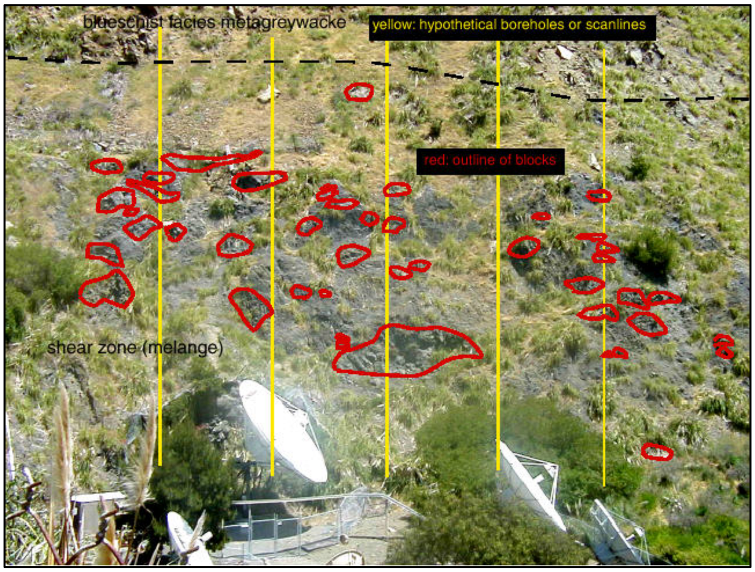
TUNNELS THROUGH FAULT ROCKS AND TECTONIC MELANGES: A SHORT COURSE FOR ENGINEERING GEOLOGISTS AND GEOTECHNICAL ENGINEERS

FIELD TRIP GUIDEBOOK -- MAY 31, 2002

Edited by: Elizabeth Lincoln Mathieson, RG, CEG

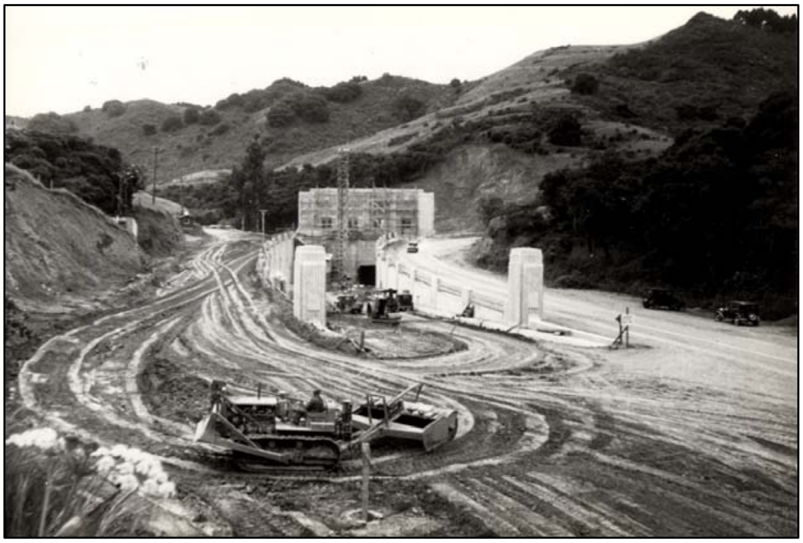


Fault Rocks and Franciscan Melange at an Abandoned Quarry, Schmidt Lane Recycling Center, El Cerrito, California

Photograph by John Wakabayashi and
Ed Medley:
May 9, 2002

Geologic and Geotechnical Engineering Aspects of the Caldecott Tunnel, Highway 24, Oakland to Orinda, California

Photograph provided by Caltrans:
Caldecott Tunnel under construction, 1930s



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Edited by: Elizabeth Lincoln Mathieson, RG, CEG,
Managing Scientist, Exponent Failure Analysis Associates,
Oakland, California

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John Wakabayashi, Ph.D., RG, Consultant, Hayward, California

Edmund W. Medley, Ph.D., PE, CEG, Principal Engineer,
Exponent Failure Analysis Associates, Menlo Park, California

Geologic and Geotechnical Engineering Aspects of the Caldecott Tunnel, Highway 24, Oakland, California

Grant Wilcox, PE, RG, Senior Engineering Geologist,
Caltrans District 4, Oakland, California

Christopher Risden, Geologist,
Caltrans District 4, Oakland, California

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Wakabayashi, J., 1999, The Franciscan Complex, San Francisco Bay Area: A record of subduction processes: in Wagner, D.L., and Graham, S.A., eds., Geologic field trips in northern California, California Division of Mines and Geology Special Publication 119. **(COPYRIGHT 1999 BY CALIFORNIA DIVISION OF MINES AND GEOLOGY. Reproduced with permission of CALIFORNIA DIVISION OF MINES AND GEOLOGY.)**

Wakabayashi, J., 1999, Subduction and the rock record: Concepts developed in the Franciscan Complex, California: in Sloan, D., Moores, E.M., and Stout, D. eds., Classic Cordilleran Concepts: A View From California: Geological Society of America Special Paper 338, p. 123-133. **(COPYRIGHT 1999 BY GEOLOGICAL SOC OF AMERICA. Reproduced with permission of GEOLOGICAL SOC OF AMERICA via Copyright Clearance Center.)**

INTRODUCTION

Elizabeth Lincoln Mathieson, RG, CEG, Exponent Failure Analysis Associates, 1970 Broadway, Suite 250, Oakland, CA, 94612, USA; emathieson@exponent.com; and Edmund W. Medley, Ph.D., PE, CEG, Exponent Failure Analysis Associates, 149 Commonwealth Drive, Menlo Park, CA 94025; emedley@exponent.com; **http://www.exponent.com**

This guidebook was prepared for a half-day field trip to be held on May 31, 2002. The field trip will be followed by a full day of lectures (on June 1) at the Caltrans (California Department of Transportation) Auditorium in downtown Oakland, California. Together the field trip and the lectures constitute a Short Course entitled, "***TUNNELS THROUGH FAULT ROCKS AND TECTONIC MELANGES: A SHORT COURSE FOR ENGINEERING GEOLOGISTS AND GEOTECHNICAL ENGINEERS.***" In addition to this field trip guidebook, a binder of handouts from the lectures will be available for purchase from the San Francisco Section of the Association of Engineering Geologists. The June 1 lecturers are Dr. Richard Goodman, Professor Emeritus of the University of California, Berkeley; Dr. Gunter Riedmüller, the senior Professor at the Institute of Engineering Geology and Applied Mineralogy at the Technical University of Graz, Austria, and Principal Engineering Geologist of 3G (Gruppe Geotechnik Graz); and Dr. Wulf Schubert, the senior Professor of the Institute for Rock Mechanics and Tunnelling at the Technical University of Graz, and Principal Tunnel Engineer at 3G. Dr. Edmund Medley, PE, CEG, Principal Engineer of Exponent Failure Analysis Associates, Menlo Park, California, will briefly review some fundamental aspects related to the characterization of melanges and similar block-in-matrix rocks (bimrocks).

Relatively little is known about engineering geological characterization and geomechanical properties of complex brittle fault rocks and tectonic melanges, although these troublesome block-in-matrix rocks are common throughout the world. The idea for the short course grew out of past collaborations among the field trip leaders and the lecturers, all of whom have had experience working with brittle fault rocks and tectonic melanges, and wished to collectively share their knowledge with colleagues. The short course is designed to introduce engineering geologists and geotechnical engineers to techniques useful for the characterization, design, and construction of tunnels in fault rocks and melanges. The course is topical given that several tunnels and excavations are currently in design, or are proposed for construction, in fault rocks and melanges of the San Francisco Bay Area. The course also provides background useful to geo-professionals interested in characterizing melanges, fault rocks, and similar block-in-matrix rocks for excavations and other earthworks.

Our two field trip stops, an abandoned quarry in El Cerrito, California, and the very active Caldecott Tunnel on Highway 24 between Oakland and Orinda, California, showcase 1) the geology and mechanical properties of a famous tectonic melange-bearing unit, the Franciscan Complex, and 2) the design and construction experiences of the builders of a series of existing and proposed automobile tunnels through brittle fault rocks. The field trip leaders hope to impress upon participants that, first, tectonic melanges and brittle fault rocks are challenging materials to characterize and with which to build, and, second, systematic methods of characterization can be used by the geo-practitioner to minimize construction surprises and expensive delays, and to minimize needless overdesign in chaotic rock masses.

ABOUT THE ASSOCIATION OF ENGINEERING GEOLOGISTS

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This field trip guidebook is published by the San Francisco Section of the Association of Engineering Geologists (AEG). AEG has been reviewed and approved as an Authorized Provider of continuing education and training programs by the International Association for Continuing Education and Training (1620 "I" Street, NW, Suite 615, Washington, D.C. 20006). The following description of AEG is a quote from the organization's web site, http://www.aegweb.org:

> The Association of Engineering Geologists was originally founded as the California Association of Engineering Geologists (**CAEG**) in 1957. In 1963, **CAEG** became the **Association of Engineering Geologists** (**AEG**) after the first non-California Section was formed in Denver, Colorado. AEG was developed to meet the professional needs of geologists who are applying their scientific training and experience to the broad field of civil and environmental engineering. Engineering geologists work in close coordination with construction, foundation and highway engineers, hydraulic engineers and hydrologists and with environmental professionals in environmental remediation, city planning and natural hazard risk reduction. The mission of AEG is to provide leadership in the development and application of geologic principles and knowledge to serve engineering, environmental and public needs. AEG members represent geological engineers and geologists in practice, academic and governmental positions.

For more information about the San Francisco Section of AEG, visit http://www.aegsf.org.

ACKNOWLEDGEMENTS

The San Francisco Section of the Association of Engineering Geologists would like to acknowledge the generous assistance of the following people, in addition to our hard-working field-trip leaders:

- Ernest Solomon, AEG San Francisco Section Short Course Committee Chair; Julie Keaton, AEG Director of Education; Joe Cota, AEG Continuing Education and Short Courses Committee Manager; Chris Mathewson, AEG Executive Director; Lisa Paulick, AEG San Francisco Section Newsletter Editor and Webmaster

- Darren Mack, American Society of Civil Engineers, San Francisco Section, Geotechnical Group

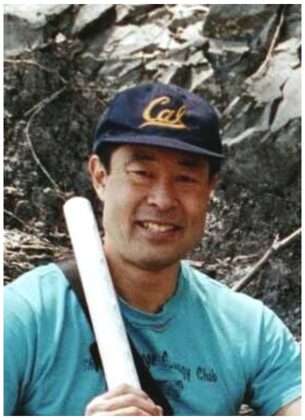
- Heather Abrams, City of El Cerrito Integrated Waste Services Manager

- Joan Van Velsor, Caltrans Chief of Geotechnical Services; Ray Mailhot, Caltrans Superintendent Tunnels and Tubes

- Hubert Vogel, Geologist, Exponent Failure Analysis Associates; Margaret Benton, Administrative Assistant, Exponent Failure Analysis Associates; Michael O'Neill, Senior Engineer, Exponent; Rosalie Galindo, Office Admin, Exponent; Joanna Meldrum, Senior Engineer, Exponent Failure Analysis Associates

FIELD TRIP LEADERS

John Wakabayashi, Ph.D., RG – El Cerrito quarry stop

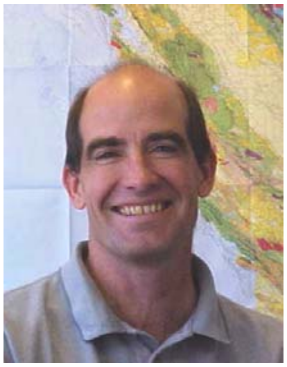


Dr. John Wakabayashi, RG, is a geologist with over 14 years of experience that spans a wide range of applied geoscience disciplines, including engineering geology, environmental geology, and neotectonics/seismic hazard studies. He has worked as an independent consultant for the last 9 years, but he is perhaps best known for his research on active and ancient plate boundaries, research that has gained him international recognition. The core of his research, which has been conducted largely as a hobby, has concerned the evolution of subduction complexes, particularly the Franciscan Complex of California. He has also taught classes at local unversities. Dr. Wakabayashi has been particularly active as a field trip leader, especially for localities in the Franciscan Complex and San Andreas fault system. He has led field trips for international, national, and local geologic organizations, and university departments (including several from outside of the USA). For more information, including his c.v. and a project list, see Dr. Wakabayashi's website at: http://www.tdl.com/~wako/.

Edmund W. Medley, Ph.D., PE, CEG – El Cerrito quarry stop

Dr. Edmund Medley, PE, CEG, is a geological engineer with over 20 years of international experience in geological and geotechnical engineering. His career includes chapters as a mineral exploration prospector, teacher, university lecturer, vagabond and bimrock researcher. He is a Principal Engineer at Exponent Failure Analysis Associates in Menlo Park, California, where he performs geo-forensic investigations. In his spare time, he pursues his passion for researching melanges and other species of geological complexity, which is a particularly apt area for him, given his surname and his chaotic life style…. Dr. Medley is a Certified Engineering Geologist in California and Registered as a Civil Engineer in California and Hawaii. He also holds professional geologist and professional engineer registrations in British Columbia and the United Kingdom. Ed can be reached at emedley@exponent.com, and additional professionals details are available at www.exponent.com (search under "Medley").

Grant Wilcox, PE, RG – Caldecott Tunnel stop



Grant Wilcox, PE, RG, is a Senior Engineering Geologist for Caltrans. He has been with Caltrans for 14 years. Prior to Caltrans, he worked 5 years for the Texas Highway Department. He has a BS in Geology from Texas Tech University and a BS in Civil Engineering from the University of Texas at Austin. Grant arrived in California in time to enjoy the 1989 Loma Prieta Earthquake and has spent the majority of his Caltrans career doing emergency landslide and storm damage repairs. Grant enjoys his work enormously and is still undecided if he is a Geologist or an Engineer. Grant loves the outdoors, camping, backpacking, golf, reading, music and spending quality time with friends and family.

Christopher Risden – Caldecott Tunnel stop

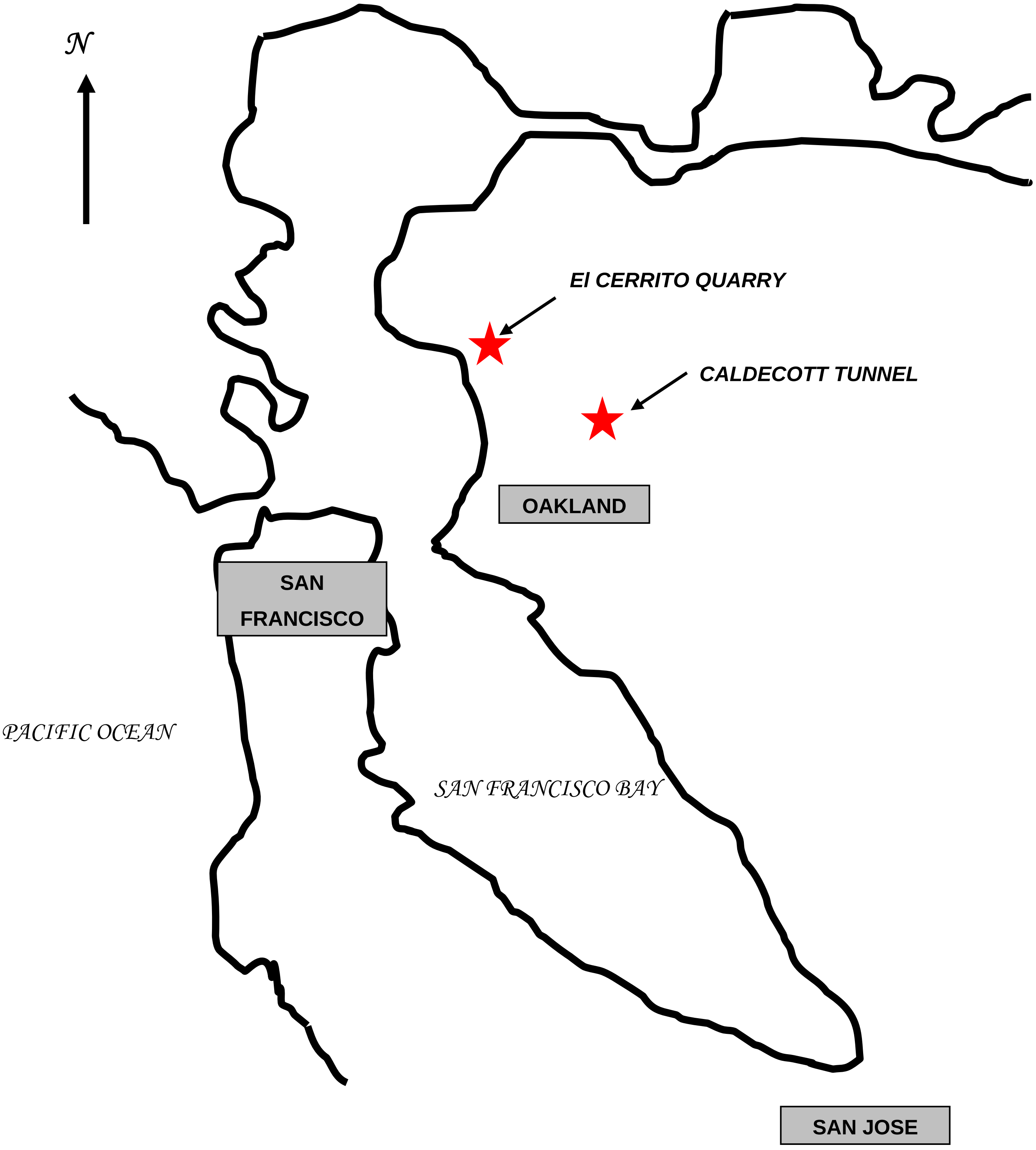
Chris Risden has been an engineering geologist with Caltrans for two years. Prior to that he worked as an environmental scientist for EVS Environment Consultants in Alameda, California. He has his BS in Geology from California State University at Hayward and spent three years studying at the University of California at Davis working on an as-yet-uncompleted master's degree. While primarily studying the evolution of peraluminous magmas in the northern Sierra Nevada, he has pursued other educational interests included mineral chemistry, Rb/Sr isotope systematics, and paleomagnetism. His field experience includes geologic mapping projects throughout the San Francisco East Bay, the Cascade Range, the Peninsular Range in Baja California, Mexico, and the northern Sierra Nevada. He also had the privilege of participating in an NSF-funded cruise along the Baja California coast as part of a study of the oxygen-minimum zone in the eastern Pacific Ocean. Since joining Caltrans, Chris has thrown most of his education out the window to better focus on landslide repairs and mitigation. He has attempted to impart to engineers the very basics of Franciscan Geology (if there are any "basics"), with few tangible results. His real passion is golf, which only now and again conflicts with his above-mentioned pursuits.

Elizabeth Lincoln Mathieson, RG, CEG – Field Trip Guidebook Editor

Betsy Mathieson has more than 20 years of experience in engineering and environmental geology. She holds a bachelor's degree in Geological Sciences from Harvard and a master's degree in Engineering Geology from Stanford, and is a licensed geologist in California, Oregon, and Tennessee. In addition to her work on failures real and imagined at Exponent Failure Analysis Associates she serves as Chairman of the Enforcement Oversight Committee of the California Board for Geologists and Geophysicists, and Past President and Building Code Development Committee Chair of the California Council of Geoscience Organizations. Betsy can be reached at: emathieson@exponent.com, and additional professional details about Betsy are available at www.exponent.com (search under "Mathieson").

FIELD TRIP STOPS

LOCATION MAP SHOWING FIELD TRIP STOPS



NOTE: DISTANCE BETWEEN STOPS IS ABOUT 12 MILES BY ROAD.

SEE DRIVING DIRECTIONS FOR EACH STOP, IN THIS GUIDEBOOK.

DRIVING DIRECTIONS

ABANDONED QUARRY
SCHMIDT LANE RECYCLING CENTER
EL CERRITO, CALIFORNIA

From Interstate 80 take the Central Avenue exit in El Cerrito. Turn (ENE) onto Central Avenue after exiting the freeway. Drive on Central Avenue to San Pablo Avenue then turn left (NNW) onto San Pablo Avenue. After several blocks (about 0.6 mi.) on San Pablo Avenue turn right (ENE) onto Moeser Lane. Proceed to a stoplight at Richmond Avenue and turn left (NNW). Proceed two blocks to Schmidt Lane, then turn right (ENE) and drive on Schmidt Lane to the recycling center (near the end of the road). Park just short of the recycling center entrance (which is on the left side of the road). Ample parking is available on both sides of the street. Access to the hillside (public property) west of the Recycling Center is on foot via a dirt road at the sign that says “El Cerrito Foundation Memorial Grove, City of El Cerrito, Hillside Nature Area.” If you wish to view the outcrops in the slopes directly above the recycling center at some time other than during the May 31, 2002, field trip, you will need to secure prior permission from the City of El Cerrito.

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

John Wakabayashi, Ph.D., RG, Consultant, 1329 Sheridan Lane, Hayward, CA 94544, USA; wako@tdl.com; http://www.tdl.com/~wako/
Edmund W. Medley, Ph.D., PE, CEG, Exponent Failure Analysis Associates, 149 Commonwealth Drive, Menlo Park, CA 94025, USA; emedley@exponent.com; http://www.exponent.com

INTRODUCTION

In California, 500 million years of active plate tectonics has created an abundance of fault rocks, melanges and similar bedrock composed of complexly mixed, often heterogeneous strong blocks embedded in a sheared, weaker matrix. Such rocks have been called *bimrocks* (for block-in-matrix rocks) by Medley (1994a). Volumetrically, the most significant bimrocks are melanges (from the French, *mélange*, or mixture) that are associated with subduction complexes. One major exception is the basal Great Valley Group of California (see Appendix A), which is not a fault rock but has the same mechanical properties. Bimrocks are of particular significance in California, because they constitute a significant fraction of the Franciscan Complex, a subduction complex deposit that makes up about a third of the bedrock in the central and northern Coast Ranges. Moreover, although the Franciscan is a famous locality for bimrocks, such materials are common in many other geologic units in California and the world, essentially all in orogenic ("mountain forming") belts, so the engineering problems associated with them are global in scope.

Melanges in particular, which occur in more than 60 countries, pose considerable challenges to engineering geologists, geotechnical engineers, contractors and owners, given their considerable spatial, lithological, geohydrological and geomechanical variability. However, as described below, and throughout the Short Course of which this Field Trip is part[1], fault rocks are also present in non-melange settings, and the dimensions of faults (up to tens or even hundreds of meters in thickness) are such that they can possess as much engineering significance as melanges. In the San Francisco Bay Area, melanges and other bimrocks are very well represented. The geological character of melanges has been recognized since the 1960s (e.g. Hsü, 1968), However, despite their abundance in California, practical and rational approaches to working with bimrocks are only now being appreciated by engineering geologists and geotechnical engineers due to pioneering work by local workers (Medley, 1994a,b; Lindquist, 1994a,b; Lindquist and Goodman, 1994: Medley and Lindquist, 1995, Medley, 1997, Goodman and Ahlgren, 2000; Medley, 2001).

For the purposes of this brief treatment, we present background information on some geologic aspects of fault rocks and melanges, and (in Appendix A) explain their occurrence in California as a product of their tectonic history. We describe the specific exposures at an abandoned quarry in El Cerrito that contains a classic exposure of a regionally significant Franciscan Complex thrust fault that is marked by a melange zone a few tens of meters thick (Stop 2 of Wakabayashi, 1999a). This field locality allows a view of a spectrum of bimrocks and fault-related structures. Appendix B provides guidelines to characterizing bimrocks that may be of use to the interested observer in correlating the features viewed during the field trip to his/her own experience and practice.

The goals of the Field Trip and associated Short Course are to alert geologists and engineers to the engineering significance of bimrocks (of which melanges and many fault rocks are a subset) and give geologists guidance to more clearly communicate the nature of such materials to engineers. We also wish to introduce geo-practitioners to the problems of bimrocks, as well as some rational approaches that have been developed to characterize such rocks. In reviewing the information and outcrops, questions you may ask yourself and the trip leaders could include:

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[1] "Tunneling through Fault Rocks and Tectonic Melanges: A Short Course for Engineering Geologists and Geotechnical Engineers," May 31 to June 1, 2002, Oakland, California; sponsored by San Francisco Sections of the Association of Engineering Geologists, and American Society of Civil Engineers, Geotechnical Group.

- How can I produce dependable maps and cross sections in bimrocks?
- What is a block? What is matrix?
- What should I measure?
- Everything is so chaotic: why bother describing it at all?
- What is the strength of a melange?
- What does all this geology stuff have to do with tunneling and/or excavations?

And so on……..

Some answers to these questions, and guidelines to characterization, can be found in this paper and its appendices, and the associated Short Course lectures.

FAULT ROCKS: THEIR OCCURRENCES AND SIGNIFICANCE FROM A GEO-PRACTITIONER'S VIEWPOINT

Most fault rocks having engineering significance are types of bimrocks. Many melanges are of tectonic origin and are thus fault rocks (e.g. Cloos 1984; Cowan, 1985; Jeanborquin, 2000). Some melanges are of entirely depositional origin (olistostromal, resulting from submarine landslides and thus not fault related) (e.g. Phipps, 1984) whereas some other melanges are of both depositional and tectonic origin (Aalto, 1981; Cowan, 1985). Regardless of the origin of a melange all are similar from an engineering standpoint because they represent the same sorts of challenges to characterize, tunnel through, or excavate.

As presented by Riedmüller et al. (2001), there are several different types of fault rocks, but the ones of engineering significance, and the types covered in the Short Course, are fault rocks produced by *brittle faulting*. The term brittle faulting means that the fault rock material was formed by brittle failure of rock; resulting in "milling" or breakage and fragmentation of the wall rocks by fault movement (cataclasis) producing a variety of fault rocks and rock particle sizes. In contrast, *ductile faulting* occurs at temperatures above 300°C, when plastic flow initiates in quartz, the mineral that controls the ductile strength of most crustal materials on Earth (Sibson, 1982). The difference between brittle and ductile faulting is important for geologists to understand because there are geomechanical consequences to the two very different processes. There are many major ductile faults that do not contain comparatively weak cataclastic deposits. For example there are mylonite zones in the Montara Mountain area, south of Pacifica, California, that, because of the recrystallization of quartz in them, are actually harder and more resistant than the quartz diorite they cut across (Wakabayashi and Moores, 1988). Much of the central Sierra Nevada foothills region is composed of sheared melange zones, but the matrices of the melanges have been recrystallized at elevated temperatures, generally 400°C or more, as quartz mica schist (e.g. Sharp, 1988), so that they probably do not behave as bimrocks from an engineering standpoint. This emphasizes the importance that a geologist recording field observations uses terminology that is meaningful to an engineer. If a geologist logs such material as a "shear zone," which is geologically correct, the description may mislead an engineer who believes that such a description implies a weak material.

Here we will briefly describe some geologic occurrences of fault rocks. Brittle fault zones range from a few mm thick to shear zones, usually melanges, up to tens of kilometers wide. The widest (thickest) zones (km in thickness) tend to be melange zones associated with thrust/reverse faulting in subduction complexes such as the Franciscan Complex. In general, strike-slip and normal fault shear zones do not reach tens of km in thickness, but thicknesses of 100 m or more can occur.

Brittle fault rocks are not limited to geologically recent (say Late Cenozoic) faults. Much older fault zones can have physical properties similar to active fault zones if they have not undergone significant cementation or recrystallization since their formation. In California the largest volumes of fault rocks are associated with brittle melange zones; these are common in the Franciscan Complex and are also present in the Klamath Mountains and the northern Sierra Nevada (Fig. 1). Many of the non-melange units in these areas, sometimes referred to by geologists in the literature as "coherent," are highly deformed and themselves are cut by fault zones on a variety of scales. In the Franciscan Complex most of the exposed melange zones likely formed more than 80 million years ago (e.g. Wakabayashi, 1992). These melange zones constitute the largest volume of brittle fault rocks in the California Coast Ranges.

Late Cenozoic strike-slip faulting accompanied by subordinate thrust faulting, associated with the tectonics of the San Andreas transform fault system, has contributed to the production of a much smaller volume of fault rocks. In the northern Sierra Nevada, much of the exposed basement experienced relatively low temperature metamorphism (e.g. Day et al., 1988), so brittle fault rocks are abundant; some of these features may be hundreds of millions of years old.

It is important to realize that fault rocks are not limited to structures associated with obvious fault offsets. Folding of interbedded strong and weak material, such as interbedded sandstone and shale, results in slip that is accommodated within the weak layers. For those unfamiliar with this concept, this type of shearing can be easily visualized by flexing a deck of cards (where the cards are the equivalent of the strong rock layers) resulting in offsets between cards at the ends of the folded deck. The layer-parallel flexural slip faulting (movement between the cards) does not offset any bedding, but it can create fault rocks that are no different in physical characteristics from those produced by other types of faults. Given that nearly all Cenozoic and older rocks of the California Coast Ranges have been folded, flexural slip deformation is to be expected in most parts of the Coast Ranges.

RECOGNIZING MELANGES, OR A BRIEF CASE HISTORY OF HOW GEOLOGIC THEORY IMPACTS FIELD "OBSERVATIONS"

The gradual and still changing history of the recognition of melanges as geologic features dramatically demonstrates the interpretative aspect of geologic field work. Some individuals in the geosciences, many of whom reside in research-oriented academic departments or engineering firms, feel that because much of the land surface of the Earth has been mapped, field geology is an unnecessary waste of time and resources. However, such opinions ignore the interpretive nature of field geology. Seldom is the exposure of rock 100%, and even if it is, the complexity of structure can make projection of mapped geologic relations at the surface into the subsurface a poorer bet than forecasting the weather. The geologist must always interpret what rocks lie between outcrops, or, in the subsurface, between exploratory boreholes. The geologic theories holding sway at any given time strongly influence how one "connects the dots," or (more aptly for the engineering geologist attempting to develop cross sections from exploration boreholes) how one “reads between the lines.”

The development of the melange concept illustrates the influence of geologic theory on geologic mapping (illustrated diagrammatically in Fig. 2 for map view and Fig. 3 for cross sectional interpretations based on boreholes). Prior to the late 1960s, geologists working in what was then called the Franciscan Formation (the “Formation” name implying that all internal contacts were depositional) would map scattered outcrops and then draw contacts on their maps so that the interpreted geology fit a stratiform depositional package. Then, Ken Hsü (Hsü, 1968) described melanges (blocks in a sheared, weak matrix) and formalized their classification. Following Hsü's approach, geologists mapping in the Franciscan and similar complicated geological regions began to map outcrops as blocks in the usually unseen matrix. Partly as a consequence of the recognition of melanges, but also as a result of the recognition of the connection of rock assemblages such as the Franciscan to the emerging theory of plate tectonics, the Franciscan Formation was renamed the Franciscan Complex, the name that is still used today. Some field geologists may have taken things too far, classifying the entire Franciscan Complex as melange and neglecting the internal details. One still encounters such simplifications today, even in some academic research papers.

Starting in the mid 1970s (Maxwell, 1974 and supporting references), some geologists began to delimit non-melange "coherent" Franciscan rock units (fault-bounded sheets) and discrete melange units. For example the Tin Cabin melange, the Poison Rocks melange, and the Hull Mtn. greywacke (coherent unit) were named as distinct subunits of the greater Franciscan Complex of the northern Coast Ranges (see Fig. 4, column A). In the 1980s geologists expanded on the mapping of coherent and melange units as the *terrane* concept gained favor in the North American Cordillera (e.g. Blake et al., 1982, 1984). (Terranes are defined as fault-bounded geologic units that bear no genetic connection to units adjacent to them; some such units have been transported thousands of kilometers from their original site of deposition. To learn more about terranes in a relaxed fashion, the interested reader may enjoy the popular book “Assembling California,” by John McPhee). Although differentiation of coherent units improved during this time, it may be argued that identification of melanges regressed during the era of Franciscan terrane mapping, as all Franciscan melanges were classified as one "Central Terrane" based on a model that all Franciscan melanges formed at the same time. (Readers of Franciscan literature beware: "Central Terrane" and "Central Belt" do not mean the same thing!!)

Wakabayashi (1992, 1999b) returned to the earlier interpretational style of Maxwell (1974) in delimiting discrete melanges as well as coherent units. He also correlated both melanges and coherent units throughout the Franciscan Complex with discrete structural levels in a complex composed of a stack of thrust nappes (sheetlike units bounded by thrust faults) (Fig. 4).

In conclusion, in over a century of geologic mapping in the Franciscan Complex, the rocks and outcrops have not changed (give or take a few road cuts), but the geologic maps have changed dramatically.

FAULT ROCKS AND MELANGES EXPOSED AT QUARRY AND ADJACENT HILLSIDE NEAR THE EL CERRITO RECYCLING CENTER

The El Cerrito portion of the field trip is a visit to one of the finest thrust fault exposures in northern California. This is a contact between two Franciscan units of different metamorphic grade exposed at the east end of Schmidt Lane in El Cerrito (Wakabayashi, 1999b) (see Fig. 5 for location in the San Francisco Bay Area). The fault exposed in the lower face of an abandoned quarry (now occupied by the recycling center) is a melange zone that separates two coherent nappes in the Franciscan Complex of the San Francisco Bay Area (Fig. 5). The largely bare slopes expose parts of the two coherent nappes and the intervening shear zone (Figs. 6, 7). These nappes are part of a regional scale structure that is characterized by folded, mainly coherent nappes separated by melanges (Figs. 4 and 5). Each melange represents a regional scale thrust fault.

The structurally higher coherent sheet of rock at the quarry is composed of blueschist facies (a grade of metamorphism) metagreywacke (metamorphosed greywacke sandstone), containing high pressure metamorphic minerals such as jadeitic clinopyroxene, lawsonite, glaucophane, and aragonite (these minerals are visible only in thin section with a petrographic microscope). However, despite the seemingly exotic rock description, the metagraywacke appears in hand specimen to be fairly ordinary sandstone, although it has a weak foliation. This unit belongs to the Angel Island nappe, originally defined by Wakabayashi (1992), which includes much of the rock on Angel Island (Fig. 5).

The melange zone between the upper unit and the lower unit has a shale matrix with blocks of sandstone, and rarer blocks of greenstone (metamorphosed basalt) and chert.

The structurally lower sheet of rock consists of sandstone and shale and is mostly coherent, although variably deformed in the outcrops at Schmidt Lane. The structurally lower sandstone belongs to the Alcatraz nappe of the Franciscan, which includes rocks on Alcatraz Island and in the northeastern part of San Francisco (including Telegraph Hill) (Fig. 5). The Alcatraz nappe is metamorphosed in the prehnite pumpellyite metamorphic facies, and the sandstone shows no visible fabric in hand specimen. The structurally lower sandstone is exposed in the slopes directly above the sidewalk along the north side of Schmidt Lane, to the west of the Recycling Center. Some block-in-matrix structure is exposed in these outcrops, which are otherwise mostly bedded sandstone and shale.

The difference in burial depth between the two sandstone units, as indicated by the different metamorphic grades (blueschist facies for the upper sheet, and prehnite pumpellyite facies for the lower sheet) is about 15 km (Wakabayashi, 1999b). The juxtaposition of the more deeply exhumed rocks of the hanging wall with the less deeply exhumed rocks of the footwall indicates that this is a thrust fault. Depending on the original dip of this melange zone, the amount of interpreted thrust displacement of the upper sheet over the lower sheet may be 20 km or more.

Asymmetric shear sense indicators, such as shear bands, asymmetric fabrics, and tails on porphyroclasts (large crystals deformed during the structural development of the rock), suggest a southwest sense of shear, which movement is consistent with the thrust fault relationship suggested by the juxtaposition of metamorphic grades of the upper and lower sheets. This thrust fault is a critical contact for understanding the history of the formation of the

Franciscan, for it preserves evidence contributing to an interpretation of the exhumation of the originally deeply buried (~30 km depth) blueschist facies rocks (Wakabayashi, 1999a, b).

Although the quarry lies only 500 m west of the active Hayward fault (Fig. 6), the regional structural relationships and textural relationships of metamorphic mineral growth indicate that the block-in-matrix fabrics exposed in the quarry appear to have been formed during the accretion of Franciscan, in the case of these two nappes, over 100 million years ago (Wakabayashi, 1999a). It is possible that a Quaternary fault with a reverse component may be present west of the quarry, defining the base of the natural slope. Such faults exhibit narrow, discrete zones of displacement (mm to centimeters thick), instead of broad melange zones, as has been learned from studies of similar faults on the San Francisco Peninsula (e.g. Hengesh et al., 1996).

The melange zone is exposed along the lower part of the quarry face (Fig. 7B). We will view this melange zone at one or two different places along the quarry wall. A view of the quarry wall shows the bimrock fabric, and it is clear that this chaotic structure would be difficult to recognize from borehole data alone. Indeed, Fig. 7B shows the quarry face with superimposed yellow lines that can be regarded as either borings or scanlines (geological traverses performed on outcrops for the purposes of characterizing rocks masses). A close up of this melange is shown in Fig. 9. Note that the block-in-matrix structure is scale independent; one can observe this fabric at tens of meters scale on the quarry face, at meter scale in outcrop, and on centimeter scale if we look closely at the matrix of the outcrop, as recognized by Medley (1994a, b; Medley and Lindquist, 1995; see also Appendix B). In other words, no matter at what scale one looks at the melange, one will find blocks.

Furthermore, the block size distributions also appear to be relatively similar: a few large blocks with increasing numbers of smaller blocks. However, we should also be aware that any block "sizes" that we could measure from outcrop exposures of the blocks (or the length intersected in a borehole) are only rarely equivalent to the "diameter" or the largest actual dimensions of the blocks (see Appendix B, Fig. B3). Because block measurements are generally smaller than actual maximum block dimensions, attempts to re-construct the actual block size distribution from measurements made in the outcrops or from boreholes will generally fail (Medley, 2002, in press, and Appendix B).

Via access up the dirt road west of the recycling center, we shall examine rocks on the upper part of the quarry wall, observing the transition from lower sheet, through the melange zone and up to the upper sheet. Note that the structurally higher part of the shear zone has itself undergone metamorphism at blueschist facies, because syn-and post-deformational glaucophane and lawsonite are present (Wakabayashi, 1999a). These exposed rocks, although part of the shear zone, were recrystallized and ductily deformed and are not brittle fault rocks.

SOME PRACTICAL PROBLEMS OF CHARACTERIZING BIMROCKS (AS APPARENT AT THE EL CERRITO SITE)

Field trip participants are encouraged to inspect and discuss the variety of rocks at this classic exposure. Inspection of the outcrops extending from the road level at Schmidt Lane to the upper slopes of the quarry will show a spectrum of rock from comparatively intact bedrock, partly sheared rock, and thoroughly sheared rock. In the melange there are zones with high areal proportions of blocks and zones with relatively low proportion of blocks. It is not known, of course, to what extent these surficial exposures of block proportion persist into the hillside; drilling is required to add data in order to begin to estimate the volumetric block proportion of a volume of interest. Estimates of volumetric block proportion would be particularly useful to a contractor if a slope excavation were contemplated at this site, for example. Also, estimates of volumetric block proportion are required in order to estimate rock mass strength (Lindquist, 1994, a, b; and Appendix B).

Melanges typically do not form good exposures except in steep artificial cuts, stream canyons, and sea cliffs (see Appendix B, Figs. B9 and B10). The matrix of a melange tends to consist of sheared shale, serpentinite, or both. Because of the weak nature of the matrix it is seldom exposed, although the harder blocks are exposed in many areas. This contrast creates a topographic form that has been referred to as "melting ice cream." Experience with the melanges of a given area, such as the Franciscan Complex, can be helpful in identifying typical block types of melanges in contrast to scattered outcrops of a coherent terrane. For example, a blueschist-eclogite thrust sheet in the Panoche Pass area mapped by Wakabayashi is exposed on hillsides only as isolated outcrops of blueschist or eclogite. In most areas of the Franciscan such a pattern of outcrop would almost certainly mean that the outcrops represent discrete blocks in an unseen melange matrix; many geologists today would probably interpret this field area as being underlain by melange. However, several dirt roads that cross the area exhibit continuous strip exposures that show that the metamorphic rock outcrops are part of a continuous thrust sheet of metamorphic rock rather than discrete blocks in melange; in other words, the rock beneath the grass is the same as the rock sticking above the grass. Clearly, from a tunnel engineer's or excavation contractor's point of view there is a considerable difference in the rock conditions implicit in the two contrasting interpretations!

Consistent bedding or foliation is not a diagnostic indicator of a coherent unit instead of a melange, because longer dimensions of the blocks are generally rotated to near parallelism with the foliation of the melange matrix. In other words, elongated or flat blocks are generally aligned parallel to their own internal bedding or foliation. When one sees a variety of lithologies and metamorphic grades exposed over a small area, it is likely that one is in melange terrane. In interpreting whether one is dealing with melange or relatively coherent rock it is always helpful to have a nearby continuous outcrop, whether it be a road cut, stream channel, or sea cliff. But, Geo. Murphy's Law states: "When good outcrops are REALLY needed, it is almost certain that Fortune will not bless the geologist."

Observations from geological borehole exploration represent even greater problems for interpretation (Fig. 3). Recovery of core tends to be much better in blocks than in matrix because the blocks survive the drilling process, where as the weak matrix generally does not (Riedmüller et al, 2001; Medley, 2001) (The geologist can improve Fortune by hiring a committed and careful drilling contractor.) The recovery of much core from blocks alone can give the mistaken impression that one has sampled largely coherent rock (with spotty recovery). Moreover, even if a bimrock structure is recognized, the lower recovery of the matrix will result in erroneously high block proportions unless this sampling bias is accounted for.

In addition, interpolation of geology between boreholes in block-and-matrix materials is so difficult and/or inaccurate that it should not generally be attempted. The prudent geologist should not draw straight lines between the observed lithologies in boreholes!! When surface mapping, one can use geomorphology, vegetation, and float to interpret the distribution of rock types between outcrops; no such tools exist for most subsurface interpretation in chaotic rocks. However, boreholes are of course sometimes useful for securing specimens for testing rock , although it is only with great difficulty that suitable specimens of intact matrix can be obtained (see Appendix B). Further, estimates of volumetric block proportion of a melange rock mass can be made from observations of the proportion of blocks intercepted to the total length of drilling (linear block proportion) as described by Medley (1994b), subject to adjustments that must be made to accommodate uncertainties due to inevitably insufficient drilling (Medley, 1997).

Accurate descriptions of bimrocks are critical, otherwise grave misinterpretation of the geologic data by non-geologists may result (see examples in Medley, 2001, and Appendix B). Terms such as "melange" are geologically correct, although basic descriptions such as "elongate masses of sandstone and siltstone in a sheared shale matrix" are more specific and useful. It is a good idea to accompany textual descriptions with photographs from local outcrops, or sketches, to communicate the characteristics of the heterogeneous, block-in-matrix fabric.

Terms such as "cataclasite" are also technically correct, but, again, a more specific description expressed in layperson's terms is better. A term such as "mylonite" may be close to the original definition of the term, but the term has recently been used by many research geologists to describe highly strained ductile rather than brittle rocks, so it should not be used for brittle fault rocks. Indeed, Medley (1994a) coined the word "bimrocks" because of the differing individual experience of readers of geological reports, the enormous variety of geological synonyms and aliases for mixed and fragmented rocks, and the "foreign language" flavor of geological terminology.

A description such as "interbedded sandstone and shale" for a bimrock composed of sandstone blocks in shale matrix is not only functionally incorrect, but it also gives the false impression of a stratabound (continuously bedded) unit rather than a chaotic unit of blocks separated by matrix. Such a false impression may survive geological borehole logs to become part of the interpretative process used to generate maps and cross sections, which in turn become the basis for engineering design and construction. Ultimately, the mislabeling can come with a price - the unexpected cost of change orders and construction disputes.

Because of the soft and highly sheared nature of the matrix of many melanges, some geologists logging boreholes may believe that they are exploring surficial soils. This ignorance leads to shocks when it is discovered that the "soil" may extend to a depth of several kilometers! Such a misinterpretation can also lead to problems when a borehole through mostly soft matrix encounters a big block and the geologist or geotechnical engineer believes that the hole has passed through soil to coherent bedrock. It is a common practice to drill 5 feet into bedrock in Northern California. But if boreholes do not terminate in continuous bedrock, but rather in separate blocks, characterization, design and construction based on the faulty interpretations can have expensive consequences (Medley, 2001 and Appendix B, Fig. B13).

CONCLUSIONS

The El Cerrito site provides engineering geologists and geotechnical engineers with a reasonably accessible place to study the problems associated with characterizing bimrocks. This exposure and the many others that can be found in the Bay Area and in northern California should convince visitors that they cannot ignore the chaos of bimrocks. It is not good enough to shrug your shoulders and say "This stuff is a mess: let's design for the weak component." Instead, the geo-practitioner is now able to take advantage of procedures that have been developed (and referred to here) that can be used to render more tractable the disorderly geology that distinguishes the San Francisco Bay Area from tamer terranes! It is hoped that this Field Trip and associated Short Course Lectures will encourage our engineering geologist and geotechnical engineer colleagues to be more thoughtful in their characterization of bimrocks, and in doing so lessen the difficulties of contractors and owners.

REFERENCES (including references for Appendix A)

Aalto, K.R., 1981, Multistage melange formation in the Franciscan Complex, northernmost California: Geology, v. 9, p. 602-607.

Atwater, T., Stock, J., 1998. Pacific-North America plate tectonics of the Neogene southwestern United States: An update: International Geology Review 40, p. 375-402.

Aydin, A., and Page, B.M., 1984. Diverse Pliocene-Quaternary tectonics in a transform environment, San Francisco Bay region, California. Geological Society of America Bulletin v. 95, p. 1303-1317.

Blake, M.C., Jr., Howell, D. G., and Jayko, A. S., 1984, Tectonostratigraphic terranes of the San Francisco Bay Region: in Blake, M. C., Jr., ed., Franciscan Geology of Northern California: Pacific Section Society of Economic Paleontologists and Mineralogists, v. 43, p. 5-22.

Blake, M.C., Jr., Howell, D. G., and Jones, D. L., 1982, Preliminary tectonostratigraphic terrane map of California: United States Geological Survey Open File Report 82-593.

Böhlke, J.K., 1999, Mother Lode gold, in Moores, E. M., Sloan, D., and Stout, D. L., 1999, Classic Cordilleran Concepts A View from California, Geological Society of America Special Paper 338, p. 55-67.

Cloos, M., 1984, Flow mélanges and the structural evolution of accretionary wedges: Geol. Soc. America Special Paper 198, p. 71-80.

Cowan, D.S., 1985, Structural styles in Mesozoic and Cenozoic melanges in the Western Cordillera of North America: Geological Society of America Bulletin, v. 96, p. 451-462.

Day, H.W., Schiffman, P., and Moores, E.M., 1988, Metamorphism and tectonics of the northern Sierra Nevada: in Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 737-763.

Dilek, Y., and Moores, E. M., 1992, Island-arc evolution and fracture zone tectonics in the Mesozoic Sierra Nevada, California, and implications for transform offset of the Sierran/Klamath convergent margins (U.S.A.), in Bartholomew, M.J,., Hyndman, D. W., Mogk, D. W., and Mason, eds., Characterization and comparison of Ancient (Precambrian-Mesozoic Continental Margins-Proceedings of the 8th International Conference on Basement tectonics at Butte, Montana USA, Kluwer, Dordrecht, p. 166-186.

Goodman, R.E., and Ahlgren, C.S., 2000, Evaluating safety of concrete gravity dam on weak rock: Scott Dam: Journal of Geotechnical and Geoenvironmental Engineering, ASCE, v. 126, No. 5, p. 429-442; with Discussion (by J. H. Hovland, E.W. Medley and R.L. Volpe; and Authors) in Vol 127, October 2000, p. 900-903.

Hengesh, J.V., Wakabayashi, J., and Nolan, J.M., 1996, Paleoseismic investigation of the Serra fault, San Francisco Peninsula, California: Final Technical Report, U.S. Geological Survey National Earthquake Hazards Reduction Program Fiscal Year 1995, Award No. 1434-95-G-2549.

Hsü, K.J., 1968, The principles of melanges and their bearing on the Franciscan-Knoxville paradox: Geological Society of America Bulletin, v. 79, p. 1063-1074.

Jeanborquin, P., 2000, Chronology of deformation of a Franciscan melange near San Francisco (California, USA): Eclogae geologicae Helvitiae, v. 93, p. 363-378.

Lindquist, E.S., 1994a, The strength and deformation properties of melange: Ph.D. dissertation, Dept. of Civil Engineering, University of California, Berkeley, CA, USA.

Lindquist, E.S., 1994b, The mechanical properties of a physical model melange: Proceedings of the 7th Congress of the Interational Association of Engineering Geologists, Lisbon. Rotterdam, Balkema. p. 819-826.

Lindquist, E.S., and Goodman, R.E., 1994, The strength and deformation properties of a physical model melange: in Nelson, P.P., and Laubach, S.E., eds., Proceedings of the 1st North American Rock Mechanics Conference (NARMS), Austin, TX. Rotterdam, Balkema, p. 843-850.

Maxwell, J.C., 1974, Anatomy of an orogen: Geological Society of America Bulletin, v. 85, p. 1195-1204.

Medley, E.W., 1994a, The engineering characterization of melanges and similar block-in-matrix (bimrocks): Ph.D. dissertation, Dept. of Civil Engineering, University of California, Berkeley, CA, USA.

Medley, E.W., 1994b, Using stereologic methods to estimate the volumetric block proportion in melanges and similar block-in-matrix rocks (bimrocks): Proceedings of the 7th Congress of the International Association of Engineering Geologists, Lisbon. Rotterdam, Balkema. p.1031-1040.

Medley, E.W., 1997, Uncertainty in estimates of block volumetric proportion in melange bimrocks, Proc Int. Symp. On Engineering Geology and the Environment, ed. Marinos, P.G., Kpukis, G., Tsiambous, G., and Stournaras, G., Rotterdam, Balkema, p. 267-272

Medley, E.W., 2001, Orderly characterization of chaotic Franciscan melanges: Felsbau, v. 19, p. 20-33.

Medley, E.W., 2002 (in press), Estimating blocks size distributions of melanges and similar block-in-matrix rocks (bimrocks), Proc. 5th N. Amer. Rock Mechanics Symp., Toronto, Canada, July 2002

Medley, E.W., and Lindquist, E.S., 1995, The engineering significance of the scale-independence of some Franciscan melanges in California, USA: in Daemen, J.K., and Schultz, R.A., eds., Proceedings of the 25th US Rock Mechanics Symposium, Rotterdam, Balkema, p. 907-914.

Moores, E.M., and Day, H.W., 1984, An overthrust model for the Sierra Nevada: Geology, v. 12, p. 416-419.

Namson, J.S., and Davis, T.L., 1988, Seismically active fold and thrust belt in the San Joaquin Valley, California: Geological Society of America Bulletin, v. 100, p. 257-273.

Phipps, S.P., 1984, Ophiolitic olistostromes in the basal Great Valley sequence, Napa County, northern California Coast Ranges: in Raymond, L.A., ed., Melanges: Their nature, origin, and significance, Geological Society America Special Paper 198, p. 103-125.

Riedmüller, G., Brosch, F.J., Klima, K., and Medley, E.W., 2001, Engineering geological characterization of brittle faults and classification of fault rocks: Felsbau, v. 19, p. 13-19.

Schweickert, R. A., and Cowan, D. S., 1975, Early Mesozoic tectonic evolution of the western Sierra Nevada, California: Geological Society of America Bulletin, v. 86, p. 1329-1336.

Schweickert, R.A., and Snyder, W.S., 1981, Paleozoic plate tectonics of the Sierra Nevada and adjacent regions: in Ernst, W.G., ed., The geotectonic development of California, Rubey Volume I: Englewood Cliffs, New Jersey, Prentice-Hall, p. 182-201.

Sharp, W.D., 1988, Pre-Cretaceous crustal evolution in the Sierra Nevada region, California: in Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 823-865.

Sibson, R.H., 1982, Fault zone models, heat flow, and depth distribution of earthquakes in the continental crust of the United States: Bulletin of the Seismological Society of America, v. 72, p. 151-163.

Unruh, J.R., Loewen, B. A., and Moores, E. M., 1995, Progressive arcward contraction of a Mesozoic-Tertiary forearc basin, southwestern Sacramento Valley, California, Geological Society of America Bulletin, v. 107, p. 38-53.

Wakabayashi, 1989, Tectonics and metamorphism of the Franciscan and related rocks, San Francisco Bay Area, California: Ph.D. dissertation, Dept. of Geology, University of California, Davis, CA, USA.

Wakabayashi, J., 1992, Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California: Journal of Geology, v. 100, p. 19-40.

Wakabayashi, J., 1999a, The Franciscan Complex, San Francisco Bay area: A record of subduction processes: in Wagner, D.L., and Graham, S. A., eds. Geologic field trips in northern California, California Division of Mines and Geology Special Publication 119, p. 1-21.

Wakabayashi, J., 1999b, Subduction and the rock record: Concepts developed in the Franciscan Complex, California: in Sloan, D., Moores, E.M., and Stout, D. eds., Classic Cordilleran Concepts: A View From California, Geological Society of America Special Paper 338, p. 123-133.

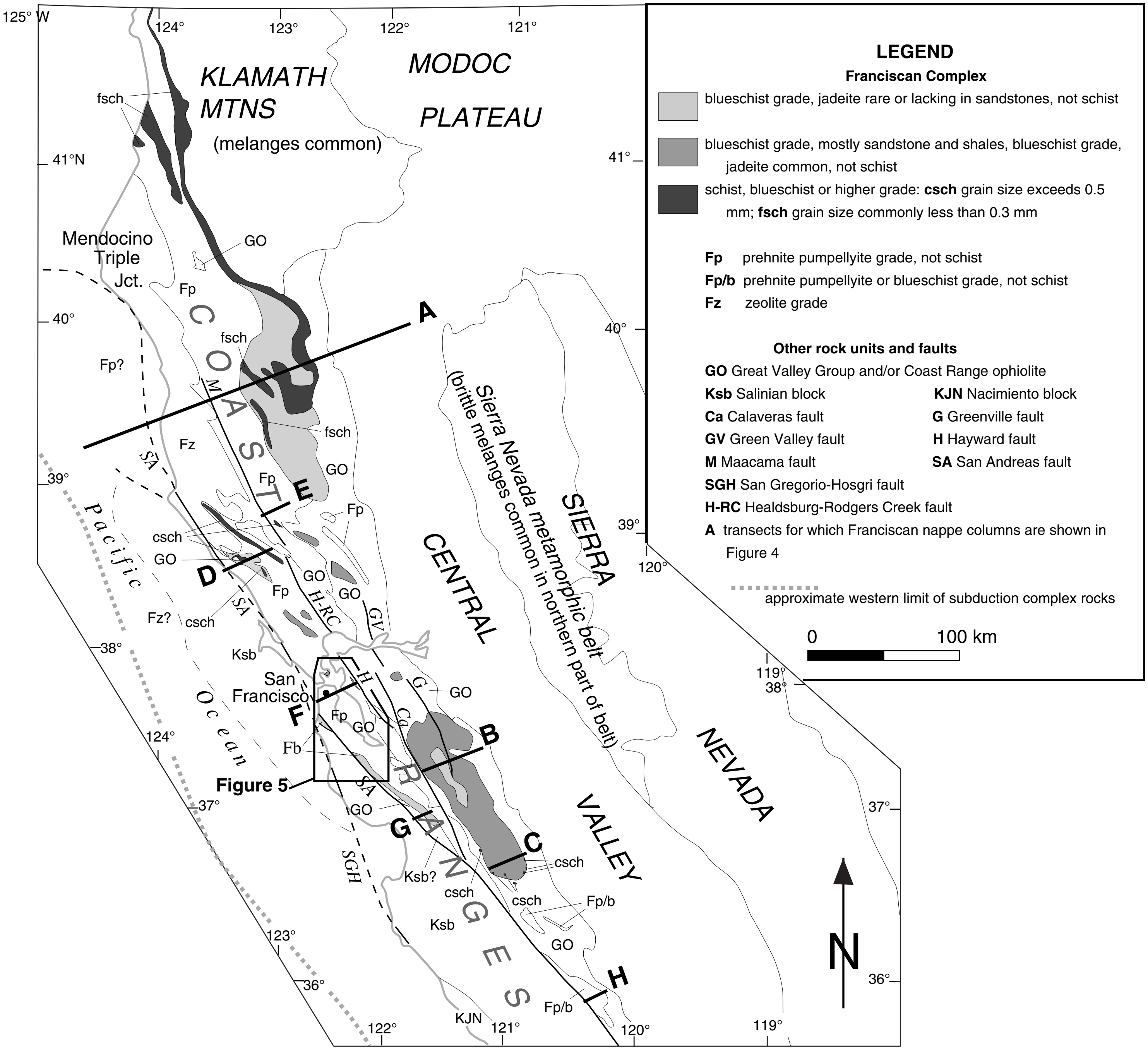
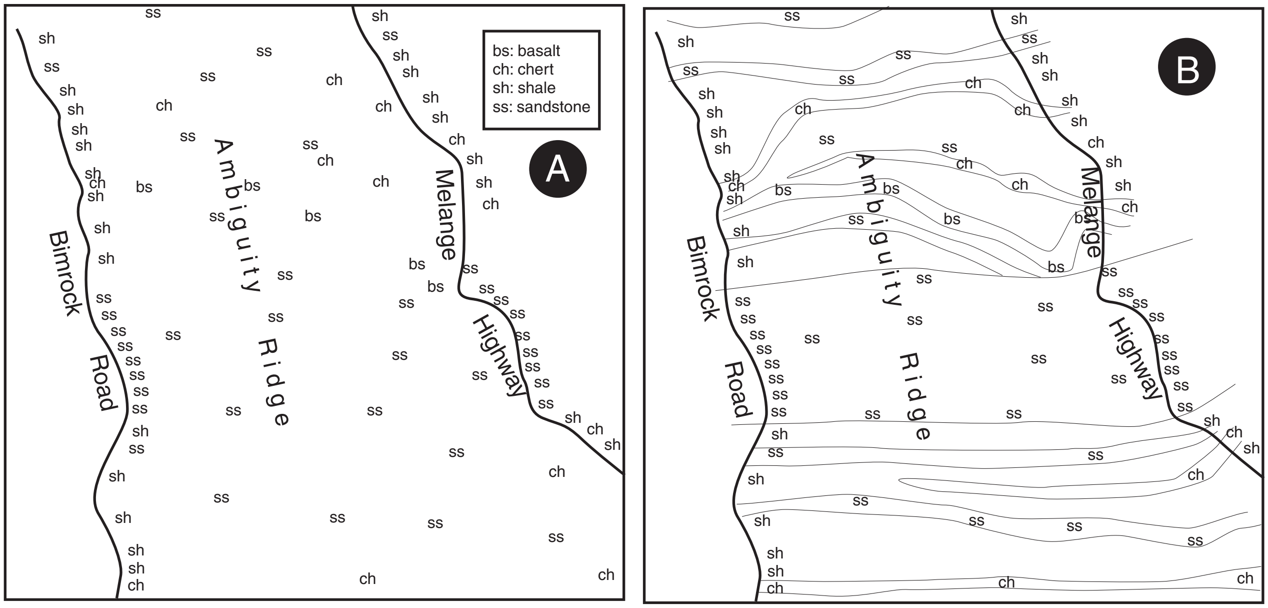


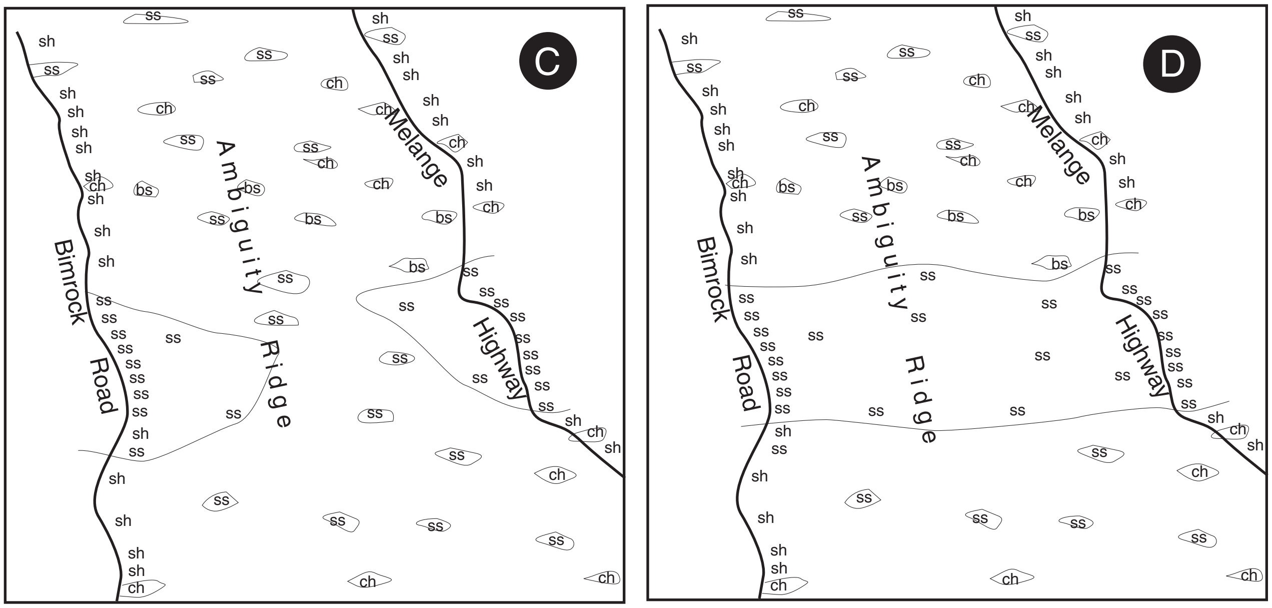
Figure 1: Distribution of Franciscan and other basement rocks of central and northern California, showing Franciscan of different metamorphic grades. Adapted from Wakabayashi (1999b). The Franciscan of prehnite-pumpellyite metamorphic grade is the part of the Franciscan that includes the most voluminous melanges (as illustrated in the nappe column diagram, Fig. 4). Note that in addition to the Franciscan Complex, brittle melanges are common in the northern part of the Sierra Nevada metamorphic belt (they are recrystallized in the central and southern part of the belt), and parts of the Klamath Mountains basement terranes. The Nacimiento block, situated west of the granitic Salinian block, is essentially the same type of subduction complex as the Franciscan (and is commonly considered part of the Franciscan); consequently, melange constitutes a significant fraction of this terrane.

The Rocks Stay The Same, But The Maps Change



Outcrops

Drawing contacts conforming to stratabound model

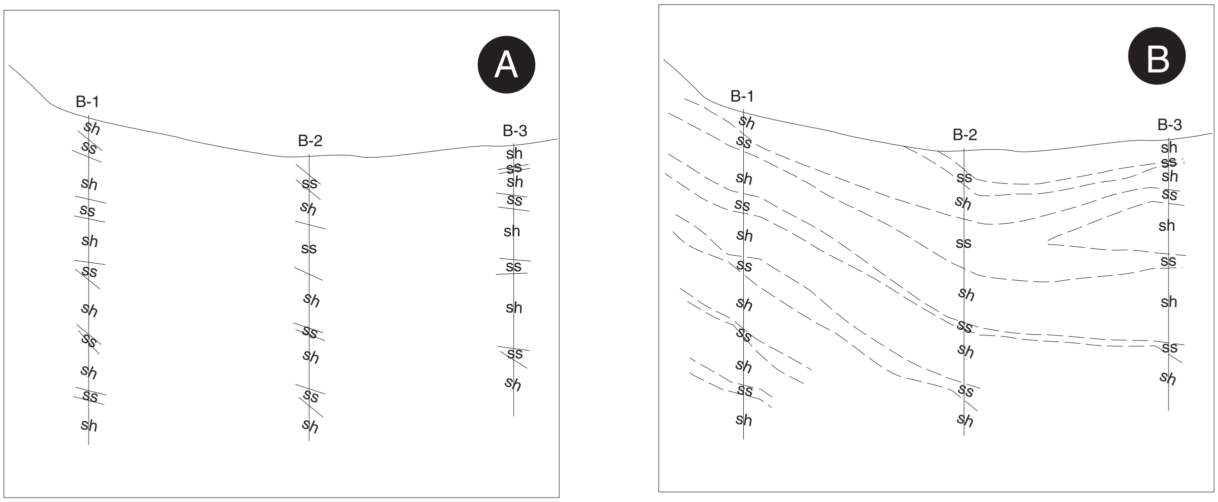


Drawing contacts conforming to melange model

Drawing contacts conforming to melange and coherent model

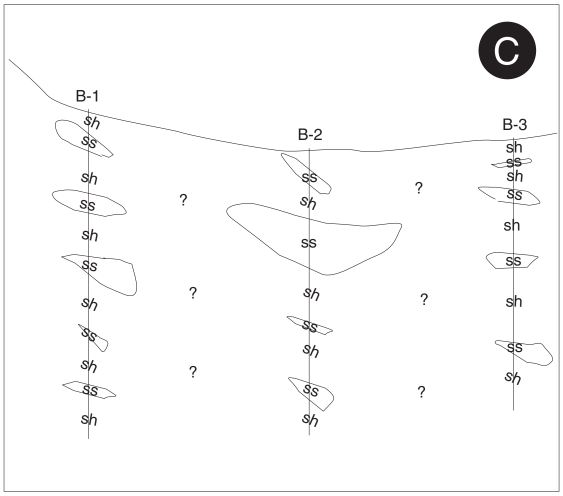
Fig. 2: Schematic geologic maps showing how prevailing geologic theories influence how contacts are drawn on maps. Outcrops are represented by abbreviations. Map B shows how geologists mapped in melange areas prior to the recognition of melange structures by Hsü (1968). Map C, shows how such outcrops were mapped after recognition of melanges in the Franciscan. This map shows the type of contact interpretation for geologists that considered the entire Franciscan Complex as a melange. Map D shows how the area may be interpreted as having both melange areas and a "coherent" sandstone unit: this is the current state of geologic field interpretation following that of workers such as Maxwell (1974), Blake et al. (1984), and Wakabayashi (1992).

The Core Does Not Change, But The Cross Section Does



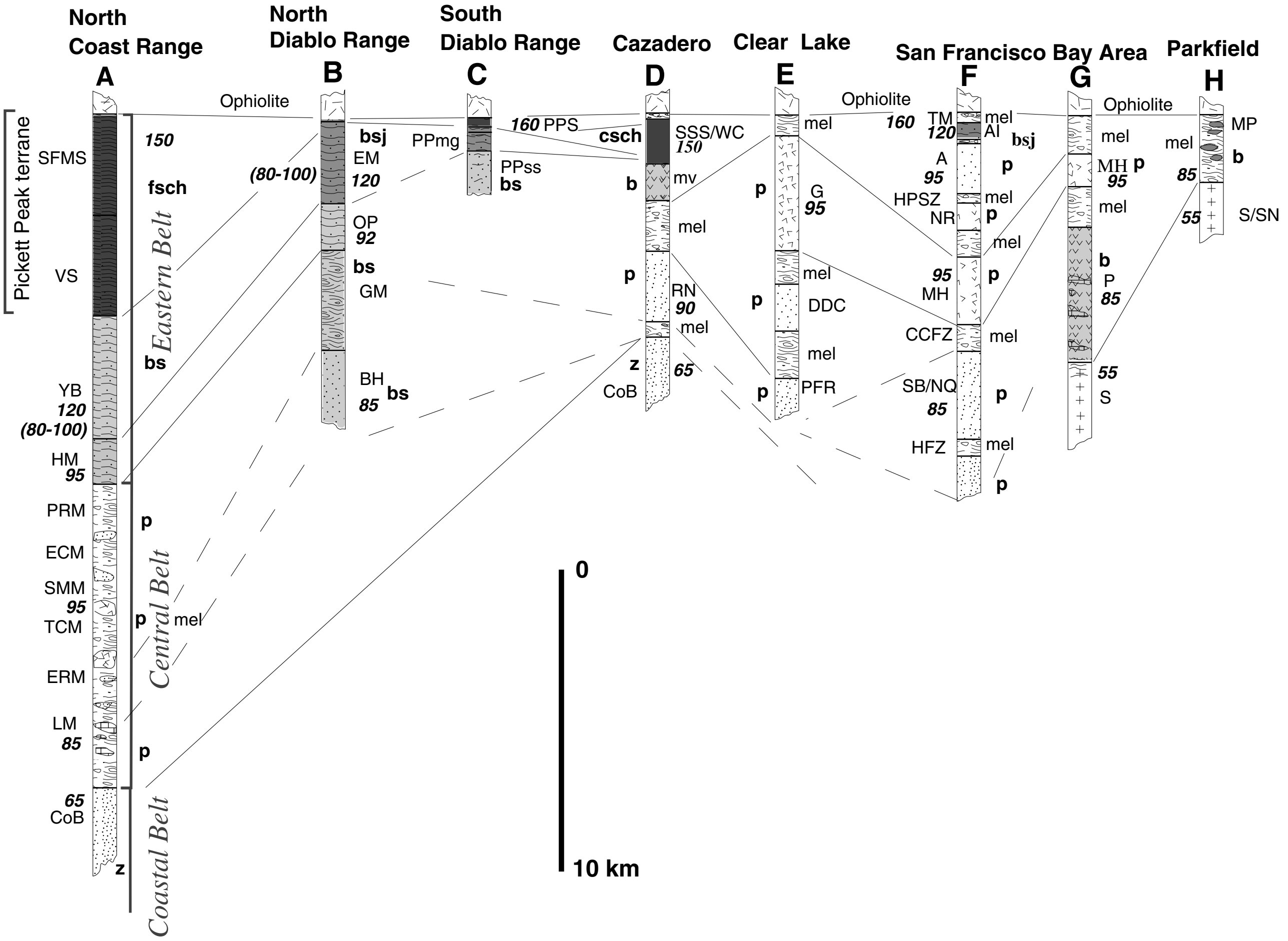
borehole intercepts

cross section conforming to stratabound model



cross section conforming to melange model

Figure 3: Cross sectional diagrams showing how prevailing geologic theory has influenced the interpretation of subsurface data obtained by exploratory drilling. Cross section B shows interpretation of subsurface structure including coherent stratigraphy. Cross section C shows shows interpretation of subsurface structure using a melange model. Note that unlike geologic mapping where float, vegetation and other indicators can allow the geologist to infer relationships between outcrops, the boreholes cannot predict what specific type of block and matrix relations will be found between the holes.



Abbreviations: Column A: SFMS: South Fork Mountain schist, VS:Valentine Springs formation, YB:Yolla Bolly terrane, HM: Hull Mtn. metagreywacke; PRM: Poison Rocks melange, ECM: Elk Creek melange, SMM: Sanhedrin Mtn. melange; TCM: Tin Cabin melange, ERM: Eel River melange, LM: Laytonville melange, CoB: Coastal Belt; **Column B:** EM: Eylar Mountain terrane, OP: Ortigalita Peak metagreywacke; GM: Garzas melange; BH: Burnt Hills terrane; **Column C:** PPS: Panoche Pass blueschist, PPmg: Panoche Pass jadeite-bearing metagreywacke, PPss: Panoche Pass jadeite-free metagreywacke; **Column D:** SSS/WC: Skaggs Springs schist and coherent schists of Ward Creek, mv: metavolcanics, incipient blueschist, RN: Rio Nido terrane, CoB: Coastal Belt; **Column E:** G: Geysers terrane, DDC: Devil's Den Canyon terrane, PFR: Pine Flat Road terrane; **Column F:** TM: Tiburon melange, AI: Angel Island nappe, A: Alcatraz terrane, HPSZ: Hunters Point shear zone, NR: Nicasio Reservoir terrane, MH: Marin Headlands terrane, CCFZ: City College fault zone, SB/NQ: San Bruno Mtn./Novato Quarry terranes, HFZ: Hillside fault zone; **Column G:** MH: Marin Headlands terrane, P: Permanente terrane, S: Salinia; **Column H:** S/SN:Salinia/Sierra Nevada, MP: Melange with blocks of Permanente terrane. **For all columns: b**: incipient blueschist metamorphism of mostly volcanic rocks, **z:** zeolite facies; **p:** prehnite pumpellyite facies, **bs:** blueschist metamorphism-jadeite absent or rare, **bsj**: same as **bs** except jadeite common, **fsch:** fine grained schists (completely recrystallized), **csch:** coarse grained schists (completely recrystallized), mel: major melange zone. ***120*** : estimated age of accretion in millions of years, ***(80-100)***: age of exhumation in millions of years

Figure 4: Correlation of Franciscan units as thrust nappes to relative structural position and estimated accretion ages. Blueschist facies units are shaded. Column locations keyed to Figure 1. All contacts are tectonic; incorporation age (not depositional age) decreases downward. Scale is approximate. Note that the depiction of melange units is schematic only--no block proportion or block size distribution is implied. Adapted from Wakabayashi (1999b).

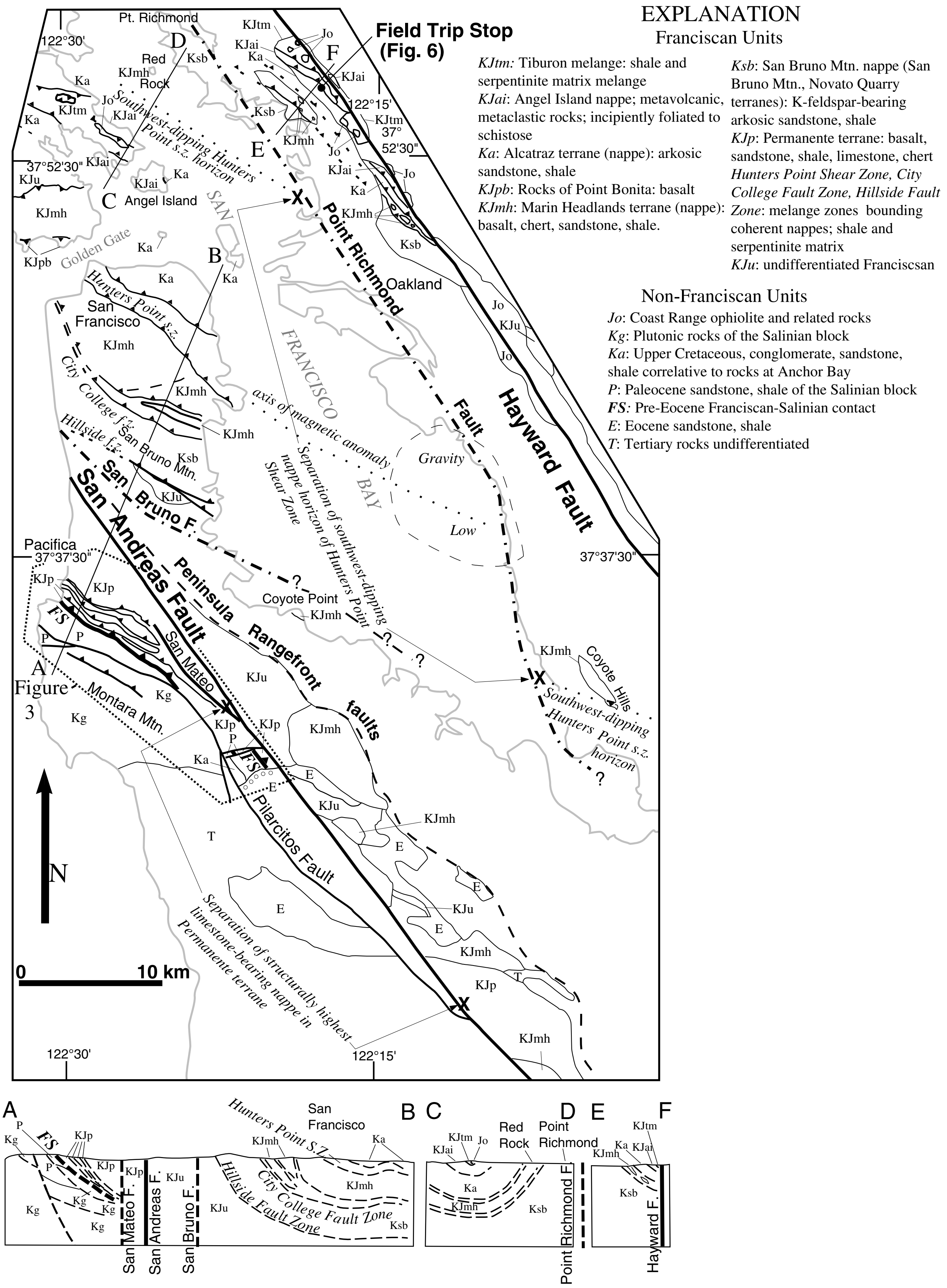


Figure 5: Franciscan Complex geology of the San Francisco Bay area. Adapted from Wakabayashi (1999c). Note that the Franciscan in this area is composed of mostly coherent nappes with intervening melange zones. The location of the field trip stop is shown.

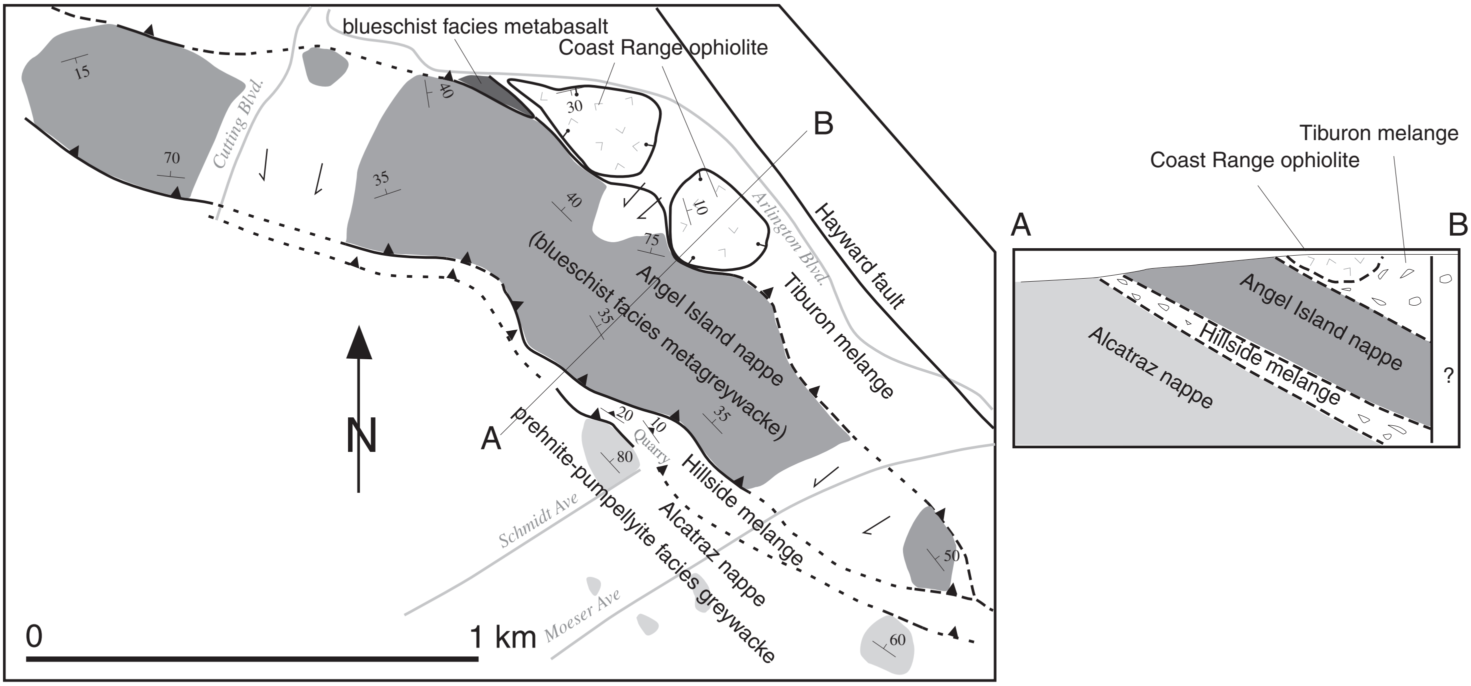


Figure 6: General geology in the vicinity of the field trip stop. Adapted from Wakabayashi (1989).

Figure 7A: View northwestward from the recycling center at the east end of Schmidt Lane, El Cerrito, showing the contact between the structurally higher, blueschist facies metagreywacke and the shear zone melange that places the blueschist facies rocks above prehnite-pumpellyite facies sandstone, shale and broken formation (outcrops to the left (west) of the photo along the northern border of Schmidt Lane). This shear zone dips northeast and the difference in metamorphic burial between the hanging and footwalls is 15 km; thrust fault displacement is likely in excess of 20 km.

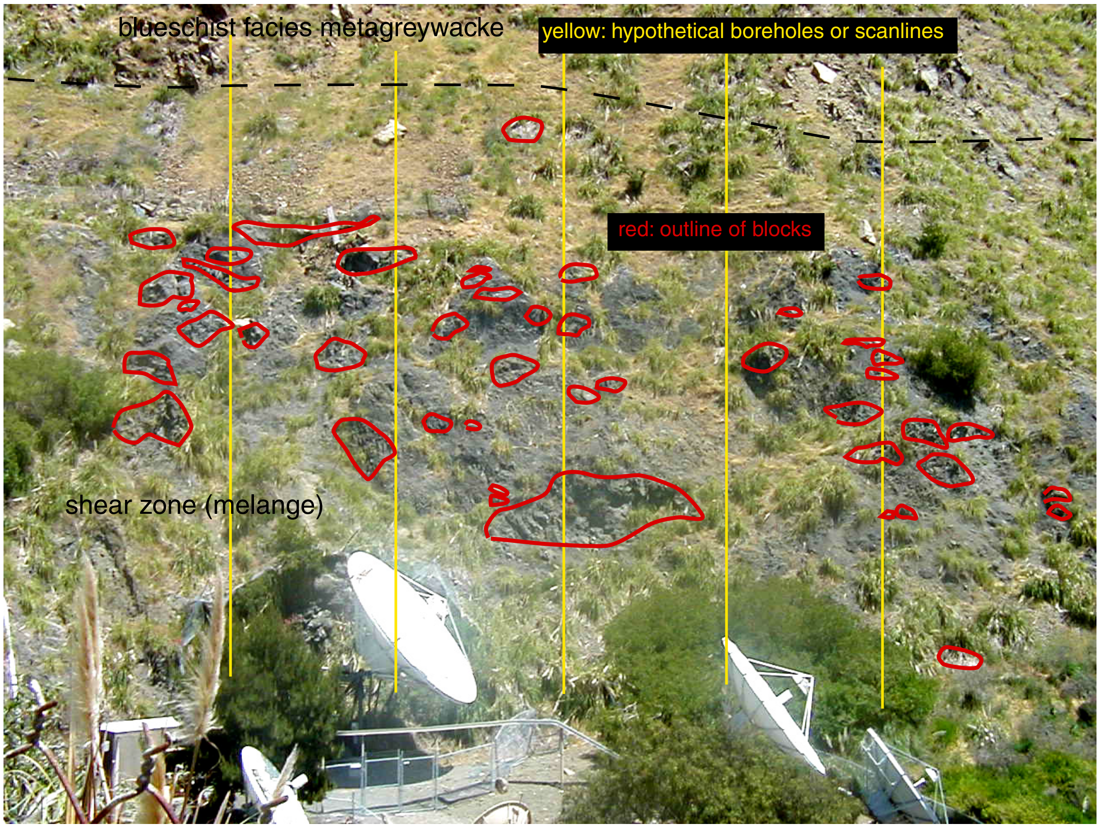


Figure 7B: View northeastward toward the lower part of the quarry face above the El Cerrito recycling center. Some blocks in the melange are outlined in red. Note that if one had boreholes intersecting such material (depicted in yellow) that lithologies cannot be correlated between boreholes. Moreover block proportions are not the same in each borehole, and the regions between the boreholes are also different.

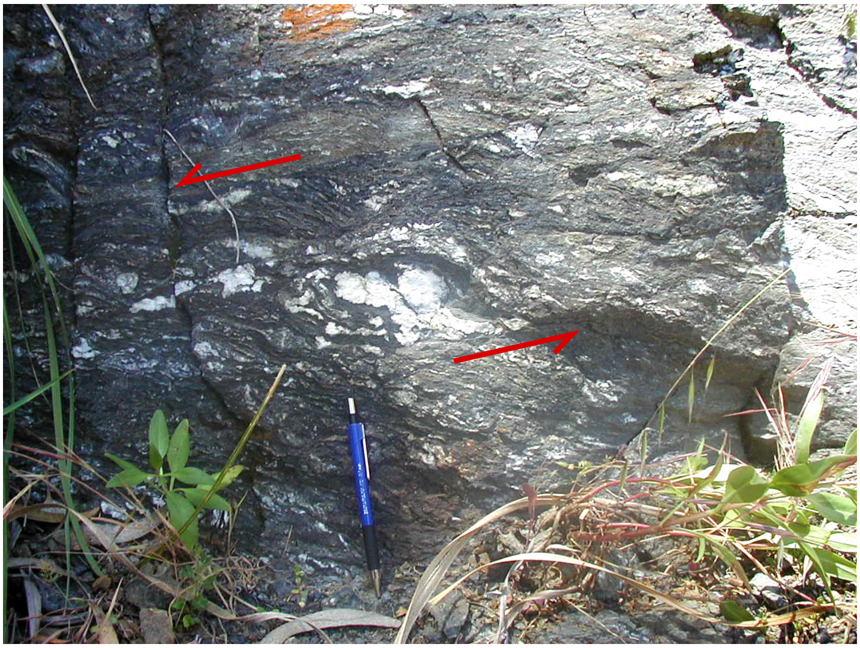


Figure 8: Exposure of the structurally highest part of the shear zone, view to the northwest. Here the shear zone material itself is recrystallized in the blueschist facies and is a coherent rock; it is not brittle fault rock. Tops to the southwest sense of shear is indicated by shear bands, c and s surfaces, and asymmetric porphyryoclasts.

Figure 9A: Part of the shear zone a few meters structurally below the blueschist facies structurally highest zone. Here we see brittle block-in-matrix structures. The matrix is shale and the upper part of the exposure is composed of a large sandstone block. View to the northwest.

Figure 9B: This view is just to the right of the photo 9A (it is below the root that is below the big sandstone block). In this photo we see a much smaller basalt block. The basalt block was clearly not part of an original bedded sandstone and shale sequence, so its presence indicates a large amount of strain and mixing in the development of this shear zone. Note also the different scales of block-in-matrix structures illustrated in Figure 7, 9A and 9B. If we zoom in on the matrix of 7B we see something like in Fig. 9A. If we zoom in on the matrix in Fig. 9A we see the features of Fig. 9B. If you look at the matrix in Fig. 9B you can see still smaller blocks. This series of photos illustrates the scale independence of melanges (and bimrocks in general), as noted by Medley (1994a; 2001).

APPENDIX A

to

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

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THE LARGER GEOLOGIC CONTEXT OF CALIFORNIA TECTONICS, BIMROCKS, AND FAULT ROCKS

California has some of the most diverse geology in the world. This complexity is partly a result of California having been assembled by a series of interactions along active plate boundaries for the last 500 million years. The basement rocks of California preserve multiple subduction zones, scraps of ocean crust, island arcs, and batholiths, and record many episodes of deformation. Because of this history of active tectonics, fault rocks and bimrocks are commonplace. Although bimrocks are most famous in the Franciscan Complex, older subduction complexes with similar structures occupy both the Sierra Nevada and Klamaths. Brittle fault zones formed and preserved in various parts of California range in age from several hundred million years old to Holocene.

The following is a brief chronology of geologic events recorded in a transect from the northeastern Sierra Nevada to the northern California coast (this is another version of "Assembling California" by John McPhee!). It should be kept in mind that this chronology is largely a two dimensional (cross sectional) analysis and that there is considerable variation of geology and tectonic history along the northwest-southeast strike of the orogenic belt.

The oldest subduction complex in the Sierra is the Shoo Fly Complex of Devonian age. Similar to the Franciscan, this subduction complex contains units of melange up to several km thick. The grade of metamorphism of this complex in the northern Sierra is lower greenschist, so the fault structures (including the melange matrix) are brittle. In the central Sierra Nevada the grade of metamorphism in this unit is generally upper greenschist facies or higher, so most of the melange matrix and shear zones have been annealed. Following a Devonian collision between the west-dipping Shoo Fly subduction zone and the continental margin, a volcanic arc developed across the amalgamated margin (e.g. Schweickert and Snyder, 1981). Subsequently the closure of a large ocean basin, possibly in the Triassic or early Jurassic, led to the emplacement of the Feather River peridotite belt, a unit that contains abundant serpentinite and locally serpentinite matrix melange, over an east-dipping subduction zone. Much of this unit was metamorphosed in the amphibolite facies, but the Feather River belt was likely affected by strain later in the Jurassic and possibly the Cretaceous (e.g. Sharp, 1988). The later deformation took place under low-temperature conditions in the northern Sierra and included the development of brittle shear zones and further deformation of existing serpentinite matrix mélange, resulting in the development of brittle fabrics.

West of the Feather River belt are one or possibly two subduction complexes that have been juxtaposed by collisional tectonics (either a single west-dipping subduction zone or two subduction zones dipping away from each other; compare Schweickert and Cowan, 1975, and Moores and Day, 1984). These comprise part of the "Central Belt" of the northern Sierra Nevada and include the Calaveras Complex and other units that have a high proportion of chert and shale (Moores and Day, 1984). Significant parts of these units are composed of melange. The grade of metamorphism is greenschist or lower in the northern Sierra Nevada, so the shear zones and melanges exhibit brittle fabrics (there was higher grade metamorphism with ductile fabrics to the south). Fault rocks in the Sierran basement are by no means confined to subduction complexes; numerous brittle shear zones cut volcanic arc rocks and slices of oceanic crust and mantle in the northern Sierra Nevada. The Paleozoic to Mesozoic terranes of the Klamath Mountains are similar to those of the Sierra Nevada in structural and lithologic character, although one-to-one correlation is not as straightforward as was once thought (e.g. Dilek and Moores, 1992).

During the most recent chapters of active plate margin history in California, the Coast Ranges have had the starring role. Following the mid-Jurassic collision in the Sierra Nevada that blocked one or more subduction zones (Schweickert and Cowan, 1975; Moores and Day, 1984), subduction stepped west and east-dipping Franciscan subduction began at 165-160 million years ago (Wakabayashi, 1992). All but the first few million years of Franciscan metamorphism took place at low temperatures (but high pressures), so most of the major fault zones in the Franciscan are brittle ones; these include melanges up to several kilometers thick. Franciscan subduction with intermittent accretion of various units took place continuously for over 140 million years and is still occurring north of the Mendocino Triple Junction (e.g. Wakabayashi, 1992).

The Franciscan in a gross sense can be viewed as a stack of thrust nappes, some of which are coherent, some of which are melanges (Wakabayashi, 1992; 1999b) (Fig. 4). Most of the coherent terranes are themselves imbricated, and the thrust faults within these coherent terranes range from discrete faults of centimeter width to melange zones up to several hundred meters in width. The stack of nappes is a consequence of progressive accretion (off scraping from the downgoing plate) of both trench sediments and far-traveled oceanic rocks. As a consequence of this progressive accretion, the incorporation ages of the nappes, and hence the ages of formation of melanges of the nappe stack, young progressively down structure (Wakabayashi, 1992).

Coeval with Franciscan subduction, deposition of the Great Valley Group took place in a forearc basin between the Franciscan subduction zone to the west and the Sierra Nevada magmatic arc to the east. The Great Valley Group consists of bedded siltstones, sandstones, and shales that underwent negligible burial metamorphism (in contrast to the common blueschist facies metamorphism in the Franciscan). The Great Valley Group is commonly seen as the well ordered mate to the chaotic Franciscan, but it is not altogether free of fault rocks or bimrocks. In particular, a 1-km-thick serpentinite-matrix melange occurs at the base of the Great Valley Group in the northern Coast Ranges (Phipps, 1984). Unlike the melanges of the Franciscan Complex that have tectonic upper and lower contacts, the Great Valley Group melange is of depositional (olistostromal) origin with depositional upper and lower contacts. Despite having a different genesis than Franciscan melanges, from an engineering standpoint it is the same type of material, blocks in a weak matrix. In addition to the basal melange, the Great Valley Group does contain some fault rocks because it did not entirely escape deformation. Large-scale shortening resulting in fold and thrust belt development affected the Great Valley Group during both the subduction regime and the subsequent transform regime (e.g. Unruh et al., 1995). This has resulted in significant layer-parallel shearing generally hosted within the shale horizons.

During Franciscan subduction, additional deformation took place to the east in the Sierra Nevada, locally forming penetrative brittle fabrics and faults in the northern Sierra Nevada that locally cut across older lithologic boundaries. Among these later faults are the faults along which Mother Lode gold mineralization occurred (e.g. Böhlke, 1999).

The timing of the cessation of subduction along coastal California depended on latitude, with the earliest cessation starting at about 25 million years ago, and the San Andreas dextral transform system beginning at about 18 million years ago and lengthening with time (e.g. Atwater and Stock, 1998). This tectonic regime has led to the development of the major strike-slip faults and also fold and thrust belts that are related to both partitioning of a minor amount of compression across the plate boundary, and to local restraining bends in the strike-slip faults (e.g. Aydin and Page, 1984; Namson and Davis, 1988). The major strike-slip faults have developed zones of long-term displacement that are up to several km wide; the Holocene trace locally carries but a fraction of the total late Cenozoic displacement along many of the major dextral faults in the San Andreas system (Wakabayashi, 1999c). However, the broad zones of long-term strike-slip displacement are generally different from Franciscan melanges in character in that they are largely blocks with volumetrically subordinate shears between them. Nonetheless the mechanically weaker nature of the zones along strike slip faults is illustrated by the common occurrence of linear valleys (erroneously called "rift" valleys in some areas) that have formed as a consequence of preferential stream erosion along these faults.

In summary, 500 million years of active plate tectonics has created an abundance of fault rocks and bimrocks in California. Volumetrically, the most significant fault rocks or block in matrix rocks are melanges that are associated with subduction complexes. One major exception is the basal Great Valley Group, which is not a fault rock but has the same mechanical properties. However, as described above, fault rocks are present in non-melange settings, and the dimensions of these features (up to tens or even hundreds of meters in thickness) are such that they can be of engineering significance. Melanges and other bimrocks and fault rocks are common in many places of the world; they occur in essentially all orogenic belts, so the engineering problems associated with them are global in scope.

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, √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 √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 √A (for $d_{mod}/\sqrt{A} = 1$), but about 99 percent of blocks are smaller than about 0.75√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√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√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.

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REFERENCES FOR APPENDIX B

1. Medley, E.W.: The engineering characterization of melanges and similar block-in-matrix rocks (bimrocks): Ph.D. Dissertation, Dept. of Civil Engineering, University of California at Berkeley, California, 387 p.; UMI, Inc. (Ann Arbor, Michigan); 1994a

2. Laznicka, P.: Breccias and Coarse Fragmentites: Petrology, Environments, Ores: in v. 25, Developments in Economic Geology, Elsevier, 832 p.; 1988

3. AGI: Proceedings of the International Symposium on the Geotechnics of Structurally Complex Formations: Associazone Geotechnica Italiana (Capri, Italy); 1997

4. Raymond, L.A.: Classification of melanges: in Melanges: Their nature, origin and significance; Raymond, L.A. (ed.), Geological Society of America (Boulder, Colorado), Special Publication 228, p. 7-20; 1984

5. Popiolek, S., Sala, H., and Thiel, K.: Geotechnical Flysch Rock Mass Classification (KF): in Thiel, K. and Zabuski, I., eds., Proc. of Seminar on underground structures in complex geological conditions, Swinna Poreba, Poland; Institute of Meteorology and Water Management, Warsaw, p. 27-39; 1993

6. Bieniawski, Z.T.: Engineering rock mass classifications: John Wiley and Sons, New York, 251 p.; 1989

7. Riedmüller, G., Brosch, P.J., Klima, K., and Medley, E.: Engineering geological characterization of brittle faults and fault rocks, Feldsbau: Journal of the Austrian Society of Geomechanics and Tunelling, no. 4; 2001

8. Goodman, R.E., and Ahlgren, C.S.: Evaluating safety of concrete gravity dam on weak rock: Scott Dam: Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, May 2000, v. 126, no. 5, p. 429-442; 2000

9. Aversa, S., Evangelista, A. Leroueil, S., and Picarelli, L.: Some aspects of the mechanical behaviour of “structured” soils and soft rocks: Proceedings of the International Symposium on Geotechnical Engineering of Hard Soils-Soft Rocks, Athens, Greece, v. 1, p. 359-366, A.A. Balkema (Rotterdam, Netherlands); 1993

10. D’Elia, B., Distefano, D., Esu, F. and Federico, G.: Slope movements in structurally complex formations: in Tan Tjong Kie, Li Chengxiang and Yang Lin (eds.), Proceedings of the International Symposium on Engineering in Complex Rock Formations (Beijing, China); 1986

11. Irfan, T.Y. and Tang, K.Y.: Effect of the coarse fraction on the shear strength of colluvium in Hong Kong: Hong Kong Geotechnical Engineering Office, TN 4/92, 128 p.; 1993

12. Blake, M.C.: Franciscan geology of Northern California: The Pacific Section of the Society of Economic Paleontologists and Mineralogists, (Los Angeles, CA), 254 p.; 1984

13. Cowan, D.S.: Structural styles in Mesozoic and Cenozoic melanges in the Western Cordillera of North America: Bulletin of the Geol. Society of America, v. 96, p. 451-462; 1985

14. Hsü, K.J.: A basement of melanges: A personal account of the circumstances leading to the breakthrough in Franciscan research: in Drake, E.T., and Jordan, W.M., (eds.), Geologists and Ideas: a history of North American geology, Geological Society of America, (Centennial Special Volumes), v. 1, p. 47-64; 1985

15. Wahrhaftig, C.: Streetcar to subduction: American Geophysical Union, (Washington, D.C), 76 p.; 1984

16. Blake, M.C. and Harwood, D.S.: Tectonic evolution of Northern California, Field trip guidebook for Trip 108, American Geophysical Union (Washington, DC); 1989

17. Wakabayashi, J.: The Franciscan complex, San Francisco Bay Area: A record of subduction complex processes: in Wagner, D.L. and Graham, S.A., (eds.), Geologic Field Trips in Northern California, Centennial Meeting of the Cordilleran Section of the Geological Society of America; Special Publication 119, California Division of Mines and Geology, (Sacramento, California), p. 1-21; 1999

18. Savina, M. E.: Studies in bedrock lithology and the nature of down slope movement: Ph.D. Dissertation, Department of Geological Sciences, University of California at Berkeley, California, 298 p.; 1982

19. Ellen, S. D., and Wentworth, C.M.: Hillside bedrock materials of the San Francisco Bay Region: United States Geological Survey, Professional Paper 1357; 1995

20. Priest, S.D.: Discontinuity analysis for rock engineering: Chapman & Hall, (New York, New York), 473 p.; 1993

21. Medley, E.W. and Lindquist, E.S.: The engineering significance of the scale-independence of some Franciscan melanges in California, USA: Proceedings of the 35th US Rock Mechanics Symposium; Daemen, J.K. and Schultz, R.A (eds.); A.A. Balkema, (Rotterdam, Netherlands), p. 907-914; 1995

22. Sammis, C.G. and Biegel, R.L.: Fractals, fault gouge and friction: Journal of Pure and Applied Geophysics, v. 131, p. 255-271; 1989

23. Nagahama, H.: Technical Note: Fractal fragment size distribution for brittle rocks: International Journal of Rock Mechanics and Geomechanics Abstracts, v. 30, p. 173-175; 1993

24. Bagnold, R.A. and Barndorff-Nielsen, O.: The pattern of natural size distribution; Sedimentology, v. 27, p. 199-207; 1980

25. Lindquist, E.S.: The mechanical properties of a physical model melange: Proceedings of 7th Congress of the International Association Engineering Geology, Lisbon, Portugal; A.A. Balkema (Rotterdam, Netherlands); 1994b

26. Lindquist, E.S.: The strength and deformation properties of melange: Ph.D. Dissertation, Department of Civil Engineering, University of California at Berkeley, California, 262 p., UMI Inc., (Ann Arbor, Michigan); 1994a

27. Lindquist, E.S. and Goodman, R.E.: The strength and deformation properties of a physical model melange: in Proc. 1st North American Rock Mechanics Conference (NARMS), Austin, Texas; Nelson, P.P. and Laubach, S.E., eds., A.A. Balkema (Rotterdam); 1994

28. Volpe, R.L., Ahlgren, C.S., and Goodman, R.E.: Selection of engineering properties for geologically variable foundations: in Question 66, Proceedings of the 17th International Congress on Large Dams, Vienna; ICOLD - International Committee On Large Dams (Paris, France), p. 1087-1101; 1991

29. Savely, J.P.: Comparison of shear strength of conglomerates using a Caterpillar D9 ripper and comparison with alternative methods: International Journal of Mining and Geological Engineering, v.8, p. 203-225; 1990

30. Goodman, R.E., Medley, E.W., and Lindquist, E.S..: Final R&D Report: Characterization of dam foundations on melange-type mixtures - A methodology for evaluating the shear strength of melange, with

application to the foundation rock at Scott Dam, Lake Pillsbury, Lake County, California: unpublished report prepared for Pacific Gas & Electric Company, San Francisco, California; University of California at Berkeley, Department of Civil Engineering, (UC Award Number Z10-5-581-93), 43 p.; 1994

31. Underwood, E.E..: Quantative stereology: Addison Wesley Publishing Company, 272 p.; 1970

32. Weibel, E.R.: Stereological methods, Volume 2: Theoretical foundations: Academic Press, (New York, New York), 340 p.; 1980

33. Medley, E.W.: Using stereologic methods to estimate the volumetric block proportion in melanges and similar block-in-matrix rocks (bimrocks): Proceedings of 7th Congress of the International Association of Engineering Geologists, Lisbon, Portugal; A.A. Balkema, (Rotterdam, Netherlands); 1994b

34. Medley, E.W.: Estimating block sizes in Franciscan melanges: Abstracts of 38th Annual Meeting of the Association of Engineering Geologists, Sacramento, California; 1995

35. Medley, E.W.: Uncertainty in estimates of block volumetric proportion in melange bimrocks: Proceedings of the International Symposium of International Association of Engineering Geologists, Athens, Greece, A.A. Balkema (Rotterdam, Amsterdam), p. 267-272; 1997

36. Medley, E.W.: Relating the complexity of geological mixtures to the scales of practical interest: Abstracts of the Annual Meeting of the Association of Engineering Geologists, Salt Lake City, Utah, September 1999b

37. Medley, E.W. and Goodman, R.E.: Estimating the block volumetric proportion of melanges and similar block-in-matrix rocks (bimrocks): Proceedings of the 1st North American Rock Mechanics Conference (NARMS), Austin, Texas; Nelson, P.P. and Laubach, S.E. (eds.); A.A. Balkema (Rotterdam, Netherlands), p. 851-858; 1994

38. Medley, E.W.: Order in chaos: The geotechnical characterization of melange bimrocks: Proceedings of First International Conference On Site Characterization, Atlanta, Georgia; (American Society of Civil Engineers, New York), p. 201-206 1998

39. Medley, E.W.: Systematic characterization of melange bimrocks and other chaotic soil/rock mixtures: Feldsbau Rock and Soil Engineering, Journal for Engineering Geology, Geomechanics and Tunnelling, Austrian Society for Geomechanics; v. 17, no. 3, p. 152-162; 1999a

40. Geological Society Engineering Geology Working Party: The description and classification of weathered rocks for engineering purposes: Quarterly Journal of Engineering Geology, v. 28, no. 3, p. 207-242; 1995

41. Rocha, M.: A method of integral sampling of rock masses: Journal of Rock Mechanics, v.3, p. 1-12; 1971

42. Brosch, F. J., Pischinger, G., Steidl, A., Vanek, R. and Decker, K.: Improved site investigation results by kinematic discontinuity analysis on drill cores. Proc. ISRM Reg. Symp. EUROCK 2001/ Espoo/Finland, 2001, in print (A. A. Balkema, Rotterdam); 2001

43. Harer, G.; Riedmüller, G.: Assessment of ground condition for the Koralm Tunnel during the early stages of planning. Felsbau 17(1999) no. 5, p. 374 – 380; 1999

44. Attewell, P.B.:, Tunnelling and site investigation: Proceedings of the International Conference on Geotechnical Engineering of Hard Soils-Soft Rocks; v. 3, p. 1767-1790; A.A. Balkema (Rotterdam, Netherlands); 1997

45. Bro, A.: A weak rock triaxial cell; Technical Note: International Journal of Rock Mechanics and Mining Science, v. 33, no. 1, p. 71-74; 1996

46. Bro, A.: Analysis of multi-stage triaxial test results for a strain-hardening rock: International Journal of Rock Mechanics and Mining Science, v. 34, no. 1, p. 143-145; 1997

47. Medley, E.W.: Orderly characterization of chaotic Franciscan melanges, Feldsbau, v. 19., no. 4, p. 20-33, 2001

48. Riedmüller, G., Brosch, F.J., Klima, K. and Medley, E.W.: Engineering geological characterization of brittle faults and classification of fault rocks. Feldsbau, v. 19, no. 4, p. 13-19, 2001

49. Medley, E.W.: Estimating block size distributions of melanges and similar block-in-matrix rocks (bimrocks), accepted for Proceedings 5th North American Rock Mechanics Symposium, Toronto, Canada (2002, in press)

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.

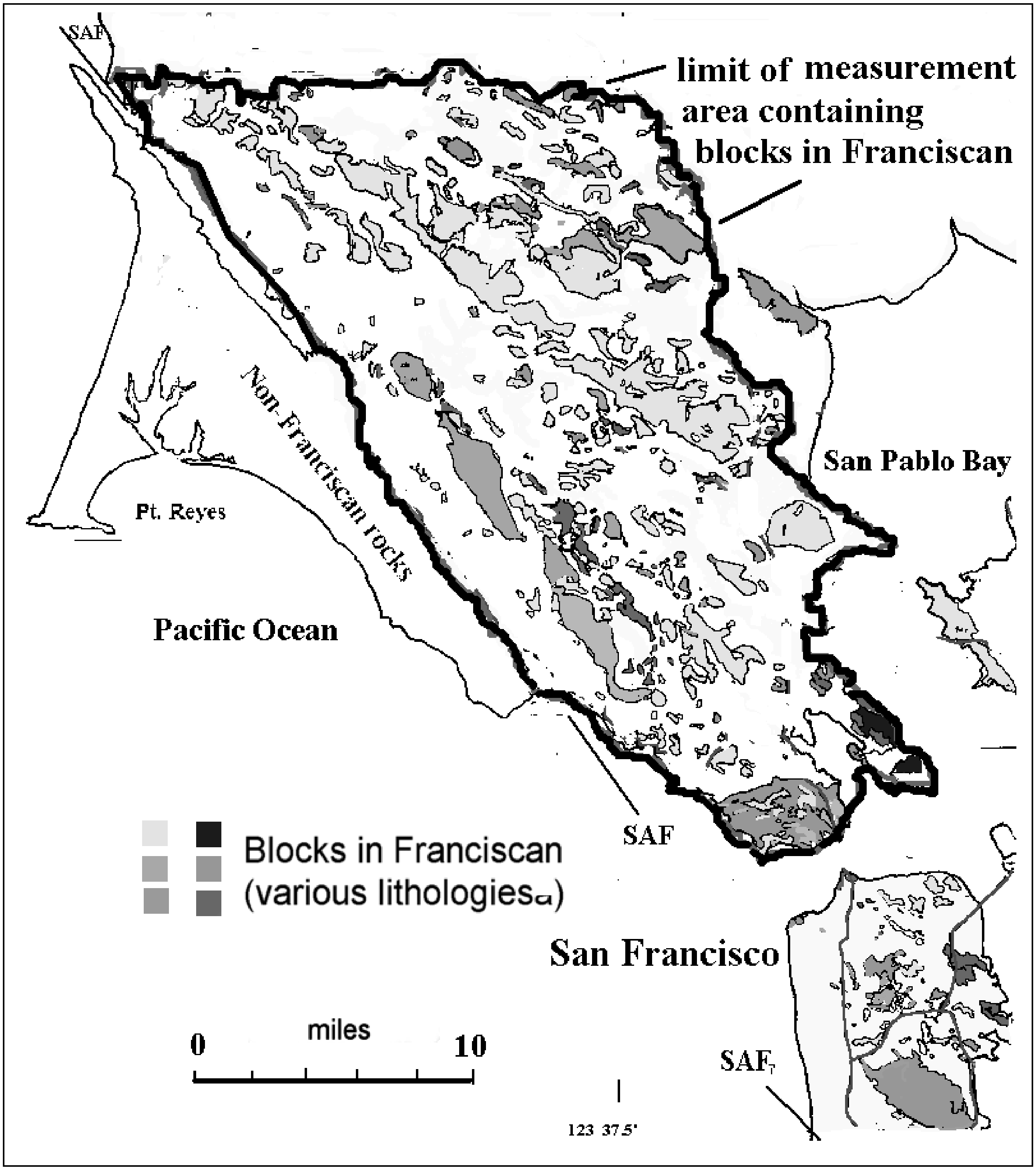


Figure B2. The Franciscan Complex in Marin County, north of San Francisco. Mapped blocks range to nearly 20 km in length. SAF is the San Andreas fault. Area of interest within indicated boundary is about 1000 km^2. (After Medley (1); base map after Ellen and Wentworth (19).)

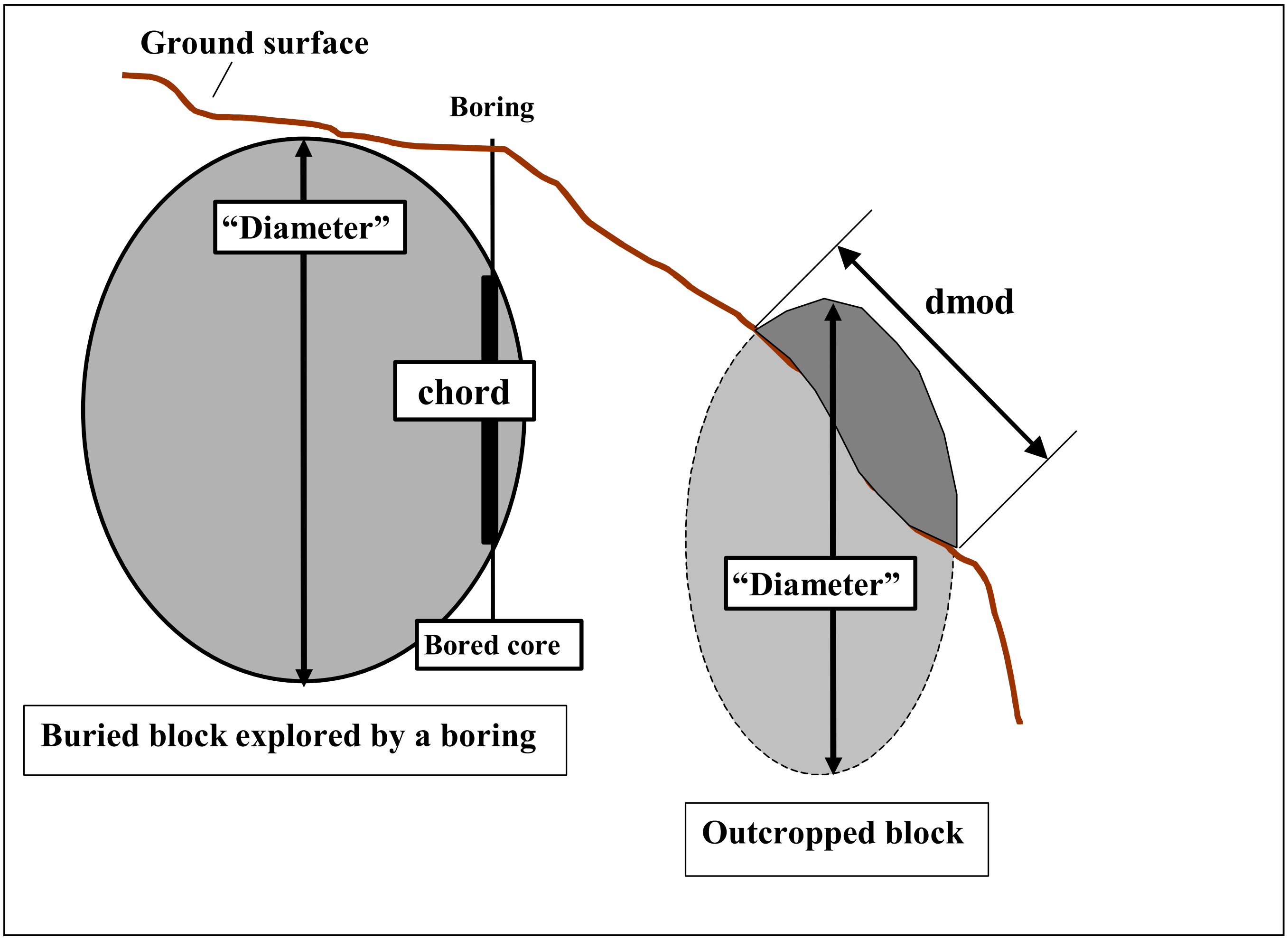


Figure B3. In two dimensions a block has apparent block size of d_{mod}, the maximum observed dimension. In one dimension, the block size is indicated by the chord length, or intercept between a boring and a block. Only rarely is d_{mod} or a chord length equivalent to the actual "diameter" or maximum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

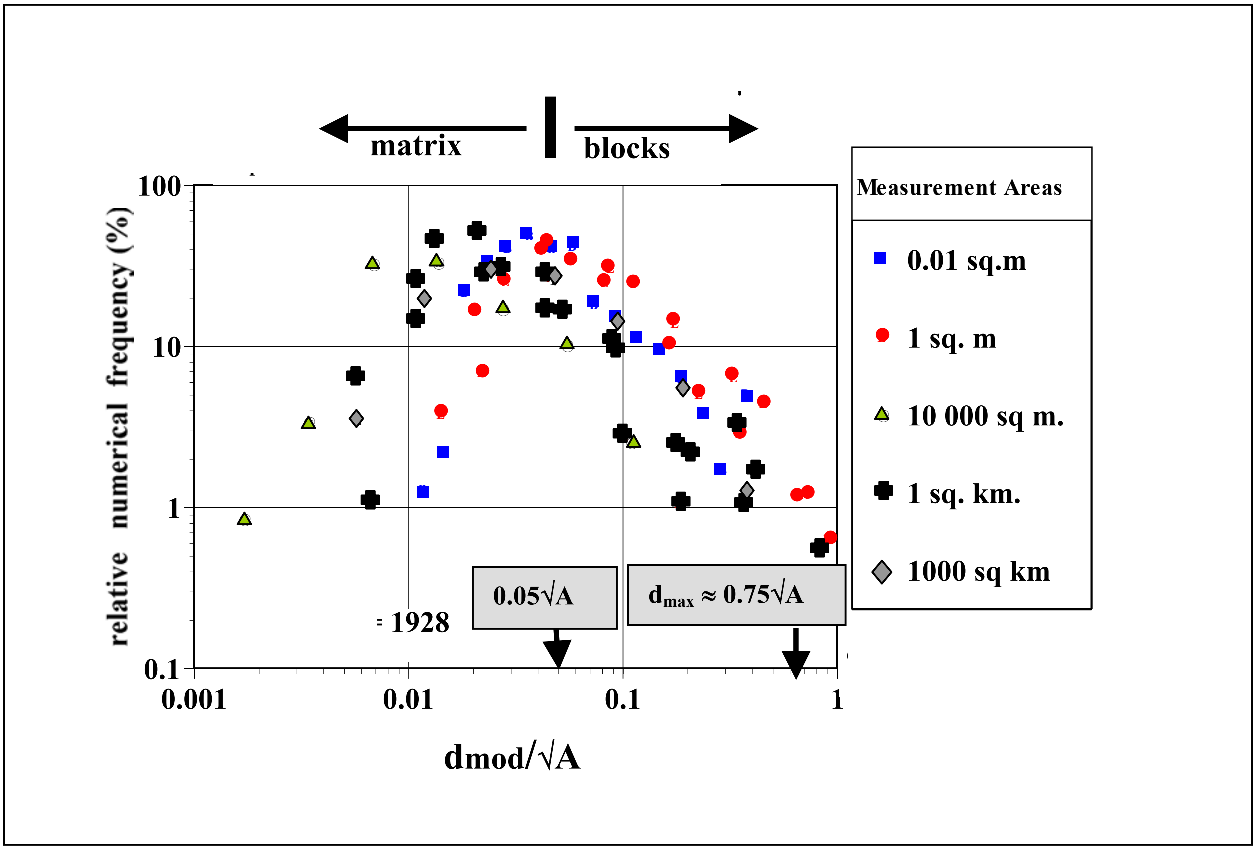


Figure B4. Normalized block size distribution curves for 1,928 blocks measured from outcrops and geological maps of several Franciscan melanges ranging over seven orders of magnitude in scale, ranging from centimeters to kilometers (after Medley (1)). The sizes of blocks are characterized by d_{mod}, 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 $0.05d_{mod}/\sqrt{A}$, which is defined as the block/matrix threshold size at any scale. Blocks smaller than $0.05d_{mod}/\sqrt{A}$ 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.

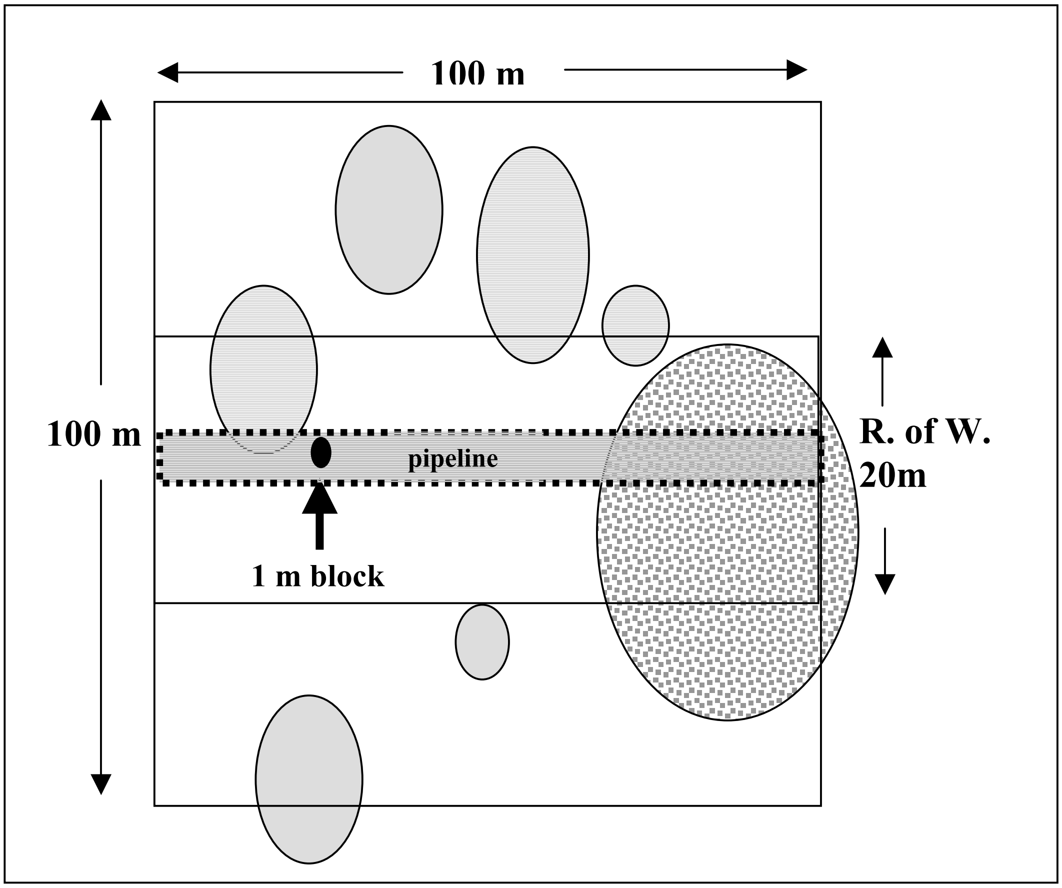
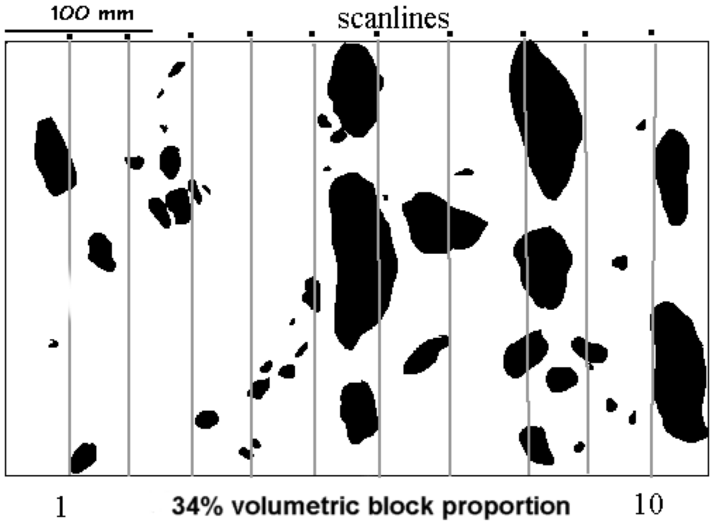


Figure B5. Sketch showing various scales of interest for an area where a 20 m wide road and 2 m wide, 2 m deep pipeline trench will be excavated in a melange bimrock:

(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.



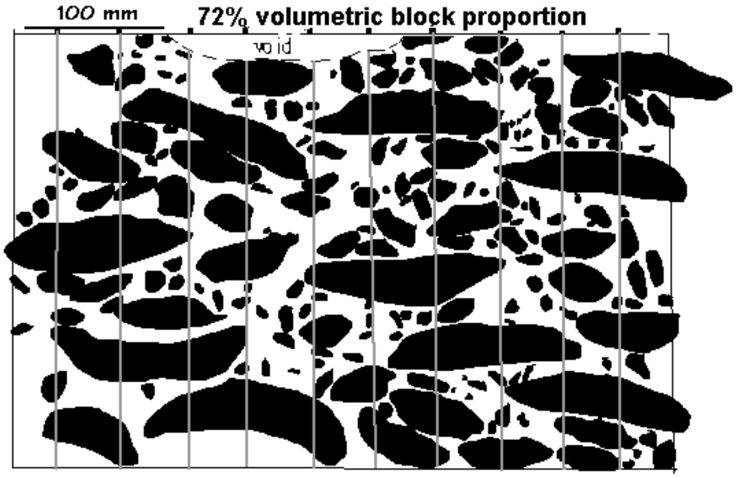


Figure B6. Tracings of physical model melanges (Medley (1), after Lindquist (25)), with known volumetric block proportions and three dimension (3-D) block size distributions. The tracings were measured by one-dimension (1-D) model borings ("scanlines") to yield linear block proportions and chord length 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.

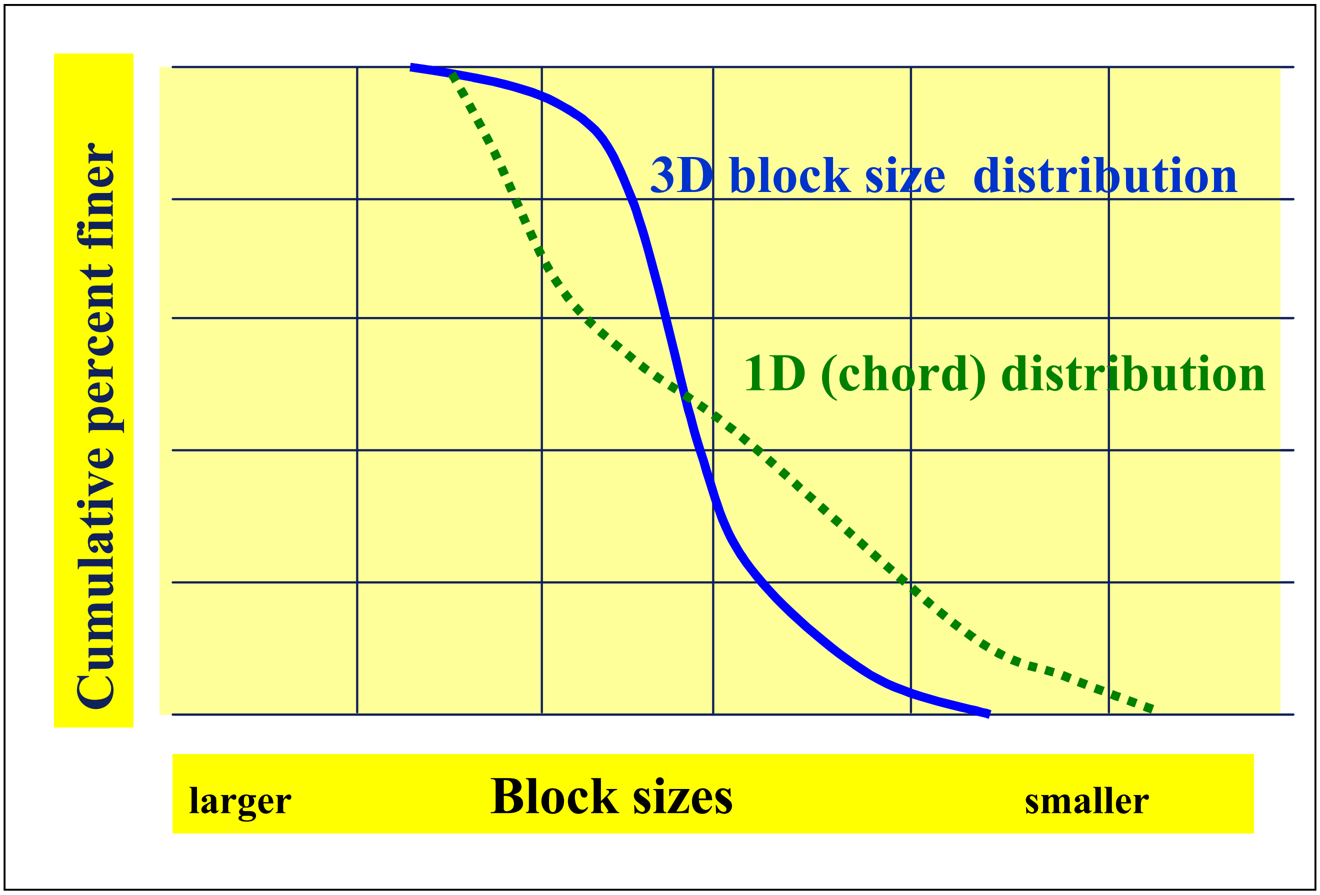


Figure B7. Schematic block size distribution plots for physical melange models with blocks oriented vertical and parallel to the model borings, such as shown in the second case of Fig. B6. 3-D block size distributions for blocks (as measured by the actual "diameter," or the largest dimension in three 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.

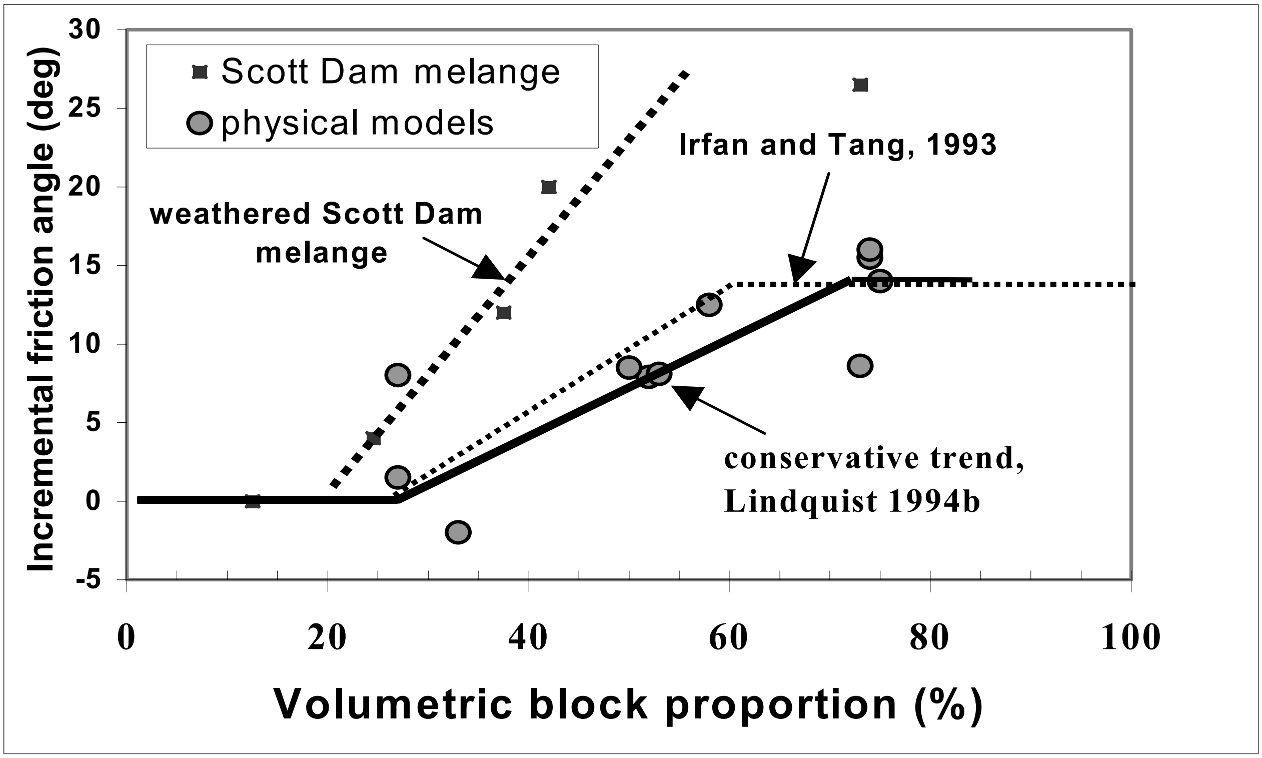


Figure B8. The strength of bimrocks increases directly with volumetric block proportion. The increase in friction is added to the frictional strength of the matrix. There is marked similarity between the data of Lindquist (25, 26), for physical model melanges, and that of Irfan and Tang (11), for Hong 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.

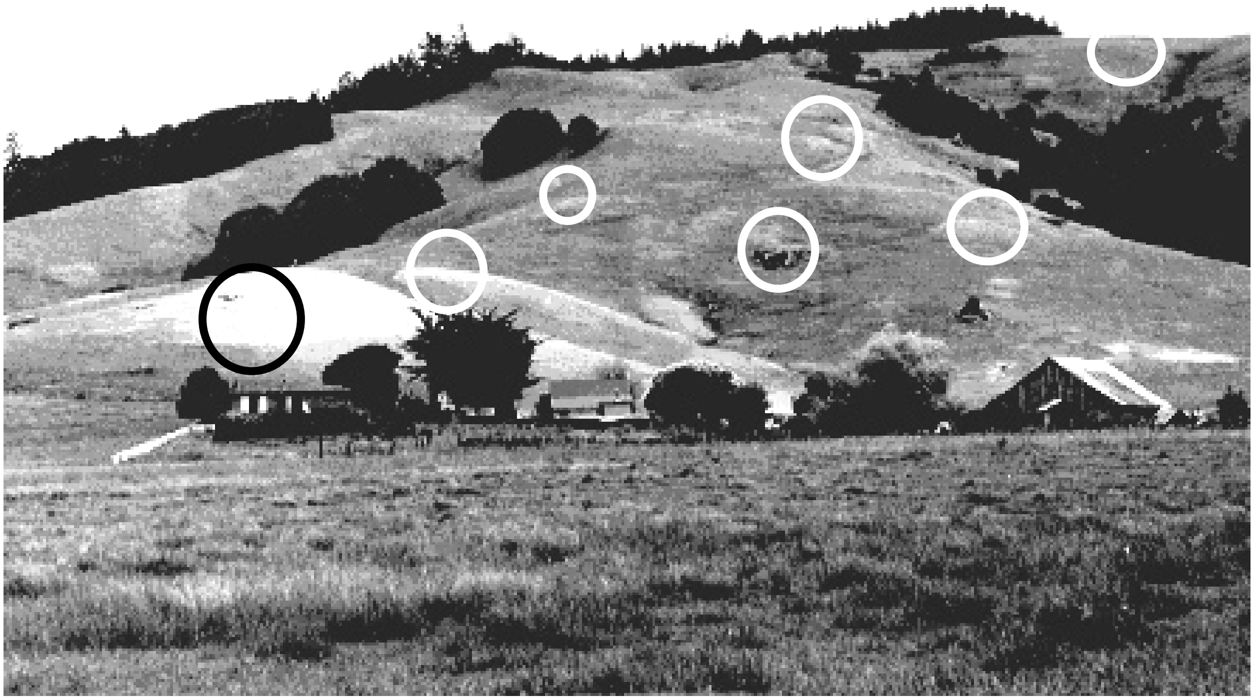


Figure B10. Franciscan melange photographed in the spring/early summer. Mottling of lighter tones indicates blocks underlying the hillside (circled).

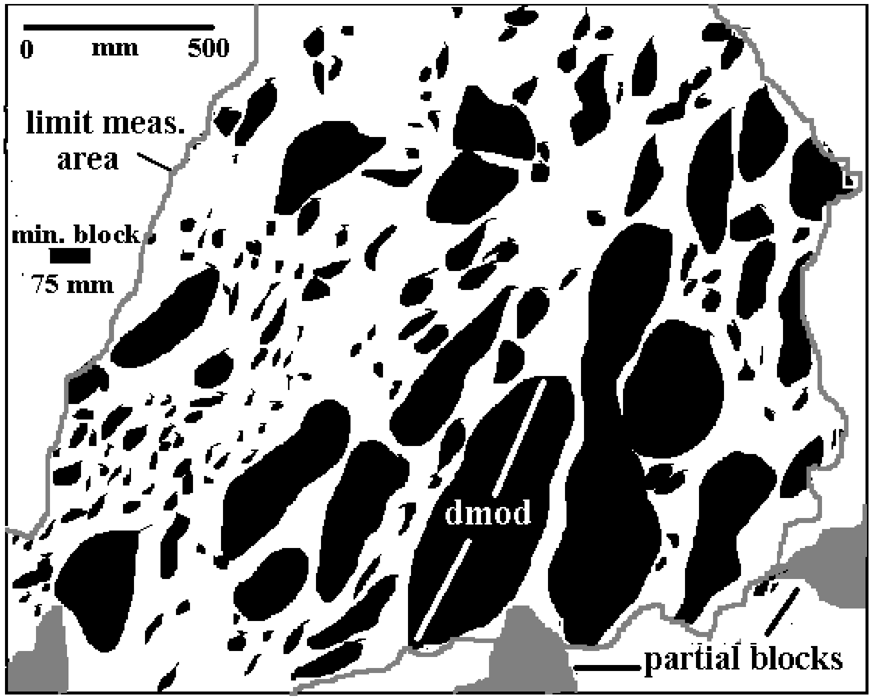


Figure B11. Photograph and sketch of outcrop of Franciscan melange at Caspar Headlands, Mendocino County, Northern California. The scale bar in the photograph is 1.5 m (5 feet) long. The sketch shows the blocks discriminated by image analysis software. Block sizes are characterized by d_{mod} (maximum 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).

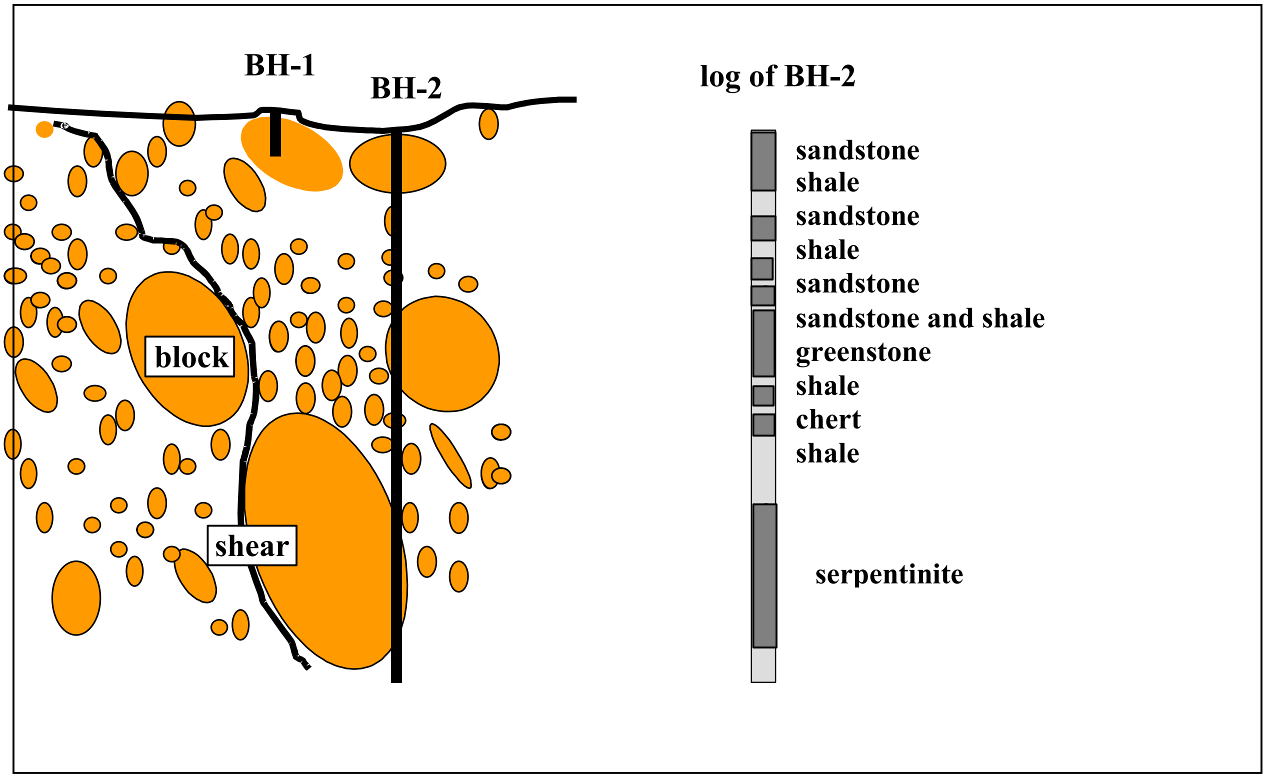


Figure B12. Shears in melanges typically tortuously negotiate around blocks at the block/matrix contacts. Sketch also shows exploration of a bimrock by borings (BH). BH-1 terminates in a block, a situation that, in Northern California, often results because the investigator identifies the block as "bedrock." 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.

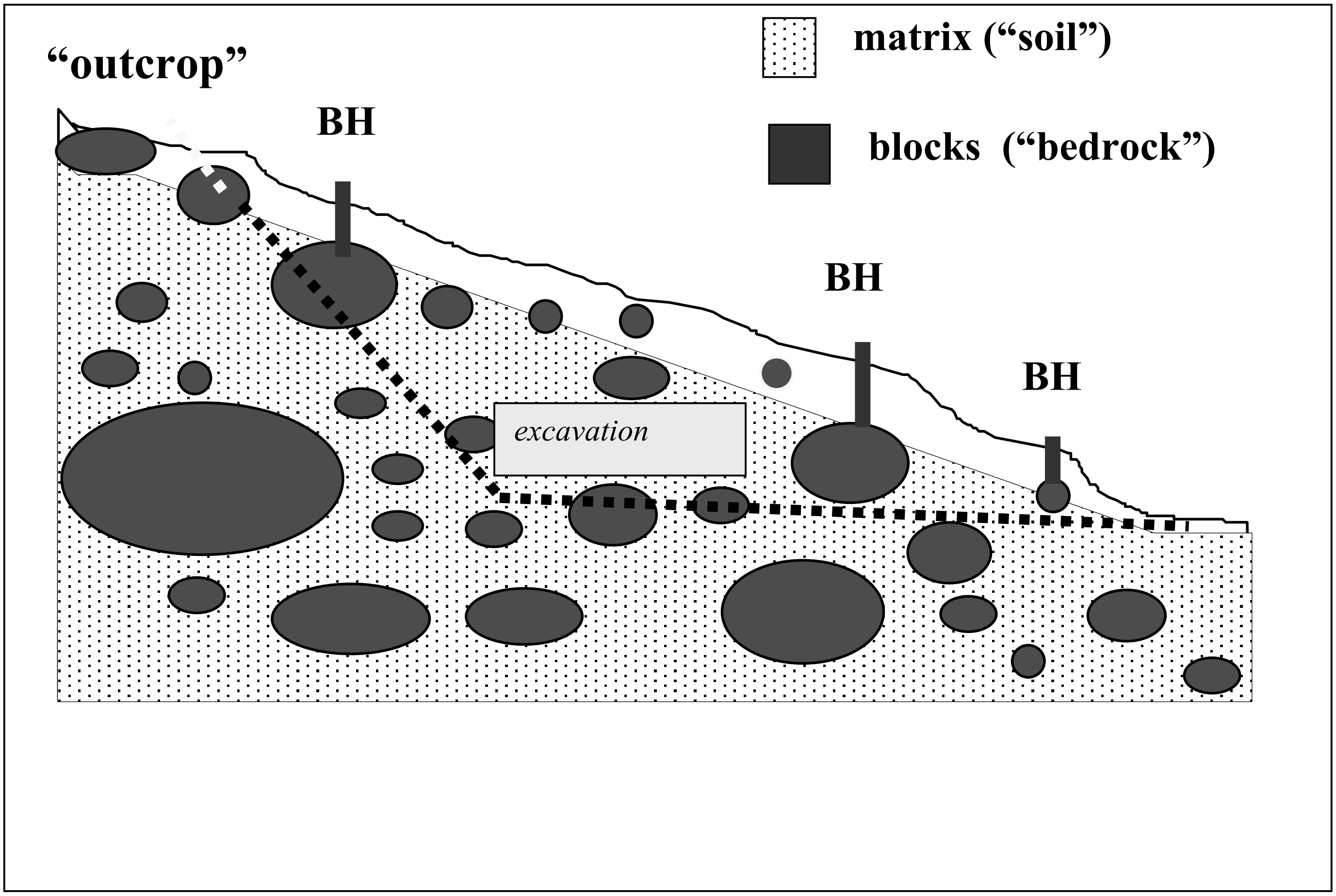


Figure B13. Borings (BH) in melange. Borings have been terminated in rock interpreted as continuous "bedrock" rather than blocks, and the matrix as "soil" or "soil with boulders." Because of this misinterpretation, the slope will be troublesome for two reasons: (1) rather than continuous bedrock, the 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.

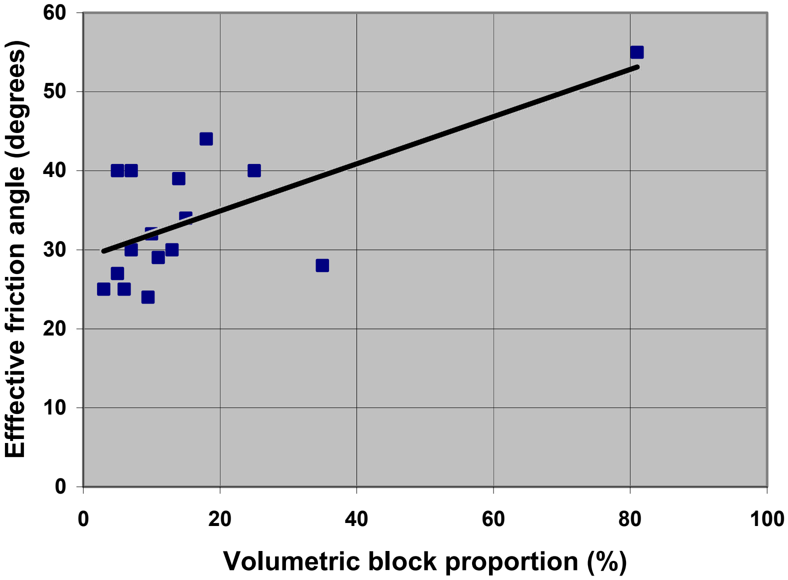


Figure B14. Plot of effective friction angle as a function of volumetric block proportion, generated from laboratory testing of Franciscan melange specimens obtained from core drilling at Scott Dam, Northern California (after Goodman and Ahlgren (8). The correlation is not good, but a straight-line fit 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.

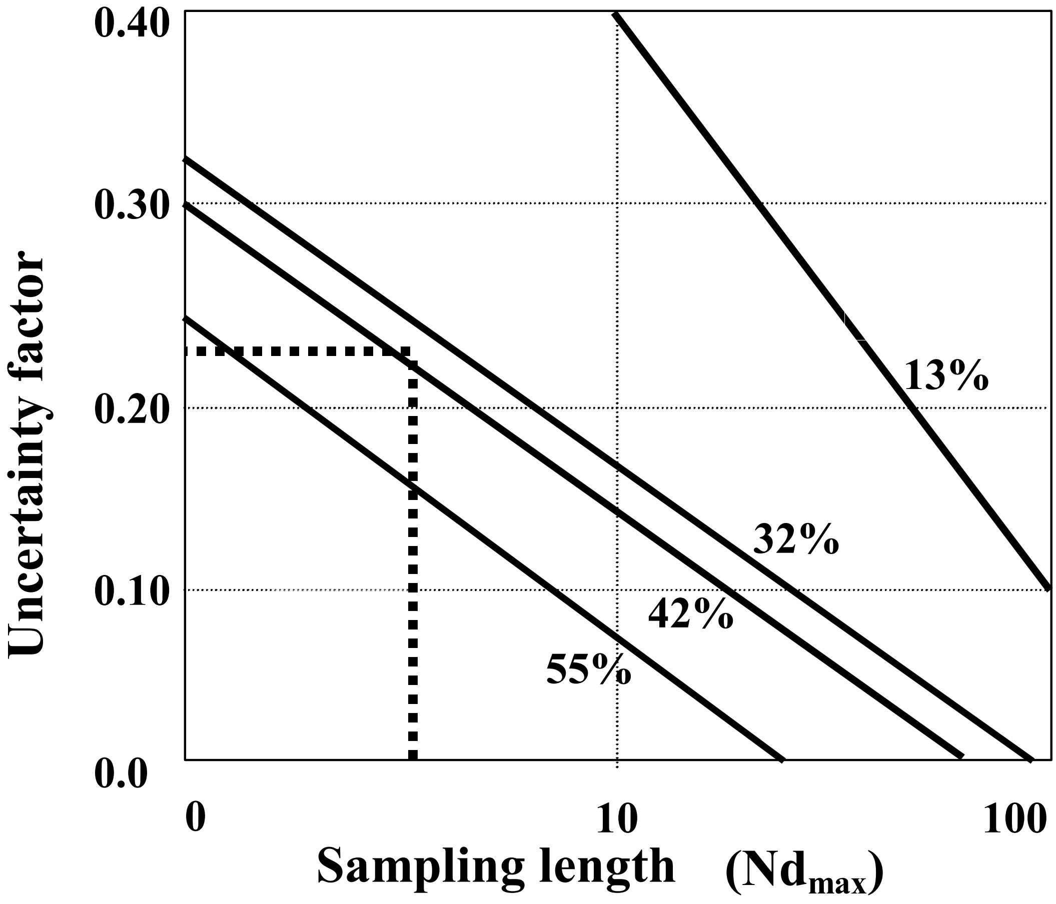


Figure B15. Uncertainty in estimates of volumetric block proportion as a function of the length of linear measurement, expressed as a multiple (N) of the length of the largest block (d_{max}), and the measured linear block proportion (13% to 55%). (From Medley (35)). The dashed line shows the use of 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.

II. Caldecott Tunnel
Oakland to Orinda, California

DRIVING DIRECTIONS

CALDECOTT TUNNEL
HIGHWAY 24
OAKLAND, CALIFORNIA

Driving from Oakland and points west:

Take Highway 24 East (toward Walnut Creek). Exit on Tunnel Road / Old Tunnel Road (last exit before Caldecott Tunnel). Turn right at stop sign and drive west along frontage road to stop sign at intersection with “Fwy overpass.” Turn right toward Berkeley/East Oakland/Tunnel Road and cross freeway. Turn right at stop sign, onto Caldecott Lane, and drive east on other frontage road. Go left at next stop sign to stay on Caldecott Lane. At Parkwoods condominiums at end of street, continue straight up hill through electric gate and past “Authorized Vehicles Only” sign. Park along road and walk to Superintendent’s Office (sign is hidden by tree), a one-story, tan building on the left, between the two tunnel portals. If you wish to visit the tunnel operations area at some time other than during the May 31, 2002, field trip, you will need to secure prior permission from Caltrans.

Driving from Walnut Creek and points east:

Take Highway 24 West. Stay in right lane and drive through right tunnel bore. Do not drive through the center tunnel bore. Exit at Tunnel Road (first exit after passing through Caldecott Tunnel). Turn right at end of ramp. Drive east on frontage road (aka Caldecott Lane). At Parkwoods condominiums at end of street, continue straight up hill through electric gate and past “Authorized Vehicles Only” sign. Park along road and walk to Superintendent’s Office (sign is hidden by tree), a one-story, tan building on the left, between the two tunnel portals. If you wish to visit the tunnel operations area at some time other than during the May 31, 2002, field trip, you will need to secure prior permission from Caltrans.

GEOLOGIC AND GEOTECHNICAL ENGINEERING ASPECTS OF THE CALDECOTT TUNNEL, OAKLAND TO ORINDA, CALIFORNIA

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This paper describes the geology in the vicinity of the Caldecott Tunnel and the various geotechnical engineering problems related to the building of the Caldecott Tunnels. In addition, it is intended to report on the status of the proposed fourth bore of the Caldecott Tunnel.

A. GEOLOGY OF THE CALDECOTT TUNNEL AND VICINITY

The following is taken almost exclusively from two papers: Ben Page's 1950 report on the Caldecott Tunnel[1] and Steven Graham's 1984 paper from the AAPG Bulletin[2]. The geology in the vicinity of the tunnel is illustrated in Figure 1, Page's geologic map; Figure 2, Page's geologic cross section; and Figure 3, a USGS geologic map (Graymer et al., 1995).

The geology of the Caldecott Tunnel provides a unique opportunity to examine the changes in sedimentation that took place during the transformation from a convergent plate margin to a transform plate margin at this latitude.

Prior to the passing of the Mendocino Triple Junction and the birth of the San Andreas Fault, the western edge of North America was part of a convergent tectonic regime. This is reflected to the east in the Sierra Nevada Batholith, the product of millions of years of east-directed subduction. In the Bay Area, Cretaceous and Early Tertiary marine rocks like those of the Tertiary Monterey Group represent much of this convergent environment. The Monterey Group is found throughout California and is a leading oil producer in the state. The Miocene Claremont Formation, a thinly bedded chert and shale unit, is the predominant Monterey member in the Berkeley Hills. This unit comprises much of the west end of the tunnel and lies stratigraphically over Sierran-derived sands (the Portal Sandstone). The entire unit is overturned and dips steeply to the west. Bathymetric analyses indicate deposition of the Claremont Formation occurred at depths between 1,500 and 1,600 m in a forearc basin west of the Sierra Nevada. Farther east, the Monterey Group rocks become more clastic consisting of sandstones and minor conglomerates and mudstones. This east-to-west Monterey transect reveals shallow, clastic, proximal deposition in the east giving way to deeper-water deposits in the west.

Stratigraphically above the Claremont Formation is the Upper Miocene Orinda Formation, part of the non-marine Contra Costa Group. Conglomerates, conglomeratic sandstones, and mudstones comprise the Orinda Formation in the vicinity of the Caldecott Tunnel. These were deposited probably as part of an alluvial system originating from a western high. Provenance studies indicate that a majority of the sediments are reworked Franciscan rocks. Minor basaltic-andesite to andesite flows of the Grizzly Peak volcanics interfinger with fluvial sediments of the Orinda near the east portal. The contact between the Orinda and the underlying Claremont is a shallow angular unconformity. Angular clasts of Claremont cherts and shales are found in conglomerate beds at the base of the Orinda.

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[1] B. M. Page, "Geology of the Broadway Tunnel, Berkeley Hills, California," Bulletin of Economic Geology, v. 45, no. 2, March-April 1950.

[2] S.A. Graham, C. McCloy, M. Hitzman, R. Ward, and R. Turner, "Basin Evolution During Change from Convergent to Transform Continental Margin in Central California," The American Association of Petroleum Geologists Bulletin, v. 68, no. 3, March 1984, p. 233-249.

The juxtaposition of these two formations provides a contrast in depositional environments and marks the onset of a transform tectonic regime. The Claremont Formation was deposited in deep waters within a forearc basin while the Orinda Formation is primarily fluvial in origin. Moreover, while Monterey sediments were shed from east to west, the paleoslope upon which the Orinda was deposited sloped west to east. The paleoslope direction, in conjunction with the Franciscan provenance, suggests a Franciscan high probably located near the modern San Francisco Bay. The cessation of subduction, the closing of the forearc basin, and the migration of what is now the Mendocino Triple Junction precipitated the ascension of the Franciscan high.

As subduction ended, mantle material quickly filled the region vacated by the downgoing slab and volcanism ensued. This period of volcanic activity is represented throughout California as a string of small basaltic to rhyolitic volcanic deposits. It was once thought that these volcanic units young from south to north, nicely tracing the northward migration of the triple junction. However, better age dates have disrupted this hypothesis. The volcanic flows and plugs in the Berkeley Hills (the Moraga volcanics or Grizzly Peak volcanics) are approximately 9.5 Ma and are thought to have erupted along a proto-Hayward fault. Volcanic units roughly along strike to the north of the Moraga volcanics have been dated to about 12.5 Ma, thus disrupting the migration hypothesis. Regardless of the ages of these rocks (which may yet be refined to reflect a northward migration of volcanism concomitant with a migrating triple junction) there is a distinct linear trend developed by these Tertiary volcanic centers. More importantly for the builders of the Caldecott Tunnel, volcanic dikes are common throughout the tunnel's length and, where abundant, have weakened the rocks as the dikes have weathered to highly plastic clays.

Two features of the rocks within the limits of tunnel construction made building the tunnel difficult. Both igneous and sandstone dikes occur within the Claremont Formation, with the former occurring throughout the length of the tunnel. Page (1950) describes both of these geologic features in great detail and discusses their effect on the building of the tunnel. The following descriptions of these dikes are taken from Page's work.

The sandstone dikes are thought to have originated from the "second sandstone" which lies stratigraphically below the more abundant cherts of the Claremont Formation. After deposition, the cherts and the shales lithified much faster than the second sandstone, becoming brittle and fractured. Increased pore water pressures created by the mobile hydrocarbons within the Monterey sediments prevented the sands from lithifying. Once fractures began to develop in the overlying strata, sand-rich fluids filled the voids and created dikes. During construction it was not uncommon to have these sandstone dikes "run," or flow, out of the newly cut walls.

Similar problems were encountered in tunnel sections where igneous dikes are plentiful. The igneous dikes are primarily plagioclase and clinopyroxene and were described by Page as diabase, although he pointed out that the term implies a specific texture which these rocks lack. When encountered during construction, the dikes made for very weak walls. Page concluded that some dikes had weathered to as much as 30% clay, thereby becoming extremely soft. Samples recovered by Caltrans Geologist Bob Baker during recent work in the tunnel were considerably harder and less weathered than those described by Page.

The stratigraphy of the Caldecott Tunnel and the Route 24 corridor reflect the onset of a transform tectonic regime along western North America. Changes in sedimentation that took place during this transformation are recorded within the tunnel itself and extend east toward Mt. Diablo. Page did a significant amount of geologic work during the construction of the original tunnels, and during construction of the fourth bore we hope to add a small piece of the puzzle ourselves.

B. GEOTECHNICAL ENGINEERING PROBLEMS ENCOUNTERED DURING CONSTRUCTION

The majority of the information presented in this section was obtained from Ben Page's 1950 paper, "Geology of the Broadway Tunnel, Berkeley Hills, California;" Dorothy Radbruch's 1964 paper, "Log for Field Trip through Caldecott Tunnel, Berkeley Hills;" and George Louderback's 1932 paper, "Report on Geologic Conditions Along the Line of the Proposed New Low Tunnel Highway Between Alameda and Contra Costa Counties." Figure 4 shows the first and second bores (the former Broadway Tunnel) under construction in the 1930s.

1. No Thorough Geotechnical Investigation Performed for First and Second Bores

The initial problem, and in my opinion the largest problem faced by the construction of the first and second bores, was the fact that the contractor relied upon a preliminary geologic report for design and cost estimating.[3] The contractor felt that a more thorough investigation would involve needless duplication. A direct quote from this preliminary geologic report follows:

> "The rock and rock structures that would be encountered in the proposed tunnel are favorable from the engineering standpoint. The strata mostly dip at high angles and are intersected by the tunnel at a high angle to their trend. Such a condition restricts much water and presents the strong arrangement of the type of strata involved." [4]

Page's report stated the flaws of this reasoning as follows:

> "The expected advantages of meeting the strata more or less at right angles to the strike were not fully realized because of the unsystematic arrangement of irregular dikes and the prevalence of diagonal faults."[5]

In other words, there were so many irregularly shaped dikes (as will be described later) and diagonal faults creating zones of weakness comparable to adverse bedding conditions, and alternative pathways for ground water to travel, that the assumed advantages were not to be.

In addition, the preliminary report stated:

> "Throughout the main belt of cherts, the rocks may be expected to be entirely self-supporting; in the fault belt of cherts and in the Orinda, with proper care, the rocks should stand well and be self-supporting – except possibly along certain shear zones which may require local reinforcement. These statements refer to general support of the mass of rock and not the detachment or falling of fragments or blocks."[6]

The contractor discovered that the ground was anything but self-supporting. Costly measures of support were required for the majority of the tunnel. The contractor was expecting free-standing walls. Instead, the tunnel conditions required that closely spaced timber sets and thick gunite concrete be applied to the timbered walls and arch before the final concrete lining could be placed. Because of

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[3] I believe that this report was the 1932 paper by George Louderback, "Report on Geologic Conditions along the line of the Proposed New Low Tunnel Highway Between Alameda and Contra Costa Counties."

[4] G.D. Louderback, "Report on the Geologic Conditions Along the Line of the Proposed New Low Tunnel Highway Between Alameda and Contra Costa Counties," June 23, 1932.

[5] Page

[6] Page

these costly measures and the fact that the contract was arranged on a firm unit-price basis, the original contractor completed only 70% of the tunnel. Another contractor had to complete the project.[7]

The construction of the first and second bores of the Caldecott tunnel is a classic example of the importance of an accurate and thorough geologic investigation as opposed to crossing your fingers and relying on a preliminary reconnaissance.

2. Site of Tunnel "Topographically Dubious"

The southwest portals of the first and second bores are located in a canyon, and the tunnels underlie the upstream continuation of the canyon for a distance of 1600 feet. This choice of alignment reduced the overall length of the tunnel, but the canyon follows an ill-defined zone of weakness in which the rocks are highly fractured, and soft, altered dikes exist in great numbers.[8] Significantly fewer problems were encountered during the drilling for the third bore.

3. Running-Ground Conditions

"Running ground" is a term commonly used in mining to mean soil or rock that will not stand when wetted and that tends to flow into the mine workings. At Caldecott this condition existed within the "preliminary" belt of chert and shale. This belt proved to be highly shattered and wet, and locally tended to stream into the tunnels. This condition was also found in the Claremont Formation.

The first cave-in was thought to be a result of this condition. On August 28, 1935, after the north tunnel had been full excavated for 1,053 feet and the south tunnel for 1,289 feet, and the timbers in the unlined portions had been locally forced out of position and had to be trimmed or replaced to allow for a full thickness of concrete lining, the first cave-in occurred. It occurred at the contact of the "preliminary chert and shale" with the "second sandstone" (see Figures 1 and 2). This cave-in caused the deaths of three workers and the suspension of work. The cave-in filled the tunnel for a distance of 125 feet. The debris became compacted and had to be drilled and blasted to be removed.

The anticipated advantages of the Claremont Formation, assumed because of conditions at the Kennedy Tunnel (opened in 1903 high above the present Caldecott Tunnel) were nullified by the presence of running-ground conditions at Caldecott.

4. Altered Diabase Dikes

Diabase intrusions are particularly abundant in the chert and shale of the Claremont Formation, some are found in the "second sandstone," and a few are found in the Orinda Formation.

The great majority of the diabase intrusions have been hydrothermally altered to a soft aggregate. These altered dikes were moist when penetrated underground. The clay minerals were plastic. The dikes mainly occurred in minor faults where movement had occurred since the emplacement of the dikes. So in addition to being soft and plastic they have undergone varying amounts of shearing and slickensiding accompanied by intense crushing of the bordering cherts and shales. The resulting instability can hardly be exaggerated.

The second cave-in occurred at an altered diabase intrusion. No one was injured in this cave-in.

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[7] Page
[8] Page

5. **Other Significant Geotechnical Engineering Problems**

Miscellaneous Fractures

In many places the rocks are intensely fractured with or without proximity to definite faults. About 35% of the entire tunnel length exhibited this problem.

Minor Faults

Several minor faults in the tunnel have cut the rock mass into large polygonal blocks separated from one another by gouge or fault breccia. The width of the tunnels was such that the partial weight of some of these blocks had to be borne by the timbers and concrete, whereas many of the individual blocks would have spanned the width of a small tunnel (as was the case with the Kennedy Tunnel).

The majority of the minor faults formed during the folding of the Claremont and Orinda Formations in the late Miocene Epoch.

Major Fault

The Wildcat Canyon fault is exposed in the Claremont formation on Old Tunnel Road approximately 800 feet east of the west portal (see Figure 2). The Wildcat Canyon fault is shown on two maps of this area – Lawson's (1914, San Francisco Folio) and Untermann's (1935, U.C. master's thesis). Untermann showed it at the boundary between the Claremont Shale and an underlying sandstone; Lawson showed it within the Claremont Shale. Radbruch found that most of the formations exposed in the tunnel were highly sheared, and it has not been possible to identify a specific shear zone in the first three bores as the Wildcat Canyon fault.[9]

Irregular Rock Distribution

According to Page, it was difficult to plan the daily tunneling procedure because of the sporadic occurrence of crushed rock, haphazard arrangement of soft, altered diabase dikes, and unpredictable distribution of comparatively hard sandstone dikes. While the headings of one tunnel might expose rock firm enough to justify plans for advancing a vertical face with a drilling jumbo, the headings of the other tunnel at a comparable point might suddenly enter running ground.[10]

Numerous Rock Units

The many clastic and igneous dikes provide a multitude of lithologic contacts, along which differential movement has occurred in many instances. These contact surfaces cross the tunnels at all angles. The instability of the excavation may be partly ascribed to the numerous small rock units separated by discontinuities.[11]

Engineering Effects of Water

No real difficulties with groundwater were experienced during construction. During the tunneling all the rocks except parts of the Orinda Formation were damp and some sections locally yielded a flow of one to 150 gallons per minute. This production dwindled as the hill above the tunnels was gradually drained, but during the wet season the flow was renewed promptly after rainfall. Some units were soft, plastic, and unstable when wet. This is especially true of the mudstone of the Orinda Formation.

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[9] Dorothy H. Radbruch, "Log for Field Trip Through Caldecott Tunnel, Berkeley Hills, California," March 30, 1963, prepared for Association of Engineering Geologists field trip.

[10] Page

[11] Page

Local presence of water also aggravated the weakness of altered diabase dikes. The chert and most of the shale of the Miocene formations are not softened appreciably by water, but where crushed they contain troublesome "pockets" of water. The fragmental material, which would have been difficult to control in any case, was locally swept down into the pilot drifts by pent up water under appreciable hydrostatic head.[12]

The effects of water were not entirely adverse. The Claremont chert and shale actually stand better when slightly damp than when dry. Films of moisture in the cracks serve to preserve some degree of cohesion between adjoining fragments or blocks of rock. Destruction of the films by prolonged exposure to air permits some disintegration of the mass.[13]

Gas and Oil

There was the potential of encountering oil, gas, hydrogen sulfide, or methane. Safety equipment was on hand and routing gas tests were performed after each round of blasting. The construction of the Claremont Tunnel, a water tunnel in nearby Berkeley, California, had an explosion and a persistent fire where the rocks contained oil and gas.

6. Geotechnical Engineering Properties Conclusion

The history of the Caldecott Tunnel emphasizes the need for an accurate geologic examination rather than just a preliminary geologic reconnaissance before construction. In addition, the original contractor's cessation of work at 70 percent completion emphasizes the great risks involved with undertaking a tunnel project at a fixed cost.

C. THE PROPOSED FOURTH BORE OF THE CALDECOTT TUNNEL

The majority of this discussion is from material obtained in the URS Greiner Woodward Clyde Technical Memorandum, "Route 24/Caldecott Tunnel Corridor Transportation Study, Task 4.3 – Corridor Improvement Cost Report, Cost Estimates for Alternative Tunnel Concepts".[14]

A fourth bore has been proposed for the Caldecott Tunnel. The new bore would be located just to the north of the existing bores. In fact, if you look out from the west portal of the third bore you can see an existing pad where Caltrans had planned to build the fourth bore when the third bore was constructed.

The MTC (Metropolitan Transportation Commission), Caltrans, Alameda County Congestion Management Agency, and Contra Costa Transportation Authority hired Wilbur Smith Associates to prepare a Route 24/Caldecott Tunnel Corridor Study.

This study found that a fourth bore would improve the reverse commute considerably, especially in the future when backups on the reverse commute side are predicted to extend beyond the Orinda BART Station.

URS Greiner Woodward Clyde developed tunnel design concepts and cost estimates.

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[12] Page
[13] Page
[14] URS Greiner Woodward Clyde Technical Memorandum, "Route 24/Caldecott Tunnel Corridor Transportation Study, Task 4.3 Corridor Improvement Cost Report, Cost Estimates for Alternative Tunnel Concepts," February 9, 2000.

The basic tunnel alternatives:

1) 2-lane with standard shoulders
2) 2-lane with standard shoulders and bike path
3) 3-lane with standard shoulders
4) 3-lane with standard shoulders and bike path
5) Either 2- or 3-lane with a separate bike path (talk of reopening Kennedy Tunnel for bike path)

Cost Estimates:

$26 million to design
$133 to $353 million to build (depending on width)

Comparison:

1937: $3.7 million for first and second bores
1964: $24 million for third bore

Schedule:

Begin construction in 2007
Finish 2012

1. Anticipated Geologic Conditions that Affect Tunnel Design

The following is a summary of geologic conditions pertinent to design and construction of the proposed fourth bore of the Caldecott Tunnel:

- Conditions similar to those encountered during construction of the three existing bores; interbedded, extremely weak to moderately strong cherts, shales, sandstones, and mudstones that are intersected by hydrothermally altered diabase dikes.
- Closest Active Fault – Hayward fault, which is located ¾ of a mile west of the portals.
- Numerous other faults and shears that intersect the tunnel alignment, the most prominent being the Wildcat Canyon fault. Although considered to be inactive, these faults and shears have weakened the rocks.
- Gassy Conditions – the Claremont Chert and Shale unit contain significant amounts of naturally occurring hydrocarbons or bituminous deposits. Methane, hydrogen sulfide, tar, and heavy oils were encountered in some fractured zones.

It should be noted that, in general, well-constructed tunnels withstand earthquakes better than surface structures because the ground around the tunnel supports the lining and actually attenuates the ground deformations generated by the earthquake.

2. Environmental Mitigation and Considerations

Fortunately, the environmental impacts of a fourth bore will be minimal. The major impacts will be the loss of a wetland at the base of the cut slope at the portal on the Orinda side, and the disposal of the tunnel construction spoils.

3. Construction Methods for Original Tunnel Bores

The first two tunnels, built in the 1930's, were excavated using a multiple drift excavation sequence to install the timber supports before the center portion of the tunnel was excavated. Timber sets and lagging were used as the initial support. The concrete lining operation followed behind the tunnel excavation and support operation by about 1,000 feet. This led to the development of ground loads and deformation of the timber supports in the tunnels, resulting in difficulties in achieving desired tolerances for the final concrete lining. Repairing misaligned timber supports led to at least one of the large tunnel collapses that occurred during construction.

The Caldecott third bore was excavated using two wall plate drifts, and then a top heading and bench sequence. Initial support consisted of W14x99 steel sets on 3-foot centers with wall plates.

The entire length of each of the three existing tunnel bores required a considerable amount of support to stabilize the tunnel excavation prior to construction of the final concrete lining. Heaving ground led to distortion of timber sets and required use of supplementary measures including gunite and extra timbering in the first two bores. Use of a shield to construct the top heading of the third bore greatly improved progress. Some ground required blasting of the face and the use of spiles for pre-reinforcement of the ground ahead of the face.

4. Tunnel Alignment

The required separation distance between the third and fourth bores needed to provide a stable pillar of rock will depend on the width of the fourth bore. A pillar about 110 to 115 feet wide would be adequate for a proposed tunnel 44 feet wide or less (2 lanes with standard shoulders). A wider pillar would be needed for a wider tunnel. Regardless, at the entrance and exit of the fourth bore the pillar will have to be narrower than the required 115 feet width in order to conform to the existing traffic lanes. This will have a destabilizing effect on the third bore. The installation of rock anchors or other rock reinforcement in the third bore will be required to control ground movements.

5. Tunnel Excavation and Support Methods

Two approaches for tunnel excavation have been proposed by URS Greiner Woodward Clyde. Both involve performing the excavation in a series of smaller drifts. A probe hole would be drilled first along the initial drift alignment. This would be used to explore for possible pockets of gas or groundwater.

For a tunnel width of 44 feet or less (2 lanes with standard shoulders) a side drift, top heading and bench excavation sequence would be used. Steel sets and shotcrete would be used for tunnel support. Timber would not be allowed because of the potential for encountering gas.

The stacked drift approach would be proposed for any tunnel wider than 44 feet. This approach involves excavating drifts around the perimeter of the future tunnel opening and filling them with concrete prior to excavating the top heading. Together, the drifts form a permanent arch support for the final tunnel opening. Once the arch is complete, the tunnel can be excavated. It could be possible to use a less expensive method in those parts of the tunnel length where ground conditions are found to be more favorable.

6. Final Lining

The fourth bore is anticipated to be built with a 12-inch-thick reinforced concrete lining, with a waterproof membrane and drainage system, covered with a reflective tile finish.

7. Portals and Approaches

The portal structures for the fourth bore can be much smaller than the existing portal structures because the use of jet fans within the tunnels would eliminate the need for a building to house the ventilation fans. Retaining walls will probably be required on the East approach because of the steep terrain. The size of the walls will depend on the tunnel width chosen.

REFERENCES CITED

S.A. Graham, C. McCloy, M. Hitzman, R. Ward, and R. Turner, “Basin Evolution During Change from Convergent to Transform Continental Margin in Central California,” The American Association of Petroleum Geologists Bulletin, v. 68, no. 3, March 1984, p.233-249.

Gramer, R.W., Jones, D.L., and Brabb, E.E., “Geologic map of the Hayward fault zone:” U.S. Geological Survey Open-File Report 95-597, 1995.

G.D. Louderback, “Report on the Geologic Conditions Along the Line of the Proposed New Low Tunnel Highway Between Alameda and Contra Costa Counties,” June 23, 1932.

B. M. Page, “Geology of the Broadway Tunnel, Berkeley Hills, California,” Bulletin of Economic Geology, Volume 45, Number 2, March-April 1950.

Dorothy H. Radbruch, “Log for Field Trip Through Caldecott Tunnel, Berkeley Hills, California,” prepared for Association of Engineering Geologists field trip, March 30, 1963.

URS Greiner Woodward Clyde Technical Memorandum, “Route 24/Caldecott Tunnel Corridor Transportation Study, Task 4.3 Corridor Improvement Cost Report, Cost Estimates for Alternative Tunnel Concepts,” February 9, 2000.

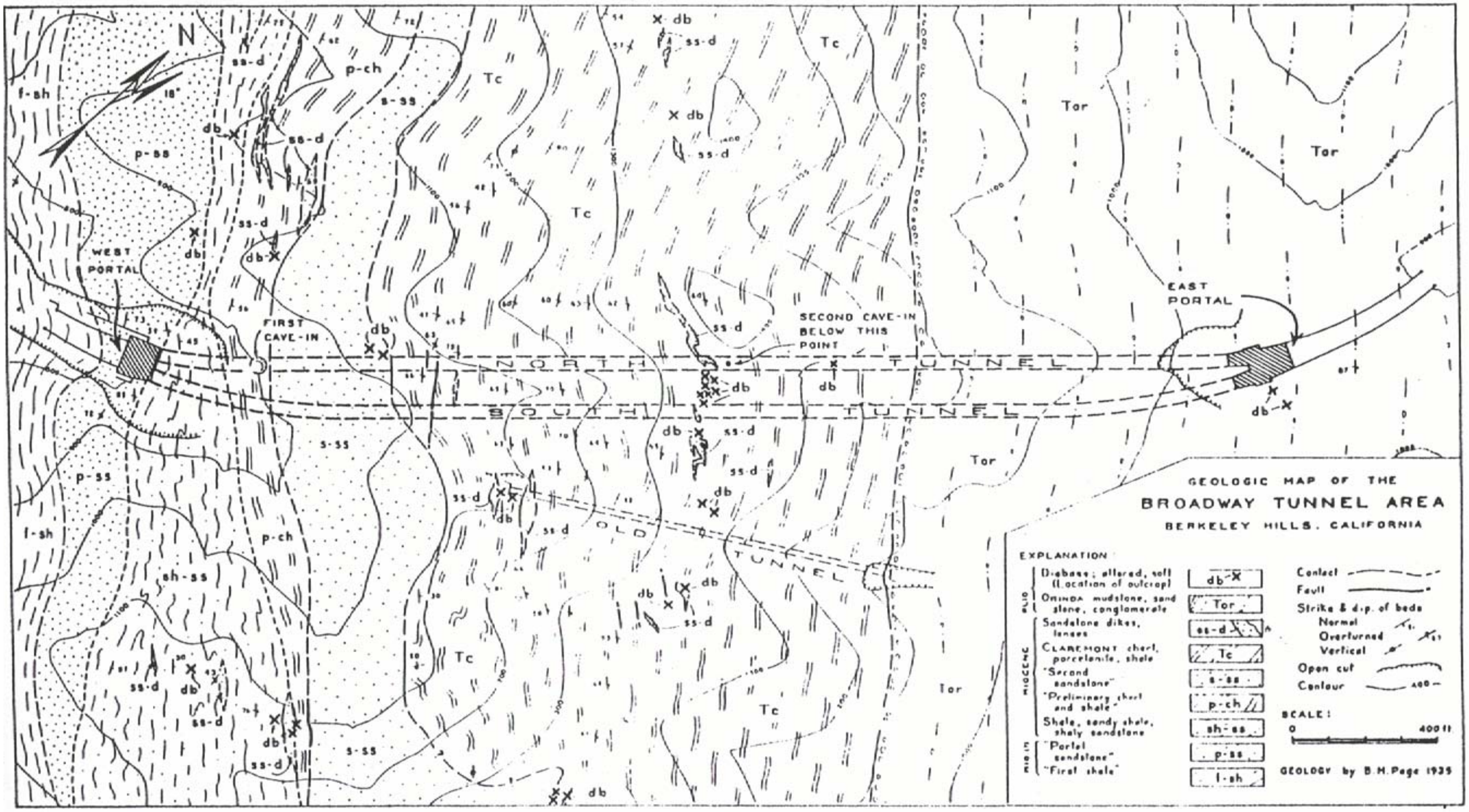
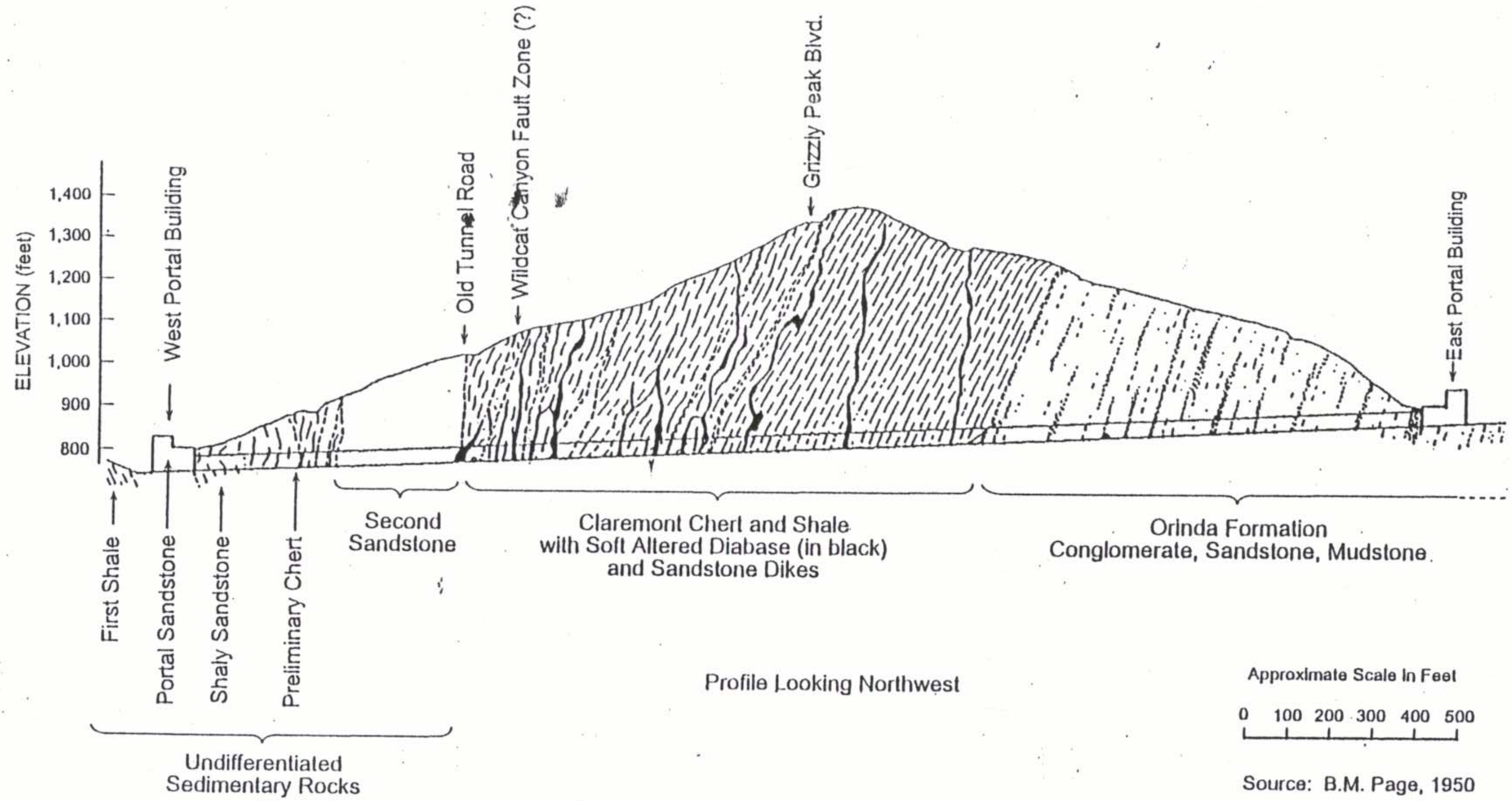
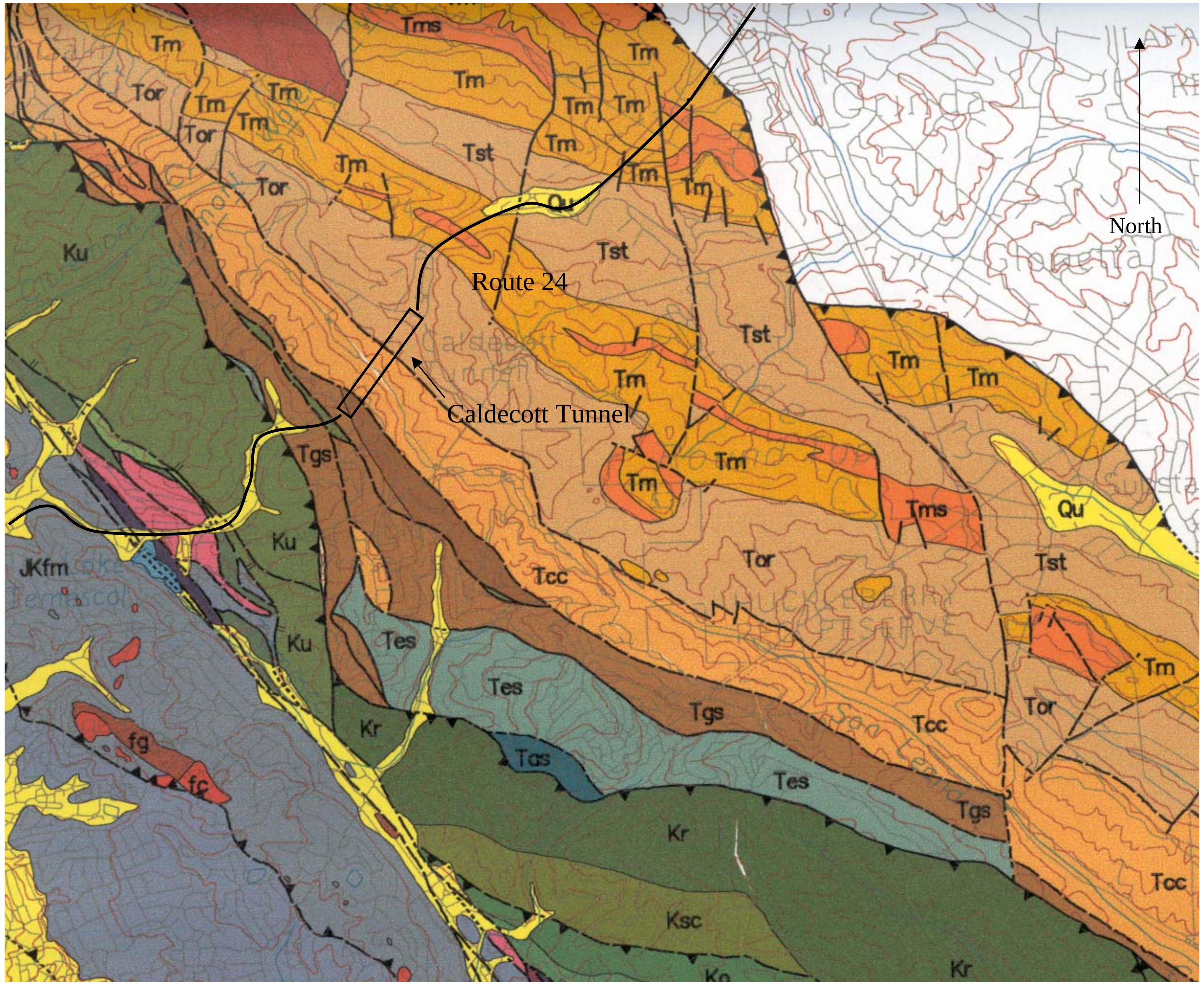


Figure 1. Geologic map showing the first and second bores of the Caldecott Tunnel, formerly known as the Broadway Tunnel, which opened in 1937. The "Old Tunnel" south of the two long bores is the Kennedy Tunnel, which opened in 1903. (From Page, 1950.)



Source: B.M. Page, 1950

Figure 2. Geologic cross section along the alignment of the first two bores of the Caldecott Tunnel (Page, 1950; reproduced by URS Greiner Woodward Clyde, 2000).



Scale 1:36000

Source: Graymer, R.W., Jones, D.L., and Brabb, E.E., 1995, Geologic map of the Hayward fault zone, USGS Open File Report 95-597

Map Legend

Surficial Deposits
Qm – Manmade deposits
Qls – Landslide deposits
Qu – Undivided Quaternary deposits
Qoa – Older alluvial deposits
Pliocene and Pleistocene gravels
QTi – Irvington gravels
QTl – Livermore gravels
QTp – Packwood gravels
QTs – Undivided gravels
Tsk – Silver Creek gravels
Tertiary strata
Tss – Unnamed sandstone and conglomerate
Tv – Unnamed volcanic rocks
Tn – Neroly Sandstone
Tbp – Bald Peak basalt
Tst – Siesta Formation
Tm – Moraga basalt
Tms – Moraga interflow sedimentary rocks
Tor – Orinda Formation
Torv – Orinda interbedded dacite
Tbr – Briones Formation
Tt – Tice Shale
To – Oursan Sandstone
Tcc – Claremont chert and siliceous shale
Tccs – Claremont interbedded sandstone
Ts – Sobrante Sandstone
Tte – Temblor Sandstone
Tsh – Unnamed early Miocene sandstone and shale

Tgs – Unnamed glauconite bearing mudstone (Oligocene(?) and Miocene)
Tgss – Unnamed sandstone (Oligocene(?) and Miocene)
Ttls – Tolman Formation, limestone member
Tts – Tolman Formation, glauconitic sandstone member
Tes – Unnamed mudstone (Eocene)
Tps – Unnamed siltstone and sandstone (Paleocene)
Tas – Unnamed glauconitic sandstone (Paleocene)
Great Valley Sequence
Kp – Pinehurst Shale
Kr – Redwood Creek Formation
Ksc – Shephard Canyon Formation
Kcv – Unnamed sandstone and shale of Castro Valley area
Kslt – Unnamed siltstone
Ko – Oakland Sandstone
Kjm – Joaquin Miller Formation
Ku – Undivided sandstone and siltstone
Kc – Undivided conglomerate
Ksh – Undivided shale
Knc – Sandstone and shale of Niles Canyon area
JKk – Knoxville Formation
JKkc – Knoxville conglomerate beds
JKkv – Knoxville volcanogenic conglomerate beds
Arc Volcanics
Jsv – Keratophyre
Coast Range Ophiolite
Jpb – Pillow basalt and basalt
Jgb – Gabbro and diabase

sp – Serpentinite
sc – Silica carbonate rock
Franciscan Complex
JKfn – Sandstone of Novato Quarry
JKfgm – Quartz diorite
JKfm – Melange
fc – chert block
fg – greenstone block
fs – meta-graywacke
JKf – Undivided Franciscan complex
Contact
Contact, approximately located
Contact, inferred
Fault
Fault, approximately located
Fault, inferred
Fault, uncertain
Fault, concealed
Fault, concealed and uncertain
Thrust or reverse fault
Thrust or reverse fault, approximately located
Thrust or reverse fault, inferred
Thrust or reverse fault, concealed

Figure 3.

Geology Map of the Caldecott Tunnel

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Figure 4. Photograph of the Caldecott Tunnel under construction in the 1930s (photo provided by Caltrans).