APPENDIX B

to

MELANGE AND FAULT ROCKS EXPOSED IN AND AROUND ABANDONED QUARRY AT THE SCHMIDT LANE RECYCLING CENTER, EL CERRITO, CALIFORNIA

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SOME GUIDELINES TO CHARACTERIZATION OF FRANCISCAN MELANGES AND OTHER BIMROCKS

INTRODUCTION

Engineering geologists and geotechnical engineers are commonly challenged by weak, heterogeneous and geologically complex mixtures of strong blocks of rock embedded in soil-like matrices. Melanges (French: *mélange,* meaning *mixture*, such as in Fig. B1) are a common example of such complex geological mixtures. (It is customary in the USA to neglect the acutely accented "*é*" in the word *mélange*.) Melanges and other soil/rock mixtures are well represented in Northern California: the Franciscan Complex contains abundant melange bodies. Elsewhere in Northern California, the geo-professional is challenged by fault and shear zones, lahar deposits, decomposed granites, glacial tills, and colluvium. However, geologically complex mixtures do not pose uniquely American troubles, but represent global problems. For example, melanges have been mapped worldwide (1), and the lessons learned in California are applicable globally.

Given their considerable spatial, lithological, and mechanical variability, characterization, design and construction of melanges and other rock/soil mixtures is daunting. Accordingly, geo-practitioners often make the simplifying assumption that the mechanical behavior of rock/soil mixtures is adequately represented by the properties of the weak matrix materials and that there is no need to consider the contribution of blocks. But such assumptions lead to improper and expensive engineering geological and geotechnical engineering mischaracterizations.

This Appendix:

- shows that blocks do influence the mechanical behavior of melanges and other rock/soil mixtures;
- describes a scheme for the systematic characterization of block lithologies, block proportions, and block size distributions to reduce inconvenient and expensive surprises during tunneling, earthwork, and foundation construction; and
- summarizes recent research and practical experience on the geotechnical and geological characterization of melanges and other rock/soil mixtures.

MELANGES AND OTHER BIMROCKS

Bimrocks

Melanges contain competent blocks of varied lithologies, embedded in sheared matrices of weaker rock (Fig. B1). The fabric of hard blocks of rock within weaker matrix is fundamental in geology. There are over 1000 geological terms for rock mixtures and fragmented rocks (2), including more than 20 aliases for melanges, such as *olistostromes, argille scagliose, complex formations, friction carpet, wildflysch, mega-breccia* and *polygenetic breccia*. Attempts have been made to simplify the confusing geological lexicon associated with chaos. The Italian

Geotechnical Society (3) devised a simple, geotechnically-oriented classification scheme for "structurally complex formations" which included melanges, colluvium, and residual soils. Raymond (4) also attempted to simplify the confusing array of geological theories and descriptions for melanges and similar rocks. Laznicka (2) organized a Universal Rudrock Code to classify fragmented and mixed rocks. Popiolek and others (5) defined a Geotechnical Flysch Rock Mass Classification (KF) and correlated it to the Rock Mass Rating Scheme of Bieniawski (6) for use with coherent and brecciated rock of the Carpathian Flysch in underground excavations. Riedmüller (aka Riedmueller) and others (7) introduced an engineering geological characterization for brittle faults and fault rocks.

Because the vast collection of geological terms describing the fundamental fabric of mixed strong blocks in weak matrix tends to be confusing, Medley (1) introduced the term *bimrocks*, a contraction of the term "block-in-matrix rocks," first introduced by Raymond (4) to describe "block-in-matrix" melanges. The word "bimrock" has no geological or genetic connotations and was defined by Medley (1) to be "*a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture*." The expression "geotechnically significant blocks" means that there is mechanical contrast between blocks and matrix, and the proportion and size range of the blocks influences the mechanical properties of the strong block/weak matrix mixture at the scale of interest. There are many geological materials that can be described as bimrocks, as long as they conform to the criteria proposed by Medley (1). Amplification of these criteria are presented later in this Appendix.

In this Appendix, the term "bimrock" is used wherever the results obtained from studies of melanges can be applied to the characterizations of other rock/soil mixtures, which conform to the definition of bimrocks.

Geological aspects of Franciscan melanges

Melange bodies are present in more than 60 countries. Medley (1, Appendix A) lists references and shows maps of worldwide locations of melange bodies. Although there are more than 2000 geological references on melanges there are few references on the engineering geologic or geotechnical engineering aspects. However, there was a series of works in 1993 to 1995 by the writer and his former colleagues Dr. Eric Lindquist and Professor Richard E. Goodman, at the University of California at Berkeley. A seminal paper applying some of these findings was recently published by Goodman and Ahlgren (8).

In parallel with these American works, there have been the significant contributions by Professor Gunter Riedmüller, Professor Wulf Schubert, and their colleagues in Graz, Austria, particularly in the application of engineering geology and rock mechanics theory and practice to the problems of rock mass characterization, design and construction for tunnels, dam foundations, highway excavations and slope repairs in fault rocks and melanges. Geotechnical research on generally block-poor, argille scagliose olistostomes has also been performed in Italy by AGI (3), Aversa et al. (9), and D'Elia et al. (10). An important contribution by Irfan and Tang (11) summarizes the geotechnical behavior of soil/boulder mixtures in Hong Kong, with findings applicable to other complex geological mixtures.

This Appendix specifically considers experience with melanges in Northern California, which are abundant in the jumbled Franciscan Complex (the Franciscan) that covers about one third of Northern California. Blake (12), Raymond (4), Cowan (13), and Hsü (14) described the geology of Franciscan melanges, and Wahrhaftig (15), Blake and Harwood (16), and Wakabayashi (17) prepared useful field guides. (Other references appear in the main text of the El Cerrito portion of the Field Trip Guidebook, to which this Appendix is joined). Fig. B2 illustrates the mapped appearance of the Franciscan at the scale of Marin County, north of San Francisco. Fig. B1, also showing melange but at outcrop scale, shows how similar the fabric is to the fabric of fault and shear zones.

The matrix of Franciscan melanges is composed of shale, argillite, siltstone, serpentinite or sandstone, and may be pervasively sheared to the consistency of soil. Blocks are not evenly distributed within melanges and congregate to form block-rich and block-poor zones (see Fig. B11). The most intense shearing within melanges is often in block-poor zones adjacent to the largest blocks. Savina (18) measured as many as 800 shears per meter. Earthflow landslides commonly occur in block-poor zones bounded by large immobile blocks, or by block-rich zones.

The weakest elements in a melange are the contacts between blocks and matrix. Contacts may be marked by a lustrous surface on the blocks and a wafer of sheared material that weathers to a slick film of clay. Shear surfaces generally pass around blocks via the block/matrix contacts (Figs. B11 and B12). Blocks within the shears may be entrained within, and oriented parallel to, the shears (Figs. B1 and B11).

Medley (1) estimated that in the Franciscan of Marin County, California (Fig. B2), as mapped by Ellen and Wentworth (19), about 60 to 70 percent of blocks are graywacke, 15 to 20 percent are volcanic, generally greenstones (metamorphosed basalts), 15 to 20 percent are serpentinite, 5 to 10 percent are chert, and the remaining blocks are rare limestone and exotic metamorphic rocks such as eclogites. Blocks may also be composed of intact siltstone and sandstone/siltstone sequences. Large blocks in Franciscan melanges range between smoothly ellipsoidal and irregular in shape and, where measured, have major/minor axis lengths in the approximate ratio of about 2:1 (1).

Block sizes

Block measurements from field mapping or drilling are invariably shorter than the true "diameter" of a block as illustrated in Fig. B3. Block sizes are indicated by the length d_{mod} (the maximum observed dimension) of blocks exposed in two dimensions (outcrops or geological maps). In one dimension, block sizes are also measured from sampling lines traversing outcrops ("scanlines" of Priest (20)), or in drill core, by the chord length formed by the intersection between the block and the core.

Scale independence of block size distributions

Many rock/soil mixtures contain a few large blocks and increasing numbers of smaller blocks. Hence, using common geological parlance, the block size distributions tend to be *fractal* (conforming to negative power laws), or using soils-engineering parlance, "well-graded." Medley (1) and Medley and Lindquist (21) observed fractal block size distributions at many scales of geological interest in Franciscan melanges, which supported observations of fractal block size distributions in other comminuted geological materials such as fault gouges ((22), (47)) and fractured rock masses (23). In Franciscan melanges, the range in block sizes is extreme, exceeding seven orders of magnitude, between sand (millimeters) and mountains (tens of kilometers) as illustrated in Fig. B4. Despite the considerable difference in scales, the melanges depicted in Figs. B1 and B2 show block size distributions with similar well-graded appearances.

The block size distributions of Franciscan melanges are also *scale independent*, meaning that blocks will always be found, regardless of the scale of interest or observation. Over a smaller range of scales, the block size distributions of other rock/soil mixtures (such as glacial tills and fault zones) also show scale independence. Because blocks will always be found in melanges, the distinction between blocks and matrix depends solely on the scale of interest. Small blocks at one scale (e.g. 1: 1,000) are part of the matrix at a larger scale (1:10,000) (Fig. B5). Likewise, large blocks at one scale of interest (e.g. 1:10,000) are not geotechnically significant blocks at a smaller scale (e.g. 1:1,000) because they are too large to be considered as individual blocks within the rock/soil mixture. Instead, they can be considered as strong, massive and unmixed rock masses. Fig. B5 illustrates the point, which is explained further below.

Characteristic engineering dimension (L_c)

Because of scale independence, any reasonable dimension can be used to scale a melange rock mass for the problem at hand. Medley (1) called such a descriptive length the *characteristic engineering dimension*, L_c (the "*ced*" of Medley (1), and later papers). The use of a characteristic engineering dimension is analogous to showing a measuring tape, coin, hand or spouse in a photograph, without which object the observer cannot appreciate the scale of the image. For example, Fig. B1 could represent a melange at any scale, because it contains no clear scaling feature other than the information provided in the caption. L_c may variously be (1) an indicator of the size of a site, such as $\sqrt{A}$, where A is the area of the site, (2) the size of the largest mapped or estimated largest block (d_{max}) at the site, (3) the thickness of a failure zone beneath a landslide, (4) a tunnel diameter, (5) a footing width, or (6) the dimension of a laboratory specimen. The characteristic engineering dimension changes as scales of interest change on a project (as indicated in Fig. B5).

Largest and smallest geotechnically significant blocks

In Fig. B4, $\sqrt{A}$ is the characteristic engineering dimension (L_c) for areas of outcrops and geological maps at scales of measurement that range from less than 0.01 square meters (portion of an outcrop) to more than 1000 square kilometers (Marin County, Fig. B2). Block sizes are characterized by d_{mod}, which, as indicated above, is rarely the actual maximum dimension of individual blocks. In Fig. B4, block sizes for each set of data are normalized, or rendered dimensionless, by dividing the block size by the length $\sqrt{A}$ of the measured area of each outcrop or area of geological map. The relative frequency in Fig. B4 is the proportion of blocks in each size class divided by the total number of blocks in each of the measured maps or outcrops. Fig. B4 uses logarithmic axes in its compilation of the log-histogram depiction of the block size distributions. (The term log-histogram was first introduced by Bagnold and Barndorff-Nielsen (24).)

Fig. B4 shows that, at all the scales of measurement, the largest blocks are equivalent in size to $\sqrt{A}$ (for $d_{mod}/\sqrt{A} = 1$), but about 99 percent of blocks are smaller than about $0.75\sqrt{A}$ ($0.75L_c$), which is a reasonable maximum block size (d_{max}). Accordingly, the largest geotechnically significant block (d_{max}) within any given volume of Franciscan melange is about $0.75L_c$. Blocks greater than 0.75Lc result in such a diminished proportion of matrix in a local volume of rock mass, that the volume can be considered to be massive, unmixed rock composed mostly of the block. (For example, in Fig. B5 the very large block at the right side of the sketch is very much larger than the scale of pipeline trench width.)

At all scales of measurement in Fig. B4, the graphed data plots of normalized block sizes have peak relative frequencies at about $0.05\sqrt{A}$ (equivalent to $0.05L_c$). At block sizes smaller than $0.05L_c$ the blocks tend to become too small to observe and are undercounted, although in reality there are a myriad of them, and they become obvious once the scale of observation becomes smaller. For any given volume of Franciscan melange, blocks less than $0.05L_c$ in size constitute greater than <u>95 percent of the total number</u>, but contribute <u>less than 1 percent to the total volume</u> of melange and thus have negligible effect on the mechanical behavior of the melange. For these reasons, the threshold size between blocks and matrix at any scale is taken to be $0.05L_c$ (equivalent to $0.05\sqrt{A}$).

Fig. B5 illustrates how a block at one scale of interest can be part of matrix at a larger scale, but massive rock at a smaller scale. The illustration shows that it is essential to consider the possibility of having to penetrate very large blocks when constructing linear facilities such as roads, pipelines and tunnels. Fig. B5 also illustrates examples of the selection of L_c for various scales of interest for an area of bimrock.

Block size distributions based on chords

True three-dimension (3-D) block size distributions in bimrocks are poorly estimated by one-dimension chord length distributions obtained from the limited linear sampling of typical geotechnical exploration core drilling. The degree to which chord length distributions match actual 3-D block size distributions is dependent on the orientation of blocks relative to the boring directions, volumetric block proportion, and total length of drilling (Fig. B6). Since observed chord lengths are almost invariably smaller than the actual block diameters (Fig. B3), the frequency of larger block sizes tends to be underestimated and the frequency of smaller sizes overestimated. Indeed, larger blocks are mischaracterized as smaller blocks to the degree that small block sizes are indicated that may not even be part of the actual 3-D block size distribution, as shown in Fig. B7. For this reason, it is unlikely that drilling and coring into a melange rock mass can recover an actual 3-D block size distribution curve. The practical consequence of underestimating block sizes from exploration drilling is that unpleasant and costly surprises are common during excavation and tunneling of bimrocks. The writer is developing practical guidelines to constructing 3-D block size distributions from 1-D measurements (49).

Mechanical contrast between blocks and matrix

The mechanical contrast between competent blocks and weaker matrix forces failure surfaces to negotiate tortuously around the perimeters of blocks (see Fig. B12). Sufficient contrast is afforded by a friction angle ratio (tanϕ of weakest block)/(tanϕ of matrix) of between 1.5 and 2.0, as suggested by the work of Lindquist (25, 26, 27) and Volpe and others (28). Another means of identifying strength contrasts is to use rock stiffness. Lindquist (25) used a ratio of block stiffness (E, Young's modulus) to matrix stiffness, (E_{block}/E_{matrix}) of 2.0 to generate block/matrix contrasts for physical models of melange. Satisfaction of block/matrix mechanical contrast criteria such as these is necessary for a block-in-matrix rockmass to be considered a bimrock. For strength ratios or stiffness rations less than the lower bounds described above, there will be an increased tendency for shears and failure surfaces to pass through blocks rather than around them.

A wide range of block sizes in bimrocks tends to force failure surfaces to negotiate through matrix and along block/matrix contacts in contorted, tortuous paths. The tortuosity of pre-existing and induced shear surfaces increases shear resistance, as demonstrated by Savely (29), for boulder-rich Gila Conglomerate in Arizona; by Irfan and Tang (11) for boulder-rich colluvium in Hong Kong; and by Lindquist (25, 26) for physical model melanges. When blocks are uniformly sized, failure surfaces tend to have smoother, undulating profiles (Medley (1), his Fig. 4.4), and hence the mixed rock mass has less shear resistance.

Clearly, however, there is a dependence on the normal stresses to which the melange rock mass is subjected. At sufficiently high normal stresses, failure surfaces will penetrate blocks regardless of the mechanical contrast between matrix and blocks. Inherent defects in the blocks will aggravate the effect.

Relation of volumetric block proportion to melange strength

The overall strength of a Franciscan melange or other bimrock is independent of the strength of the blocks. As long as there is mechanical contrast between blocks and matrix, the presence of blocks with a range of sizes adds strength to the bimrock mixture by forcing tortuous failure surfaces to negotiate around blocks. Strength and deformation properties of a rock/soil mixture increase directly and simply with increasing volumetric block proportions as shown in Fig. B8, which is compiled from the results of Irfan and Tang (11) for boulder-rich colluvium in Hong Kong, and Lindquist (25) and Goodman and others (30) for physical model melanges and melange from Scott Dam, Northern California.

By testing over one hundred 15-cm-diameter specimens of physical model melanges, Lindquist (25, 26) determined a conservative relationship between volumetric block proportion and increased strength for physical model melanges (Fig. B8). Lindquist showed that below about 25 percent volumetric block proportion, the strength and deformation properties of a melange is that of the matrix; between about 25 percent and 75 percent, the friction angle and modulus of deformation of the melange mass proportionally increase; and, beyond 75 percent block proportion, the blocks tend to touch and there is no further increase in melange strength. Lindquist's results for model melanges closely matched the findings of Irfan and Tang (11) for actual boulder colluvium in Hong Kong, where some boulders were more than 2 meters in diameter.

However, as shown in Fig. B8, some rock/soil mixtures may have different strength/volumetric proportion relationships, as indicated by the trend of the data for weathered Scott Dam melange. Nevertheless, the important feature of Fig. B8 is that there is a simple and direct dependence between volumetric block proportions and bimrock strengths.

Lindquist (25, 26) also determined that cohesion tends to decrease with increasing volumetric block proportion for physical model melanges. However, Goodman and Ahlgren (8) observed that cohesion inexplicably increased with volumetric block proportion for Franciscan melange in the foundation of Scott Dam in Northern California. Because of the as-yet-unresolved contradiction between these findings, it is prudent to neglect any benefit of uncertain increased cohesion with increased volumetric block proportion.

Estimation of volumetric block proportion

As described above, the volumetric block proportion of a Franciscan melange or other bimrock is necessary to predict the geomechanical properties. The volumetric block proportion is approximated by measuring areal block proportions from outcrops, or linear block proportions from scanlines and exploration core drilling. The areal block proportion is the sum of the measured areas of blocks to the total area of rockmass measured. The linear block proportion is the ratio of the total length of block/boring intersections (chord lengths) to the total length of sample lines. The assumption that measured areal or linear block proportions are equivalent to the required volumetric block proportions is only valid given that there is enough sampling. Such equivalence is one of the fundamental laws of *stereology*, an empirical and mathematical study relating point, line and planar observations to the true geometric properties of objects (31, 32).

Since blocks in melanges are not uniformly sized or distributed, the volumetric block proportion cannot be accurately determined from a few borings, but given sufficient total lengths of sampling lines (at least $10d_{max}$) the linear block proportion approaches the volumetric block proportion with an error, or uncertainty, that can be roughly estimated (1, 33, 34, 35, 36, 37).

Although the desirable minimum total length of exploration drilling is equivalent to at least $10d_{max}$, optimum geotechnical exploration is rarely performed, even when subsurface conditions are relatively straightforward. Medley (35) considered the error in estimates of volumetric block proportion based on the assumption that they are the same as the measured linear block proportions. He fabricated physical models of melange with known block size distributions and volumetric block proportions and explored the models with hundreds of model boreholes. The experiments showed that measured linear block proportions had to be adjusted by an uncertainty factor to yield an appropriate estimate of the volumetric block proportion.

Uncertainty depends on both the total length of the linear measurements, such as from drilled core, and the linear block proportion itself. The uncertainty factor to be applied to the linear block proportion is both positive and negative. The actual volumetric block proportion may lie anywhere within the range defined by the adjusted lower and upper volumetric block proportions. As described by Medley (35), it is prudent and conservative to apply the uncertainty adjustment to reduce (negative adjustment) the calculated estimates of volumetric block proportions for the purpose of assigning strength parameters for a bimrock. On the other hand, because of the economic consequences of underestimating volumetric block proportions to be excavated by tunneling or earthwork construction, it is prudent and conservative to increase (positive adjustment) the calculated estimates of volumetric block proportions. (The uncertainty factor is shown in Fig. B15, the use of which is described later in this paper).

PRACTICAL GUIDELINES FOR ENGINEERING GEOLOGICAL CHARACTERIZATION OF MELANGES AND SIMILAR BIMROCKS

Elements in a program to characterize a volume of Franciscan melange or other rock/soil mixture include (a) establishing characteristic engineering dimensions (L_c), (b) estimating the sizes of smallest and largest blocks, (c) mapping; (d) exploration drilling; (e) geologic interpretation; (f) laboratory testing; (g) estimating rock mass volumetric block proportion; (h) estimating rock mass strength; and (i) estimating block size distributions. Guidelines for performing each of these nine elements are provided in the following sections. The guidelines are derived from case histories (1, 38, 39).

a. Establishing of Characteristic Engineering Dimensions (L_c)

Flexibility is exercised in the selection of L_c, as illustrated in Fig. B5. For an entire site or outcrop, determine the area of interest (A). Choose L_c as equivalent to $\sqrt{A}$ (Fig. B5). For an excavation or trench use the height of the excavation. At the scale of the entire excavation or trench, measure the explored area (A) and use $\sqrt{A}$ (Fig. B5). For a landslide use a critical cross-section depth or the thickness of the failure zone, as described by Medley (1, 39) for the Lone Tree Landslide in Marin County, Northern California. For foundation footings use the foundation width. If piles or caissons will be driven or drilled through the bimrock, use the pile diameter. For tunnels, at the scale of the entire tunnel length, measure the explored area (A) and use $\sqrt{A}$. At the scale of the tunnel face, use the tunnel diameter. (Medley (1, 39) provided examples of the use of characteristic engineering dimensions for the Richmond Transport Tunnel excavated in 1994 through Franciscan melange in San Francisco). For dam foundations use the most critical of dam width, dam height, $\sqrt{A}$ of footprint area, or some minimum design dimension such as the thickness of a critical shear failure zone, as described by Medley (1) and Goodman and Ahlgren (8).

b. Estimating the Sizes of Smallest and Largest Blocks

As described above, geotechnically significant blocks that influence bimrock strength range between about $0.05L_c$ at the block/matrix threshold and $0.75L_c$ for the largest block (d_{max}). Select the most conservative block/matrix threshold that can be justified. As shown in Fig. B5, blocks smaller than $0.05L_c$ are demoted to matrix at an overall site scale of interest, but may still be of substantial size at a contractor's smaller scale of interest, and where excavation equipment capabilities must be considered.

c. Mapping

Block-poor zones in Franciscan melange landscapes are geomorphologically expressed as valleys and landslides. Block-rich regions and individual blocks form erosion-resistant outcroppings, hills, rocky protuberances and stacks and craggy headlands along rivers and coastlines (Fig. B9), where they act as buttresses. Blocks may be vegetated with trees, whereas surrounding mobile, creep-prone matrix soils are sparsely vegetated. The sandier soils above blocks lose moisture more quickly than clayey matrix soils, and in the spring and early summer, large blocks at shallow depths may be identified by browning grasses and shrub vegetation overlying them. Matrix soils host greener vegetation. In air photos, the presence of near-surface blocks shows as tonal mottling (Fig. B10).

At outcrops, the mechanical contrast between blocks and matrix can be established using a rock pick. Friction angles of blocks and matrix can be estimated using standard strength scales such as those provided by the Geological Society Engineering Geology Working Party (40). The geologist should observe the nature of exposed block/matrix contacts, the matrix fabric, the block lithologies, and the array and nature of the discontinuities in the blocks (1). A highly fractured block is a weak block that may have little mechanical contrast and should be assigned to the matrix. Zones of weakness in large blocks may also act as "channels" for developed failures. Shearing at different scales is common in melanges and should be mapped.

Photographs of outcrops should be taken at different scales with an indicator of the scale, such as a tape measure, included in the photograph (as shown in Fig. B11). The procedure is described in more detail by Medley (1) and Medley and Lindquist (21). The maximum observable dimensions (d_{mod}) of exposed blocks can later be measured, either manually or using image analysis software, as described by Medley (1) and Medley and Lindquist (21).

d. Exploration Drilling

There should be no expectation that exploration drilling will adequately intercept all, or even many, of the blocks within a mass of bimrock. As indicated above, the desirable minimum total length of exploration core drilling is about $10d_{max}$. For example, at a site where $\sqrt{A}$, equivalent to L_c, is 100 m, the largest block (d_{max}) will be about 75 m in size. Hence, at least 750 m of drilled core is preferable, but the total length of drilling is likely to be less due to cost and time constraints. In this case, conservative adjustments to the linear block proportion must be made to provide prudent estimates of volumetric block proportions and block size distributions.

It is difficult to recover good-quality core in melanges and similar rock/soil mixtures because of the abrupt variations between blocks and matrix, varying block lithologies (Fig. B12), extensive shearing, and highly fractured small blocks. Alternate dry and flush drilling is considered poor practice in the drilling of bimrocks (7). Exploring of bimrocks by core drilling requires an experienced geologist, a skilled and dedicated drilling crew, and high-quality drilling equipment, although the provision of these does not preclude disappointing results; Goodman and Ahlgren (8) describe the poor sample recovery of Franciscan melange at Scott Dam, Northern California, even when using triple-barrel samplers and the Integral Sampling Method of Rocha (41) (a method in which friable rock is pre-grouted and then cored). As described by Riedmüller and others (7), good results have been obtained in faulted rocks by drilling continuously with double or triple tube core barrels and using a polymer as a flushing agent. The agent tends to prevent the disintegration of the drill core and promotes drill hole stability by the formation of a transparent filter skin on the borehole wall.

When logging core, measure all block/core intercepts (chord lengths) greater than 2 to 3 cm long, even if the block/matrix threshold is larger. The information on small blocks will be useful for work performed at laboratory scale. The degree of alteration and fracturing, as well as the surface properties of discontinuities and their inclination to the borehole axis, should also be recorded. Estimates of the linear block proportion should be made during core logging, and the core should be photographed. Wrap the core promptly since matrix, particularly in sheared melanges, may dry and slake. Examples of suggested practice in the logging of melange core is provided by several case histories described by Medley (1). Brosch and others (42) and Harer and Riedmüller (43) were able to discriminate rockmass features using an Acoustic Borehole Televiewer combined with visual inspection of the drill cores and a computerized evaluation of the detected features.

e. Geological Interpretation

The problems of characterizing Franciscan melanges and other rock/soil mixtures are compounded by inappropriate use of common geological terms. For example, a succession of shale matrix and sandstone blocks in drill core may result in Franciscan melange being logged as "interbedded sandstones and shales" (Fig. B12, BH-2), which incorrectly suggests lateral continuity. True blocks of coherent sequences of shales and sandstones are generally unsheared and the shales lack small blocks as described by Medley (1, his Fig. 5.16). Melanges also contain juxtaposed blocks of diverse lithologies that represent improbable depositional environments (as logged in BH-2, Fig. B12). A mental picture of the spatial and lithologic variety of bimrocks, similar to Fig. B12, will reduce errors in geological interpretations.

Melanges should not be described as "soil with boulders," a term that can mean different things to the geologist who encounters blocks during exploration and the contractor who has to construct through or around them. Boulders are often considered to range in size between 200 mm and 2 m. A practitioner may observe blocks in outcrops or in a boring and call them "boulders," which implies to a contractor that they can be excavated and can be considered "soil." However, an unexpectedly large block that substantially fills a tunnel face will not likely be considered "soil" by the tunnel contractor, as pointed out by Attewell (44). Furthermore, since chord lengths usually underestimate the true "diameter" of blocks, the apparent "diameter" of observed "boulders" may actually be misleadingly short chord lengths close to the edges of large blocks (Figs. B3 and B12; BH-2). The excavation or penetration of blocks larger than about 1.5 to 2 m diameter may require expensive blasting or jack hammering.

Borings are commonly terminated about 1 to 2 m into bedrock as shown in Figs. B12 and B13. But logging the material encountered in the borings as soil above bedrock increases the probability that the blocks will be interpreted as continuous bedrock, which could result in erroneous slope design and troublesome excavation, as shown in Fig. B13.

As an example: In Marin County, Northern California, a mischaracterization similar to the one depicted in Fig. B13 resulted in a landslide repair costing ten times as much as originally estimated. Following exploration by conventional drilling, the geotechnical characterization of the landslide was that it was a shallow slide of a few feet of "soil over bedrock" with a "failure surface" at the "soil/bedrock" contact. However, during construction, the contractor excavated deep into the shale "soil" seeking the "failure plane" and the "bedrock." In doing so, the contractor removed and jack-hammered many large blocks. The excavation finally stopped tens of feet below the level of the road, after an infinity of "failure planes" were exposed, and no "bedrock" appeared. In actuality, the "bedrock" had been interpreted by the geotechnical engineer when he drilled into two blocks in Franciscan melange and drew a straight line between his interpreted "soil/rock" boundaries. However, large blocks protruded from the neighboring hillside, and the area was clearly shown to be Franciscan melange on the local geology map.

f. Laboratory Testing

Because of scale independence, laboratory specimens of melange are scale models of melange at rock mass scale. The results of laboratory testing are thus more directly applicable to in-situ melange rock masses than for many other geological materials. Specimens of melange with varying block proportions have been tested to develop relationships between block proportions and strengths at laboratory scale (8, 25, 26, 27). Specimen testing should be performed by laboratories experienced in rock testing, using multi-stage testing methods, where specimens of melange are subjected to several loads, each applied to the onset of increased strain at peak stress (8, 25, 26, 27, 45, 46). For each specimen tested, a series of Mohr's circles can be drawn to identify the effective friction angle and cohesion.

The volumetric block proportion of each specimen can be determined after carefully disaggregating them and wash sieving to retrieve the blocks. Given that the characteristic engineering dimensions of the laboratory specimens are their diameters, blocks are those intact inclusions that have maximum dimension between about 5 percent and 75 percent of the diameters of the specimens. The volume of blocks (and hence the volumetric block proportion) is measured by weighing the blocks once the specific gravity of the blocks is known. The testing of specimens with different proportions of blocks yields plots of effective friction angle as a function of volumetric block proportion, such as that shown in Fig. B14. Plots can also be developed for cohesion and deformation parameters (8, 25).

g. Estimating Rock Mass Volumetric Block Proportion

For the selected characteristic engineering dimension (L_c), identify the block/matrix threshold size as $0.05L_c$, and ignore all chord lengths shorter than the threshold size. Calculate the linear block proportion by dividing the sum of the chord lengths by the total scanline or total length of borings. To estimate the volumetric block proportion, the linear block proportion must be adjusted for uncertainty using a plot such as that shown in Fig. B15. To use Fig. B15, first estimate d_{max} (size of largest expected block), and calculate multiples (N) of d_{max} (Nd_{max}) by dividing the total length of sampling by d_{max}. Enter the graph at Nd_{max}, and for the estimated linear block proportion identify uncertainty at the left axis. Interpolate between the diagonal lines if necessary. To obtain the range of volumetric block proportions, multiply the linear block proportion by the uncertainty, and subtract the product from the linear block proportion (for the lower bound), and add for the upper bound. The lower bound is used for purposes of estimating bimrock strength and the upper for estimating block proportion for earthwork construction, particularly excavation.

At Scott Dam, Northern California, the likely mode of potential dam failure was considered to be sliding along an assumed 3-m-thick shear zone within the melange adjacent to the base of the dam. On the basis of field mapping, the size of the largest block (d_{max}) in the area of the dam was estimated to be about 30 m. Because of the significance of the anticipated failure mode, the 3 m thickness of the shear zone was selected as the characteristic engineering dimension (L_c). The block/matrix threshold was calculated as 0.15 m (i.e. 5 percent of 3 m).

About 360 m of exploratory drilling had been performed during the life of the dam, but only about 150 m of core had been recovered. Accordingly, the total length of coring was equivalent to about $5d_{max}$ (i.e. 150m/d_{max} where d_{max} was 30 m.) Inspection of drill logs and photographs of core penetrating the assumed potential failure zone indicated that the linear block proportion, for blocks greater than 0.15 m, was about 40 percent. As shown in Fig. B15, for a linear block proportion of 40 percent, and a sampling length of $5d_{max}$, the uncertainty factor is about 0.23. Hence the estimated range of volumetric block proportion was 40%+/-(0.23)(40%), or about 40%+/-(9%) to yield a lower bound of 31 percent and an upper bound of 49 percent. Since it is prudent to take the lowest estimate of the volumetric block proportion for the purposes of estimating melange strength, the 31 percent estimate is the most appropriate. As described by Goodman and Ahlgren (8), a value of 31 percent was actually adopted as a conservative estimate of the average block proportion in the Franciscan melange at the base of the dam.

h. Estimating Rock Mass Strength

The overall strength of Franciscan melange rock masses is determined by using the estimates of in-situ volumetric block proportion and the laboratory test plots of effective friction angle and cohesion as a function of volumetric block proportion, such as the one shown in Fig. B14. It may be necessary to determine strengths for block-poor and block-rich zones within the rock mass, which may vary significantly from the overall average. In the case of Scott Dam, the friction angle was estimated to be 39 degrees for the overall volumetric block proportion of 31 percent (8).

i. Estimating Block Size Distributions

Although the strength of the blocks does not influence the overall strength, the lithology, discontinuity fabric, number, and size distribution of blocks are of concern to tunneling and earthwork contractors. For example, blocks greater than about 0.2 to 0.6 m in diameter are too large to be plucked by scrapers and must be excavated by bulldozers; and blocks larger than about 1.5 to 2 m must be blasted. Encountering blocks complicates tunneling, so there is some value in making pre-construction estimates of possible block sizes. For example, between 1994 and 1995, while tunneling through Franciscan melange for the Richmond Transport Tunnel in San Francisco, the contractor had to traverse 200 m through an unexpected graywacke block. Medley (1) had earlier predicted that the tunnel could encounter a block as large as 600 m.

Although the estimation of block size distributions from drilling data is unreliable (Figs. B3 and B7), very approximate estimations can be made for Franciscan melanges using a method described by Medley and Lindquist (21). First establish d_{max} at the appropriate scale of interest, then construct a first approximation for the block size distribution using the finding (1) that for some number of blocks (n) within a certain size class there will be about 5n in the previous size class and 0.2n in the following size class. Size classes are constructed such that the span of each class is twice that of the previous class. Next, starting with d_{max}, work backwards through the size distribution. (For example, if d_{max}, is thought to be 3.0 m, then initially assume that there is one block in the 2.0 to 4.0 m class. Hence there will be about five blocks in the 1.0 to 2.0 m class, about 25 blocks in the 0.5 to 1.0 m class, about 125 blocks in the 0.25 to 0.5 m class, and 625 blocks in the 0.125 to 0.25 m class. This last class contains the block/matrix threshold size, 0.15 m (i.e. 5 percent of d_{max}, 3 m). The volumes of individual blocks can be estimated assuming spherical or ellipsoidal blocks. The volume of all blocks in any particular class can be estimated by determining the volume of a single block with a dimension equivalent to the average size in the class, and multiplying that volume by the number of estimated blocks in the class. Finally, the total volume of blocks in all classes, divided by the volume of bimrock being considered, should match the estimated volumetric block proportion (preferably an upper bound estimate which incorporates uncertainty). If there is a difference, make adjustments to the assumed block size distribution (for example by doubling the number of blocks in the classes), and repeat the calculations until the volumetric block proportions match. This method gives approximate and conservative estimates but is useful for pre-excavation planning (34).

CONCLUSIONS

Engineering geologists and geotechnical engineers working in Northern California, and elsewhere in the world, cannot avoid encountering and working with chaotic bimrocks such as melange, faulted breccia/gouge mixtures, and other rock/soil mixtures. Despite their heterogeneity, however, such mixtures can be reasonably characterized for the purpose of geological engineering design and construction. Even where there is great uncertainty in the characterization, the work performed to produce broad estimates of block proportions, block sizes, lithologic proportions, bimrock strengths, and deformation properties will focus the attention of geologists, engineers, owners and contractors on the difficulties that may be encountered during design and construction.

ACKNOWLEDGEMENTS

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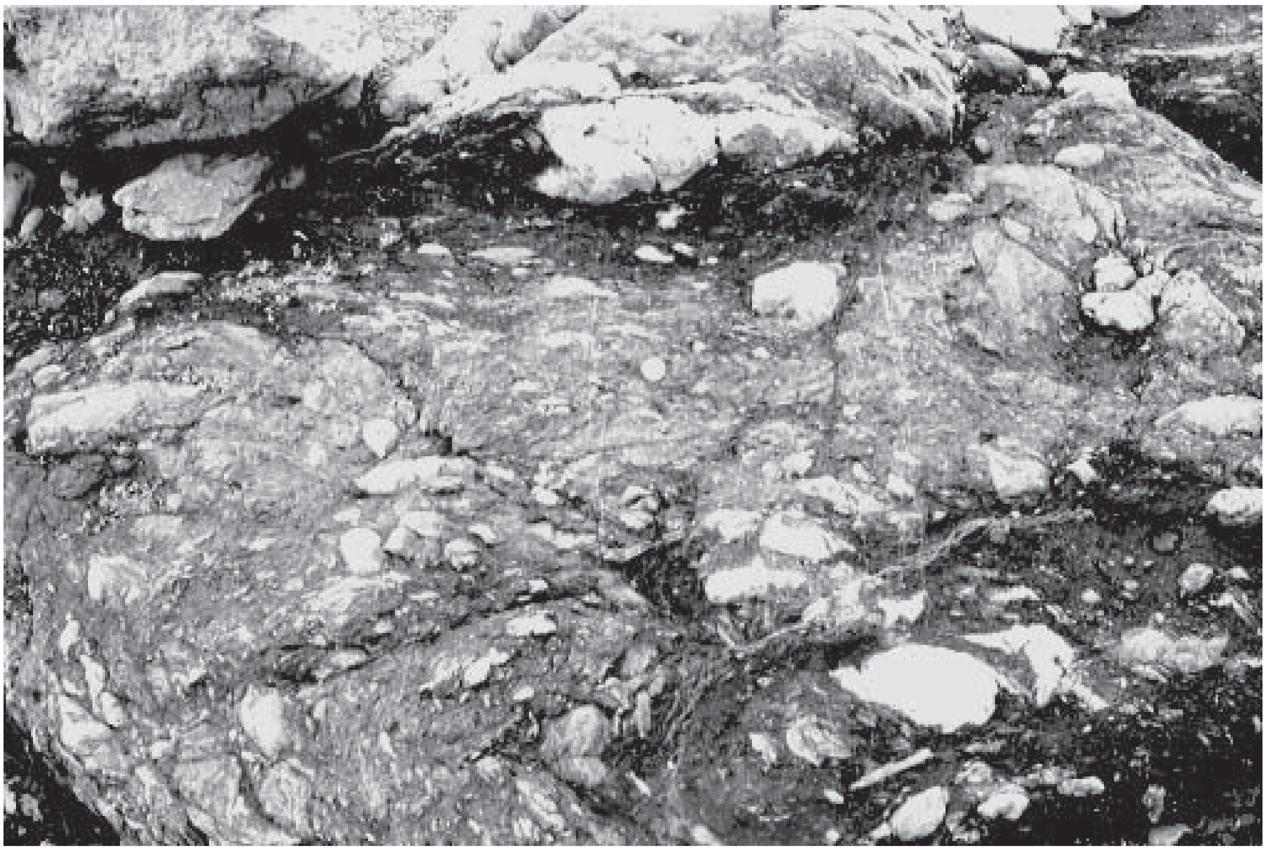


Figure B1. Franciscan melange at Shelter Cove, Point Delgada, Northern California. Matrix is dark gray sheared shale/argillite. Light colored blocks are graywacke. Outcrop is about 1m wide.

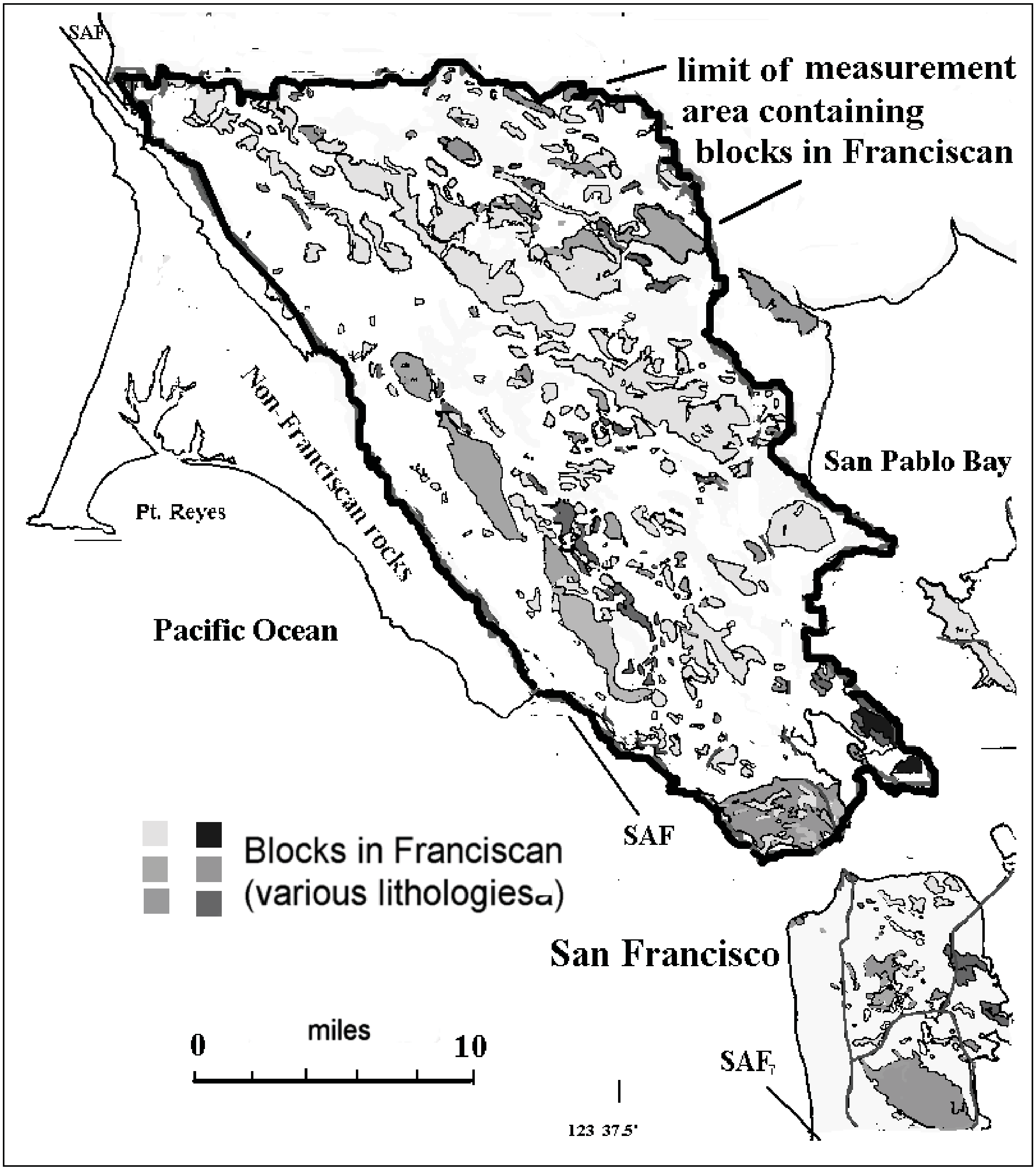


Figure B2. The Franciscan Complex in Marin County, north of San Francisco. Mapped blocks range to nearly 20 km in length. SAF is the San Andreas fault. Area of interest within indicated boundary is about 1000 km^2. (After Medley (1); base map after Ellen and Wentworth (19).)

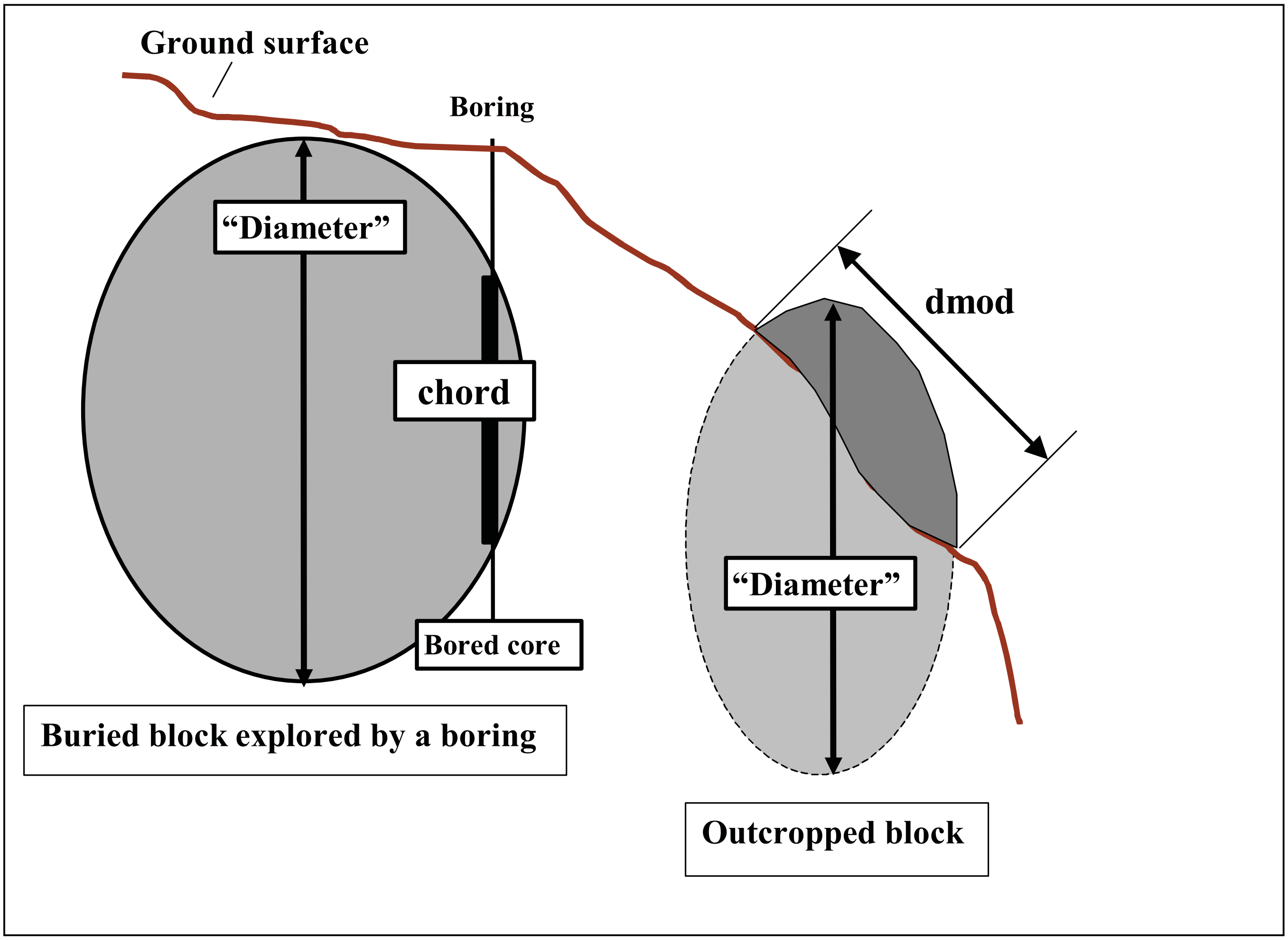


Figure B3. In two dimensions a block has apparent block size of d_{mod}, the maximum observed dimension. In one dimension, the block size is indicated by the chord length, or intercept between a boring and a block. Only rarely is d_{mod} or a chord length equivalent to the actual "diameter" or maximum dimension of a block, and hence block sizes are generally underestimated.

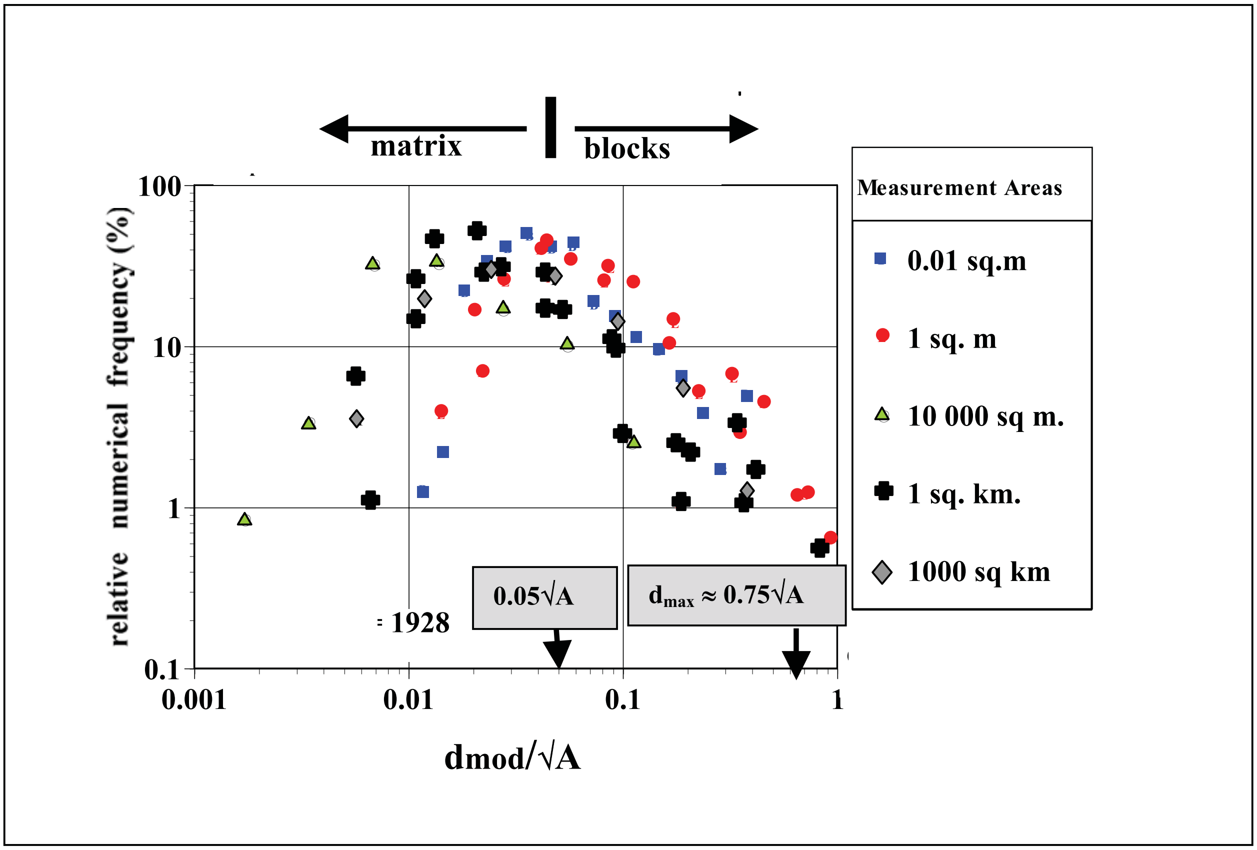


Figure B4. Normalized block size distribution curves for 1,928 blocks measured from outcrops and geological maps of several Franciscan melanges ranging over seven orders of magnitude in scale, ranging from centimeters to kilometers (after Medley (1)). The sizes of blocks are characterized by d_{mod}, the maximum observed dimension of the blocks in the outcrops and maps. The measurements of the block sizes are divided by the square root of the area ($\sqrt{A}$) containing the measured blocks to yield the dimensionless block size $d_{mod}/\sqrt{A}$. The normalizing parameter $\sqrt{A}$ is an indicator of the scale of the outcrop or geological map being measured. The relative frequency of blocks in each of the measured areas is the number of blocks in any size class divided by the total number of blocks in the measured area. The use of normalized block size and normalized numerical frequency allows the comparison of block size distributions over the extreme range in measurement scales. The data from each measurement area form graphed plots that are similar in shape to each other, regardless of the size of the measured area. The similarity in shapes indicates that the block size distributions are scale independent. The plots peak at about $0.05 d_{mod}/\sqrt{A}$, which is defined as the block/matrix threshold size at any scale. Blocks smaller than $0.05 d_{mod}/\sqrt{A}$ tend to be too small to measure and are undercounted. Blocks smaller than the threshold size are assigned to the matrix. The largest indicated block size is approximately equivalent to $\sqrt{A}$ (at $d_{mod}/\sqrt{A} = 1$), but 99 percent of the blocks are smaller than about $0.75\sqrt{A}$, which is defined as the maximum block size (d_{max}) at the scale of interest.

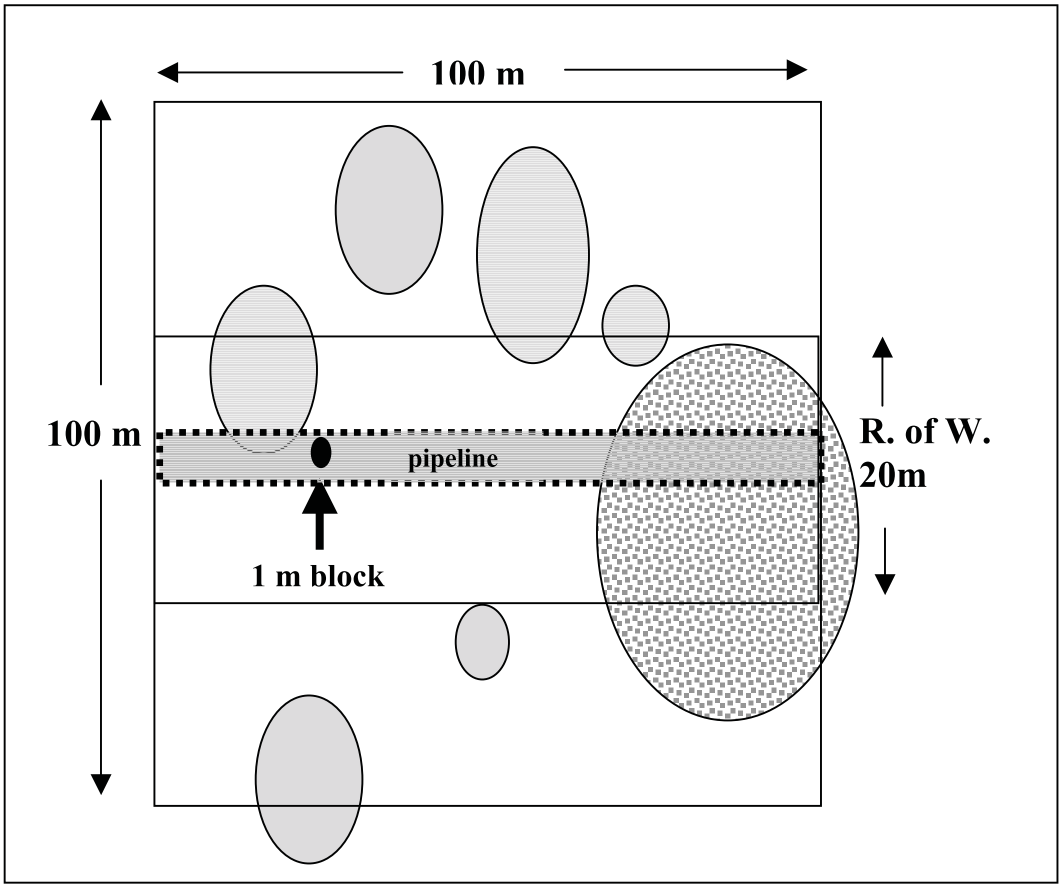
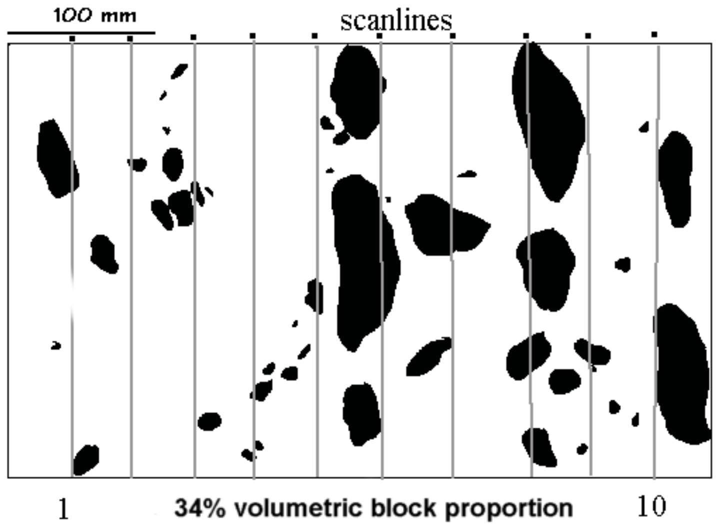


Figure B5. Sketch showing various scales of interest for an area where a 20 m wide road and 2 m wide, 2 m deep pipeline trench will be excavated in a melange bimrock:

(1) The 100 m by 100 m geological map has an area (A) of 10, 000 m^2, and hence a $\sqrt{A}$ of 100 m, which is taken as the characteristic engineering dimension (L_c) at the large scale of interest of the overall site. The block/matrix threshold at this scale is 5 m ($0.05L_c$ or $0.05\sqrt{A}$). Hence the 1 m block in the center of the sketch is part of the matrix. In contrast, at the scale of overall site, the large speckled rock mass at the right of the sketch is a block since it is less than $0.75L_c$ (75 m) in size.

(2) (2) At the scale of the road Right of Way, L_c is the 20 m width. At this scale of interest, the 1 m block is at the block/matrix threshold (0.05Lc) and the largest geotechnically significant block is 15 m ($0.75L_c$). The large speckled block is massive rock at this scale of interest. Massive rock and blocks greater than about 1m in size will present difficulties during mass grading of the road.

(3) (3) At the scale of the 2 m wide, 2 m deep pipeline trench, L_c can be taken as the depth of the trench. The block/matrix threshold will be 0.1 m, and the largest geotechnically significant block 1.5 m. At the local scale of interest of the trench represented by the trench depth, the 1 m block may present a problem for the trenching contractor. However, at the scale of the overall length of the trench, the speckled block is considered massive rock and will be more challenging since a significant portion of it must be excavated.



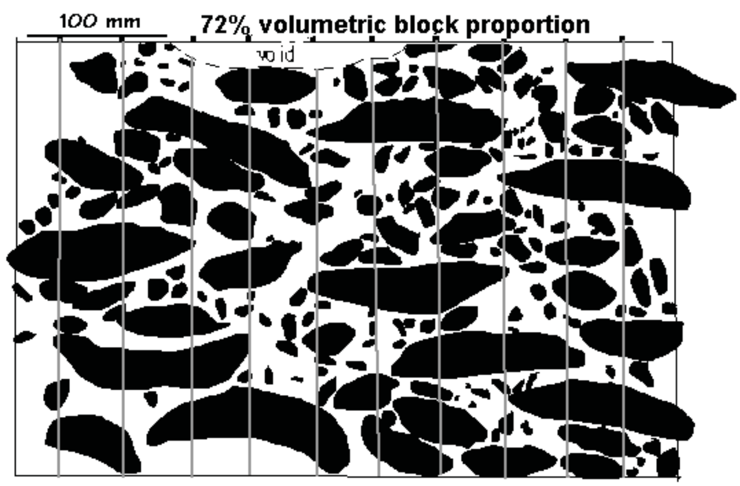


Figure B6. Tracings of physical model melanges (Medley (1), after Lindquist (25)), with known volumetric block proportions and three dimension (3-D) block size distributions. The tracings were measured by one-dimension (1-D) model borings ("scanlines") to yield linear block proportions and chord length distributions. The upper model has a relatively low volumetric block proportion (34%) where the scanlines are parallel to the orientation of the ellipsoidal blocks. When volumetric block proportion is low, there is less probability that a boring will intersect a block at all, and even less that it will intercept the actual maximum dimension of blocks. The lower model has a high volumetric block proportion (72%) with blocks oriented approximately horizontal and the exploratory borings oriented vertical. Clearly, in the latter case, even though the probability is high that borings will intersect blocks, the chord length distribution cannot match the actual block size distribution, since the vertical chords are always shorter than the horizontal maximum block dimensions.

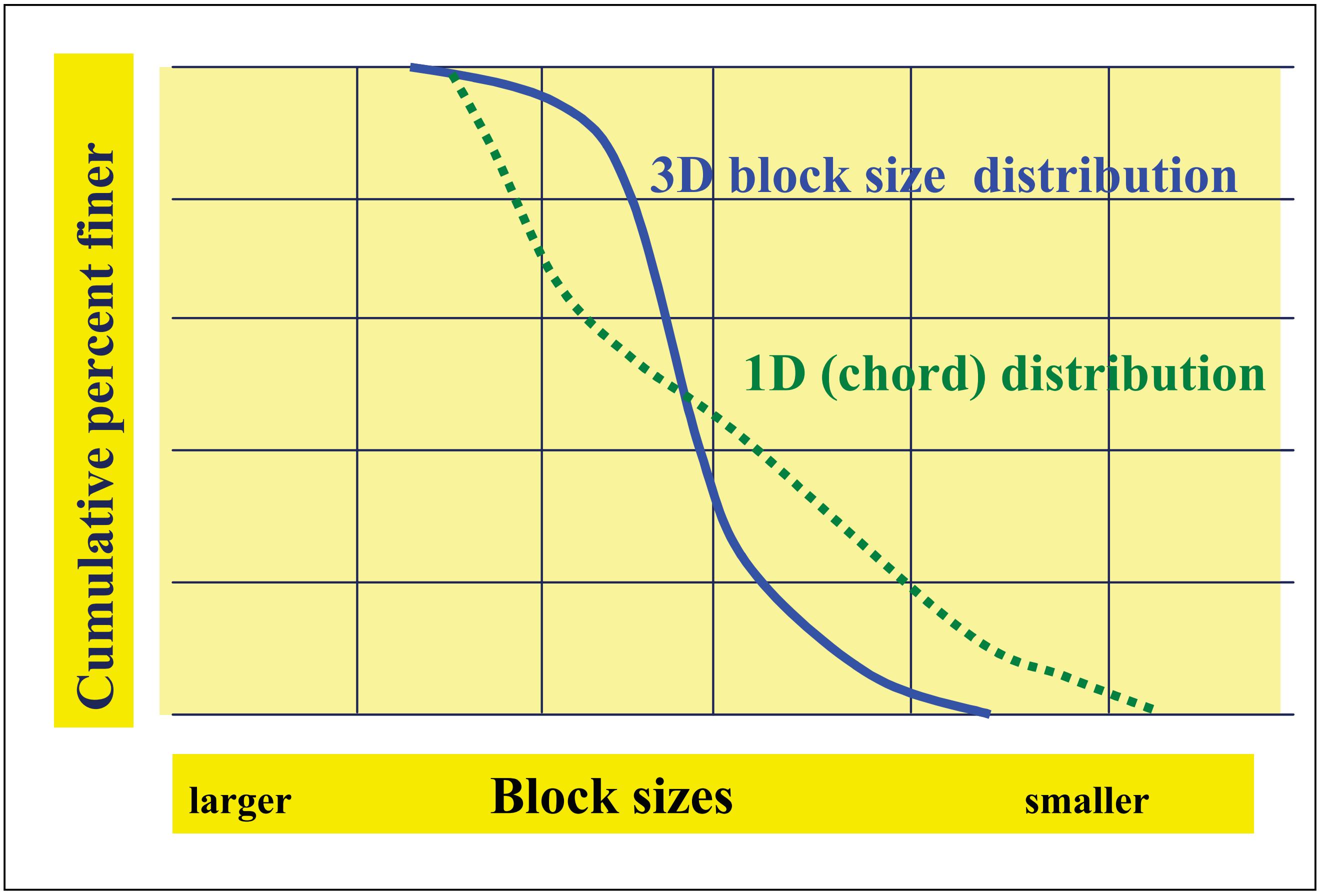


Figure B7. Schematic block size distribution plots for physical melange models with blocks oriented vertical and parallel to the model borings, such as shown in the second case of Fig. B6. 3-D block size distributions for blocks (as measured by the actual "diameter," or the largest dimension in three dimensions) compared to 1-D chord length distributions (as measured by the lengths of the intercepts between exploration borings and the block). Since chords are rarely equivalent to the maximum dimensions of blocks, the chord length distributions tend to be more "graded" than the parent block size distribution. The size distribution of smaller blocks is overestimated. Indeed, smaller block sizes are predicted that are not contained in the parent rock mass.

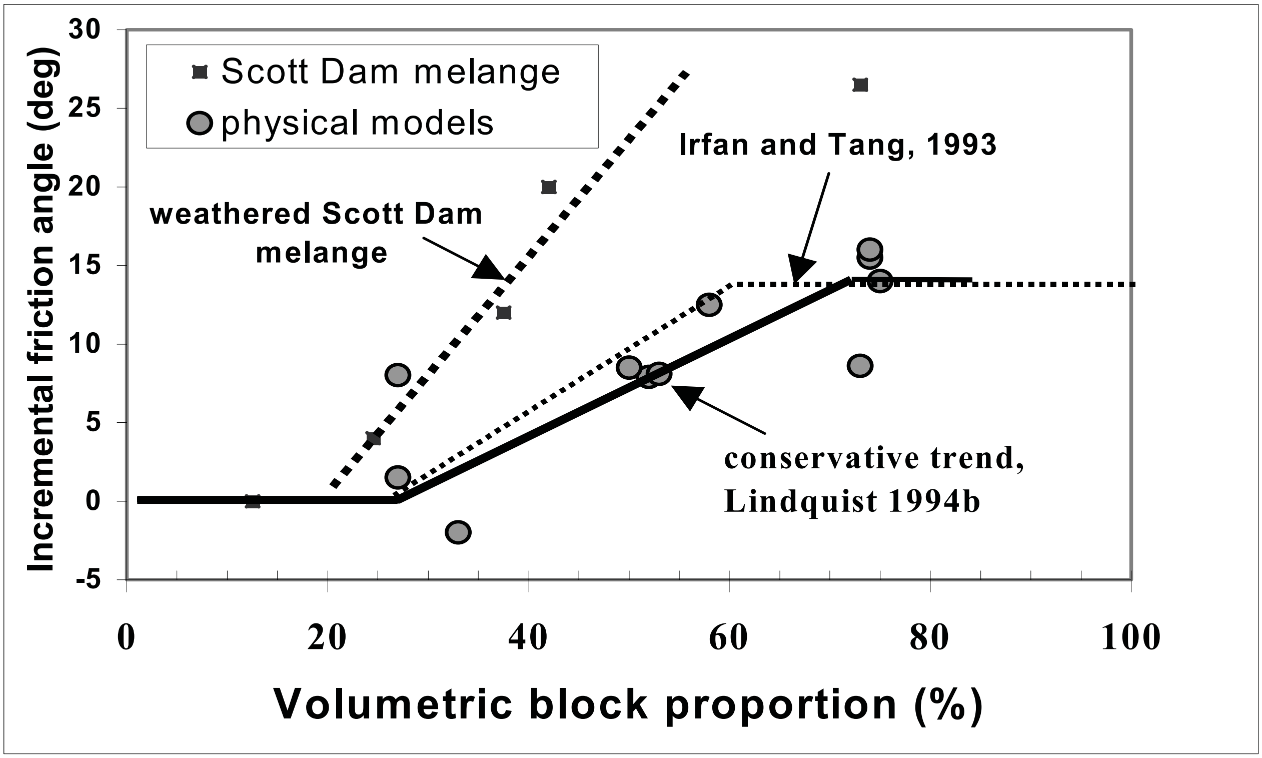


Figure B8. The strength of bimrocks increases directly with volumetric block proportion. The increase in friction is added to the frictional strength of the matrix. There is marked similarity between the data of Lindquist (25, 26), for physical model melanges, and that of Irfan and Tang (11), for Hong Kong boulder colluvium. However, the data obtained from laboratory testing of weathered Franciscan melange from Scott Dam (30) shows that for some bimrocks, blocks may provide considerably more incremental strength than indicated by the Lindquist and the Irfan and Tang experiments. The "conservative trend" of Lindquist (26) could be used in lieu of site-specific testing of Franciscan melanges. (After Medley (39).)

Figure B9. Franciscan melange at Coleman Beach, Sonoma County, Northern California. Blocks form erosion-resistant headlands and also buttress upslope weaker block-poor melange. Several homes are threatened by cliff-top retreat of block-poor melange. The near shore is strewn with relict blocks.

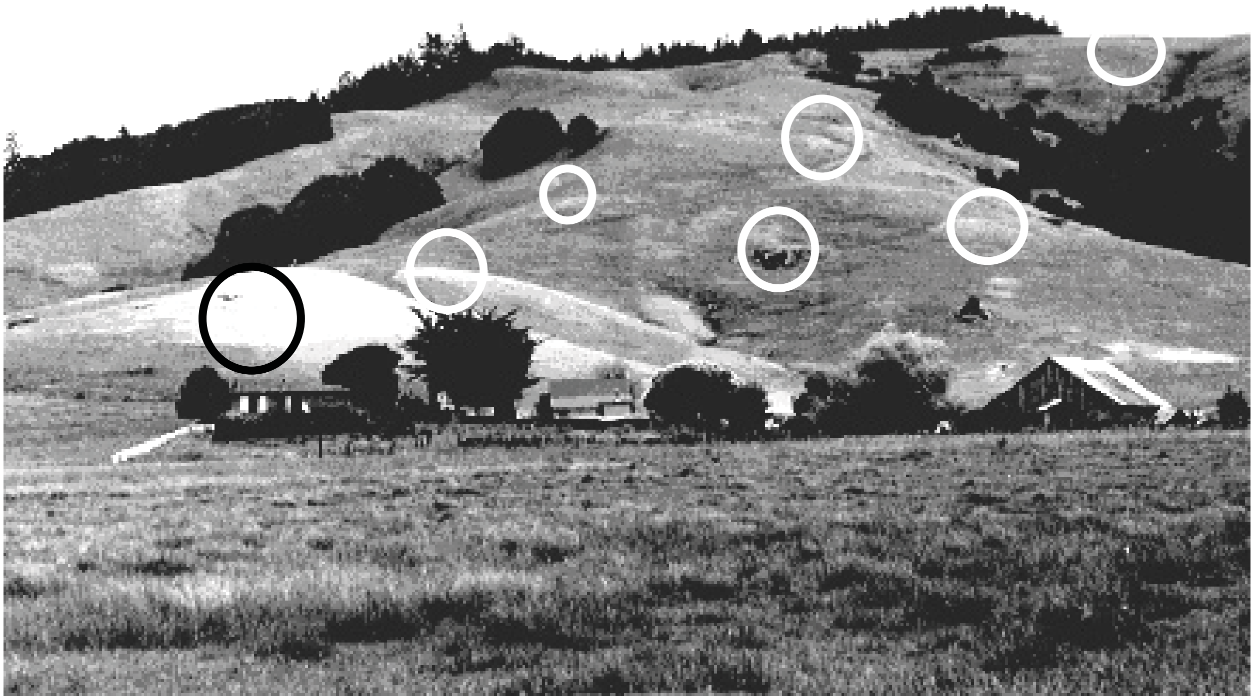
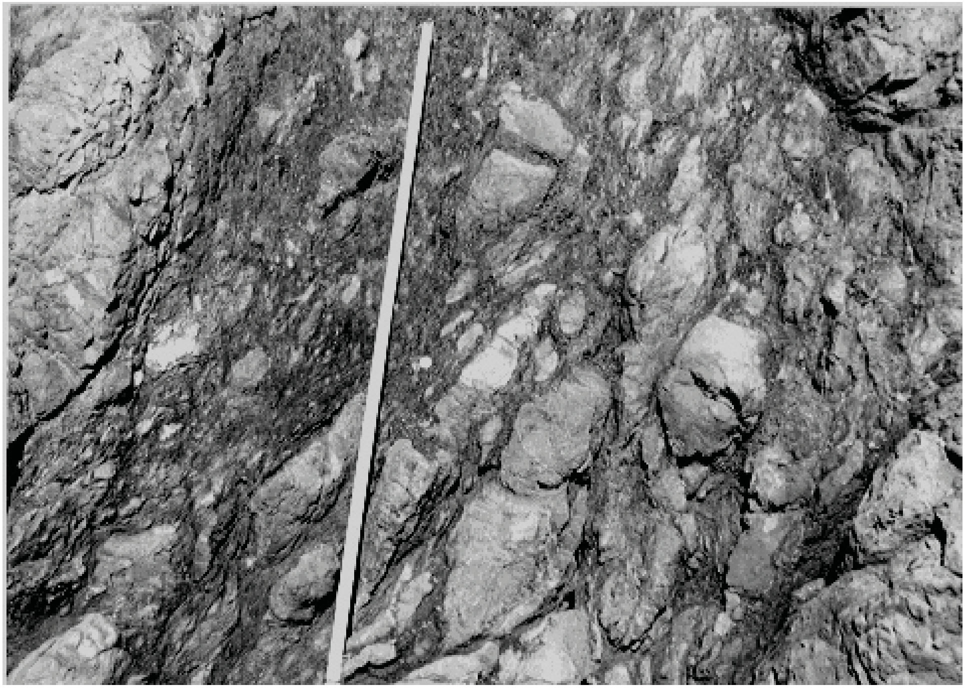


Figure B10. Franciscan melange photographed in the spring/early summer. Mottling of lighter tones indicates blocks underlying the hillside (circled).



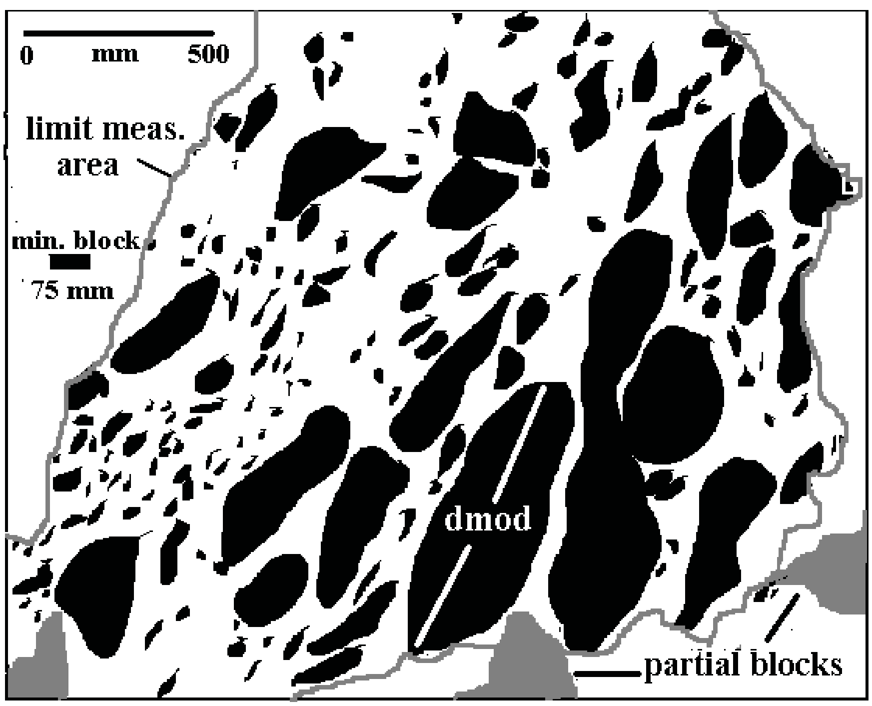


Figure B11. Photograph and sketch of outcrop of Franciscan melange at Caspar Headlands, Mendocino County, Northern California. The scale bar in the photograph is 1.5 m (5 feet) long. The sketch shows the blocks discriminated by image analysis software. Block sizes are characterized by d_{mod} (maximum observed dimension). The area of measurement excludes two partial blocks at the lower right of the outcrop. At the scale of the outcrop, the size of blocks at the block/matrix threshold (75 mm) is shown by the black bar midway on left side of sketch ("min. block 75 mm"). Note block-poor and block-rich areas. From Medley (1) and Medley and Lindquist (21).

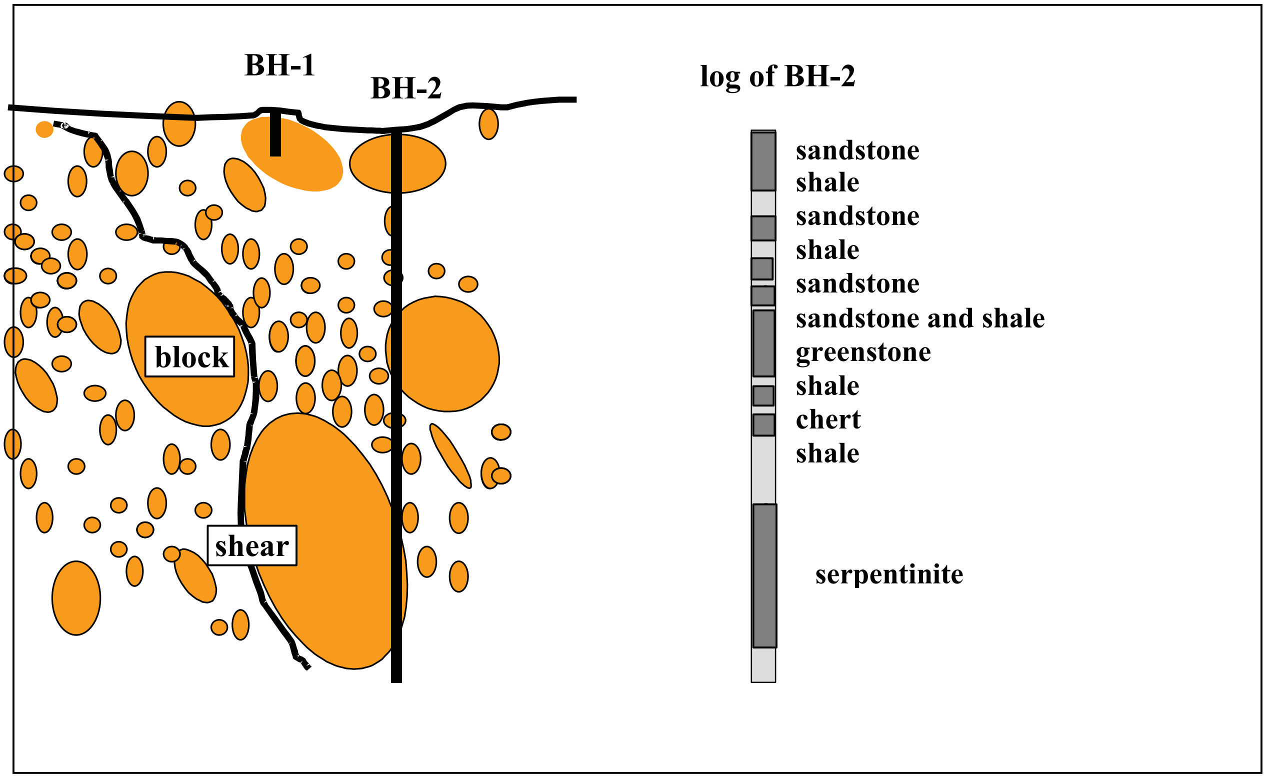


Figure B12. Shears in melanges typically tortuously negotiate around blocks at the block/matrix contacts. Sketch also shows exploration of a bimrock by borings (BH). BH-1 terminates in a block, a situation that, in Northern California, often results because the investigator identifies the block as "bedrock." The log of BH-2 shows a sequence of rocks that is not "interbedded sandstones and shales," because the juxtaposed presence of chert, greenstone, and serpentinite suggests the presence of Franciscan melange. Note that BH-2 only rarely penetrates the "diameter" of a block.

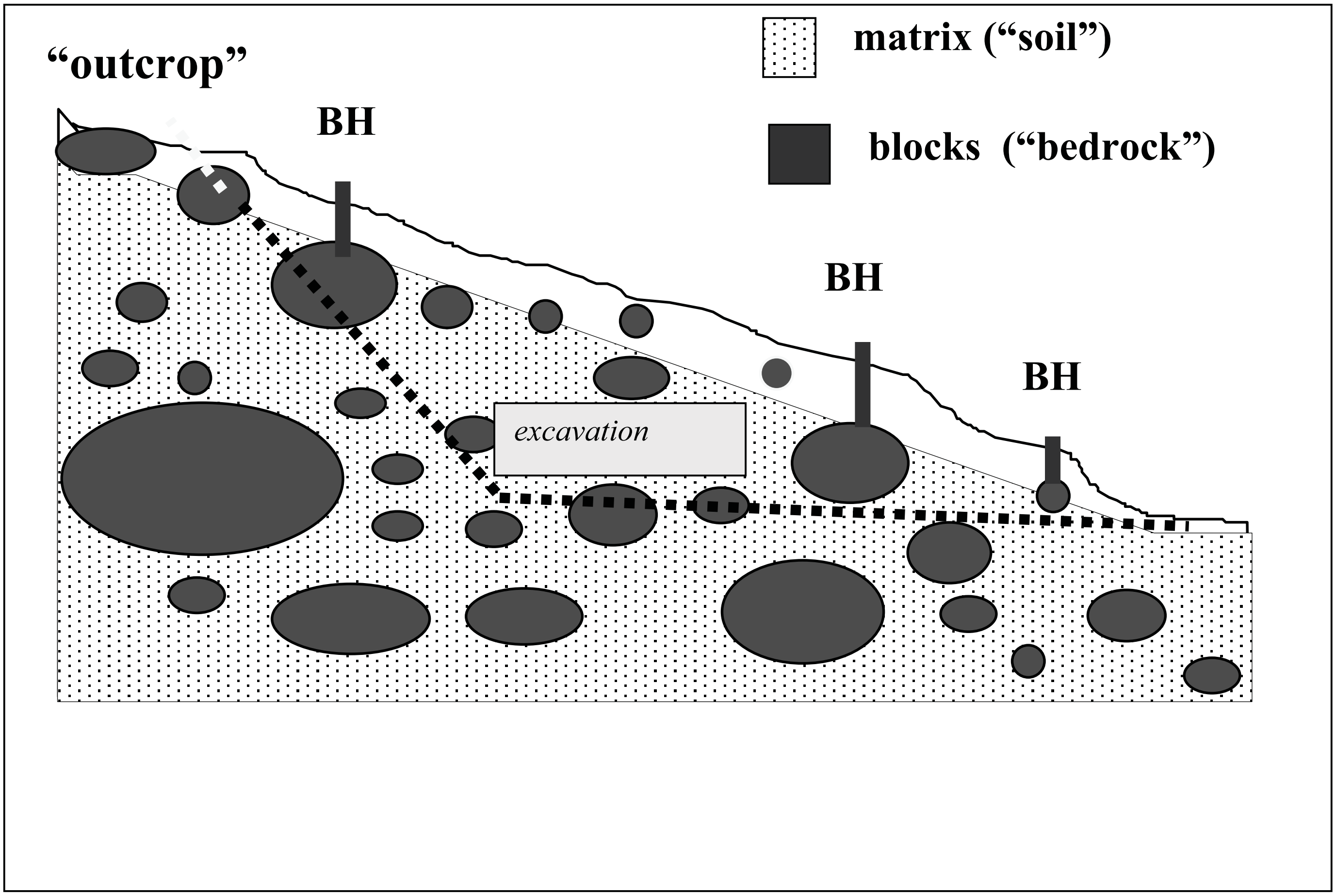


Figure B13. Borings (BH) in melange. Borings have been terminated in rock interpreted as continuous "bedrock" rather than blocks, and the matrix as "soil" or "soil with boulders." Because of this misinterpretation, the slope will be troublesome for two reasons: (1) rather than continuous bedrock, the excavated materials will be a mixture of matrix and blocks, and (2) the geotechnical properties of the matrix will influence the stability of the slope in an unexpected manner.

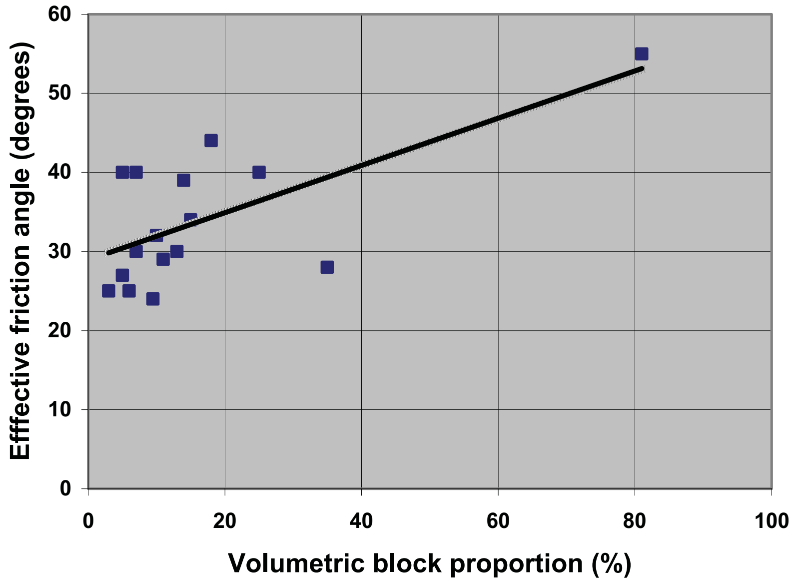


Figure B14. Plot of effective friction angle as a function of volumetric block proportion, generated from laboratory testing of Franciscan melange specimens obtained from core drilling at Scott Dam, Northern California (after Goodman and Ahlgren (8). The correlation is not good, but a straight-line fit is appropriate, given prior experience with laboratory testing of bimrocks (see Fig. B8). Inclusion of the data points at about 38 percent and 80 percent volumetric block proportions renders the best-fit line more conservative.

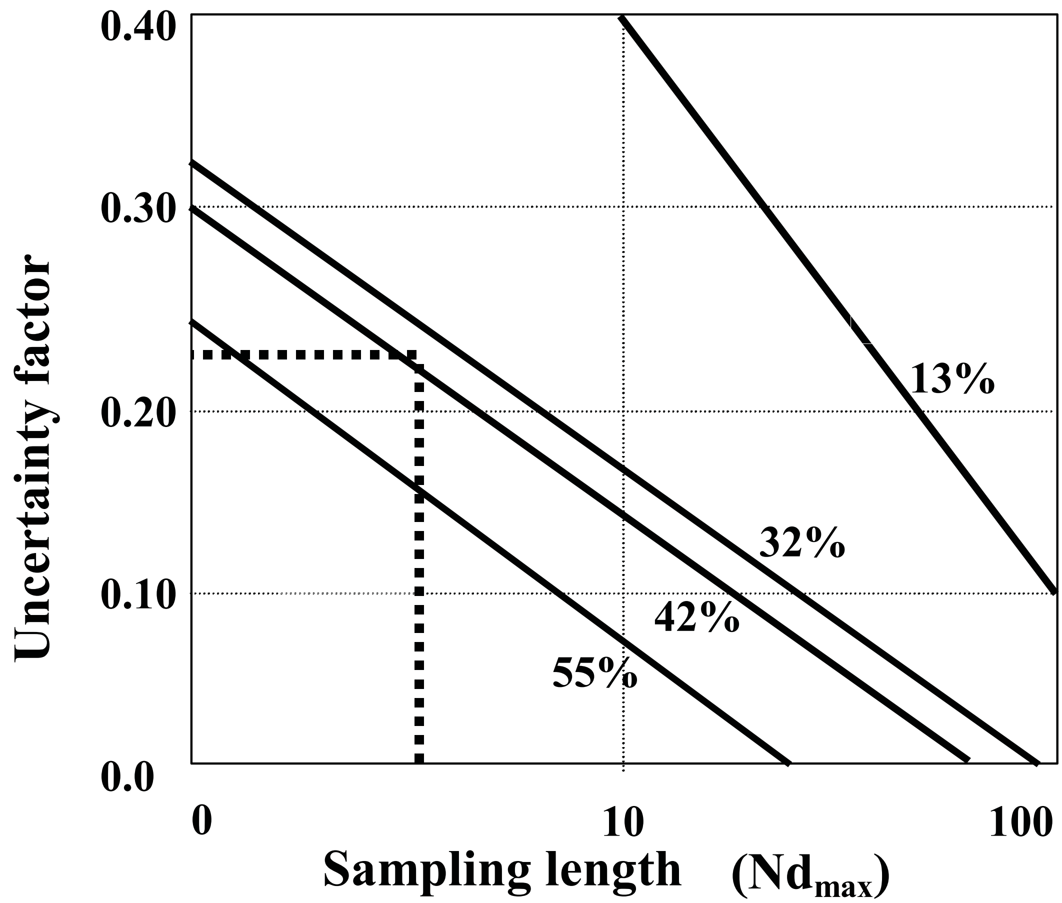


Figure B15. Uncertainty in estimates of volumetric block proportion as a function of the length of linear measurement, expressed as a multiple (N) of the length of the largest block (d_{max}), and the measured linear block proportion (13% to 55%). (From Medley (35)). The dashed line shows the use of the graph for an example (provided in the text) at Scott Dam, where the 150 m of drill core (sampling length) was equivalent to 5 times the size of the largest block expected in the region of the dam (30 m). Hence, Nd_{max} is 5. The measured linear block proportion was 40 percent. Entering the graph at Nd_{max} of 5, and intersecting the linear volumetric proportion of 40% (interpolating between 42% and 32% diagonal lines), gives an uncertainty factor of 0.22 (dimensionless). The uncertainty in assuming that the linear block proportion is the same as the volumetric block proportion is estimated as 40%+/- (0.22)(40%), or 40% +/- 9 %, giving upper and lower bounds of 31 percent and 49 percent. The actual volumetric block proportion will generally lie within the range of the lower and upper bounds. It is prudent to use the lowest estimate if the volumetric block proportion will be used to estimate bimrock strength. On the other hand, if the volumetric block proportion will be used for excavation purposes, it may be appropriate to overestimate the block proportion, in which case the upper bound could be used.