Geological Characterization of Melanges for Practitioners

By John Wakabayashi and Edmund W. Medley

Many geotechnical engineers and engineering geologists (practitioners) believe that simply drawing contact lines or other features on a geologic map or cross section produces representative characterizations of the subsurface. But the results of most investigations are often grossly incorrect when working with melanges (from French: mélange, or mixture). Melanges are mappable but discontinuous, often chaotic rock units, composed of mixtures of often pervasively sheared, weak matrix enclosing a variety of stronger blocks of different lithologies and size (Figure 1). Melanges can form as submarine landslides (olistostromes), by tectonic processes as fault rocks, or by a combination of the two processes (1, 2, 3). The origins of melanges interest research geologists to the point of producing several thousand papers, but from an engineering viewpoint, the processes all produce mixtures of weak matrix and stronger blocks.

Despite more than 40 years of geological understanding of melanges and their origins, me-

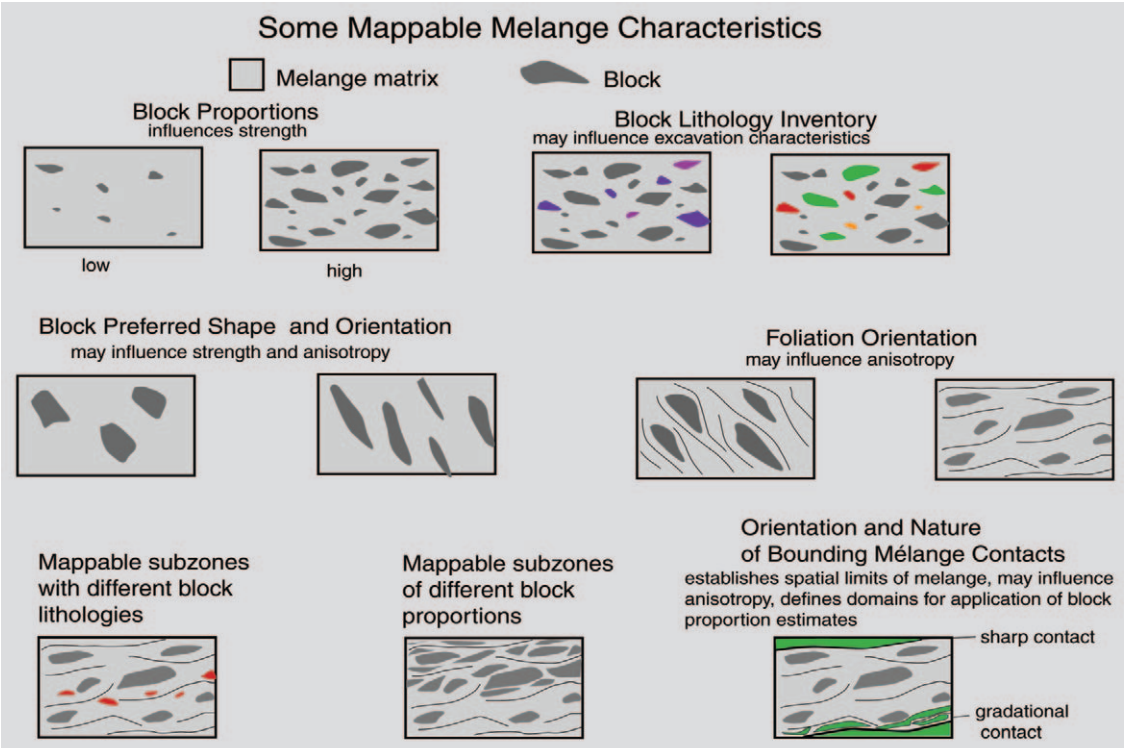

Fig. 1 Principal mappable engineering geology characteristics of a melange.

Bild 1 *Ingenieurgeologische Grundsatzmerkmale für die Kartierung von Melangen.*

Geologische Charakterisierung von Melangen für den Fachmann

Unter Melangen versteht man ungeordnete Einheiten von Fels, der aus einer Mischung aus Felsmasse mit niedriger Festigkeit und harten Gesteinsblöcken besteht. Obwohl Melangen weltweit anzutreffen sind und Gefügegeologen seit Jahrzehnten damit vertraut sind, wissen geotechnische und geologische Fachleute nicht Bescheid über die neuesten geologischen Konzepte bezüglich Melangen und deren ingenieurtechnischen Stellenwert; diese Unwissenheit resultiert in kostspieligen Planungsfehlern und unwillkommenen Überraschungen während der Baudurchführung. Basierend auf Erfahrungen in Franciscan Melange werden im Folgenden Identifizierungsmerkmale für Melangen und Zuordnungsmerkmale für externe und interne Details innerhalb der Melangeeinheiten vorgestellt und auch Richtlinien angeboten, die bei der Erstellung einer systematischen ingenieurtechnischen Charakterisierung von Melangen als Hilfestellung dienen.

Melanges are chaotic bedrock units consisting of mixtures of weak matrix and stronger blocks. Although melanges are globally common and have been familiar to structural geologists for decades, many geotechnical and geological practitioners are unaware of recent geological concepts of melanges and their engineering significance: such ignorance results in costly design errors and unwelcome surprises during construction. Based on experience with Franciscan complex melanges, criteria are provided for identifying melanges and mapping external and internal details within melange units, and guidelines offered for developing orderly engineering characterizations in melanges.

langes are unknown or misinterpreted by many practitioners. Costly and imprudent consequences derive from practitioners' errors in the mischaracterization of melange structures as "layer cake" strata, or incorrectly describing melanges as "soil containing boulders", or "miscellaneous soils", for example. To confuse matters, the word "melange" is also used by some practitioners to mean any mixture of rock and soil materials, which is inappropriate given the long-used geological meaning. Furthermore, some practitioners declare melanges as impossible to characterize and recommend geotechnical design be based on the properties of the weak matrix. Such simplification can lead to too-conservative and inappropriate designs and costly surprises and unsafe ground failures during construction.

Researchers have recently developed approaches to the engineering characterization of melanges and other bimrocks (block-in-matrix rocks) (4, 5, 6, 7, 8). Medley (9) defined bimrocks as geological mixtures of geotechnically significant blocks of rock within weaker, bonded rock matrices. Geotechnical significance means that there is sufficient mechanical contrast between the blocks and the matrix to force failure surfaces to negotiate around the blocks in tortuous fashion; and that there is a sufficient size and numbers of blocks to affect the overall mechanical properties of the geological mixture.

The authors of this paper, a Structural Geologist (Wakabayashi) and a Geological Engineer (Medley), consider it necessary to apply both first-order geologic field observations and quantitative engineering methods to the characterization of melange once it is identified, and to that end guidance for the identification, mapping, and characterization of melanges by practicing geologists and engineers is provided.

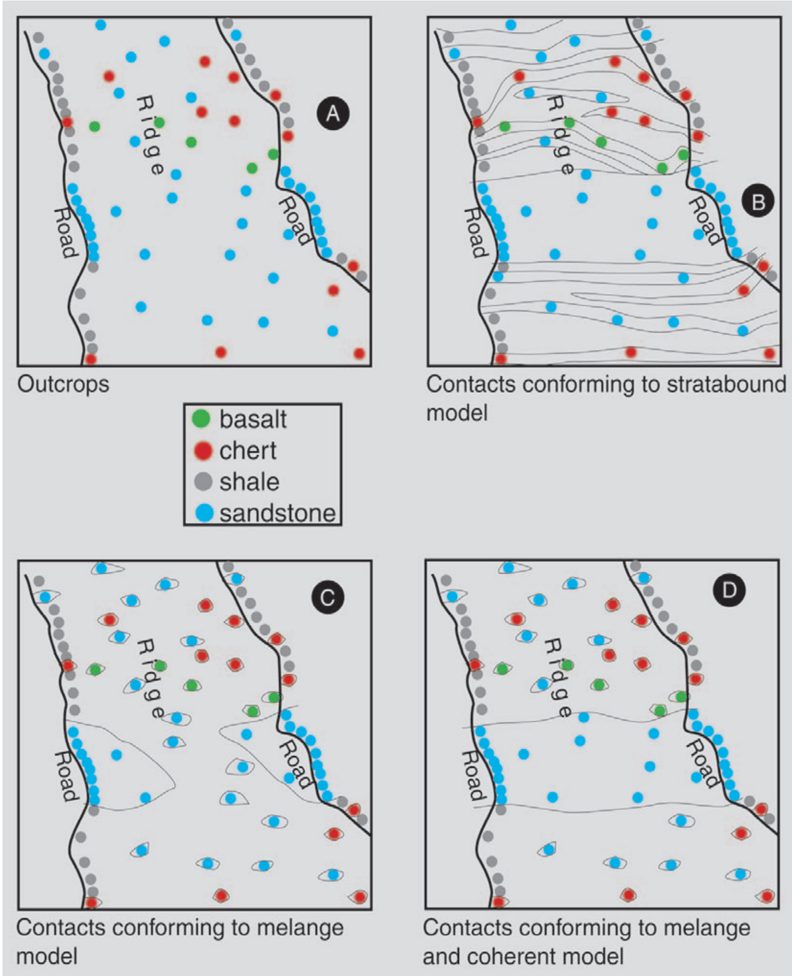

Fig. 2 Hypothetical geologic maps showing how prevailing geologic theories influence how contacts are drawn on maps. Map A: outcrops. Map B: geology interpreted as stratabound layers. Map C: entire area interpreted as melange. Map D: area composed of both melange and coherent thrust sheets.

Bild 2 *Theoretische geologische Karten, die zeigen, wie vorherrschende Theorien in der Geologie die Darstellung von Kontaktflächen beeinflussen. Abbildung A: Aufschlüsse. Abbildung B: Geologie interpretiert als stratigraphische Schichten. Abbildung C: Gesamtfläche interpretiert als Melange. Abbildung D: Fläche besteht aus Melangen und zusammenhängenden Überschiebungsdecken.*

Melanges – geologic concepts and misconcepts

A brief history of styles of mapping of melanges of the Franciscan Complex ("the Franciscan") of coastal California provides examples of how geologic knowledge influence how contacts are drawn on geologic maps and cross sections (Figures 2 and 3). The Franciscan hosts some of the world's most famous melanges (10,11), as well as engineering projects that have suffered problems because of their chaotic conditions.

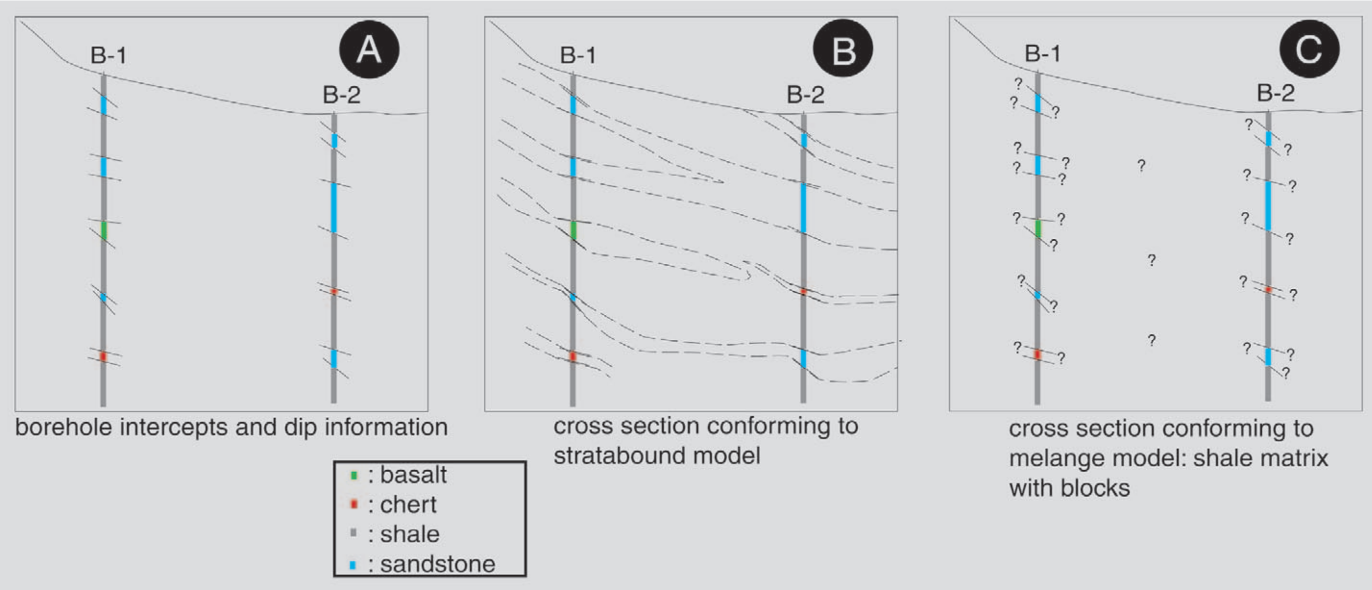

Fig. 3 Cross-sectional diagrams showing the difference between assuming stratigraphic continuity and assuming melange structure when interpreting borehole data. A: borehole observations. B: Cross-section based on interpretation of stratabound geology (layers). C: Cross-section based on melange model.

Bild 3 *Querschnittsdiagramme zeigen den Unterschied zwischen angenommener Schichtenfolge und vermuteter Melangestruktur bei der Interpretation von Bohrkerndaten. A: Kernbohrungsbeobachtungen. B: Querschnitt basierend auf Auswertung von stratigraphischen Schichten. C: Querschnitt basierend auf einem Melangemodell.*

When mapping, geologists most commonly encounter the erosion-resistant blocks of a melange (Figure 4), rather than the weak matrix, which easily erodes and seldom forms observable outcrops except in bare natural slopes, or artificial cut slopes. Hence, prior to the 1960's most geologists mapped areas with scattered outcrops of sandstone, chert, basalt, or other rock types (Figure 2A) and then interpreted the melanges into the layer-cake continuous stratigraphic framework of the Franciscan "Formation" (12) (Figure 2B). If ignorant of melanges, many practitioners still map this way.

Greenly (13) first christened chaotic units in North Wales as "Autoclastic Mélange" but widespread recognition of melange structures did not follow until Hsü (10) formalized the melange concept. Melanges were then recognized as globally common, particularly in ancient orogenic belts associated with old subduction zones (2, 11). Following the acceptance of Hsü's (10) melange concepts, geologists mapping in the Franciscan and similar geologic confusion mapped outcrops as blocks in the usually unseen matrix (Figure 2C). Some geologists even classified the entire Franciscan as one large melange body and neglected the internal details, a simplification that can still be encountered in some academic research papers. By the mid-1970s, geologists such as Maxwell (14), began to discriminate the Franciscan into "coherent units", fault-bounded sheets of intact non-melange Franciscan geologic rock units; and discrete "melange units". This concept was expanded in the 1980s as the "terrane" concept explained the complex tectonic jigsaw of the North American Cordillera, with terranes being the individual puzzle pieces (15, 16). The Franciscan was then called the "Franciscan Assemblage". Although the terrane concept led to improved categorization of coherent units, identification of melanges regressed, as all Franciscan melange bodies were then collected into one "Central Terrane", based on an interpretation that all Franciscan melanges formed at the same time.

Fig. 4 A view of landscape underlain by serpentinite matrix and shale matrix melange; Tiburon Peninsula, San Francisco area, California.

Bild 4 *Landschaftsansicht mit darunterliegender Serpentinit-Matrix und Schieferstein Matrixmelange; Tiburon Halbinsel, Bezirk San Francisco, Kalifornien.*

Wakabayashi (17, 18, 31) expanded on Maxwell's (14) concepts, by delimiting separate Franciscan melanges and coherent units, and then correlating melange units and coherent units to discrete structural levels within stacks of thrust nappes. Accordingly, an up-to-date structural geologist mapping Franciscan outcrops today might find and map both coherent and melange units, as shown schematically in Figure 2D. This modern approach reflects the appropriate current "Complex" suffix to "Franciscan Complex".

During a century of geologic mapping in the Franciscan Complex, the rocks have not changed, but the geologic maps have changed dramatically. Although geologists long ago recognized melanges and how to map them, many practitioners still treat melange bedrock as bedded geologic units. Others, also incorrectly, consider entire regions to be melange. Both groups thus fail to secure the geologic information that can be collected and used for engineering purposes.

Mapping melanges – guidelines and cautions

In the Franciscan a gradation exists between coherent units and melanges, with an intermediate level of stratal disruption, commonly referred to as a "broken formation" (2), that renders identification of melange bimrocks for engineering purposes more difficult. The origins of melanges dictate the nature of the bounding contacts of a melange body. A purely sedimentary (or olistostromal) melange has sedimentary bounding contacts unless modified by later faulting, whereas the contacts of a tectonic melange are, by definition, faults. Furthermore, in melanges, tectonic signatures may include pronounced anisotropic rock mass fabrics that control matrix shears and block orientation (7, 8).

Despite the complexity of melanges, a knowledgeable and alert geologist can identify and map much useful information, as shown in Figure 1. Assuming that the melange has been correctly recognized, the overall boundary contacts of melange bodies will require standard "external" mapping of faults or depositional contacts, depending on the origin of the melange. "Internal" mapping of melanges requires detailed observations. When working with coherent geology (intact geologic units), a geologist commonly locates a few points along a contact and interpolates between them while "contact mapping". However, internal mapping of a melange is best accomplished by "saturation" mapping of every available outcrop. Detailed mapping will define the external contacts of the melange body, delineation of the boundaries of larger blocks, provide information to estimate the proportion of the blocks in the melange, and information on the variety of block lithologies. Several guidelines and common errors are summarized below.

Recognizing melanges and geomorphologic indicators

A melange must be recognized early in an investigation. One of the most common errors by practitioners in this regard is: not consulting a geologist nor reading a geological map. Even when available geology maps identify melanges, many geotechnical engineers (in particular) seem unable to conceive of the possibility that a "clay soil" may actually be pervasively sheared shale bedrock; that "bedrock" is discontinuous blocks, and that "boulders" are blocks that may be hundreds of meters in dimension. Such ignorance leads to mischaracterizations that could be avoided by consulting with a knowledgeable geologist.

Most units termed by structural geologists "melanges" have matrices with metamorphic grades less than greenschist facies and so will conform to the engineering definition of a bimrock. However, in some mappable melange bodies there may be areas that are bimrocks in

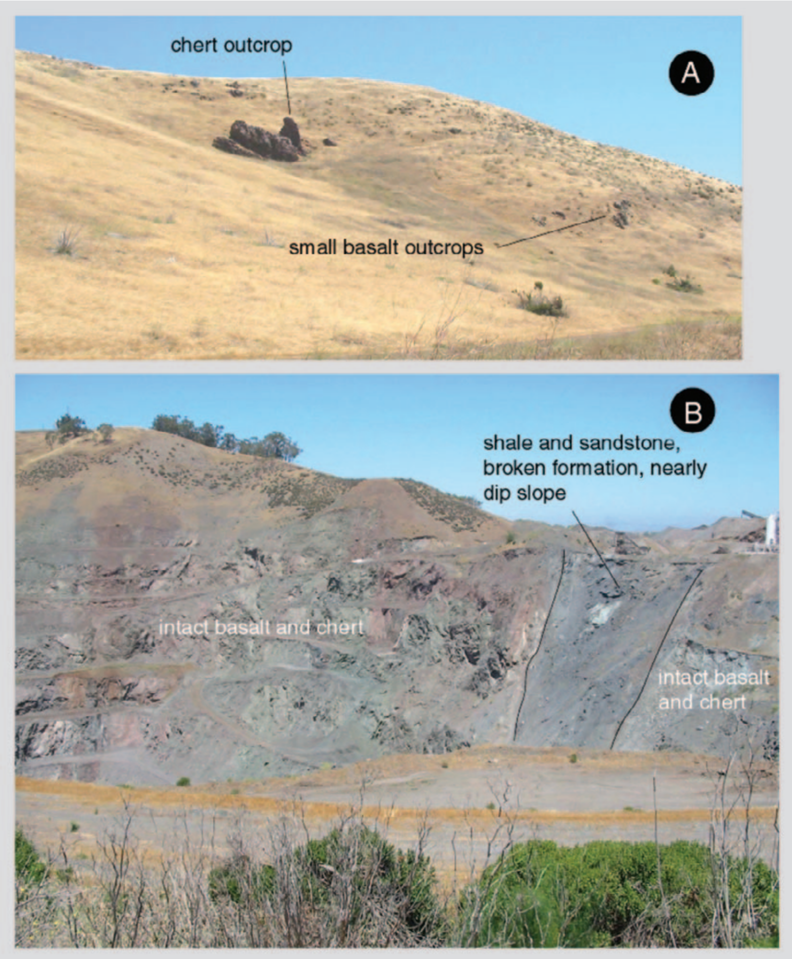

Fig. 5 Photos showing how geomorphology can be misleading in identifying melange. A: melange-like topography with a chert outcrop; B (taken a few hundred meters away from A) shows that the underlying bedrock is not melange.

Bild 5 *Fotoaufnahmen zeigen, wie irreführend Geomorphologie bei der Bestimmung von Melange sein kann. A: Melange-ähnliche Topographie mit Kieselerdeaufschluss. B: (aufgenommen aus einigen 100 m Entfernung von A) zeigt, dass das darunterliegende Felsgestein nicht Melange ist.*

one place but not in another. For example, in the northern Sierra Nevada of California, there are melange units of sub-greenschist metamorphic grade (19, 20) that are bimrocks because little recrystallization has occurred to strengthen the matrix relative to the blocks. However, further south, in the central Sierra Nevada, these same geologic units occur with upper greenschist and higher metamorphic grades (20) and the melange matrix is mechanically competent quartz-mica schist, and the melange is not a bimrock.

Melanges occur at all scales, from shear zones that are several km in outcrop dimension and structural thickness, to fault zones of meter or smaller scales. Franciscan Complex melanges are scale independent, meaning that melange have block and matrix structure at any scale of observation (9, 21, 22). Perhaps the only (and quite rare) exception to this scale independence are basalt matrix shear zones. The authors have observed such volcanic matrix limited to scales between from microscopic (millimeters) up to about a meter or so of structural thickness.

The most common field indicator of melanges is their geomorphologic expression. Because melange matrix is commonly weak, it is subject to slope movement and easily eroded. As a consequence it tends to form rolling topography with outcrops of larger blocks standing out in contrast, a geomorphology commonly referred to in California as "melting ice-cream topography" (see Figure 4). However, this characteristic geomorphic signature is not foolproof, for some coherent chert and basalt units will form somewhat similar topography with chert making up most of the blocky outcrops (Figure 5).

In some areas, scattered exposures of chert or basalt or limestone, in an area otherwise exhibiting only outcrops of sandstone and shale often indicates the presence of a melange, as does the presence of rocks such as sandstone, shale, chert, or basalt in an area that is otherwise serpentinite. Scattered metamorphic rocks that are of different metamorphic grade than surrounding rocks are also useful field indicators of a melange.

Serpentinite by itself is not necessarily an indicator of melange but it is commonly associated with melanges. Serpentinite in an area that is otherwise mostly sandstone and shale indicates the likelihood of the underlying rock unit being a melange. In serpentinite matrix melanges, the matrix is of sheared or disaggregated serpentinite and the most common blocks are usually massive serpentinites and less serpentinized ultramafic rocks, various mafic igneous rocks (gabbro, diabase, basalt), pelagic sedimentary rocks (chert, limestone), and metamorphic rocks (23, 1). But many serpentinite bodies are not melanges in a geologic sense, contrary to some misconceptions. Such bodies of rock usually occur as fault-bounded sheets or blocks and the serpentinite comprising them can range from massive and strong to sheared. Hence, a sheet composed entirely of serpentinite may exhibit block and matrix fabric, and thus be a bimrock, but not be a geologic melange.

Weathered melange exposures can be difficult to distinguish from colluvial soils, particularly if the colluvium itself has a melange source. Melanges interpreted as colluvium may lead to incorrect conclusions as to the subsurface geometry, since a colluvium deposit will have a base and a melange body may not. In a good exposure (such as the wall of a trench or test pit), some differences between melange-derived colluvium and weathered melange bedrock can be observed. Melange-derived colluvium will seldom have well-developed matrix foliation that is continuous over a square meter or so of exposure, whereas such foliation is commonly observable even in weathered bedrock. Melange-derived colluvium may have apparent foliation orientations that are fairly consistent and they will commonly be sub parallel to the slope, but the areas over which this foliation is visible will be patchy, for they will consist of individual pieces of matrix that have been incorporated into the soil. In melange-derived colluvium there may also be bits of former melange matrix that are rotated so that there are abrupt discontinuities in foliation orientation, in contrast to folding of the foliation or warping of foliation around blocks that characterize melange bedrock. The distinction between weathered melange bedrock and melange-derived colluvium may be difficult to ascertain in borehole samples because a larger area of observation is generally needed to apply the criteria noted above.

Mapping matrix and foliations

The most common melange matrix types are shale/mudstone, sandstone, and serpentinite. Basalt or volcanic matrix (or mixed volcanic/shale matrix) is rare. Some melanges have a mixed serpentinite and shale matrix in which serpentinite can be interleaved as small as centimeters, although it is more common to find serpentinite as blocks in shale matrix melange (24).

Mapping melange foliation it is no different then mapping foliation in a metamorphic rock unit. Melange matrix foliation locally wraps around blocks and will have variable orientations, but over the extent of the mappable unit will commonly have a comparatively consistent foliation. When possible, the foliation orientations should be mapped to provide clues about the general orientation of the melange fabric which likely influences anisotropy in the strength of the melange, as described by Medley and Sanz (25). Shears may be so pervasive that the matrix is soil-like. Matrix sheared into scaly clay, in which the matrix is pervasively sheared and breaks into brittle chips of shale (Argille Scagliose of Northern Italy), may also be found and is diagnostic of melange.

Blocks – size distributions, lithologies, proportions, and orientations

Melange blocks vary greatly in character and size. To be considered a block there must be mechanical contrast between the block and the surrounding matrix, which can often be decided on the basis of striking both with a rock pick and observing the penetration or sound (4, 9). The block size distributions of observed Franciscan melanges are scale-independent or fractal (9, 22), and blocks will be found at all scales of engineering interest. In outcrops blocks are found as small as sand, whereas in regional-scale melange (several km in structural thickness), blocks can exceed a km in maximum dimension. The "size" of a "block" is thus dependent on the scale of observation and various criteria have been developed for determining critical scales (4, 9, 22). However, only rarely is the observed "size" of a block the same as the "diameter" of a block, for reasons explained by Medley (26, 27) and Haneberg (28). Once a "characteristic engineering dimension" or scaling dimension is selected that represents the scale of engineering interest of the bimrock (e.g. slope height, footing width, diameter of triaxial specimen), blocks are defined as being within about 5 to 70 % of that dimension, at least until the scale of interest changes (4). Since scales will change from reconnaissance-level site mapping to the scale of the proposed facility (e.g. cut slope, tunnel, foundation) it is best to decide early in the investigation what range of block sizes to examine and measure.

The lithologies of blocks vary from melange to melange and locally within any single melange unit. In shale matrix melanges, the most common block lithology is generally greywacke, with much smaller proportions of basalt, chert, limestone, plutonic and metamorphic rocks (9, 11). Identification of block lithologies and block discontinuity fabric is important for engineering purposes because certain block lithologies may pose greater excavation challenges than others, owing to their mechanical and discontinuity properties. For example an unexpected block of intact, fresh greenstone with an unconfined compressive strength of 200 MPa (30 000 psi) can seriously frustrate tunneling that has been designed to accommodate more tractable fractured greywackes. Also, fractured, weak blocks may offer little mechanical contrast with matrix and should thus prudently be assigned to matrix when considering overall geomechanical properties of the bimrock.

The volumetric proportion of blocks in a melange is an important engineering geology parameter because studies have shown that melange strength is related to the volumetric proportion of blocks (5, 22, 29, 30). However, as described above, there are significant uncertainties to estimates of volumetric block proportions based on field observations (26, 27, 28).

Blocks in a melange will commonly have preferred shapes and orientation, much like imbricated pebbles in a gravel deposit. For blocks that are commonly disk shaped in three dimensions ("phacoids") the disk plane is generally parallel to sub parallel to the melange foliation. In addition, the long dimension of blocks in a melange may also have a preferred orientation. Similar to the matrix foliation, block shape orientation may also influence anisotropy in the overall strength of the melange so this is field geologic information that should be recorded as recommended also by Haneberg (28).

Internally, the block arrays of many melanges do not appear to exhibit any order, but some melanges have mappable sub zones within them. These sub zones can be distinguished by differences in block lithologies, block abundance, or even matrix type. For example a melange may consistently have a structurally lower zone that has common chert and basalt blocks, but have a structurally higher zone that lacks chert or basalt blocks. Different sub zones within a melange may actually correspond to spatially distinct (and thus mappable) subunits of different block proportions or block lithologies. This also applies to some melanges that have gradational contacts: mapping from the outside of the unit toward the middle one might observe a gradation from intact sandstone and shale to broken formation (block-in-matrix structure but no block types other then shale and sandstone) to a full melange with exotic blocks. This gradation corresponds to a difference in block proportions, and such a gradation is commonly mappable.

Interpretations from borehole observations

Interpretation of melanges from borehole data presents considerable additional challenges as indicated in Figure 3. Whereas surface float or geomorphic clues allows interpolation between outcrops, interpolation of block boundaries from boreholes is impossible unless the block is known to extend between the boreholes. Because of the potential for interpretation errors, backhoe pits or excavator trenches may yield more useful and economical subsurface information such as fabric orientations. Alternatively, as commonly performed in California, large diameter auger borings can be drilled to allow access by a geologist protected by a cage.

As noted previously, external contacts of melange can be interpolated between boreholes as for any geologic contact or fault. If internal sub zones are mappable, including gradations near the external contacts, it may be possible to project these sub zone boundaries between boreholes. A cautionary note: contacts, particularly external contacts of a melange body, must be recognized. For example if a borehole at the dipping external boundary of a melange body penetrates the melange and terminates within a coherent unit, the coherent unit may inadvertently be classified as a block, leading to a too-high linear block proportion.

The lengths of the intercepts between the core and blocks (chords) can be totaled for several boreholes and divided by the total length of the boreholes to yield a cumulative linear block proportion, that subject to adjustments for uncertainty (26), yields an estimate of the volumetric block proportion of the melange explored. With considerably greater potential errors, the chords may also crudely indicate blocks size distributions subject to several cautions (27). Melange foliation and block preferred shape may also be recorded in a borehole with oriented core.

A common error when logging core in melange is to describe the alternating matrix and block intersections as "inter-layered" or inter-bedded" shale and sandstone. But such descriptions incorrectly imply stratal continuity and if used to describe melanges in geological reports can lead to misunderstandings when drawing cross sections, or to differing site conditions claims from earthwork and tunneling contractors.

It is common practice in Northern California to extend exploration boreholes in Franciscan melanges through soil and terminate the drilling 1 to 2 m into bedrock. A common error when exploring melanges to characterize them as "soil above bedrock", "miscellaneous soils" or "soil with boulders". The use of these inappropriate terms for Franciscan melange has been a factor in earthwork construction disputes. For example contractor have been known to excavate deeply in attempts to locate the "basal failure surface" in a pervasively sheared "clay soil", and to jack-hammer unexpected "boulders" in excess of 5 m size. Such problems are avoided if practitioners do not draw straight lines between the "rock/soil contacts" they identify in exploration borings.

Conclusions

Melanges and similar bimrocks are common throughout the world and many engineering projects are constructed in these chaotic rock but the engineering geologic understanding applied to many of these projects has been obsolete for decades. The methods presented in this paper should help geologists and engineers learn how to identify and characterize melange, so that engineering assessment of melanges and other bimrocks can be performed. Admittedly, melanges are more difficult to characterize than "coherent" geologic units, but practitioners must learn to characterize geological chaos in an orderly fashion, or else continue to perform costly and imprudent mischaracterizations.

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