 'brighter' bands, with highest similarity (this is somewhat similar to the 'similarity matrix' of Gary et al. 2005; centre in Fig. 17.6). An advantage of this kind of plot is that it may show that there is more than one possible correlation, highlighting alternative correlation paths that can be explored.

Raw slotting outputs can produce correlation paths that are rather 'blocky' with respect to depth or height, since the method may group adjacent samples from the same core into small stratigraphically sequential blocks. The sequence blocking constraint (Thompson et al., 2012) limits this but does not eliminate it, so it is often best to fit a smoothed path (spline etc.) through the path and use that for the final correlation. Alternatively, in this case, since squared chord and city-block produce similar paths they might be averaged. This additional processing step is highlighted in the on-line spreadsheet only (GIP/DEH/17-2).

Table 17.3. Slotting models using different distance metrics. These use a block (BLK) constraint of 4,2 since the core LGM90D has approximately twice the number of data levels as the MONT82 core, covering a similar age interval. The congruence and Rv-coefficients are shown for the pollen variables 1 to 10 (those for variables 11 to 16 are shown within [..]). To compare the gross associations, represented by Rc, RV2, sRV a ranking score (1 to 4) is given to each of the 6 possible values and summed as the total ranking. That with the lowest total ranking score is the best slotting according to the association statistics. [worked example, 35 words full page width = 1/8 page]

Distance metric	D	N-CSTAT	Rc []	RV2 []/sRV[]	Total ranking
Squared-chord	0.84	0.441	0.82[0.79]	0.78[0.68]/0.50[0.43]	9
City-block	0.87	0.867	0.83[0.73]	0.77[0.58]/0.52[0.37]	10
Euclidean	0.84	0.831	0.80[0.65]	0.72[0.45]/0.37[0.21]	19
χ^2	1.00	1.032	0.65[0.31]	0.58[0.25]/0.48[0.20]	22

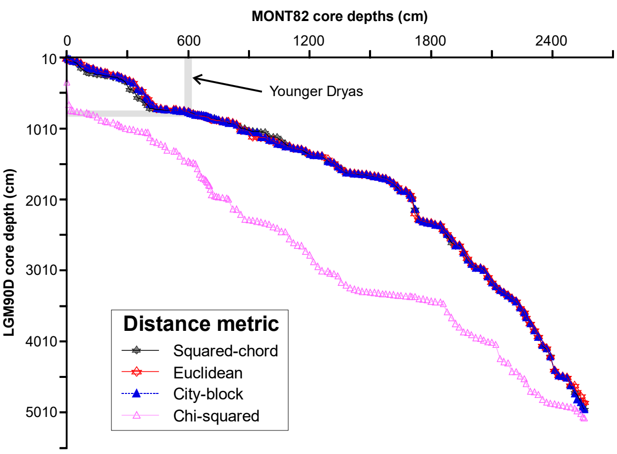


Fig. 17.7. The four correlation models for the differing distance metrics. All apart from the χ^2 metric give similar correlation relationships. The squared-chord and city-block metrics give very

similar correlation paths, with slightly larger divergences (red diamonds) for the Euclidean model. Position of the Younger Dryas inferred from the pollen data by Watts et al. (1996a and b) is shown for comparison. Note depths take no part in the slotting, which sees the datasets as sequential sample points only. Sequence A= LGM90D data, sequence B=MONT82 data. [worked example, single column width, 5.8 cm high = 1/8 page + 84 word caption]

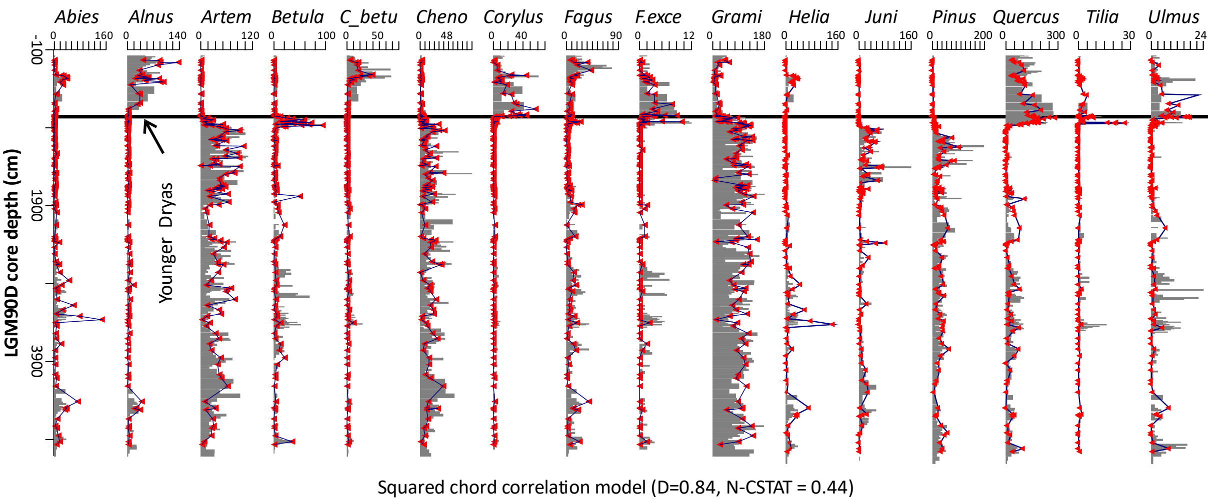


Fig. 17.8. Summary of the relationship of the 16 pollen variables for the LMGM90D core (in grey columns) and with the slotted positions of the MONT82 data in red. These use the raw slotted positions. [worked example, full page width, 6.8cm high = 1/3 page + 33 word caption]

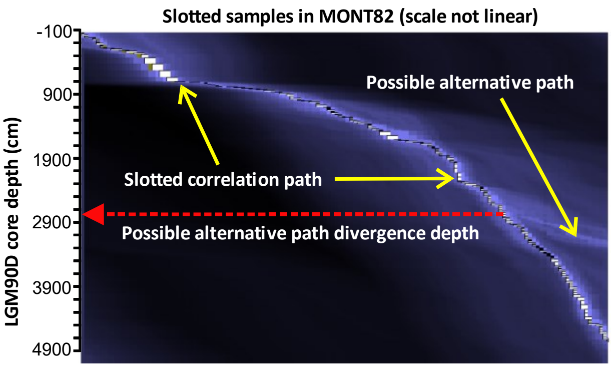


Fig. 17.9. H-matrix plot (squared chord correlation model), with correlation path shown in white and grey blocks. [worked example, single column width, 4.7cm high = 1/8 page + 15 word caption]

Correlation techniques concluding remarks

Stratigraphical correlation should seek to go beyond the application of traditional biozone-based, or pick-based correlations by incorporating data from multiple stratigraphical lines of evidence, thereby providing more holistic stratigraphical relationships. The methods focussed on here, graphic correlation and sequence slotting, are two of the simplest event-based and sample-based methods available (Fig. 17.1). Either can be used to test correlation hypotheses between coeval sections, in the ideal situation constrained by additional tie points beyond the primary data, or using multivariate data. Hiatal intervals are challenging to deal with in many correlation methods (Chapters 8 and 12), as are datasets that are below the stratigraphical resolution of the events of interest. Appropriate software (See GIP/DEH/17-1) is often a key part of using these methods, but methods such as graphic correlation can be implemented on paper.

17.3 Non-marine and marine to non-marine correlation (Marshall)

A particular problem in geology is being able to correlate between non-marine sections from these to marine deposits. Such successful correlations are essential as it is only by linking land and sea that we have been able to fully understand perturbations to the Earth System e.g. mass extinction events and climatic events. A classic successful example that gave new understanding to an event was being able to relate marine and terrestrial records of the Cretaceous-Paleogene asteroid impact (Spicer and Collinson, 2014).

Successful marine to non-marine correlations are usually achieved by combining many stratigraphical techniques in order to obtain sufficient tie points. The number of techniques employed depends on the resolution required, the certainty and resolution of individual methods in the particular setting/time period and their geographical extent (Fig. 17.10). The common approaches and methods are described below.

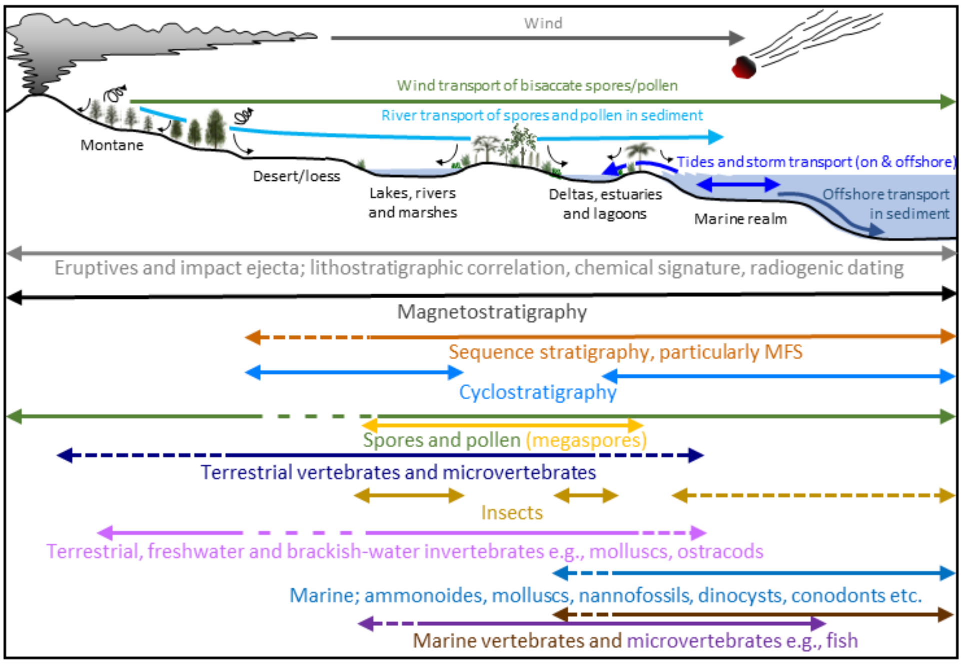


Fig. 17.10. Lateral range of stratigraphical methods along a non-marine to marine profile. Volcanic eruptions and impact events give unique isochronous signatures. Magnetostratigraphy can be widely used but requires a stable preserved magnetic signal and reversals that represent instantaneous events on a geological time scale. Sequence stratigraphy integrates marine and non-marine and is particularly successful where flooding events occur. Cyclostratigraphy requires a sedimentary system that responds to orbital forcing (e.g. lakes and loess). Spores and pollen are the most widely distributed fossil (wind and particularly by fluvial systems). They are abundant on marine shelf environments where storm transport moves them into distal marine environments. Conversely, storm and tide processes move marine invertebrates and microfossils into estuarine and lagoonal environments. Terrestrial vertebrates, often as microvertebrates, can be widely distributed but never reach the abundance of microfossils. Other groups like ostracods and insects can be found in terrestrial and marginal marine environments but are often facies restricted. [text width, 9 cm high = 1/2 page + 153 words]

Intercalated marine and non-marine facies and sequence stratigraphy: In sections where either marine and terrestrial fossils or their sedimentary facies are mixed, marine intercalations can be used to provide a stratigraphical framework. Sequence stratigraphy (Chapter 8) can be particularly helpful in these settings for understanding vertical and lateral facies distribution along the terrestrial to marine profile. Sequence stratigraphy can also be used to provide a framework for periods of flooding and any associated rises in the level of the water table as well as fluvial incision and changes in the depositional profile. An excellent example are the marine bands of the Euramerican Carboniferous coal successions (e.g. Emmings et al., 2020), where brief eustatic transgressions flooded low lying coastal environments. Some of these transgressions introduced a time specific ammonoid fauna so they can be uniquely identified.

Biostratigraphy: As terrestrial sediments do not contain the commonly used almost entirely marine biostratigraphical index fossils (chapters 4 and 13), correlation is restricted to land plants, pollen and spores, insects, ostracods, fish, bivalves, mammal teeth and gastropods. Of particular use because they have freshwater and brackish adapted taxa are: (1) fish that are either freshwater or like salmon and eels that can move between both environments; (2) bivalves e.g. Carboniferous non-marine bivalves (Amler and Silantiev, 2021); (3) gastropods e.g. correlation in East African rifts for calibrating hominid evolution (van Damme and Pickford, 2003); and (4) ostracods e.g. Horne (2009). However, these four groups have only achieved limited success zonally and are less successful across different facies. Insects have found a specific application for palaeotemperature-based zonations in the Quaternary and Holocene e.g. Francis *et al*. (2021), so can be used for stratigraphical correlation of known climatic events. Pollen and spores from terrestrial floras are particularly useful because of their small size, higher preservation potential and distribution; wind and water currents can carry them out into marginal marine and open marine environments (Fig. 17.10) e.g. Jurassic shelfal deposits from the UK have abundant terrestrial spores and pollen as well as marine fossils such as ammonites and dinocysts.

The most difficult correlation is that of entirely non-marine, non-marginal environments with standard marine stages e.g. the classic red bed successions of the Triassic and Devonian fluvial and aeolian sediments of North America-Western Europe (New and Old Red Sandstone, respectively). Biostratigraphical correlation in these facies requires fossils that are abundant on land but also in the marine environment i.e. only terrestrially sourced pollen and spores fully meet this requirement. Fossil fish were used with limited success, particularly before the application of pollen and spores, although they generally lack precision and are often restricted to correlation only within terrestrial environments e.g. Blom *et al*. (2007). However, microvertebrate fossils (isolated teeth and scales) are more useful because as they are more commonly found e.g. Young and Turner (2000).

Pollen and spores get oxidized in red bed environments and are generally rare, only being recovered from non-oxidizing/micro-reducing environments e.g. mudstones or fine-grained siltstones from lakes, silted up river channels and flood plains. Even with targeted sampling there is a high failure rate, so it is often necessary to process many samples. Sample size is not important because if there are no spores/pollen in 5g of sample then there is unlikely to be any in 500g. The recovery of spores and pollen from otherwise barren successions can have a huge impact e.g. finding spores in the Upper Old Red Sandstone of the Scottish Borders, UK took some 60 years of effort by a number of groups, but resulted in a complete reinterpretation of the age and the age relationships of the early tetrapods (Marshall et al., 2019b).

Pollen and spores: In terrestrial deposits there is a greater chance of finding pollen and spores if rock samples indicative of non-oxidizing and reducing conditions (usually black, grey or dark green) are favoured over those that are oxidized (red/purple). **[39 words]**

To facilitate non-marine stratigraphical correlations using biostratigraphy a diverse set of taxa is often used. The Mid Carboniferous palynological zonation for northern Britain (Owens et al., 2004), for example, was correlated to the regional substages and standard marine zonations across a range of wholly terrestrial to fully marine sections using rare occurrences of ammonoids and particularly sparse conodont faunas.

Magnetochronology (Chapter 5): This can be a powerful technique for marine to non-marine correlation when combined with age dating and/or biostratigraphy e.g. the Late Triassic in the USA (Worked example 17.2). Its application is not easy, even within red beds rich in iron oxides that carry a strong magnetic signal, because the magnetic signal has often been diagenetically reset so is either lost or requires careful deconvolution. Magnetic polarity patterns are non-unique requiring an approximate idea of the age of the succession for their identification.

Chemostratigraphical methods: Climatic signals/cycles are present in both terrestrial and marine environments, evidenced by a range of bulk rock mineralogical, geochemical and isotopic parameters (Chapter 6 and 10). One chemostatigraphical proxy that has received lots of attention for marine to non-marine correlation is the $\delta^{13}C_{TOC}$ of terrestrial organic matter (either dispersed organic matter such as pollen, spores and phytoclasts or macroscopic wood fragments). Carbon cycle changes to the oceans and atmosphere are coupled such as during continental scale igneous eruptions and methane hydrate disassociations (e.g. Hesselbo *et al*., 2007). Other chemostratigraphical markers such as heavy mineral assemblages defined from either isolated and picked mineral assemblages or from trace element analysis of bulk sediments (e.g. Zr/Cr ratios) have been widely applied often for typing or correlation of clastic units (see Chapter 6 and refs therein).

Marker beds: Volcanic ashes or extra-terrestrial impact layers can be traced between different environments. Some of these have the added bonus that they may contain minerals that can also provide geochronological correlations (Chapter 14). Time specific event marker beds can also be recognised although it is often a challenge to find these in both marine and terrestrial sediments e.g. the Mid Devonian Taghanic Event level; Worked Example 17.3.

Cyclostratigraphy (Chapter 9): Has significant applications in both marine and terrestrial sections for high-resolution correlation within an established stratigraphical framework. Successions that work well include mid-latitude lacustrine environments where the system switches symmetrically between deep stratified lake through to playa-lake and lacustrine margins on both precession and obliquity time scales or in loess successions (Chapter 11). A classic example, the late Triassic to early Jurassic Newark Rift System in eastern North America, where correlations use a combination of lacustrine cycles, palaeomagnetic polarity, geochronology and palynology (Olsen and Kent, 1999), has been cyclostratigraphically correlated with those in the UK (Kemp and Coe, 2007).

Worked example 17.2. Marine to non-marine correlation: Chinle Formation, Colorado Plateau, Arizona, USA

This worked example, from the entirely continental interior section of the Triassic Chinle Formation (Colorado, USA), shows how a diverse range of stratigraphical tools have been employed to give a high-resolution correlation. The Chinle Formation in Arizona includes the spectacularly coloured painted desert landscapes of the Petrified Forest National Park and abundant internationally significant tetrapod faunas. These tetrapods demonstrate a Late Triassic (Norian) faunal turnover that can be integrated with records of both terrestrial palaeoclimate and vegetation (from pollen and spores). Correlation to the international geological time scale would enable the Late Triassic biotic evolution to be better understood. A key question being, was the Manicougan asteroid impact responsible for driving this biotic evolution and the switch between the Adamian to Revueltian tetrapod faunas?

Biostratigraphy: The initial stratigraphy was based on broad correlations using tetrapod assemblages tied to contemporaneous faunas from Germany and South Africa (Lucas, 2010). As collecting increased, coupled with the ability to identify fragmentary material, the Adamian and Revueltian tetrapod biozones, Mid-West specific, were defined (Parker and Martz, 2011).

A series of increasingly detailed palynological studies (listed in Lindström et al., 2016) enabled a series of assemblage zones to be defined. However, because suitable lithologies are quite rare and surface alteration extensive, palynological recovery is limited to only parts of the Chinle Formation (e.g. Reichgelt et al., 2012; vertical bars on Fig. 17.11). These assemblage zones are not from a single section but have been integrated from across the entire outcrop. Correlation with non-marine to marginal marine sections in NW Europe indicate the formation is entirely Norian in age. This is key to establishing a magnetochronology.

Recognition of these sections international importance led to the Colorado Plateau Coring Project (Olsen *et al*., 2018), and the acquisition of a complete cored section through the formation. This is now being systematically studied, an excellent example of the integrated use of stratigraphical tools focused on marine to non-marine correlation.

Magnetochronology: The preserved magnetic fabric has enabled a magnetochronology to be established (Kent *et al*., 2019) and tied to the correlative Norian section in the Newark Basin, eastern US. The latter, deposited in a lacustrine basin, has been successfully orbitally tuned. The high density of sampling from the cored section means we can regard the magnetic reversal boundaries as time planes.

Geochronology: Zircon crystal populations have been separated and individually dated from a number of volcaniclastic sandstones, providing two different age models (Rasmussen *et al*., 2021; their figs. 4 and 5). Figure 17.11 shows selected dates (mostly age model 2) and comparison with the geochronological age of 215.5±0.5 Ma for the Manicougan impact crater, suggesting it is within the PF5n magnetochron. The tetrapod biozone boundary (Adamian to Revueltian), composited from collecting across a series of outcrops, is less resolved but lies within or close to PF5n.

Lithostratigraphy: core acquisition has enabled rock colours to be spectrometrically measured (Fig. 1B of Lepre and Olsen, 2021), providing a proxy record of Late Triassic monsoon activity that can be tested against the palaeontological records.

All these studies, when integrated, give precise stratigraphical information that enable the section to be tied to the high-resolution magnetic reversal time scale and the marine Triassic record. It must be recognised that this multidisciplinary study represents a very significant and continuing multi-decadal research effort based on over 100 years of earlier work.

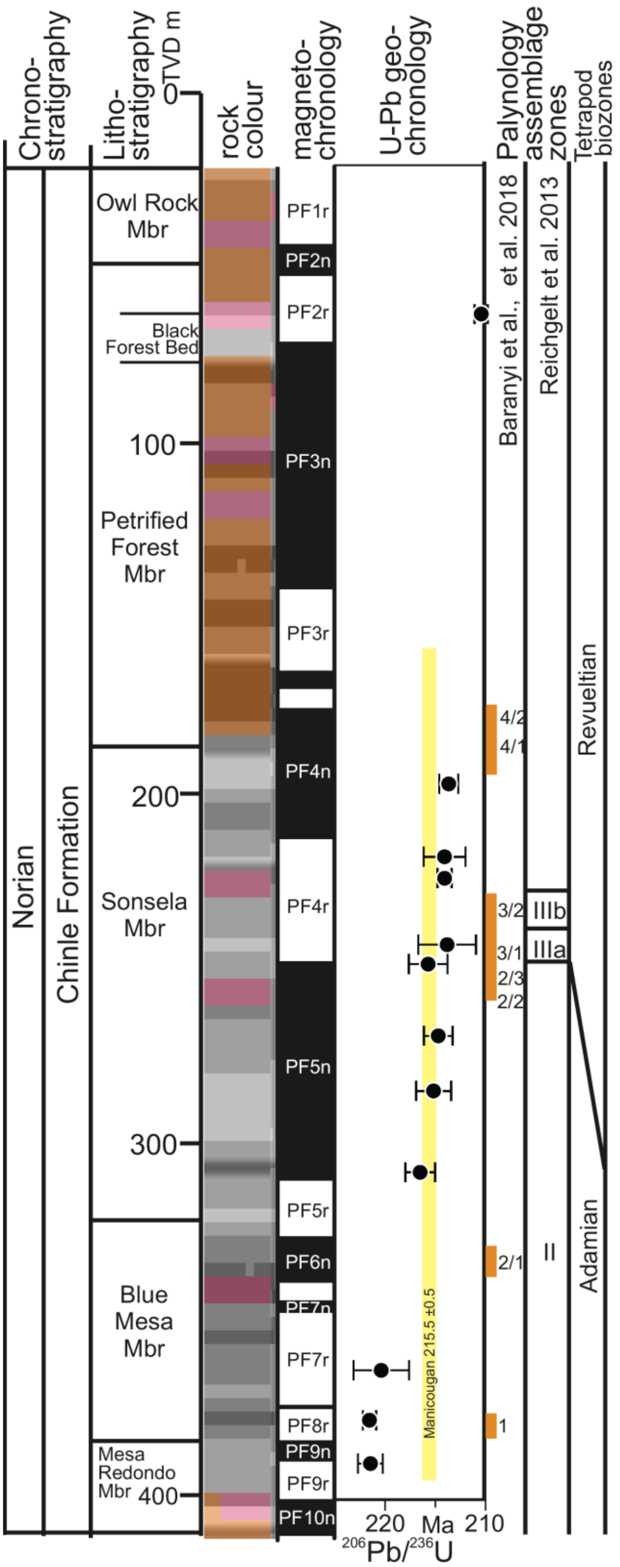


Fig. 17.11. The combination of chrono, litho, magneto and biostratigraphical (palynology and tetrapods) data for the Chinle Formation. Quantified rock colours enable the relative strength of the Late Triassic monsoon climate to be estimated; red colours indicate cool aridity from a weak monsoon system, grey shades mark a stronger monsoon with increasing seasonal humidity. Chrono- litho and magneto- stratigraphy taken from Kent et al. (2019; Fig. 3). [worked example, single column width, 21cm high = 1/2 page + 65 word caption]

Worked example 17.3. Marine to non-marine correlation; recognising the Eday Marl Formation as the Taghanic Event

This worked example is from the Devonian continental sediments of the Orkney Islands, Scotland, UK. In comparison with the Chinle Formation (Worked example 17.2), there is no preserved magnetic fabric and few volcaniclastic sandstones, but there are vertebrates (fish) and plant spores. The latter previously provided little biostratigraphical precision so stage boundaries could not be identified. The recognition of selected event levels (Marshall *et al.,* 2007; 2011), known widely from Devonian marine shelf environments, are discussed below.

The Eday Marl Formation, a distinctive homogenous red calcareous mudstone, represents an interval of sustained aridity. The overlying Upper Eday Sandstone Formation marks a return to active fluvial systems. The Eday Marl is devoid of fossils and previously could not be correlated outside the area. In Orkney, however, palynomorphs were recovered from a very few localities both above and below the interval (Marshall *et al*. (2011), which can be attributed to the ex3 and IM spore zones respectively of Turnau and Racki (1999). Palynological correlation with marine sections in Poland, also containing conodonts and ammonoids, enable a tie to the global marine standard indicating that the Eday Marl represents the Taghanic Event, a second order extinction that lasted several kyr and included significant marine transgressions (Aboussalam and Becker, 2011). In Scotland the presence of scolecodonts (the jaws of marine annelid worms) in palynological preparations indicate limited seawater incursions within sediments of the IM spore zone (Marshall *et al.,* 1996), while the S isotope composition of gypsum (+19.5‰; Parnell *pers. comm.*) has values identical to the Devonian marine sulphate isotope curve. Comparison can be made with the marine shelf sections of the Taghanic Event e.g. the Tully Formation, New York State (USA); Fig. 17.12. Intervals of aridity in the Eday Marl represent lowstands and are coincident with hiatus-bound limestones in the Tully Formation (Marshall *et al*., 2011).

The Eday Marl has been identified in offshore well sections across the Moray Firth, UK (Marshall and Hewett, 2003) from its very distinctive wireline log signature; a combination of a high homogenous gamma ray (GR) value and equally homogenous slow sonic (DT) value. For a long time, the Eday Marl was placed within the Permian (Cameron, 1993) but its Devonian age is now established from the recovery of rare Givetian spores in well 13/19-1 (Marshall *et al.,* 2019a). In both Orkney and the offshore Moray Firth, the Eday Marl is underlain by the Middle Eday Sandstone (barren of fossils), and then the Eday Flagstone Formation. The latter includes lake sediments with a distinctive fish and spore assemblage. The base of the Upper Eday Sandstone can be recognised as being correlative with the Taghanic Onlap, the proposed GSSP level for the base of the late Givetian sub-stage. These correlations give the precision of a GSSP defined time plane within a terrestrial succession from recognition of a distinct event bed, combined with palynological, palaeoclimatic, lithostratigraphical and geochemical data.

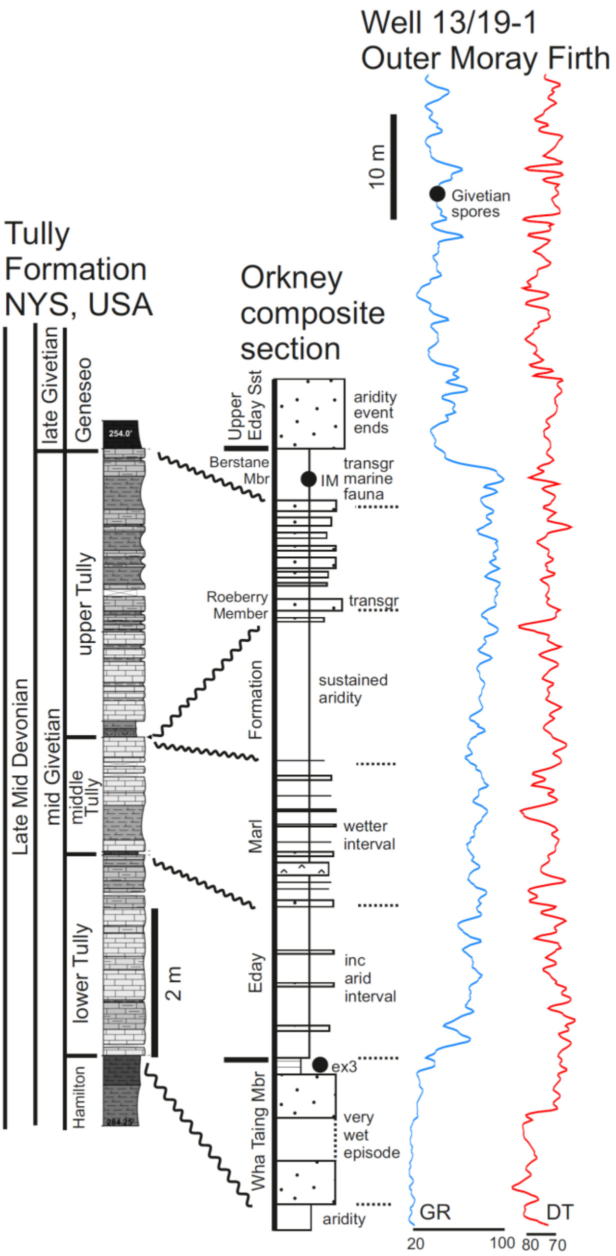


Fig. 17.12. Correlation of the Eday Marl (Orkney) with the key components of the Taghanic Event in the Tully Formation of New York State (NYS), USA. Primary correlation based on ex3 and IM palynological assemblages. Importantly palaeoclimatic and environmental interpretations for the Eday Marl can be understood in terms of the succession of transgressions in the Taghanic Event. The correlation can be extended using wireline log correlations (GR- gamma ray; DT- sonic velocity) in the sub-surface of the Outer Moray Firth and is confirmed palynologically. Tully section from Zambito *et al*. (2016, Fig. 2). [worked example, single column width, 16.6 cm high = 1/3 page + 92 word caption]

17.4. Rock Property Modelling (Newell and Woods)

A common application of stratigraphy is to use the data to create 3D rock property models (or 'digital twins') that can be used in ground engineering projects (see Section 17.5), resource extraction (water, oil and methane) and storage (methane, carbon dioxide or hydrogen). This section outlines the steps to be taken in constructing such models, illustrated with a worked example from the Chalk Group in the UK (Worked example 17.4).

Key aspects of rock property modelling include:

- **Define Model Purpose**; consider the conceptual model(s) to be tested. The purpose of the model defines the build process, with only the necessary detail included;
- **Rock Modelling**; provides the geological context for rock property values by showing the correct stratigraphy and structure in the right place at the correct scale;
- **Property modelling**; shows appropriately scaled estimates of properties based on statistical analysis of the available data;
- **Upscaling**; define the basis for estimating large scale property variations from smaller scale observations;
- **Uncertainty modelling;** understand where the errors and uncertainties occur within the model and consider whether multiple model scenarios are helpful for revealing their potential impact.

For rock fluid modelling, fluid properties (e.g. viscosity) are an additional important consideration that potentially influence each of the steps outlined above. Given that rocks are inherently 3D objects, the vehicle for carrying out rock property modelling is typically a 3D grid (Fig. 17.13a) where a large volume is discretised into smaller units often referred to as voxels (volume elements).

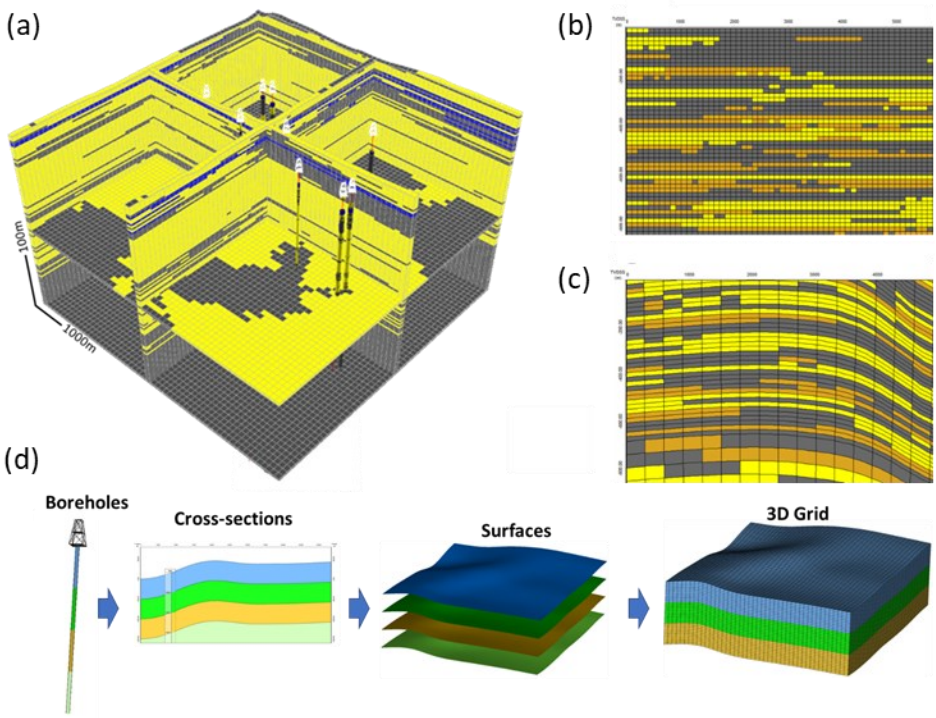


Fig. 17.13. (a) 3D grids are typically used to carry both input data (shown on the boreholes) and the modelled output shown by the voxels which here shows the modelled distribution of sandstone (yellow), mudstone (grey) and limestone (blue). Vertical sections through examples of (b) a regular or Cartesian grid and (c) an irregular or geological grid (correlative rock units shown by the coloured pixels), and (d) Typical workflow for constructing a 3D geological grid. [text width, 9.8cm high = 1/2 page + 73 word caption]

17.4.1 Step 1 Establish model purpose and context

Understanding the purpose of the rock property model is critical. For example, a simple 3D visualisation of some stratigraphical data or, in other cases, the rock model is the starting point for further numerical simulations such as subsurface fluid flow. The purpose will define the spatial extent of the model, the resolution and the required input data.

17.4.2 Step 2: Assembling the raw input data

Key subsurface sources of information include borehole core, biostratigraphy, wireline logs, seismic and other geophysical data (e.g. gravity and magnetics). Surface information such as outcrops, digital terrain models, geological maps and satellite imagery can be important sources of raw data for building the modelling grid.

Reliable data is key: Rock property models are underpinned and entirely dependent on the quality, quantity and distribution of the input data. Preparing well-organised datasets of reliable stratigraphical information is generally the most important and time-consuming task in any geological modelling project. **[42 words]**

Go into the field: Within the property model, outcrops provide information to constrain bed thickness variations, facies changes, and architecture, both laterally and down the depositional slope. Considerable effort is often expended building databases of outcrop analogue data for use in subsurface property models (see GIP/DEH/17-3). **[46 words]**

17.4.3 Step 3: Preparation of the 3D modelling grid

Rock property models plot the 3D distribution and values of input data and display the outcomes of any modelling procedure such as interpolation. Grids broadly fall into two types (Fig. 17.13b and c):

- Regular grids composed of squares (cubes in 3D) aligned with orthogonal coordinate axes. These are suitable for modelling flat-lying geology;
- Irregular grids (or geological grids) where the grid cells are aligned with the stratigraphy and mimic bedding and are generally required where rocks are inclined or folded so that correlative rock units maintain lateral continuity between boreholes.

Grid building, typically the final stage in a workflow, converts point information from boreholes (e.g. correlated stratigraphical horizon markers) and cross-sections (e.g. seismic horizons) into surfaces that bound stratigraphical units, which are used to control the shape and coarse ('formation-scale') subdivision of the 3D grid (Fig 17.13d).

Cell size depends on several factors; overall model dimensions, purpose of the model (e.g. these may vary for number and types of fluids), limitations of computing power and the level of heterogeneity and geological realism that is required. Invariably, models are simplifications of reality built to serve a particular purpose.

Implicit modelling: simplifies the task of creating grids that replicate complex geological patterns. It uses all available geological data simultaneously, and incorporates rules that specify the order of superposition and stratigraphical relationships e.g. conformity, unconformity etc. Implicit interpolators are implemented in a number of 3D modelling applications (see GIP/DEH/17-3). **[49 words]**

17.4.4 Step 4: Assigning hard data to the modelling grid

The next stage is to populate grid cells with hard information that will be used to build and constrain the rock property model e.g. a lithological log attached to a borehole object. In many cases the vertical resolution of the grid cells will be lower than that of the property (Fig. 17.14). Each cell may encapsulate a borehole interval that includes several rock types or a range of values for a property e.g. measured porosity. In this case an upscaling procedure is required, which assigns each cell to a value based on a user defined method, such as highest proportion, nearest to cell centre or an appropriate average value (Preux et al., 2016).

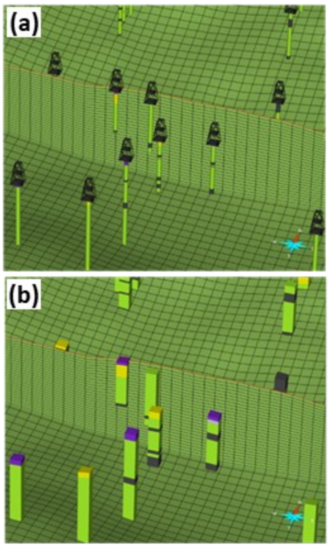


Fig. 17.14. Borehole lithology data is plotted in 3D space (a) and then transferred to the co-located grid cell by upscaling (b). In this case the vertical resolution of the grid cells is sufficiently fine to capture most of the borehole lithology information. **[marginal, 7.3cm high + 41 word caption]**

17.4.5 Step 5: Constructing the 3D Property Model

Once known property values have been assigned to the stratigraphical grid, an estimation can be made of property values within the remaining empty cells (Fig. 17.15). There are many ways to undertake this process. In the simplest 'nearest neighbour' approach cells are filled with the same property value as the nearest cell containing hard data. This may be effective where control points (e.g. boreholes) are dense and regularly distributed but, where this is not the case, it can create unrealistic geobody shapes and dimensions. Much greater control on the geometry of modelled rock bodies can be achieved by using interpolation methods such as kriging (Oliver, 1990), where the expected size and shape can be controlled by the use of variograms (graphs showing the approximate spatial continuity of the data which may be dependent on direction).

Model directionality: Geological processes often create asymmetric rock bodies with a preferred orientation. Examples include beach and river channel deposits. Kriging permits directional control on the spatial continuity so that this can be replicated in the model. **[37 words]**

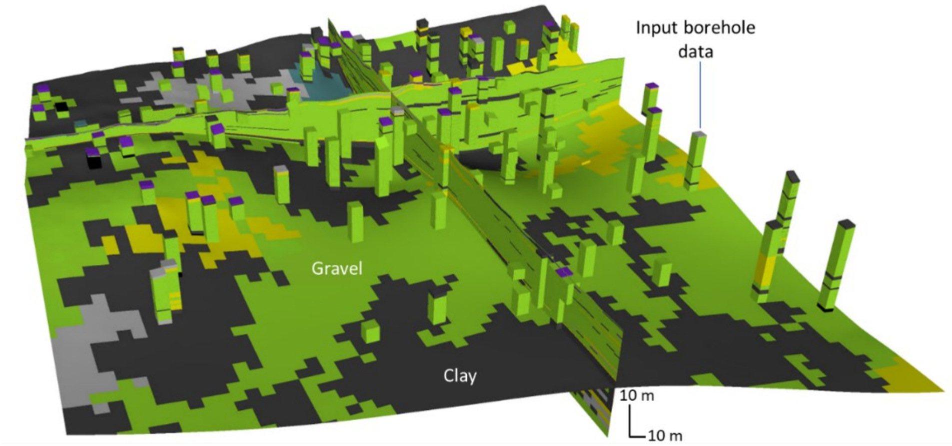


Fig. 17.15. Simple model of Quaternary river gravels showing input data from boreholes (vertical columns of cells) and vertical and horizontal sections through the interpolated property. The proportions of different lithologies (mostly gravel and clay) are controlled by a vertical proportions curve calculated from the borehole stratigraphy and the lateral dimensions by values that are considered geologically reasonable. **[Text width, 6.4cm high = 1/4 page + 56 word caption]**

The success of interpolation methods such as kriging are strongly dependant on a good distribution of control points. Where controls are clustered and the spacing is much greater than the typical geobody it may produce results that are deemed unrealistic. Some of these limitations are overcome by the use of simulation techniques rather than interpolation. Sequential Indicator Simulation (SIS) is a widely applied stochastic modelling method which incorporates some inherent randomness. The same set of input values and initial conditions will lead to an ensemble of different model outputs (Deutsch, 2006). Object-based methods can be effective in rock formations where there is a well-defined and repeating structure. For example, models of fluvial sandstones have been constructed using idealised geobodies that represent channels of a particular size, shape and direction. Similarly, Multiple Point Statistics (MPS), a facies modelling technique that offers a way to model complex and heterogeneous geological environments through the use of a training image, describes typical shapes, dimensions and lateral and vertical facies transitions (Deutsch, 2006).

Modelling cycles: Where the stratigraphy of a unit has a strongly cyclic pattern, techniques such as truncated gaussian or plurigaussian simulation can be applied to limit facies transitions to only those that are geologically plausible. **[35 words]**

Each model cell can carry multiple properties that may be discrete or continuous. Where properties are closely related (e.g. lithology and porosity), it is common to build a facies-model first and then co-vary other related properties within this framework. The range of properties will vary depending on the purpose of the model and can include porosity, permeability, relative permeability, fluid saturations and pressures, rock strength or thermal properties.

In most rock property simulations multiple realisations of a model are created and from these the most probable property value for a particular cell (or those carrying the greatest uncertainty) can be deduced. Possibly more important, however, is that the resultant model approaches something that is geologically plausible and consistent with the broader geological understanding of the formation under consideration.

Worked Example 17.4. A regional rock property model of the Chalk Group of southern England

The aim of this worked example is to show the steps involved in creating a regional lithological model of the Chalk Group of southern England, following the methodology above.

Step 1. Purpose: The Chalk Group is the major aquifer in SE England and has been the focus of many large civil engineering projects in recent years, particularly in the London region (see Section 17.5). To better understand regional trends in the thickness, stratigraphy and lithological variation of the Chalk, the British Geological Survey (BGS) developed a gridded property model extending across southern England south of The Wash (Woods et al., 2016; Fig. 2c). The geographical coverage of this model is unusually large, greatly exceeding the scale of rock property modelling typically adopted, for example, in resource extraction industries.

Step 2. Data Assembly: Coastal outcrops from Sussex and Kent and large inland quarries, especially in the London area, were used to gather critical information on the range and characteristics of the different lithofacies and their vertical stacking pattern (see also Section 17.5.1). Some cliff faces were laser scanned, greatly assisting the mapping and measurement of different aspects of the lithology for the modelling.

Assembly of the raw data for a rock property model is often the most time-intensive part of the modelling process. In this instance a vast database of boreholes and published literature was sifted and processed to obtain a uniform data set of the 3D position of key stratigraphical contacts, marker beds and intervening lithologies (see GIP/DEH/17-3). A simplified lithological classification was devised (e.g. marl, marly chalk, hard chalk, hardground), which could be consistently and unambiguously recognised across an often-limited range of geophysical log types (typically gamma-ray and resistivity) but discriminated the main lithological controls on aquifer behaviour (e.g. marls and indurated chalks); Fig. 17.16.

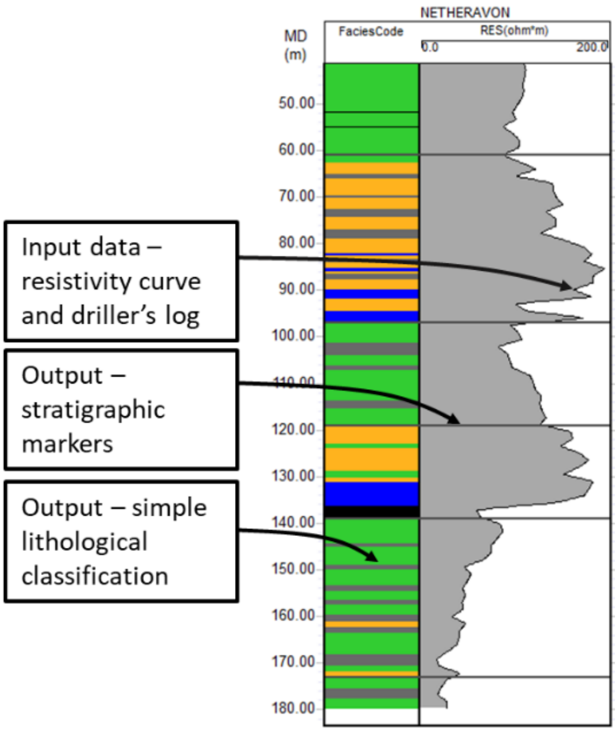


Fig. 17.16. An example of model input data extracted from a borehole that includes stratigraphical markers picked at formation boundaries and a simple lithological log based on cuttings returns and a geophysical log. **[worked example, single column width, 9.9cm high = 1/4 page + 31 word caption]**

Step 3. Creating the model framework: To create the grid for this Chalk model that is composed of many tens of millions of cells:

- Borehole paths and key stratigraphical markers were first loaded into the modelling software;
- Stratigraphical surfaces were created that pass through the associated borehole markers (Fig. 17.17);
- In areas of sparse borehole control, constraint on the form and elevation of the surfaces was provided by seismic reflection picks or by manually digitised cross-sections;
- Geological map linework was used to define the erosion limits of the various Chalk surfaces relative to topography;
- Geological surfaces were built using volumetric implicit modelling methods that consider data from all stratigraphical horizons simultaneously, allowing the automated use of thickness models to constrain elevation.

The resultant stack of stratigraphical surfaces was used to initialise a 3D grid, subdivided into regions representing different Chalk formations. Each cell layer in the model was aligned to the stratigraphy and appropriately eroded beneath the complex composite unconformity that defines the top of the Chalk Group. Many Chalk beds are thin but can extend laterally over very large distances, therefore cells were set at 1m in height and 500 m in width. Note that complex irregular grids built for the purposes of building a static geological rock model are usually resampled and converted to simple regular grids for export to groundwater flow modelling and other software.

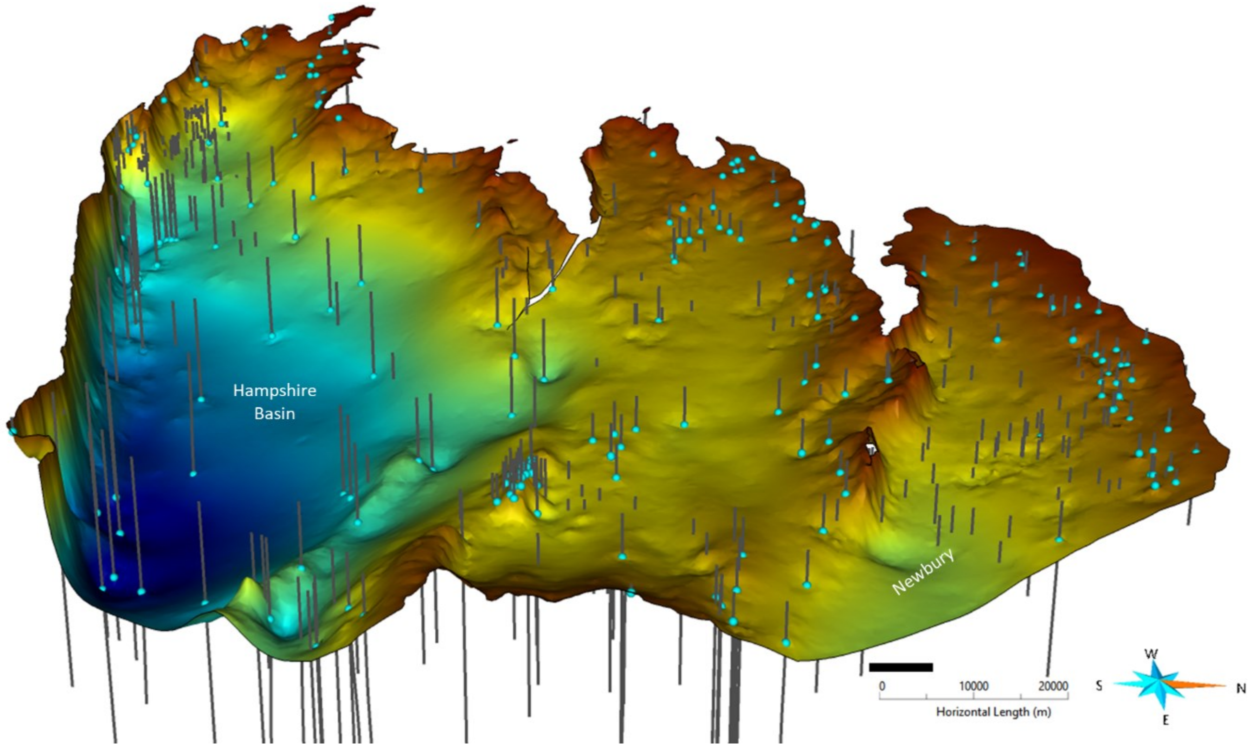


Fig. 17.17. Surface generated on the base of the Chalk Group in the Hampshire Basin, southern England. Colour ramp is elevation with blue low and brown high. Note multiple fold structures that formed above faults during Tertiary basin inversion. Vertical grey lines denote borehole paths and coloured spheres represent associated formation boundary markers. Modelling grids are initiated between stacks of surfaces representing different stratigraphical horizons. [worked example, full page width, 9.8cm high, 1/2 page + 63 word caption]

Step 4. Data assignment and grid population: Lithology data were upscaled from the borehole objects into the 3D grid. Where more than one lithology coincided with a grid cell the most common lithology was used. The input data were then flooded (interpolated) throughout the model grid (Fig. 17.18) using an indicator kriging method, setting a nominal omnidirectional correlation range that generally exceeded the distance between boreholes. This effectively forced a correlation of lithofacies between boreholes where they occurred on the same grid layer. This was considered a reasonable assumption in the case of the Chalk, given that stratigraphical subdivisions and associated lithofacies are generally laterally continuous over many kilometres. Vertically, the majority of lithofacies in the Chalk (e.g. hardgrounds, marly chalk) are strongly partitioned into discrete stratigraphical layers (Fig. 17.18). This important aspect of the property model was controlled by using lithology information captured from the borehole data.

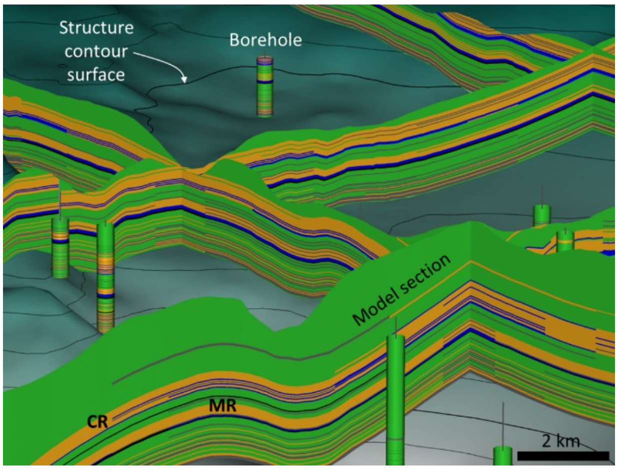


Fig. 17.18. Cross-sections through part of Chalk rock property model in the Wessex Basin. Spaced boreholes with lithological logs form the main input data for the interpolated rock property shown. The gridding follows gentle fold structures and is controlled by structure contour surfaces on key stratigraphical horizons. Note the general layer-cake nature of Chalk stratigraphy with the presence of mud-rich chalks (grey colour) at the base and two distinct intervals of hardgrounds (blue) and nodular chalks (orange) representing the Holywell Nodular Chalk (including the Melbourn Rock, MR) and Lewes Nodular Chalk (including the Chalk Rock, CR). The upper parts of the Chalk Group are more typical soft white chalk (green). [worked example, single column width, 6.1cm high = 1/8 page + 108 word caption]

Applications of the Chalk model: Property models of this type have numerous applications such as simple tasks like creating borehole prognosis in unknown areas through to aquifer modelling. Cells can carry multiple properties depending on the model application, such as rock strength for engineering or thermal conductivity for geothermal energy. 3D models can also be used to understand lateral and vertical thickness and lithofacies changes within a formation, and how those might be related to tectonics and other external drivers.

17.4.6 Model uncertainty

A common question asked of 3D rock property models is how reliable are the estimated values? This is always a problematic issue. While levels of statistical probability are calculated with most modelling algorithms, this often covers only a small proportion of the uncertainty within a geological model. In most cases, even the 'hard' input data derived from borehole descriptions is of variable quality, while geophysical log or seismic interpretation carry a large uncertainty. Model based conclusions should, therefore, always be made with careful regard to the location and quality of the nearest known information, and the geological plausibility of the model based on user experience. Several models might be required that cover a range of possible solutions to the input data.

17.4.7 Concluding remarks on rock property models

Volumetric rock property models improve the predictive power of geological science. They are an essential precursor to dynamic modelling of the subsurface environment. Knowledge of rock units is often based on large and diverse datasets that may include many thousands of boreholes, seismic reflection profiles and outcrop observations. Assimilating, plotting and analysing such data is often difficult using conventional one- or two-dimensional methods such as vertical logged sections, maps and cross-sections. A 3D approach allows more thorough investigations and understanding at scales which vary from an individual pore space to entire sedimentary basins.

17.5 Stratigraphy in Engineering Geology (Mortimore)

Engineering Geology ensures that geological factors that may impact location, design, construction, operation and maintenance of engineering works are identified and mitigated. It uses a broad range of disciplines e.g. geological hazard assessments, rock mechanics, soil mechanics (slope stability, foundation strength), structural geology, hydrogeology (surface water drainage and subsurface flooding risk), rock property modelling to understand groundwater flow (Section 17.4) and stratigraphy. This section focusses on the use of stratigraphy in engineering geology, it describes the development of the stratigraphical framework, and shows how it can be applied using examples from the Chalk Group in the UK. The principles established with the Chalk can be widely applied to other strata (see further reading section). Key stratigraphical tools used are lithostratigraphy including sedimentary logging of outcrop and core (chapter 1), borehole geophysics and petrophysical logs (Chapter 3), biostratigraphy (Chapter 4), seismic reflection profiles and velocity modelling (Chapter 7).

Stratigraphy is the cornerstone of two core aspects of engineering geology; construction of the ground model and precedent experience. A ground model requires linking all the geological information together with geotechnical and geophysical test results. Lithostratigraphy provides the basic skeleton to which all other results are attached, helping identify strata-bound geotechnical elements. Precedent experience, lessons learnt from previous contracts, can only be used if the sites have similar geology.

There are many instances where stratigraphical comparison between construction sites were based entirely on biostratigraphy and, because of a lack of understanding of the lithostratigraphy and how lithology or lateral lithological variations have a fundamental effect on engineering behaviour, there were complications. For example, during the 1960's and 1970's motorway construction in both the UK and France encountered severe engineering problems e.g. the collapse of earthworks, that lead to costly delays (Masson, 1973; Mortimore, 2012). The needs of civil engineers to better understand and predict geotechnical ground performance drove the development of high resolution lithostratigraphical frameworks for engineering geology.

17.5.1 Stratigraphical characterisation of the Chalk Group for engineering

This section shows how the recognition and characterisation of marker beds enabled a high-resolution stratigraphical and geotechnical framework to be built and applied, which is important when building the ground model (Section 17.5.2). Measuring Chalk Group exposures (Cenomanian-Early Maastrichtian) throughout southern England and northern France illustrated the continuity of marker beds (marl seams, flint bands and macrofossil and trace fossil horizons; Fig. 17.9a) that could also be consistently recognised in rock-core. Recognition of these marker beds in borehole core, when integrated with downhole geophysical logs, enabled a link to be made between the lithostratigraphy and the many existing water wells that only had geophysical logs. Therefore, basin wide lithostratigraphical correlations became possible (e.g. Mortimore, 2001; Mortimore and Pomerol, 1987), forming the framework into which all geotechnical data could be placed and, for the first time, providing a basis for back-analysing and then predicting engineering behaviour.

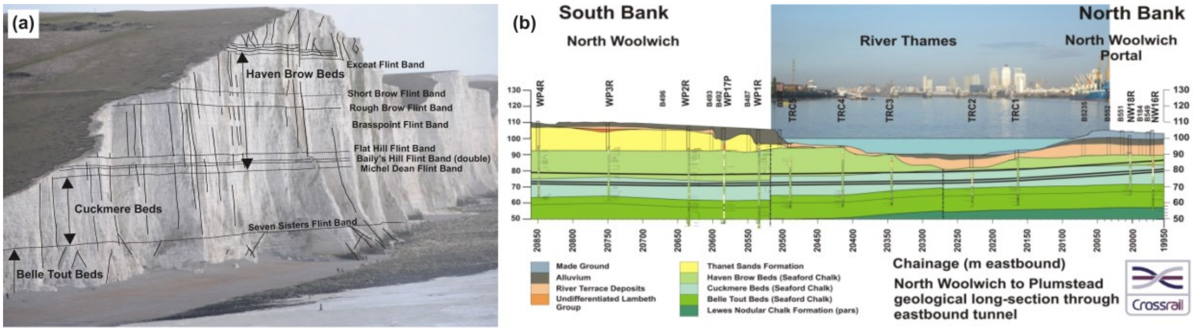


Fig. 17.19. (a) Marker beds in the Seaford Chalk Formation exposed in the first of the Seven Sisters Chalk cliffs, Sussex coast (modified after Mortimore, 2011; Fig. 13). (b) The same stratigraphy is used to construct the ground model for the Crossrail Thames Tunnel (Mortimore, 2018; Fig. 5). Also see Lenham *et al*., 2006. [full page width, 5.1cm high = 1/4 page + 52 words]

In engineering projects through the Chalk and other similar successions, particularly when tunnelling, it is important to locate at a centimetre resolution all flints and flint bands as they pose challenges:

- Rotary bit selection when coring is critical, poor selection impacts the time/cost of operations;
- *In situ* testing in flint bearing strata with a self-boring pressuremeter requires a detailed stratigraphy to accurately locate the pressure meter between flint bands;
- Size, frequency, concentration and strength of flint bearing intervals need to be known so that an appropriate design of Tunnel Boring Machine (TBM) is used.

Such information can only be fully gained where detailed lithostratigraphical measurements are made from cores, geophysical logs and suitable field sections. Before tunnelling began for the Channel Tunnel Rail Link (CTRL/HS1) and CROSSRAIL (Fig. 17.19b), the former cement works quarries at Swanscombe, London were used to record details of flint band stratigraphy and properties (Mortimore *et al*., 2011). The results from these studies have now been applied to tunnels across London (Thames Water Ringmain, Thames Water Tideway and Lee Tunnels, CTRL Thames and London Tunnels, CROSSRAIL Thames Tunnel, DLR Thames Tunnel). These quarries are no longer available so the coastal Chalk exposures along the Seven Sisters, Sussex (UK) are used as the key training ground for geologists and design teams working on London tunnels (Fig. 17.19a), where the relevant stratigraphy and details of flints can be demonstrated.

Perhaps the simplest case study linking detailed flint band stratigraphy to tunnelling is the Shoreham Harbour Siphon Tunnel. Following the discovery of a 10-20 cm thick band of very large and hard flints along the tunnelling horizon, all six available borehole cores were re-logged, as well as core from two new boreholes, to establish the detailed flint stratigraphy. Additional flint bands tied to the lithostratigraphy were recognised. A local quarry was identified that was used for sampling and strength testing of these flint bands. The tunnel was then realigned to avoid the bands of largest flints. The TBM still required reinforcing before it could be used as the strength of the flints exceeded the original design; flint strength averaged 500 MPa (max 700 MPa) as compared to the original TBM design of 330 MPa (Mortimore, 2012; pp. 291-296, figs. 76-90 and the lessons learnt section on p. 328).

A stress history, relating to folding, faulting, burial and uplift, is locked in to all rocks. Engineering, particularly excavations, changes the stress conditions, impacting engineered structures in both the short and long term. Understanding its history and lithological control is important e.g. marl seams in chalk influence stress distribution. **[49 words]**

17.5.2. Building a ground model

A detailed lithostratigraphy is essential for the correlation of marker beds between boreholes and sections, so that stratal dip and faulting can be determined. A typical example is the geological section for the Brighton and Hove Stormwater Tunnel (Worked example 17.5) where, as in many engineering cases, it was critical to understand both lithology and its relationship with fracturing as this informs on tunnel flooding and collapse. Understanding the stratigraphical distribution of fractures and associated features forms the basis for predicting these aspects of the ground conditions, enabling suitable engineering solutions to be planned. Investigation of a new site to help build a ground model may include:

- Use of existing data (including relevant precedent experience);
- A detailed site survey that may include topography (slopes, drainage etc.), surface geology, photogeology and a geophysical survey (subsurface geology);
- The drilling of core holes or excavation of the stratigraphy at critical points on site to confirm previous studies or provide additional pertinent data including, borehole geophysics, sedimentology, faults and fractures, water flow;
- Testing of soils and rocks either *in situ* or from samples.

On tunnel construction projects it is rarely possible to realign the route either vertically or horizontally to accommodate changes in the geology; tunnels can sometimes go deeper, at greatly increased cost. Engineers have to deal with whatever ground conditions are present and design accordingly. Predicting the ground ahead of a tunnel can require extrapolation between widely separated boreholes. Boreholes for the Lee Tunnel (East London), were sometimes more than 500m apart as it was not possible to drill in areas of dense population and existing infrastructure. A detailed, reliable lithostratigraphy helped identify where major faults were present bringing different strata into a tunnel face and gave confidence to the correlations far in advance of tunnelling (e.g. Lenham *et al*., 2006; Skipper *et al*., 2008).

Worked example 17.5. Ground model for the Brighton Hove Stormwater tunnel

The construction of this tunnel beneath the beach along the seafront between Black Rock, Brighton and Western Lawns, Hove (UK) is an example of a project where the initial ground model failed to use an adequate stratigraphy. This began with an oversimplistic ground investigation where cored boreholes were logged primarily for weathering grades (then known as Mundford Grades) rather than stratigraphy or other aspects of the geology. The resulting ground model (Fig. 17.20a) was used without question during construction by Contractor A who won the bid for the project based on lowest cost. Contractor B, employed an engineering geologist to re-log available cores during the short bidding time interval, resulting in a completely different ground model that identified (Fig. 17.20b);

- Detailed lithostratigraphy with marker beds including flint bands and marl seams;
- A previously unknown fold in the Chalk (the Old Steine Anticline) with significant stratal dips (25ºN) based on recognising depths to key marker beds;
- Previously unknown faults and fault zones recognised by the displacement of marker beds.

The Contractor B ground model identified potential engineering risks more accurately and made the bid more expensive. Despite being asked if they wanted to rebid for the project to bring the cost closer to the lowest bid this experienced contractor said no, the tunnel could not be constructed for such a low cost.

Contractor A experienced significant cost overruns and attempted to claim extra monies based on 'unforseeable' ground conditions. During preparation for their claim, Contractor A employed a geological team to re-log the boreholes (sedimentology, fractures, lithostratigraphy etc.) who came up with a ground model very similar to that of Contractor B. Contractor A then compared this 'new' geological model against encountered conditions that they had logged during construction of the tunnel and shafts e.g. water ingress into shafts and the tunnel, which were seen to be closely related to lithology, especially marker flint bands and marl seams, styles and intensity of fracturing, fault zones and degree of staining on fractures (Fig. 17.20c and d). The case went to court where part of the final judgement said that:

- The client should have bought Contractor B's ground model to the attention of Contractor A so that the engineering risks could have been properly considered;
- Essential to Contractor B's ground model was the lithostratigraphy of marker beds and formations. These should have been recognised by the original site investigation contractor and shown on borehole logs. Mundford Grades were not representative of the geology;
- The original Site Investigation was therefore considered inadequate.

This case study emphasises:

- The importance of stratigraphy, especially lithostratigraphy, to engineering risk analysis;
- Site investigation requires geologists trained to recognise the stratigraphy and all geological details; marker beds, fractures etc.

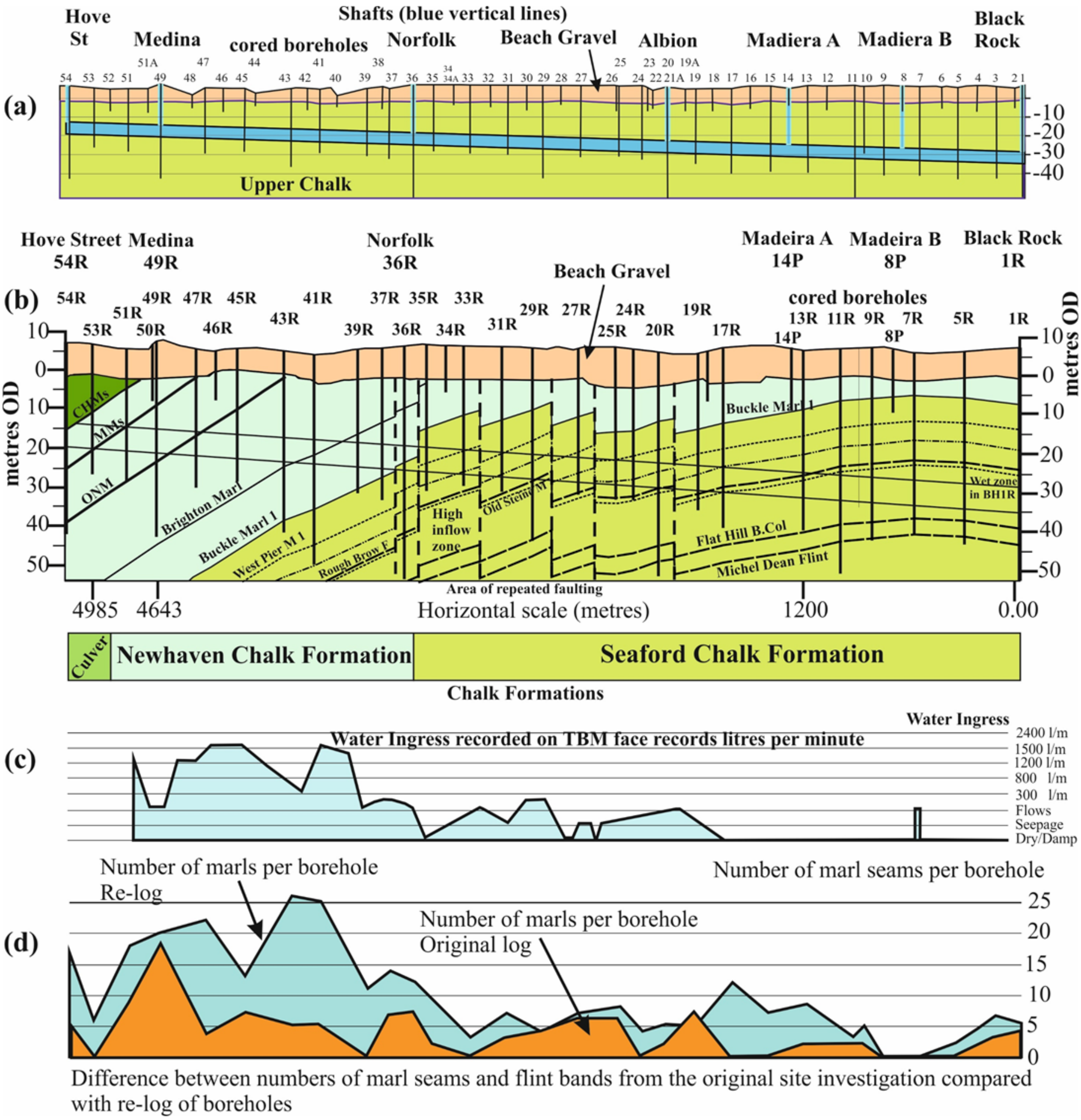


Fig. 17.20. Brighton and Hove Stormwater Tunnel comparing (a) Contractor A site investigation derived ground model with only two lithostratigraphical units Upper Chalk and Beach Gravel (tunnel route in blue). (b) Contractor B ground model with tunnel route outlined and detailed lithostratigraphy (marker beds and formations) that identify the Old Steine Anticline (steep bed dips northwards) and zones of faulting. (c) Water ingress into the tunnel in litres per metre (l/m) from Tunnel Boring Machine face records indicating influence of marl seams (d) on groundwater flow in the Chalk. Modified from Mortimore (2012; Figs. 110 and 113). [worked example, full page width, 17.3cm high = 3/4 page + 95 word caption]

17.5.3 Concluding remarks on the use of stratigraphy in engineering ground models

Construction of the ground model requires a reliable and detailed stratigraphical framework against which physical properties or rock mass character can be plotted. Only this approach enables strata-bound features to be recognised and engineering solutions planned. The lack of such a model has led to poor engineering decisions e.g. the initial alignment of the Shoreham Harbour Siphon Tunnel and the original design of the tunnelling machine (see 17.5.1). Stratigraphy is the bedrock upon which the engineering ground model is built.

17.6 Archaeological stratigraphy (Edgeworth)

Archaeological stratigraphy deals with anthropogenic strata and involves adaptations to forms of evidence not found in earlier geological contexts. In addition to deposits formed through natural processes, archaeologists investigate features of cultural origin. Standard laws of stratigraphy, such as the law of superposition, still apply. The added cultural dimension means that stratigraphical successions found are sometimes more complex, requiring extra techniques of interpretation to be deployed, as well as a shift in focus. In archaeology, much more emphasis is placed on the significance of interfaces between deposits in a similar manner to sequence stratigraphy (Chapter 8) and understanding incompleteness (Chapter 12).

Of particular importance are interfaces known by field archaeologists as 'cuts' (Roskams, 2001). Cuts are made by people digging into the ground, creating negative features such as pits, postholes, quarries and ditches, which subsequently form basins of deposition for 'fills'. In geological terms, cuts would be generally classified as unconformable surfaces, which indeed they are, but they are much more than that. As outcomes of intentional human actions, cuts may take shapes and configurations unparalleled among naturally formed unconformities, as evident in Worked example 17.6.

Significance of cuts: Anthropogenic strata are riven through with cuts and re-cuts. Acquiring the practical skill of recognizing cuts, and how to follow them along in the ground, is key to making sense of complex successions/orders of archaeological stratigraphy. **[39 words]**

17.6.1. Relative dating of intercutting features on a horizontal plane

Though cut features are three-dimensional stratigraphical entities, cuts manifest as two-dimensional outlines 'in plan' during early stages of open area archaeological excavations. By taking note of cuts, some relative dating of features can be achieved before digging is commenced (Worked example 17.6).

Worked example 17.6. A Romano-British site in a rural setting

When archaeologists excavated a Romano-British site on farmland at Ibbott's Field, West Kempston, Bedfordshire, England, their first action removed layers of ploughsoil by machine down to a level where cut features became visible. The ground was then scraped over with hoes to make soil boundaries as sharp and clear as possible so a plan could be drawn (Fig 17.21). Cut features such as pits, postholes and ditches stood out as distinctive areas of darker fill, against the lighter background of natural gravels and clays. Some inhumation graves were enclosed by square or circular gullies defining the edges of what used to be burial mounds, though the mound material had since been ploughed away. Features were observed to be cutting or be cut by others in a complex intermeshing of forms (Luke et al., 2000), typical of archaeological sites. How do archaeologists begin to unravel such convoluted stratigraphical entanglements?

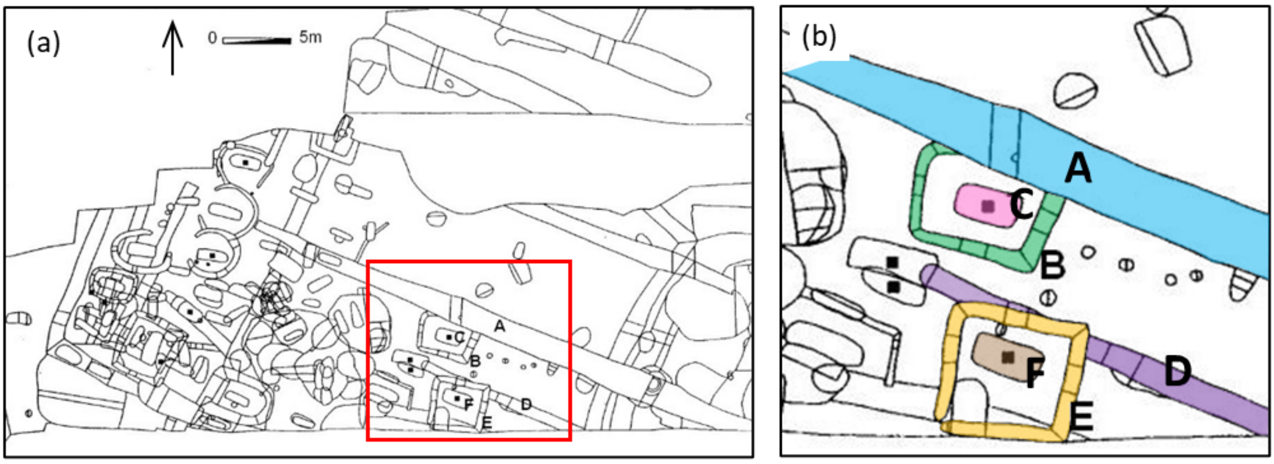


Fig. 17.21. Intercutting archaeological features at the Romano-British cemetery site, Kempston, Bedfordshire (Boylston et al., 2000) after topsoil and subsoil stripping. (a) the plan shows cuts of features as observed on a near-horizontal two-dimensional surface. (b) detail of inset. Cross-sections to be placed by archaeologists are shown as two lines crossing a feature. Letters A-F are referred to in the text. Black dots indicate where decapitated human burials would later be found (modified from Luke et al., 2006, Fig. 6). [worked example, full page width, 6.1cm high = 1/4 page + 78 word caption]

As in geology, cross-cutting relationships are important: a feature is held to be later in date than the features or layers it cuts through, and earlier in date than features it is cut by. By this general rule, field boundary ditch **A** has later construction date than the rectangular burial mound gully **B**, while the square burial mound gully **E** is later in date than ditch **D**. Extending these rationales over a wider area, a rough provisional phasing of much of the site was reached. Where the stratigraphical relationships between features were unclear, these were investigated further through targeted excavation.

This relative dating was supplemented by the evidence of artefacts or other dateable material found securely within stratigraphical contexts. Therefore, an assemblage of finds dating from the third century and fourth centuries AD from the fills of the rectangular gully **B** gave a *terminus post quem* or 'date after which' ditch **A** must have been dug. A similar assemblage from the fill of the square gully **E** indicated that **B** and **E** were broadly contemporaneous and part of the same barrow cemetery, as well giving a *terminus ante quem* or 'date before which' ditch **D** was created (though see the caveat in section 17.6.2).

For an example of the cultural dimension of archaeological stratigraphy, consider the relation between ditch **B** and the enclosed inhumation grave **C** (or the similar configuration of **E** and **F**). Here there is no contiguous stratigraphical relation. However, the features were connected and inferred to be roughly contemporary through the spatial relationship of inside/outside, or one feature being placed within and enclosed by another. Graves were deliberately dug within spaces enclosed by surrounding gullies, or gullies dug to enclose graves, providing some of the material for the covering mounds. In other words, the cuts of the features in question were created as intentional objects by purposeful human beings. They incorporated symbolic and cultural patterns of thought into the shape and layout of features, thereby instating elements of design into stratigraphical configurations.

17.6.2. Relative dating of heavily cut deposits in a vertical section

Anthropogenic ground under historic cities such as London is typically several metres deep, and in places over 10m in depth. Urban stratigraphical successions typically have a complex stratigraphical structure that is difficult to discern in borehole data and best apprehended through archaeological excavation (Roskams, 2001), using appropriate field methodology (Spence, 1990), as illustrated in Worked example 17.7.

Worked example 17.7. Dealing with complexity in urban anthropogenic ground

This worked example shows how in vertical sections, recognition of the significance of cuts is key to ordering events and making sense of evidence (Fig. 17.22), it also illustrates the use of a Harris matrix.

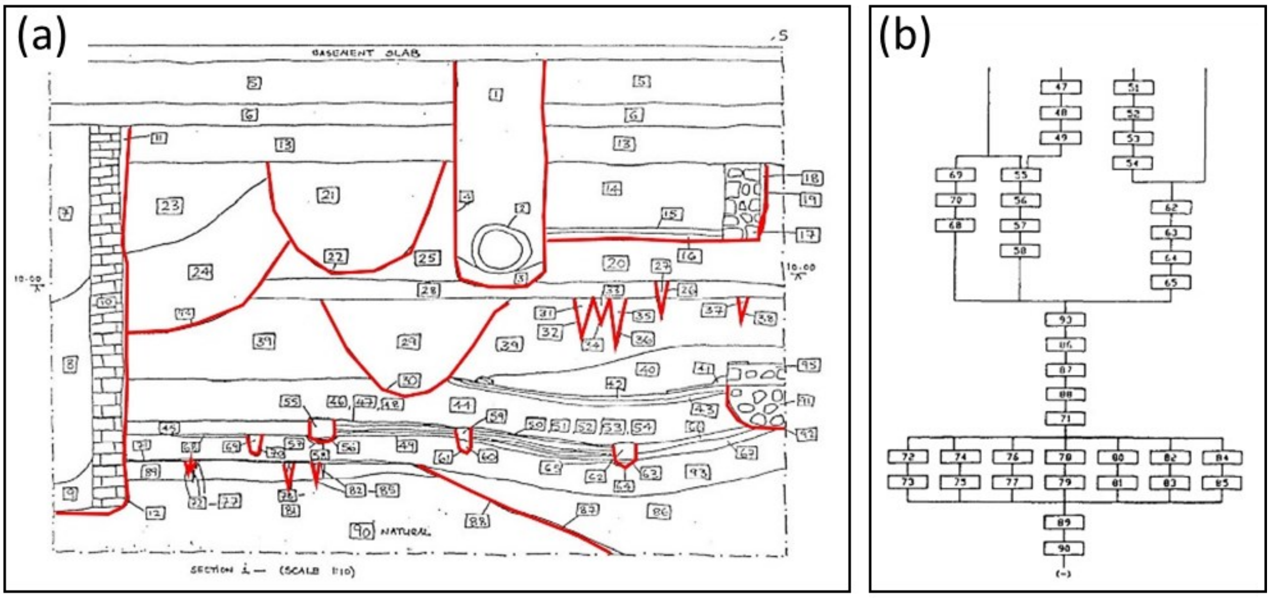


Fig. 17.22. (a) A typical vertical section through archaeological stratigraphy in London. Cuts are highlighted in red. (b) Harris matrix giving the stratigraphical succession for the lower part of the section (modified from Shepherd, 1993, Fig. 1). [To be redrawn. Worked example, full page width, 8cm high = 1/3 page + 35 word caption]

Visible in Fig. 17.22a are the cut of a modern service trench (4), the cut of a 19th century brick-lined cellar (12), the cut of an earlier stone-lined cellar (19), cuts of pits of various sizes and dates (e.g. 22, 30), cuts of post-holes (e.g. 56, 64), cuts of stake-holes (e.g. 73, 75), etc., the earliest of which date back to Roman times. These cut through or are sealed by horizontal layers, while also cutting or being cut by the cuts and fills of other features. But far from being intrusions into or disruptions of stratigraphical successions, cuts should be regarded as integral elements. It would be hard to make much sense of the overall succession without recognizing cuts and taking them into account. Accordingly, archaeologists have allotted context numbers to cuts, treating them as stratigraphical entities of equal status to deposits.

The lattice diagram in Fig. 17.22b, known as a Harris matrix (Harris, 1989), was used as a means of working out the order in which strata were laid down or cut through; crucial for dating purposes. In theory the stratigraphical succession of a whole site with thousands of contexts could be represented on a single matrix. Note however that the matrix only works when cuts, as 'containers' for the fills of features, are taken as integral parts of depositional elements. As in Worked example

17.6, the stratigraphy of the vertical section provides a relative dating framework within which contexts can be dated as earlier/later than others in the overall succession (May, 2020).

The Harris matrix: A method which applies the principles of stratigraphy in the recording of archaeological sites. Learning to construct a matrix is one of the most important skills to acquire in dealing with complex successions of archaeological strata. **[39 words]**

17.6.2. Dating and correlating strata with artefacts

The primary type of material for dating and correlating archaeological strata are artefacts contained as inclusions within layers and fills (Renfrew and Bahn, 2020). Some are made from natural materials such as stone or wood. Others are manufactured from artificial materials such as pottery and glass. These can be regarded as trace fossils of human activities, although there are major differences between artefacts and the fossil remains/traces of other biological species. Patterns of development of the latter are explainable in terms of natural selection and the theory of evolution. In the case of artefacts, natural selection plays only an indirect role. Processes of cultural selection and knowledge exchange play a large part. Availability of materials within economic systems and trading networks is another factor. The spread of ideas and techniques influencing changes in artefact form can be much faster than evolutionary change, with superficially similar but actually very different patterns of transformation through time.

Artefacts as cultural objects: Processes of cultural selection and knowledge exchange are crucial in influencing the form of artefacts that are made and developed, and the patterns of their distribution through space and time. **[34 words]**

Typologies and seriation charts for various types of novel materials and artefacts commonly found in archaeological strata, from pottery to clay pipes to glass bottles to beer can tabs, are available and serve as useful dating tools. If the evidence of stratification is poor, dates can be assigned to contexts (and correlations made with other contexts, other sites) based purely on the artefactual assemblages they contain; relative dating, the law of superposition. But it is always best to use reference material in conjunction with the relative dating gathered from the excavation and recording of a site, as encapsulated in a Harris matrix.

One caveat should be borne in mind. It is common for artefacts to remain in cultural use long after time of manufacture, so date of deposition in a stratigraphical context might be considerably delayed (Adams, 2003). This is somewhat similar to reworking of fossils but by very different processes. A Roman decorated bowl valued and retained by subsequent generations could end up being deposited in post-Roman contexts. A coin of a certain date may continue in economic circulation until dropped hundreds of years later. For this reason, archaeologists assigning a date to a context prefer to go by the whole assemblage of finds found within it, combined with the relative dating framework constituted by stratigraphical successions (Joyce and Pollard, 2010), similar to biozones based on assemblages of fossils used in biostratigraphy (Chapter 4). If necessary, evidence from archaeological assemblages and relative dating could potentially be supplemented further by dendrochronology, radio-carbon dating, thermoluminescence, archaeomagnetometry or other absolute dating methods (Wesler, 2014; see also Chapter 16), at least for significant contexts where more precise dating is crucial.

Artefact assemblages: Artefacts may remain in use for generations so the date of deposition may occur a long time after the date of manufacture. For this reason, an assemblage of several artefacts from a context is preferable for dating and correlation purposes than a single object. **[46 words]**

17.6.3 Concluding remarks on archaeological stratigraphy

Heavily cut and re-cut anthropogenic ground can be complexly stratified where, as interfaces rather than deposits, the significance of cuts is easily overlooked. More than just intrusions into strata or disturbances of ground, cuts - when treated as stratigraphical entities in their own right – are key for working out relationships between contexts in successions that would otherwise be virtually impossible to unravel. The Harris matrix method (and the practical skills of recognizing, excavating, and recording cut features that go with it) is worth learning. It makes dating and correlating of contexts using artefact assemblages so much simpler when those contexts are already placed within a relative dating framework derived from their stratigraphical position.

17.7 Forensic Stratigraphy: from the Macro to the Micro (Ruffell)

Stratigraphy can be a critical part of forensic geology. Donnelly et al. (2021) split the current approach into: (1) the search for forensic evidence (landscape interpretation, solid/drift geology, geophysics); (2) methods used at the scene (of crime) such as geological/soil sampling strategies and (3) the investigation of the sample, or trace evidence comparison e.g. using mineralogy, geochemistry and pollen/microfossils (e.g. Bailey *et al*., 2017). These three strands of forensic geology map onto the stratigraphical scale of investigation from the macro (Search; Section 17.7.3) the meso (Scene; Section 17.7.2) and micro (Sample; Section 17.7.1).

17.7.1. Micro-scale: The Sample

The first uses of soil and sediment analysis to compare that found on a suspect with the crime scene were straightforward visual and microscope-based observation, as exemplified in the Sherlock Holmes stories of Sir Arthur Conan-Doyle (Murray, 2011). Stratigraphy was first documented as being used in forensics by Georg Popp in the investigation of the murder of Eva Disch in Germany in 1904 (Murray, 2011). Her body was found in a field used for growing beans, she had been strangled with her own scarf and, near the body, a handkerchief was retrieved. Popp examined the handkerchief and found particles of coal, hornblende and snuff. The police identified a suspect, one Karl Laubach, who worked in a local gravel pit and also a coal-fired gasworks: scrapings from his fingernails also produced coal fragments (not surprising), but also hornblende – abundant in the gravel pit. Popp examined Laubach's trousers and found two layers of material, the lower of which resembled the bean field where Eva Disch's body had been found, and above it a layer rich in mica, unlike the bean field or Laubach's workplaces, but similar to a path from the bean field to Laubach's home. The combination of the handkerchief and trousers made for good evidence, but the layering of the deposits on the trousers established a succession of contact, or two-layer microstratigraphy. Unlike the comparison of one soil stain to a location, this layering provided stronger evidence, as the chance of random soil adherence diminishes. When faced with the evidence, Laubach admitted to his crime.

The analysis of layering in footwear tread, in vehicle tyres and engine components, on digging tools, within wheelbarrows, dustbins, or on fabric are critical forensic observations (Worked example 17.8). The limit to how many layers may be established on an item of forensic interest may be governed by the accommodation space (e.g. the depth of footwear or vehicle tyre tread) available for soil/sediment capture, it's adhesive and cohesive properties (stickiness) and sophistication of instrumentation when only millimetre to sub-millimetre layers are captured and preserved.

Worked example 17.8: Rural murder and burial

This example shows how microstratigraphy was used in a murder case. In this case the boots of a criminal gang member (Fig. 17.23) operating in Belfast and believed involved in the rural murder of a rival were seized by police and examined forensically. The soles were found to be covered by a clay soil. Careful removal of this clay revealed a white layer in the tread hollows, later established as chalk. Against the rubber sole of the boots a layer of brown silt was observed. Soil mapping at the burial scene revealed a spatial variation that ranged from the burial site (clay soil), along a lane with spilt agricultural chalk (for acid soil improvement) with a vehicle lay-by/gateway underlain by brown silt. Why is this succession of soil not replicated in reverse order through the boot-tread? Possibly because the cleated-soles had filled up: there was no further accommodation space, the cohesive clay soil had acted as a grout, sealing in the previous layers and maintaining them as the wearer had finished at the grave site and returned. The layers in the boots, replicated the spatial distribution of soil and sediment found along an access route to the burial site, with distinctive individual characteristics in each layer from the boots, also found at and around the scene.

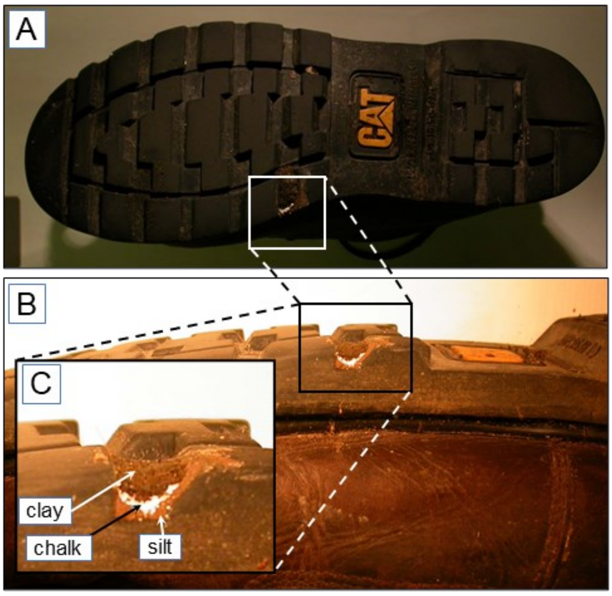


Fig. 17.23. Micro-scale forensic stratigraphy from the sole of the boots. The boot soles were originally covered in the clay-rich soil. (a) sole of the boot showing position of the evidence, (b) and (c) microstratigraphy of the cleat. Image modified from Ruffell and McKinley (2008): their Fig. 2.17, copyright © 2008 John Wiley & Sons Ltd.). [worked example, single column width, 7.8cm high = 1/6 page + 54 word caption]

Such millimetre to centimetre scale of stratigraphy is also important when sampling soil at crime scenes (below), but relates to the above idea of layering in footwear tread, vehicle parts or tools and clothing. As locations such as puddles are in effect miniature sedimentary basins, wherein a suspect (or victim) treading in such, may contact the uppermost layer or penetrate down into the microstratigraphy, each layer of which must be sampled. In some cases, the soil structure (peds) may itself be preserved (Fitzpatrick et al., 2017) and like Popp's layers on clothing (above) provide further assurance of its probative evidence.

17.7.2 Meso-scale: the crime scene

Stratigraphy and stratigraphical disturbance can be used at burial sites (be it human bodies, weapons, contraband, drugs) as a means of elucidating how, for example, a grave was dug and the order of re-filling, as well as observation of cross-cutting features such as tool marks (similar to cut marks in archaeology). The two most commonly-encountered examples that use the law of stratigraphical superposition are that of a clandestine grave, in which natural or anthropogenic layering is dug, often mixed, and replaced; shown schematically in Fig. 17.24a. Careful stratigraphical analysis during excavation can reveal how the location was dug (tool marks, succession of digging), excess material disposed of (the buried item having taken up accommodation space) as well as its infilling (Hanson, 2004). This can be critical for criminal investigations, as the type(s) of digging tool, time and/or number of people involved and behaviour of the protagonist may be considered (Cox and Hunter, 2006). Ruffell (2005) goes a stage further using geophysics (ground penetrating radar; GPR) and what is effectively grave sequence stratigraphy (Chapter 8), showing sediment progradation as it was infilled and downlaps onto the coffin, interpreted as the direction from which post-burial infill was made (Fig. 17.24b). Subtle differences in the geoscience exist in the interpretation: for instance, Fig. 17.24c shows a GPR image in Belfast (Northern Ireland) City Cemetery with a vertical-sided structure. Geologists may see this as resembling an igneous dyke, vertically surface cross-cutting the stratigraphy, when it is in fact a pre-existing subterranean wall (built by a bishop to separate Protestants from Catholics in the afterlife), with later soil infill, onlapping from either side.

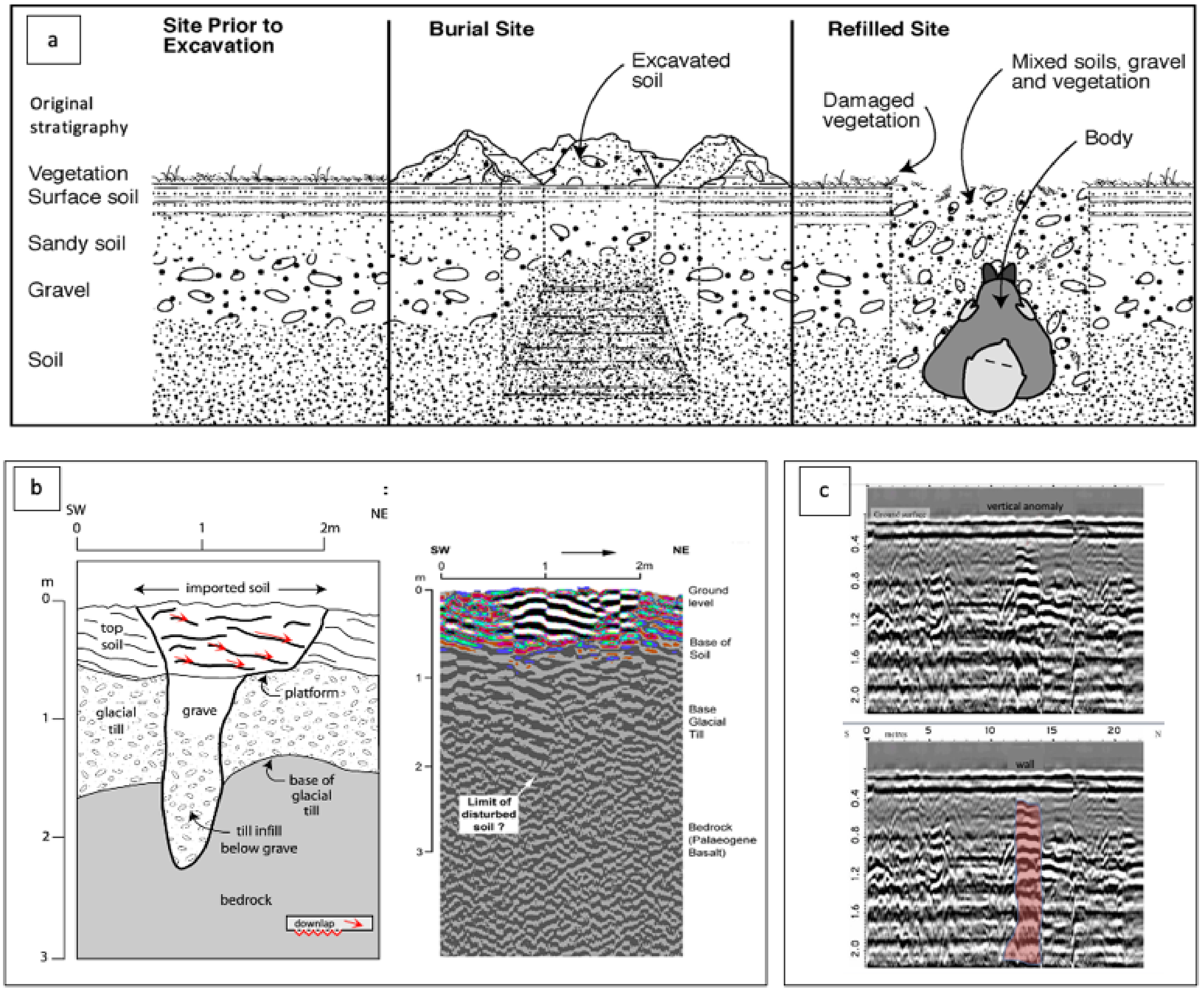


Fig. 17.24. Meso-scale forensic stratigraphy. (a) The classic schematic view of pre-burial stratigraphy, excavation of the burial site and the refilled site with human cadaver (modified after Boyd, 1979; Fig. 1). (b) Sequence stratigraphical interpretation (left) of GPR data (right), gathered over a known 1890 grave (coffin and cadaver have degraded) for a homicide search, Belfast, Northern Ireland. Note downlapping shown with red arrows indicating direction of backfill (modified after Ruffell, 2005; Figs. 4c and 5). (c) GPR profile gathered in Belfast City Cemetery (Northern Ireland) across a buried wall. [Full page width 15cm high, 2/3 page + 88 word caption]

17.7.3 Macro-scale: The Search

The search for buried objects most commonly occurs in soil and sediment, which by its nature contains stratigraphy. The idea concerns the concept of 'diggability', or the ease of excavation (Donnelly and Harrison, 2017) and in sediment-filled water 'sinkability' (Ruffell and Donnelly, 2018). The process of searching for buried objects such as victims of homicide is complex (Donnelly et al., 2021), but the stratigraphical principles are much the same as that for the meso-scale (above), in that disturbances to pre-existing layers are what the forensic geologist is looking for. This is founded upon variations to the known geomorphology, soils, vegetation and geology of the area, established through a desktop study and walk-over of the search location. Prior to investigative excavation, evaluation of stratigraphical variation is established by remote sensing, geophysics and auguring, providing areas of high, moderate and low interest, translatable to the red-amber-green (RAG) hazard maps used in engineering, environmental and military terrain evaluations (Donnelly et al., 2021). Disruptions to regional stratigraphy maybe unique enough (in area and characteristics) to warrant immediate investigation by cadaver dogs (or victim recovery dogs/canines), trial and complete excavation. However, the stratigraphy of not just the burial site itself, but its location and surrounding area may prove invaluable in reconstructing events (worked example 17.9).

Red-Amber-Green System; Use the RAG system, a landscape classification method based on military mapping of 'go' 'no-go' areas, to convey priorities in terms of locations that are visible or covert and may have thick soils that could be transferred as trace evidence. **[42 words]**

Worked example 17.9. Stratigraphy in Search

This case study illustrates how the stratigraphy of a suspicious location and surrounding area may prove invaluable in reconstructing events. In this case the police search focussed on an abandoned and flooded quarry that a suspect had visited around the time of a double-homicide some 25 years previously. While finding the deceased was a primary goal, establishing the prior excavation of the quarry, construction of an internal quarry embankment and subsequent flooding and sediment/debris infill was crucial in deciding what assets could assist in the search, the volume of water and amount/geometry of infilling sediment for archaeological removal and the preservation of potential evidence. Therefore, as well as using Sonar and GPR for target identification, these methods were combined with historical accounts of quarrying and the hydrogeology of the surrounding area into a simple model of the site; Fig. 17.25.

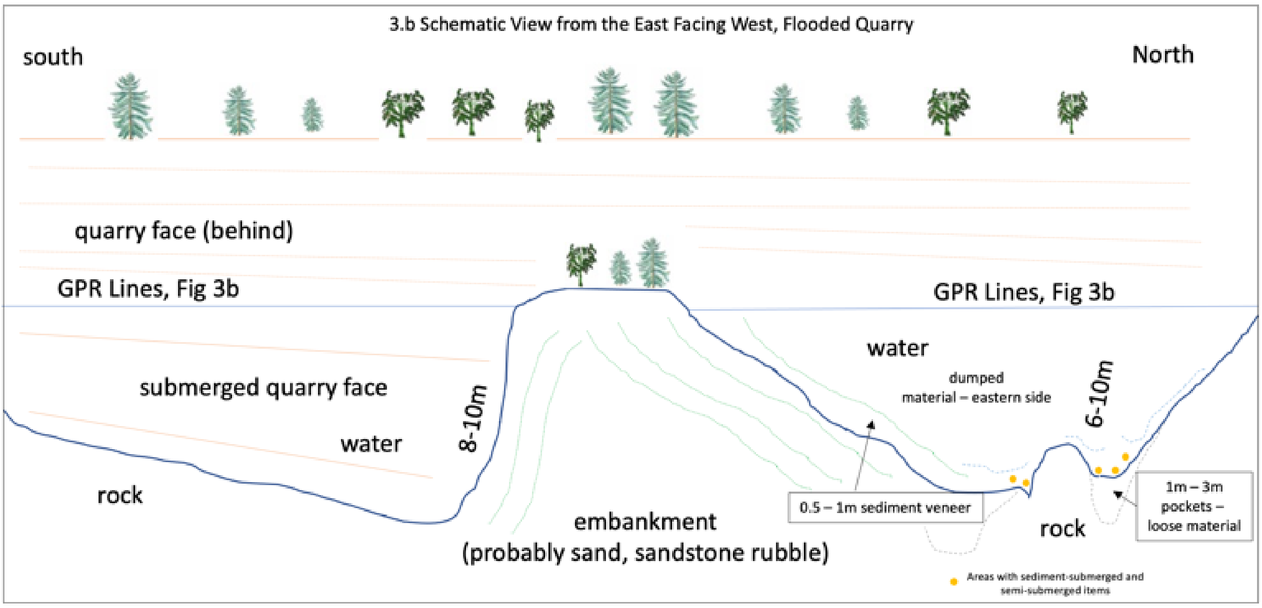


Fig. 17.25. Cartoon interpretation of GPR data used during macro-scale forensic stratigraphy; search for two homicide victims, believed to be in a flooded quarry. **[worked example, full page width, 8.2cm high = 1/3 page + 22 word caption]**

17.7.4. Conclusions on forensic stratigraphy

Stratigraphical principles such as superposition, cross-cutting surfaces and sequence stratigraphy can be applied from the micro-scale of soil/sediment layering on items, through archaeological investigations to the large-scale searching of the landscape. As Hanson (2004) summarises, this knowledge can be crucial in establishing a possible succession of events, much like other case studies in this volume, but here applied to clandestine human activity. Stratigraphical principles are applicable at all scales from ~millimetre layers down a microscope to the interpretation of soil and sediment stratigraphy over metres to kilometres of a search area. Equally expanded are the applications beyond serious crime (such as homicide) to humanitarian (e.g. mass graves), environmental (e.g. illegally-buried waste), engineering applications and the range of locations from our preconception of a rural field or peat bog, through sediment-filled water-bodies, voids and building interiors.

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The examples in this book on sequence slotting are a tribute to the late Malcolm Clark's contribution in developing this topic in Earth sciences.

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Chapter 17 title page image: Slice from a 3D geocellular rock property model showing a borehole gamma-ray log (part of the input data) and cells (voxels) picking out the stratigraphy.

Angela's length calculation = 34.4 pages