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Geology of a subduction complex in the Franciscan assemblage of Northern California

Subduction
Yolla Bolly terrane
Franciscan assemblage
Northern California

Subduction
Unité du Yolla Bolly
Série franciscaine
Californie du Nord

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ABSTRACT

The Yolla Bolly terrane of the Franciscan assemblage in Northern California is a typical subduction complex, having undergone penetrative deformation and metamorphism to the high-pressure - low temperature blueschist facies. Detailed mapping combined with sedimentological analysis has enabled us to 1) reconstruct a probable paleosedimentary environment ; 2) analyze the interaction during and after subduction between deformation and metamorphism ; and 3) speculate on subsequent deformational history including tectonic accretion to North America.

Rocks of the Yolla Bolly terrane consist of three thrust-bound lithologic units : a lower unit of disrupted mudstone and thin-bedded sandstone (broken formation) containing scarce volcanic and radiolarian chert horizons, a middle unit predominantly of thick-bedded to massive sandstone (metagraywacke) that includes several horizons of radiolarian chert, and an upper unit of mudstone and thin-bedded sandstone (broken formation) with numerous intrusive and extrusive volcanic rocks plus rare radiolarian chert. Radiolarians from all three units are of the same age (Tithonian to Valanginian) and together with the sedimentological data, suggest that the rocks represent a continent-derived submarine fan, deposited in a complex transform graben possibly similar to the present-day Gulf of California or basins of the California continental borderland.

Metagraywacke containing lawsonite and aragonite yield radiometric ages of approximately 110 m.y. and indicate that these rocks were subducted to depths of 20-30 km about 30 or 40 m.y. after there were deposited. Closely following subduction, the rocks were probably involved in a collision event that imbricated and tectonically returned the subduction complex to the surface.

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RÉSUMÉ

Géologie d'un complexe de subduction dans la série franciscaine du nord de la Californie

L'unité tectonique de Yolla Bolly de la série franciscaine du nord de la Californie représente typiquement un complexe de subduction ayant subi à la fois des déformations internes et un métamorphisme haute pression-basse température de type faciès blueschist. La cartographie détaillée, combinée avec l'analyse sédimentologique, nous a permis 1) de reconstruire l'environnement paléosédimentaire probable ; 2) d'analyser pendant et après la subduction les interrelations entre la tectonique et le métamorphisme ; 3) de formuler des hypothèses sur l'histoire des déformations qui ont suivi, en y incluant les phénomènes d'accrétion tectonique au continent nord-américain.

La formation de Yolla Bolly est constituée de trois unités lithologiques limitées par des chevauchements : une unité inférieure composée de vase lithifiée et de grès finement lités, l'ensemble étant très disloqué (broken formation) et contenant de rares horizons à chert d'origine volcanique ou à radiolaires ; une unité moyenne essentiellement constituée de grès en bancs épais ou même massifs (metagraywacke), dans lesquels on trouve plusieurs horizons de chert à radiolaires ; une unité supérieure de vase lithifiée et de grès finement lités (broken

formation) avec de nombreuses poussées volcaniques extrusives et intrusives et des cherts à radiolaires.
Les radiolaires des trois unités sont du même âge Titonique à Valanginien. Cela suggère, si l'on prend en compte les données sédimentologiques, qu'il s'agit de dépôts provenant d'un éventail sous-marin profond à matériaux d'origine continentale. L'ensemble aurait été déposé dans un graben complexe de type transformant, peut-être similaire au Golfe de Californie ou aux bassins du « continental borderland » de Californie.
Les metagraywackes contenant de la lawsonite et de l'aragonite donnent des âges radiométriques voisins de 110 millions d'années, et indiquent que ces roches ont été subductées à des profondeurs de 20 à 30 km, environ 30 à 40 millions d'années après leur dépôt. Peu de temps après la subduction, a dû se produire un phénomène de collision qui a imbriqué les uns dans les autres les éléments du complexe de subduction et les a tectoniquement ramenés à la surface.

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INTRODUCTION

The Franciscan rocks in Northern California form three major northwest-trending belts. The coastal belt consists almost entirely of sheared sandstone, mudstone, and conglomerate (broken formation) generally interpreted as the youngest (late Cretaceous to Miocene) part of the Franciscan accretionary prism (Bachman, 1978 ; Beutner *et al.*, 1980).

The central belt consists largely of tectonic melange and broken formation and includes most of the high-grade blueschist, eclogite, and exotic limestone knockers in Northern California. Paleomagnetic data suggest that at least some of the terranes within the central belt formed in southern latitudes and were subsequently accreted to North America by large-scale transcurrent plate motions (Alvarez *et al.*, 1980).

The eastern belt consists largely of clastic sedimentary rocks locally containing interbedded volcanic rocks and radiolarian chert. All of these rocks have a faint to pronounced metamorphic fabric and contain high-pressure minerals such as lawsonite, aragonite, and glaucophane. The eastern belt contains at least two distinctive tectonostratigraphic units, the South Fork mountain schist, and the Yolla Bolly terrane. The South Fork mountain schist was originally defined on the basis of metamorphic grade (Blake *et al.*, 1967) but subsequent work (Bishop, 1977 ; Worrall, 1979 ; Blake *et al.*, in prep.) indicates that the primary lithology is significantly different from adjacent fossiliferous Franciscan rocks.

The purpose of this paper is to briefly describe the lithology, age, metamorphism, and structure of the Yolla Bolly rocks and to relate these characteristics to plate tectonic models.

YOLLA BOLLY TERRANE

Lithology and sedimentology

The Yolla Bolly terrane (Fig. 1) consists of three lithologic units separated by thrust faults. The lower unit consists largely of disrupted mudstone and thin-bedded quartzofeldspathic sandstone (broken formation) but also contains coherent lenses of medium- to thick-bedded sandstone and conglomerate, plus minor volcanic rocks and radiolarian chert. The structural thickness is on the order of 1,000 m.

The middle unit is made up predominantly of thick-bedded to massive quartzofeldspathic sandstone that includes several thick horizons, of thin-bedded radiolarian chert. Igneous rocks are rare and consist of small diabase-gabbro sills, largely intrusive into the chert-rich portions of the unit. The thickness of the unit, as deduced from the structure sections is 1,000-2,000 m.

The upper unit is composed predominately of mudstone and thin-bedded quartzofeldspathic sandstone but includes very abundant intrusive and extrusive bodies of basalt and quartz keratophyre. Lenses of radiolarian chert are less common than in the other units. The structural thickness is about 1,000 m.

Smooth, water-worn exposures display an abundance of primary sedimentary structures in all three units. The observed structures are common constituents of flysch, and in particular, turbidites and associated mass-flow deposits. Many beds can be related to the Bouma sequence, and small scale crossbedding (ripple-drifted siltstone) are ubiquitous. Sandstones commonly have normal grading and some pebbly beds are inversely graded. The principal clast in the coarser-grained beds are intra-basinal mud rip-up fragments, though extrabasinal felsic volcanics and granitics are included. Flame structures, dewatering pillars and slurry bedding are seen within most sandstone beds, but surprisingly, dish structures have not been observed ; load structures, flutes and grooves are displayed on the basal surfaces of some beds.

The classification of lithofacies for redeposited, mass flow sediments by Mutti and Lucchi (1972), and Lucchi (1975), is a convenient means of describing the sedimentary rocks of the Yolla Bolly terrane. Examples of all seven lithofacies (A to G)* can be found in this terrane though abundance of each is highly variable.

* Facies A : conglomerate, pebbly sandstone and coarse sandstone, thick to massive bedding, lenticular beds with cut and fill structures, nongraded and graded, Bouma Ta or Tae sequences ; facies B : pebbly sandstone, coarse- to medium-grained sandstone, beds 0.4 to 2.0 m thick, beds often amalgamated, pelitic partings often present, broad erosional concave lower surface, diffuse lamination, sole marks, generally nongraded, facies C : fine- to coarse-grained sandstone, beds 0.2 to 1.5 m thick mudstone or siltstone interbeds, generally even and parallel bedding surfaces, sole marks, Bouma Tabcde to Tae sequences, graded ; facies D : thinner and finer grained than facies C, sequences, beds laterally persistent. These strata in the past have been called "distal" turbidites ; facies E : very fine- to coarse-grained sandstone, mudstone interbeds, beds 3 to 20 cm thick, lenticular bedding, parallel bases and wavy tops of beds 3 to 20 cm thick, lenticular bedding, parallel bases and wavy tops of beds, generally nongraded, Bouma Tce or Tde ; facies F : chaotic slump deposits, pebbly mudstone, all retransported deposits ; facies G : hemipelagic pelite, massive bedding.

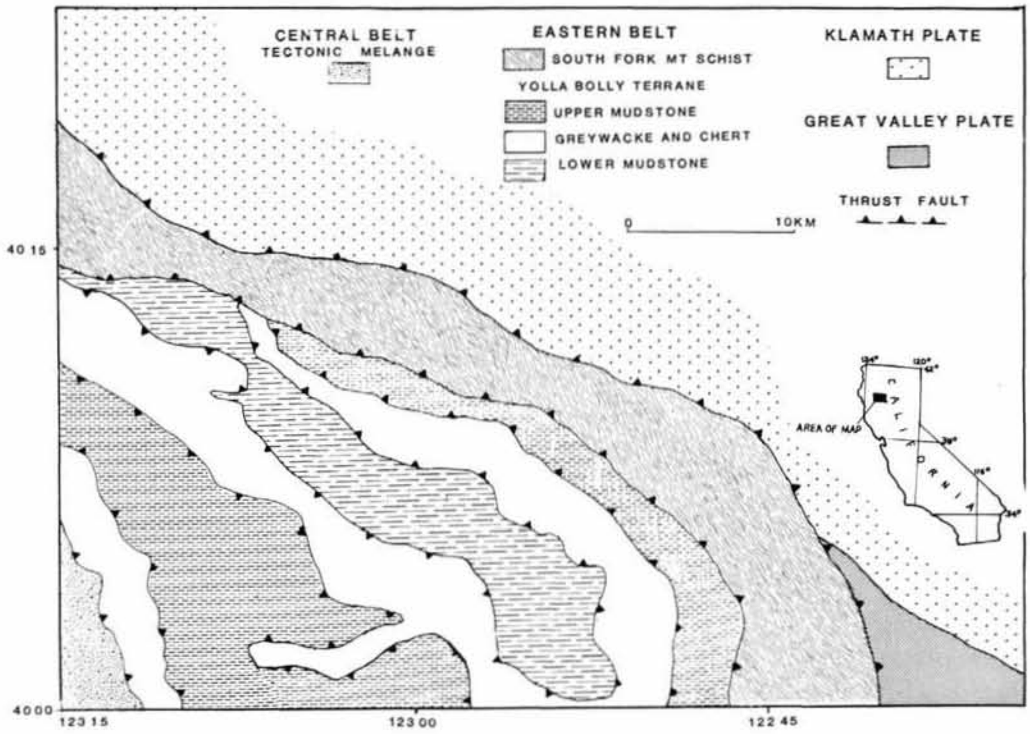
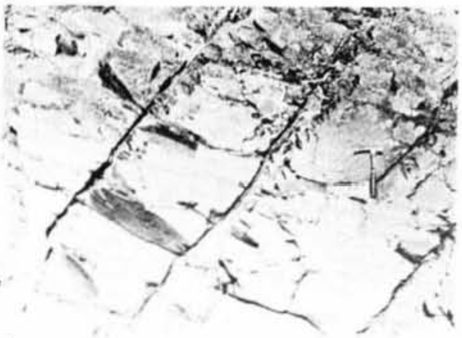


Figure 1

Generalized geologic map of the Yolla Bolly area, Northern California. Geology from Worrall (1979) and unpublished mapping by M. C. Blake Jr., A. S. Jayko, R. Neumann, and B. Wilson.

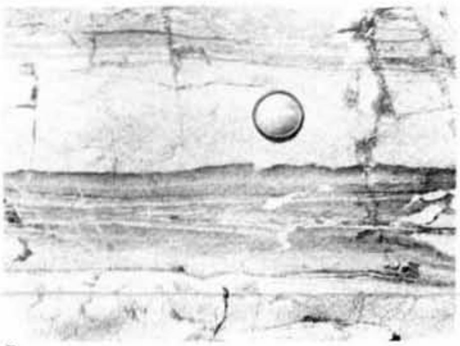
The lowest stratigraphic unit is characterized by ripple drifted siltstone (facies E) in association with thin-bedded turbidites (facies D) and minor amount of massive mudstone (facies G). In the lower part of this unit is a 100 to 200 m thick interval of sandstone (facies B and C) with interbeds of conglomerate (facies A), thinner bedded turbidites (facies D and E) as well as pebbly mudstone and slump folded strata (facies F). Within this sandstone interval there are at least four thinning- and fining-upward megasequences, each 30 to 50 m thick. Examples of these facies are shown in Figure 2.

The above association of lithofacies specifies an environment of principally tranquil, dilute turbidite deposition (overbank ?) with episodes of much higher energy turbidite



A

C



B

Figure 2

Examples of coherent strata from the Yolla Bolly terrane, textural zone 1 : A, lithofacies B, composite (amalgamated) beds of thick bedded sandstone ; B, lithofacies D and E thin bedded turbidites ; C, lithofacies ; E, ripple drifted sandstone (Bouma tde and tce turbidites).

deposition (feeder channels). The conglomerate in basal parts of the inferred channelized sequences is coarser grained than any other conglomerate in the Yolla Bolly terrane. The preponderance of mudstone cut by channels filled with coarse material suggests either an inner fan or slope with feeder channels as a depositional setting. It is probable that the lower unit is the most proximal of the three stratigraphic sequences to be discussed.

The middle unit is principally massive bundles of composited (amalgamated) thick-bedded turbidites, fluxoturbidites or grain-flow deposits (facies B and C), with thin intervals of thin-bedded turbidites (facies D or E). No vertical asymetric cycles of bedding thicknesses are evident. Because of the abundance of sandstone and the absence of intervals of bedding with pronounced ductility contrasts, this is the most coherent of the three lithologic sequences. Because of this coherency we have been able to map lenses of ribbon chert for up to 20 km along strike. Most chert units are 20 to 50 m thick and a common sequence involves sandstone passing upward into siliceous shale (1 to 5 m thick) which grades into pure chert. Sandstone usually overlies the chert, often with a thin (50 cm) basal breccia of chert and mudstone.

Within the context of a submarine fan model, the above lithofacies association indicates a middle or supra-fan setting, though the occurrences of interbedded chert is enigmatic. Chert occurs in all three of the stratigraphic units but stands out in the middle unit because of its structural competency. The accumulations of chert must represent periods of diminished to nonexistent clastic deposition. It is possible that the chert beds correspond to areas between places of active deposition in a supra-fan setting, analogous to mud blankets between depositional lobes ; or alternatively, chert deposition may have occurred more uniformly over the entire fan during intervals of high stands of sea level, an event that traps detrital material in inner shelf, estuarine or bay settings.

The highest lithologic unit is principally ripple-drifted siltstone (facies E) and thin-bedded turbidites (facies D and E). Near the top of this unit are several thinning upward cycles of graywacke (facies B and D giving way to D and E), which provide evidence of some channelized turbidite deposition. The channel fill is finer grained than the analogous detritus in the lowest stratigraphic unit. However, the principal feature that distinguishes this unit from the lower unit is the abundance of greenstone bodies in the upper unit. Many of the greenstone blocks are essentially knockers in a sheared matrix of facies E siltstone ; however, numerous intrusive contacts suggest a volcanic episode possibly related to the depositional environment of this upper unit. The lithofacies associations do not rigidly constrain the depositional environment of this unit ; a middle to outer fan fringe setting is possible as is a slope setting. In either case, the intrusive volcanic rocks are puzzling.

To summarize, the sedimentologic data offer some constraints for the depositional environment of strata in the Yolla Bolly terrane. All the clastic strata involve mass-flow processes. Deposition probably occurred in a deep-marine setting. Lithofacies associations suggest submarine fan styles of depositions though there are not enough data to specify fan geometries or basin configurations. A reasonable depositional environment for the Yolla Bolly strata would be restricted submarine fans within a region of crustal extension. The nature of the lithofacies associations can be imagined as basin trough (middle unit) and basin margin facies (lower and upper units). The intrusion of volcanics is also consistent with such a regime (Crowell, 1976 ; Lonsdale, Lawver, 1980). The cherts are more problematical, but they do not pose a limiting constraint.

Age

Radiolaria from all three subunits are similar, if not identical, and suggest a late Jurassic (Tithonian) age (B. Murchey, writt. comm., 1980). Megafossils were found only in the lowest structural unit and include *Buchia okensis* (upper Tithonian) and *Buchia pacifica* (Valanginian) (Blake, 1965). Rb—Sr, and $^{40}Ar/^{39}Ar$ measurements on metagraywacke from the Yolla Bolly Terrane give metamorphic ages of about 110 m.y. (Lanphere *et al.*, 1978).

Structure

At least three periods of folding have been recognized. The earliest is characterized by west- northwest-trending isoclinal folds (F_1) and associated axial-plane cleavage (S_1). Within the coherent sandstone, this cleavage defines a textural zonation that ranges from non-foliated graywacke (textural zone 1) through foliated semischist (textural zone 2) to foliated schist with well-developed quartz segregation (textural zone 3) (Blake and others, 1967). Brittle breakage of sandstone beds in the broken formations along the limbs of folds parallel to the tectonic foliation (S_1) is manifested by sheared phacoids or boudins, and small scale tectonic structures are folded around the F_2 hinges, but seemingly not around F_1 hinges. From these observations we infer that the deformational fabric seen in the broken formation (Fig. 3), and the textural zonation in metagraywacke, formed simultaneously during F_1.

A second set of folds (F_2) trend north-northeast and have a moderately well-developed axial plane schistosity (S_2). These folds are strongly asymmetric with vergence to the east-southeast.

The third set (F_3) are open, northwest-trending, and locally overturned with vergence from northeast to southwest. They are not accompanied by axial plane cleavage or schistosity.

The thrust faults shown on the geologic map (Fig. 1) are based on juxtaposition of textural grade and lithologic facies. They appear to have been folded by F_2 and clearly predate F_3.

Metamorphism

In addition to the previously described textural zonation all of the rocks contain high-pressure minerals indicative of the blueschist facies. Within metagraywacke, lawsonite, phengite, and chlorite have grown parallel to S_1, particularly in the higher textural grades. The greenstones contain, in addition, glaucophane and pumpellyite. Limited oxygen isotope data (Taylor, Coleman, 1968) suggest that these rocks formed at temperatures of about 100-300 °C. The widespread presence of aragonite indicates that pressures were on the order of 4-6 kilobars, corresponding to a depth of 15-20 km.

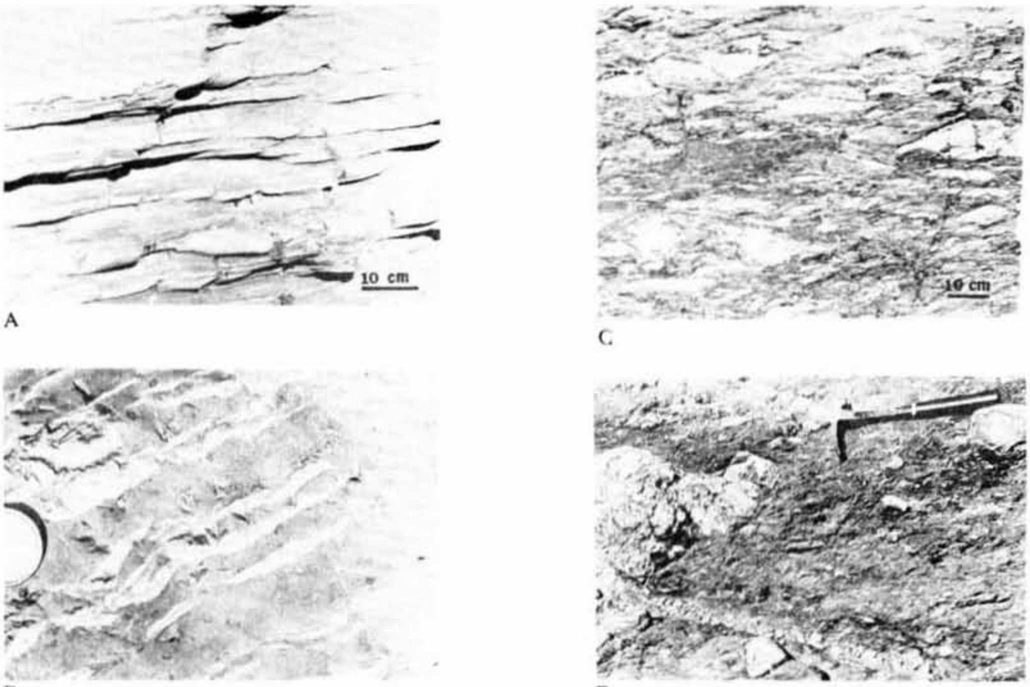


Figure 3

Examples in the stages of development of broken formation or melange : A, slightly stretched thin bedded turbidites ; B, thin bedded turbidites stretched and broken by normal faults ; C, boudins and phacoids of sandstones in a mud (Te part of a turbidite) matrix, bedding still discernible ; D, totally disrupted bedding, blocks of sandstone in a homogenized mud matrix.

CONCLUSIONS

Keeping in mind the many uncertainties, we suggest the following plate tectonic history. During latest Jurassic to earliest Cretaceous time (140 m.y. b.p.), the clastic sediments were deposited in a restricted basin that was also the site of deposition of radiolarian chert. Sandstone petrography and the abundance of submarine bimodal volcanic rocks suggests a continental margin undergoing rifting, perhaps an environment similar to the present-day Gulf of California.

Some thirty or forty million years later, all of these rocks were involved in a subduction event that resulted in the formation of metagraywacke and broken formation, together with high-pressure metamorphic minerals such as lawsonite, aragonite, and glaucophane. This was apparently closely followed by obduction of the subducted complex back to the surface in order to preserve the high-pressure-low temperature metamorphic mineral assemblage.

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